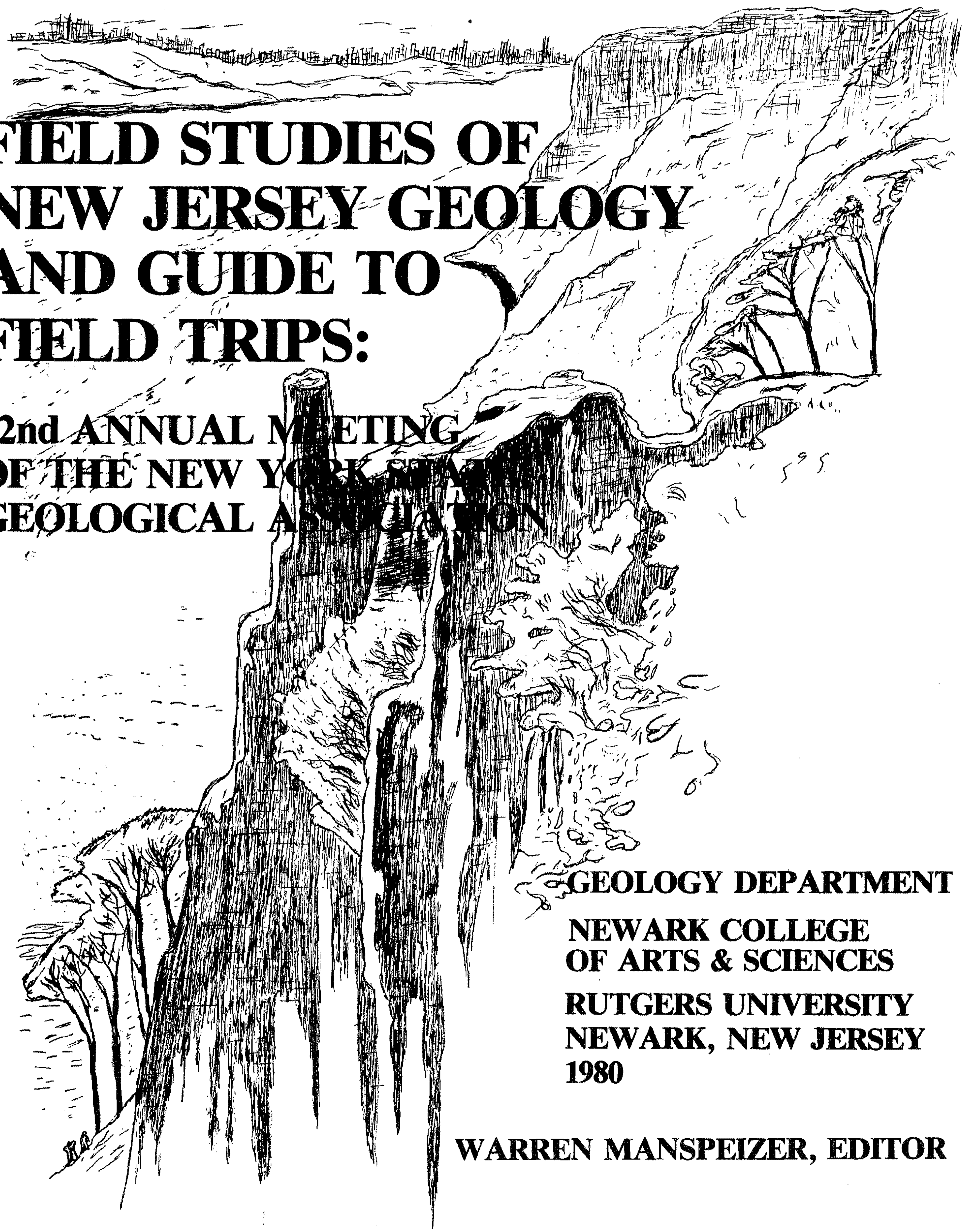
FIELD STUDIES OF NEW JERSEY GEOLOGY AND GUIDE TO FIELD TRIPS:

52nd ANNUAL MEETING OF THE NEW YORK STATE GEOLOGICAL ASSOCIATION



GEOLOGY DEPARTMENT
NEWARK COLLEGE
OF ARTS & SCIENCES
RUTGERS UNIVERSITY
NEWARK, NEW JERSEY

1980

WARREN MANSPEIZER, EDITOR

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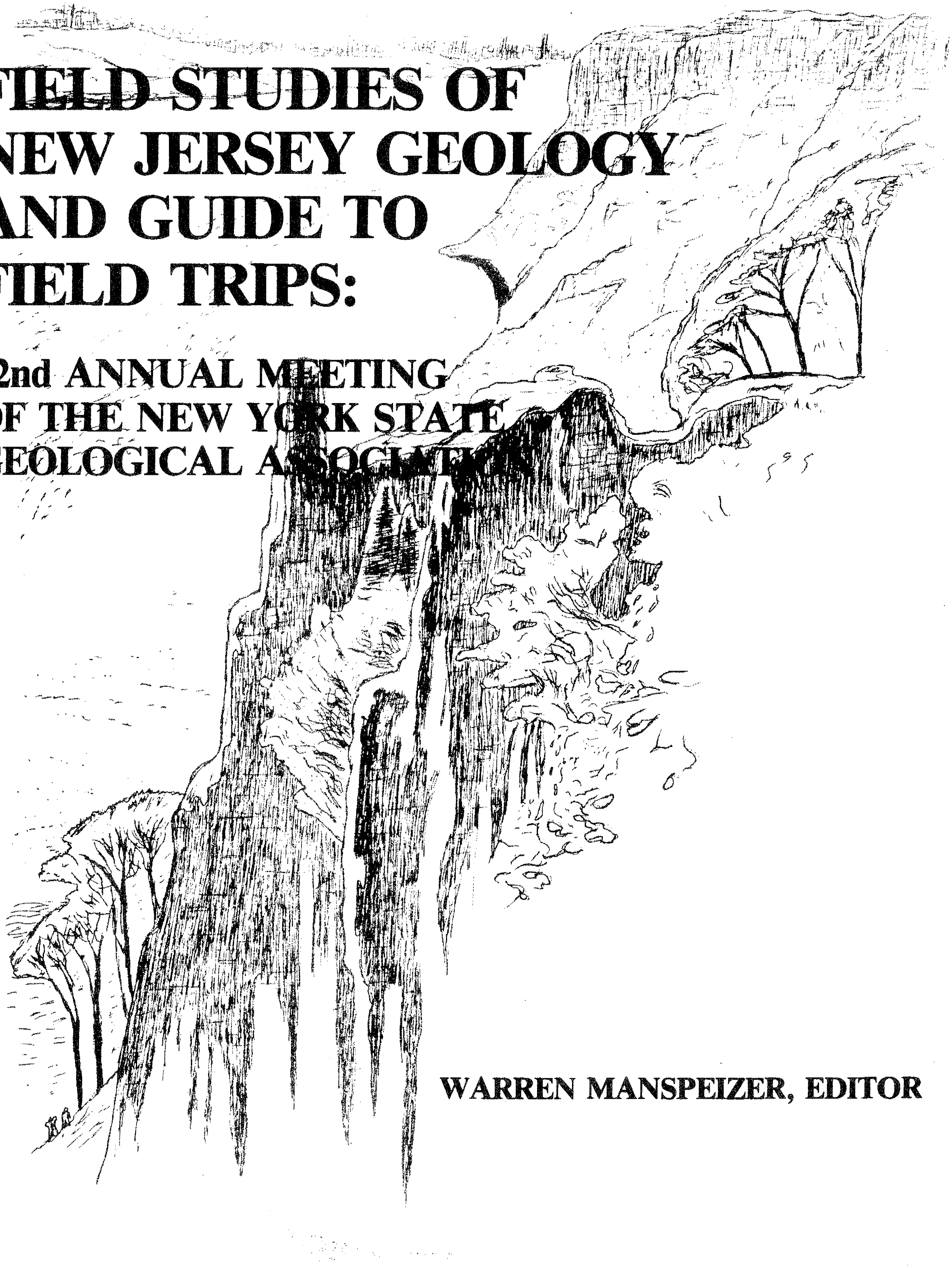


WARREN MANSPEIZER, EDITOR

TABLE OF CONTENTS

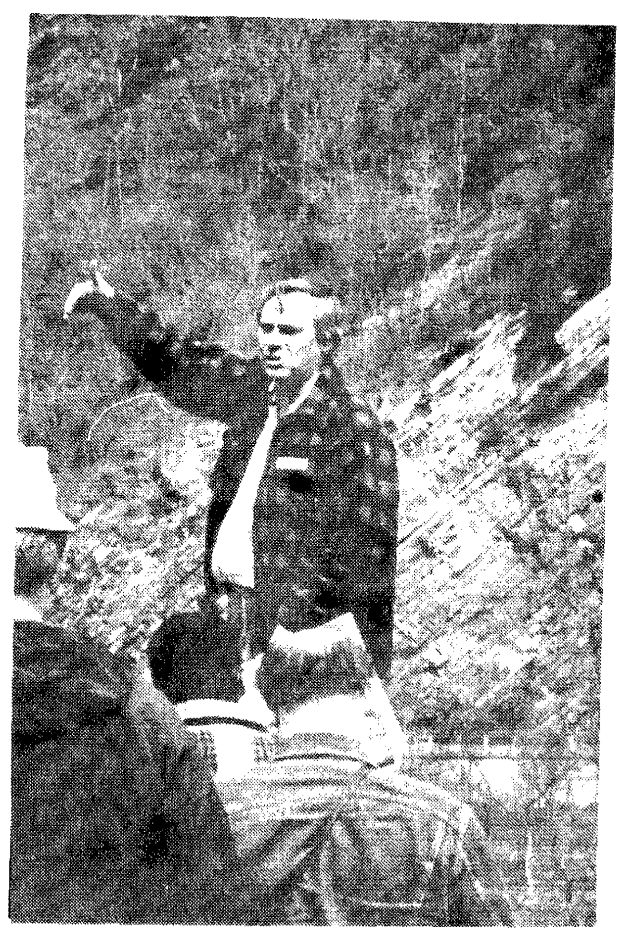
ECONOMIC GEOLOGY

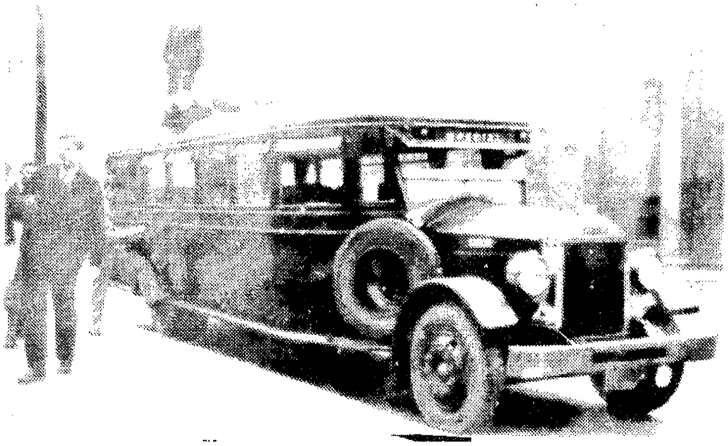
ENVIRONMENTAL GEOLOGY

RIFT BASIN

In memory of
H.P. WOODWARD
(1899-1968)
First professor of the Geology Department, first Dean of the college, and outstanding student of Appalachian Geology.

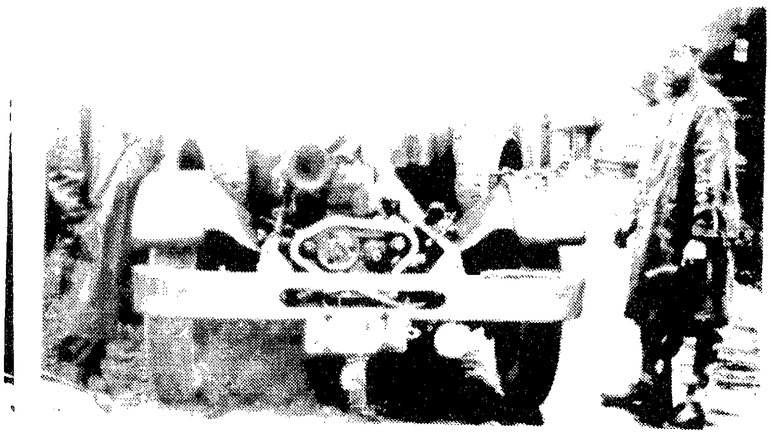
In memory of
WILLIAM W. WILES
(1927-1975)
An extraordinarily gifted and inspiring teacher, loyal colleague and trusted friend.





The bus; loading up

looking for fossils near Bushkill, Pa.



trouble

at Port Jervis

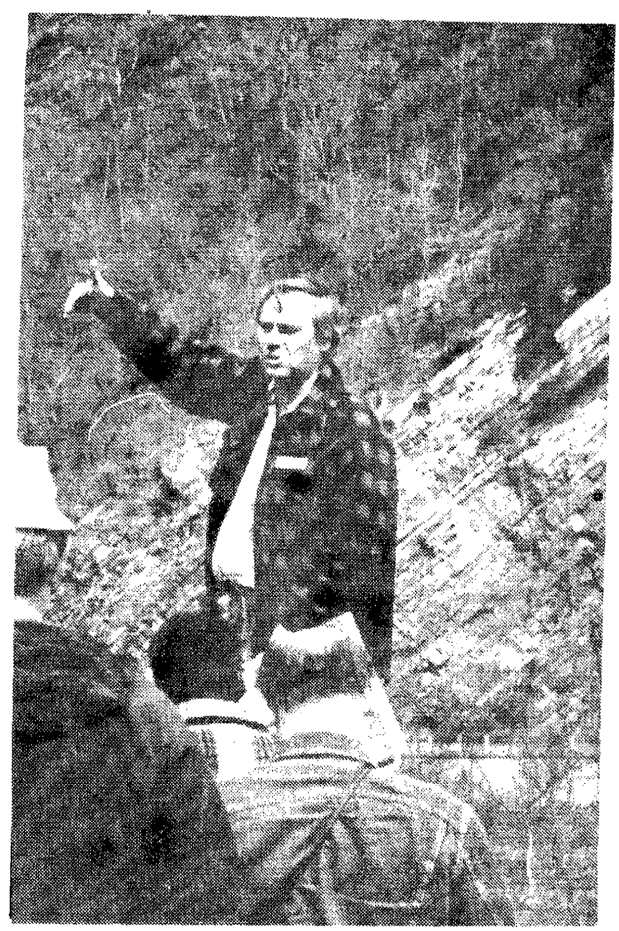
one of the stops

fossil hunting in the
Cobleskill Limestone

GEOLOGY FIELD TRIP
THE LEGAL DEPARTMENT
NEW JERSEY LAW SCHOOL

Newark–Port Jervis–Kingston
April 20-22, 1929

(captions by H.P. Woodward, 1929)



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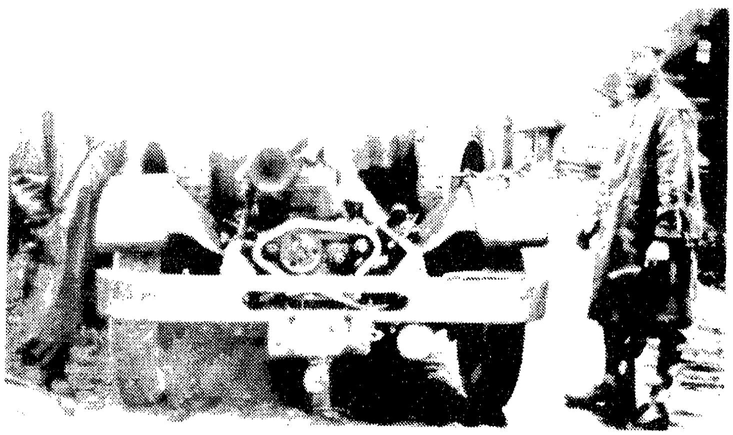

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PREFACE

Writing in 1918 shortly after the United States entered the war in Europe and the resultant need to restrict travel for field study was manifest, Professor A. K. Lobeck of Columbia University drew attention to the location of New York City as a superb center for geologic study[1]*. How fortunate, he wrote, the we have at hand a museum of landforms that invites us to take our students to see at first hand, to broaden our conceptions, to attain the confidence in teaching which comes in its broader views, and to be inspired by bringing us face to face with the fascinating problems of the earth. There are cities, he continued, situated in the plains with miles and miles of undiversified country, within one physiographic province, and miles from a seaboard. Students in those cities cannot readily experience coastal shoreline processes, the work of waves, and the formation of spits and bars. Then he asked his readers to consider students in some of our great southern cities who are denied ready access to the terminal moraine, eskers and glacial lakes. The sense of Lobeck's paper was later to be displayed in graphic form in the now classical "Physiographic diagram of the New York City Region" by E. J. Raisz*[2] *(Fig. 1).*

Ten years after Professor Lobeck's article was published, H.P. Woodward, then a young graduate student at Columbia University from Batavia, New York was appointed to the faculty of the pre-legal department of the New Jersey Law School in Newark. There, he offered the first science course in the curriculum, a course in geology. In 1930, the pre-legal department had grown to a four-year liberal arts institution, Dana College, with a faculty of fifteen serving a student body struggling with the great depression and in 1936, Dana College was subsumed into the Newark College of Arts & Sciences within the then new University of Newark; in its time, the University of Newark was absorbed by Rutgers University in 1946.

H.P. Woodward was to become a leading authority on Appalachian Geology[3]*. He gained further recognition as an educator, as founder of the Geology Department at Dana College and as first academic Dean of the Newark College of Arts and Sciences of Rutgers University in 1946. Today, as the college celebrates its 50th Anniversary as a four-year institution, it is pleased to sponsor the 52nd Annual Meeting of the New York State Geological Association and to recall that in 1928, 52 years ago, it also sponsored its first geology field trip (see photographs facing this article).*

While the geology of the New York region remains much the same as in Professors Lobeck's and Woodward's day, the need to conserve energy is now critical to our national *economy, the challenges of the day are much more complex, and the focus of our inquiry differs. We still take our students on field trips to study coastal plain sedimentation, Pleistocene glaciation, Appalachian folding and Devonian brachiopod communities. And we still raise questions about correlation, granitization and evolutionary trends in strophomenid brachiopods. But now we also take them to sanitary land fills and flood-prone communities, and we study the rocks as possible sites for toxic waste disposal, sources of alternative energy, and as potential carcenogenic agents.*

Field trips prepared for this guidebook reflect both the spirit of Professor Lobeck's remarks and the excitement of doing field work in metropolitan New Jersey-New York. Our field trip program for these meetings is extensive, ranging throughout the geologic column and addressing such diverse subjects as: plate tectonics, environmental geology, Alleghenian thrusting, Pleistocene glaciation, zinc, iron and uranium mining, the Baltimore Canyon Trough, vulcanism, coastal processes, seismicity, Appalachian folding, carbonate deposition, the Pine Barrens, etc.

During the past 15 years the unifying theory of plate tectonics has captured our imagination. When applied to old problems, the new concepts stimulate new insight and present new challenges. It is in this spirit, in order to facilitate the exchange of ideas and data between geologists studying onshore basins and those studing offshore basins, that we have convened the symposium on marginal rift basins. A special welcome and acknowledgement is extended to the participants of the symposium.

Publication of this book required considerable effort by many, and therefore, it is a pleasure to acknowledge the assistance extended to me in preparing this publication, and to give thanks to:

My colleagues in the Geology Department for their enthusiastic and helpful cooperation throughout the preparation of this book. Each author for his or her contribution to a collection of superior papers.

Commissioner Joel Jacobson, Ms. Gwen Watson, Mr. Stan Kulp and the print shop of the New Jersey Department of Energy for their grant and assistance enabling us to publish a quality book. Deans Samuels, Caprio and Panson, and Provost Young of Rutgers University for their financial assistance and encouragement.

Cris Car, Maria Holinaty, Rick Wray and Professor Judith K. Brodsky of the Art Department for their commitment, extraordinary service and superior talents composing this book. My students Sharon Hall, Richard

Bizub and Michael McGowan for their assistance, patience and understanding.

The Hammond Map Company and New York Geographical Society and for permission to reproduce respectively, "Physiographic Diagram of New York Region" by E. J. Raisz (1930), and sketches from the New York Walk Book, by R. L. Dickinson (1971). Mr. Frazier and his staff at the New Jersey Historical Society for their assistance photographing old etchings, and two members of the Geology Department, Mr. John Szalkowski who faithfully photographed the old etchings and maps included in this book and Miss Muriel Meddaugh, who patiently retyped many of the manuscripts.

And finally to my wife Sylvia, who proof read galleys night after night with dedication and care.

Warren Manspeizer, President
New York State Geological Association

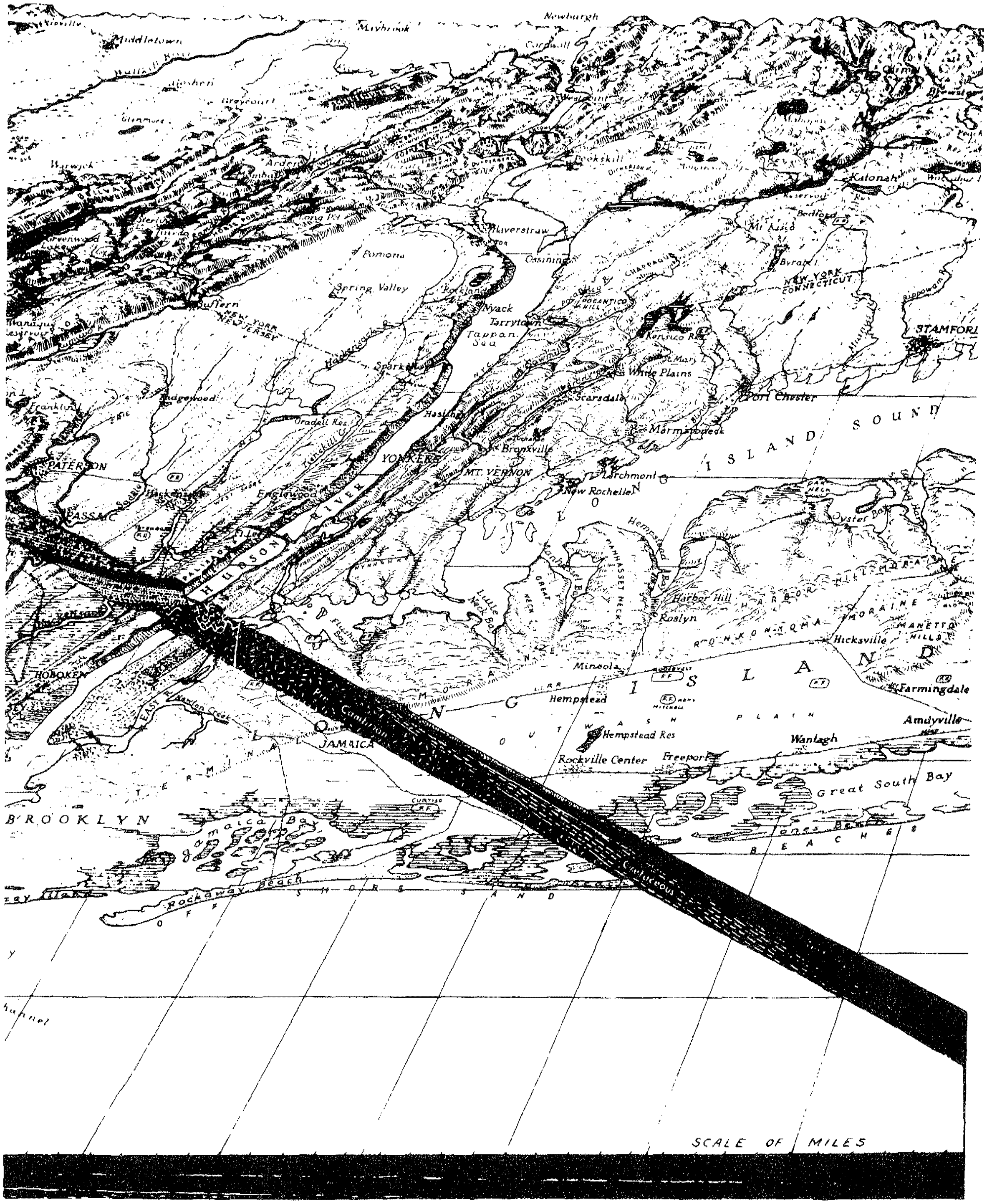
Newark, N.J.
October, 1980

[1] Lobeck, A. K., 1918, The superb position of New York City as a center for physiographic study: *Annals of the N.Y. Acad. Sci.*, vol. 28, P. 1-50.

[2] Raisz, E. J., 1930, Physiographic Diagram of the New York Region: The Geographic Press, Hammond Map. Co., Maplewood, N.J.

[3] Bates, R. L., 1969, Memorial to: Herbert Preston Woodward, 1899-1968: *Geol. Soc. America, Proceedings for 1968, P. 1-6.*

FIG 1. Physiographic Diagram of the New York Region



Drawn By Erwin J. Raisz

(Map courtesy of Hammond Incorporated, Maplewood, N.J.)

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PROGRAM OF THE SYMPOSIUM
FRIDAY, OCTOBER 10, 1980
ROBESON CENTER
RUTGERS NEWARK CAMPUS

RIFT BASINS ON THE TRAILING ATLANTIC MARGIN: BALTIMORE CANYON TROUGH TO THE NEWARK-GETTYSBURG BASIN
ONSHORE: NEWARK-GETTYSBURG BASIN

Newark Basins In Their Appalachian Framework:
John Rodgers, *Yale University*

Basalt Geochemistry and Chronology:
John Puffer and Fred Geiger, *Rutgers University*

Sedimentary Facies and Biostratigraphy:
Paul Olsen, *Yale University*

Paleogeography and Tectonics:
Warren Manspeizer, Michael McGowan, Sharon Hall, *Rutgers University*

Earthquakes and Causes in Mid-Atlantic Region:
Lynn R. Sykes, Alan Kafka and Yash Aggarwal, *Lamont-Doherty, Columbia University*

OFFSHORE: BALTIMORE CANYON TROUGH

New Jersey Looks Past The Three-Mile Limit:
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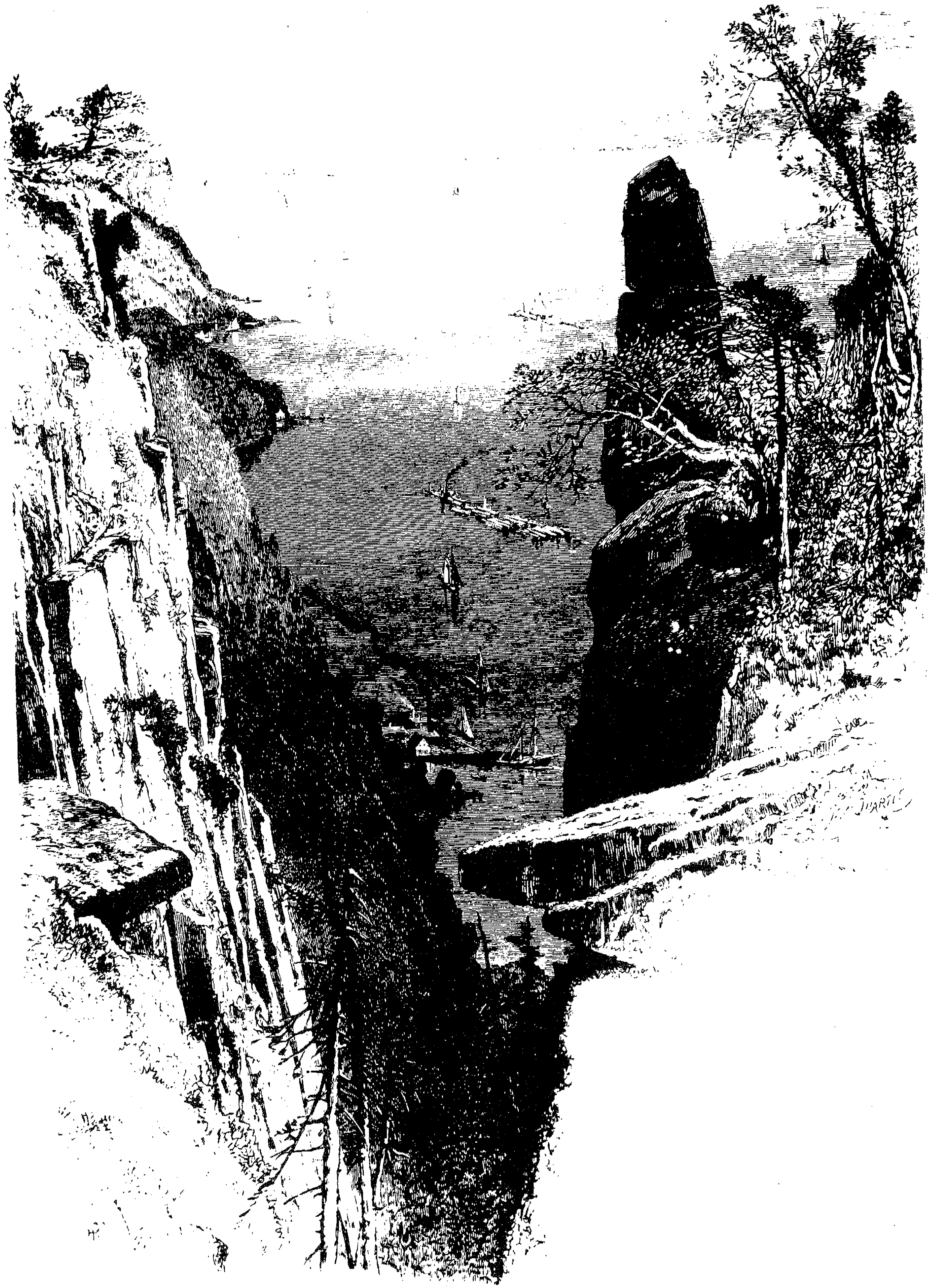


The Palisades by Harry Fenn
from Picturesque America, Vol. II, 1874

TRIASSIC AND JURASSIC FORMATIONS OF THE NEWARK BASIN

PAUL E. OLSEN

Bingham Laboratories, Department of Biology, Yale University, New Haven, Connecticut

Abstract

Newark Supergroup deposits of the Newark Basin (New York, New Jersey and Pennsylvania) are divided into nine formations called (from bottom up): Stockton Formation (maximum 1800 m); Lockatong Formation (maximum 1150 m); Passaic Formation (maximum 6000 m); Orange Mountain Basalt (maximum 200 m); Feltville Formation (maximum 600 m); Preakness Basalt (maximum +300 m); Towaco Formation (maximum 340 m); Hook Mountain Basalt (maximum 110 m); and Boonton Formation (maximum +500 m). Each formation is characterized by its own suite of rock types, the differences being especially obvious in the number, thickness, and nature of their gray and black sedimentary cycles (or lack thereof).

Fossils are abundant in the sedimentary formations of the Newark Basin and provide a means of correlating the sequence with other early Mesozoic areas. The Stockton, Lockatong, and most of the Passaic Formation are Late Triassic (?Middle and Late Carnian-Rhaetic) while the uppermost Passaic Formation (at least locally) and younger beds appear to be Early Jurassic (Hettangian and Sinemurian) in age. The distribution of kinds of fossils is intimately related to sequences of rock types in sedimentary cycles.

INTRODUCTION

Far from being the consequence of the last gasps of the Appalachian Orogeny, Late Triassic and Early Jurassic Newark Supergroup basins formed in dynamic association with the opening of the Atlantic Ocean (Sanders, 1974; Van Houten 1977; Manspeizer, Puffer, and Cousminer, 1978; Olsen, 1978). In addition, Newark Supergroup rocks, once thought to be nearly barren of fossils, are now known to be exceptionally rich in organic remains (Thomson, 1979), replete with plants, invertebrates, and vertebrates spanning some 35 million years of the Early Mesozoic (Cornet, 1977). Finally, long episodes of unusually continuous deposition coupled with an abundance of laterally extensive stratigraphic "marker" beds (McLaughin, 1946), makes this deposit ideal for studying time-facies relationships and evolutionary phenomena. These recent discoveries have focused new interest on Newark strata.

The Newark Basin (Fig. 1 and 2) is the largest of the exposed divisions of the Newark Supergroup, covering about 7770 km^2 and stretching 220 km along its long axis. The basin contains the thickest sedimentary sequence of any exposed Newark Supergroup basin and correspondingly covers the greatest continuous amount of time. Thus, the Newark Basin occupies a central position in the study of the Newark Supergroup as a whole.

In well over a century of study the strata of Newark Basin have received a relatively large amount of attention. By 1840, the basic map relations were worked out (Rogers, 1839, 1840, Cook, 1868) and by 1898, the major rock-stratigraphic subdivisions of the basin section were delimited and named (Darton, 1890; Kümmel, 1897, 1898). Despite this long tradition, fundamental aspects of its historical and structural geology have remained essentially unexplored. The lithostratigraphy of the younger sediments, in particular, has received short shrift. Recently I have revised certain aspects of Newark Basin stratigraphy with an emphasis on the younger rocks (Olsen, in press). In the process I haveproposed a number of new formational names (Table 2). Here I will review the formations of the Newark Basin and attempt to place their broader lithostratigraphic features into biostratigraphic context.

OVERVIEW OF NEWARK BASIN FORMATIONS

As currently defined (Olsen, 1978; Van Houten, 1977; Cornet, 1977), the Newark Supergroup consists of predominantly red clastics and volumetrically minor basaltic igneous rocks exposed in 13 major and 7 minor elongate basins preserved in the Piedmont, New England, and Maritime physiographic provinces of eastern North America (Figure 1, Table 1). In general, the long axes of these basins parallel the fabric of the

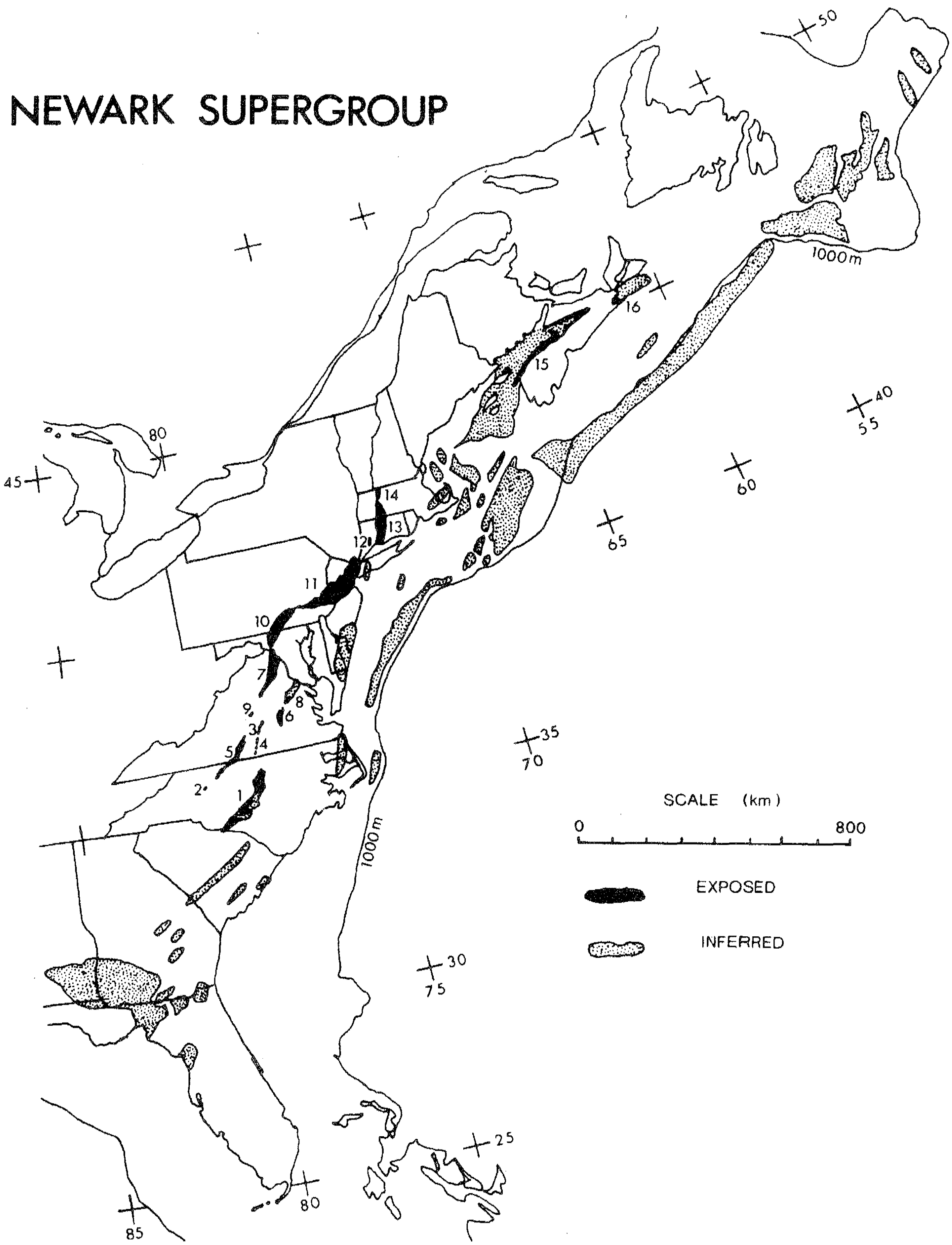


Fig. 1 Newark Supergroup of eastern North America. Key to numbers given in Table 1. The Newark Basin is 11. Data from Olsen, 1978.

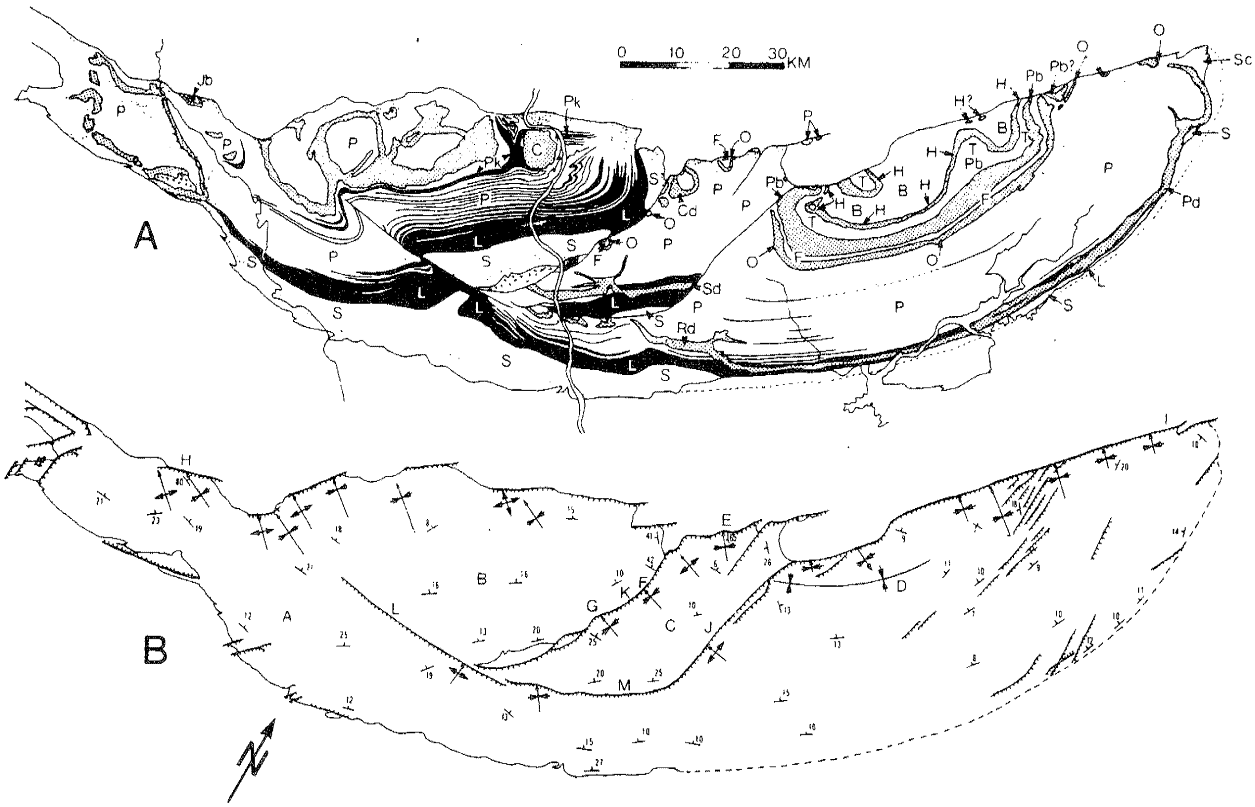


Fig. 2 The Newark Basin.

A. Geologic map showing distribution of formations, conglomeritic facies (irregular stipple), and major clusters of detrital cycles in Passaic Formation (parallel black lines) -- abbreviations of formations and diabase bodies as follows: B, Boonton Formation; C, Coffman Hill Diabase; Cd, Cushetunk Mountain Diabase; F, Feltville Formation; H, Hook Mountain Basalt; Hd, Haycock Mountain Diabase; Jb, Jacksonwald Basalt; L, Lockatong Formation; O, Orange Mountain Basalt; P, Passaic Formation; Pb, Preakness Basalt; Pd, Palisade Diabase; Pk, Perkasie Member of Passaic Formation; Rd, Rocky Hill Diabase; S, Stockton Formation; Sc, carbonate Facies of Stockton Formation; Sd, Sourland Mountain Diabase; T, Towaco Formation.

B. Structural features of the Newark Basin. Faults are all drawn as normal with dots on the down-thrown side; portions of basin margin not mapped as faults should be regarded as onlaps. While all the faults are mapped here as normal, it is clear many, if not all of them, have some component of strike slip, although the significance of this component is unclear. Symbols for the names of structural features used in this paper are as follows: A, Montgomery-Chester fault block; B, Bucks-Hunterdon fault block; C, Sourland Mountain fault block; D, Watchung syncline; E, New Germantown syncline; F, Flemington syncline; G, Sand Brook syncline; H, Jacksonwald syncline; I, Ramapo fault; J, braided connectoin between Ramapo and Hopewell faults; K, Flemington fault; L, Chalfont fault; M, Hopewell fault.

Data for A and B from Kümmel, 1897; Lewis and Kümmel, 1910-1912; Darton, 1890, 1902; Darton, et al., 1908; Glaeser, 1963; Sanders, 1962; Van Houten, 1969; McLaughlin, 1941, 1943, 1944, 1945, 1946a, 1946b; Bascom, *et al.,* 1909; Willard, *et al.,* 1959; Faille, 1963; Manspeizer, pers. comm.; Olsen, in press, and personal observation.

Appalachian Orogene (Rodgers, 1970; Van Houten, 1977). The rocks of these basins present a relatively unified lithology and structure and unconformably overlie (or intrude) Precambrian and Palaeozoic rocks. They are in turn overlain by post-Jurassic rocks of the Coastal Plain, Pleistocene deposits or Recent alluvium and soils. In addition, early Mesozoic red clastics, basaltic volcanics, and evaporites at the base of some sequences on the continental shelf and also at least 12 units recognized beneath the Atlantic Coastal Plain probably should be grouped in the Newark Supergroup (Figure 1).

Precambrian and early Paleaozoic rocks of the southwestern prongs of the New England Upland border the Newark Basin along its northeast and northwest margins (Figure 2). The southeastern and southwestern portions of the Newark Basin overlie and are bordered by Palaeozoic and Precambrian rocks of the Blue Ridge and Piedmont Provinces. Newark Basin sediments rest with a profound unconformity on basement rocks and mostly dip 5° - 25° to the northwest. The entire stratigraphic column reaches a cumulative trigonometrically calculated thickness of over 10,300 m (the sum of the maximum thicknesses of all the formations), although the total thickness of sediments actually deposited at any one spot was probably much less. Red clastics are the dominant sediments; intrusive and extrusive tholeiites are the dominant igneous rocks. The oldest sediments are probably middle Carnian (early

Table 1

Key to Figure 1	Rock-stratigraphic term	Basin name	Age range
1	Chatham Group	Deep River Basin	Carnian-?Norian (Late Triassic)
2	undifferentiated	Davie County Basin	?Late Triassic
3	undifferentiated	Farmville Basin	?Carnian (Late Triassic)
4	undifferentiated	4 small basins south of Farmville Basin	?Carnian (Late Triassic)
5	Dan River Group	Dan River and Danville Basins	Carnian-?Norian (Late Triassic)
6	Tuckahoe and Chesterfield Groups	Richmond Basin and subsidiary basins	Carnian (Late Triassic)
7	none	Culpeper Basin	Norian-?Sinemurian (Late Triassic-Early Jurassic)
8	none	Taylorsville Basin	Carnian (Late Triassic)
9	undifferentiated	Scottsville Basin and 2 subsidiary basins	?Late Triassic-Early Jurassic
10	none	Gettysburg Basin	Carnian-Hettangian (Late Triassic-Early Jurassic)
11	none	Newark Basin	Carnian-Sinemurian (Late Triassic-Early Jurassic)
12	none	Pomperaug Basin	?Late Triassic-Early Jurassic
13	none	Hartford Basin and subsidiary Cherry Brook Basin	Norian-?Bajocian (Late Triassic-?Middle Jurassic)
14	none	Deerfield Basin	?Norian-?Toarcian (Late Triassic-Early Jurassic)
15	Fundy Group	Fundy Basin	?Middle Triassic-Early Jurassic
16	Chedabucto Formation (=Eurydice Formation?)	Chedabucto Basin (=Orpheus Basin?)	?Late Triassic-Early Jurassic

Table 2

Lyman, 1895	Kummel, 1897; Darton, 1890	Baird and Take, 1959; Baird, 1964; Colbert, 1965	(Olsen, in press) This Article
American New Red Sandstone	Newark System (of Newark Basin)	Newark System (of Newark Basin)	Newark Supergroup (of Newark Basin)
	Brunswick Formation	Boonton and Whitehall Beds	Boonton Formation
	"3rd" Watchung Basalt	Hook Mountain Basalt	Hook Mountain Basalt
	Brunswick Formation	Brunswick Formation	Towaco Formation
	"2nd" Watchung Basalt	"2nd" Watchung Basalt	Preakness Basalt
	Brunswick Formation	Brunswick Formation	Feltville Formation
	"1st" Watchung Basalt	"1st" Watchung Basalt	Orange Mountain Basalt
Pottstown Shales Perkasie Shales Lansdale Shales	Brunswick Formation	Brunswick Formation	Passaic Formation
Gwynodd Shales	Lockatong Formation	Lockatong Formation	Lockatong Formation
Norristown Shales	Stockton Formation	Stockton Formation	Stockton Formation

Late Triassic) in age while the youngest appear to be Sinemurian (middle Early Jurassic) (Cornet, 1977; Olsen, McCune, and Thomson, in press). Cretaceous and younger Coastal Plain deposits overlap Newark beds with an angular unconformity along the basin's eastern edge. The northern quarter of the basin is mantled by Pleistocene and recent deposits.

The first lithostratigraphic terms for the sedimentary formations of the Newark Basin were introduced by Lyman in 1895 (Table 2). Although he clearly demarcated the units in their type areas (southeastern Pennsylvania), mapped and briefly described them, his terms never gained wide acceptance. In 1897, Kümmel introduced his own nomenclature for equivalent rocks in New Jersey (Table 2). Since their introduction, Kümmel's terms have been widely used. While the rule of priority applies to stratigraphic names, no practical purpose is served by resurrecting those of Lyman. This is in accordance with Code of Stratigraphic Nomenclature, 1961 (hereafter C. N. S.), article 11b, and with the International Stratigraphic Guide, 1976 (hereafter I. S. G.), chapter 3e.

Kümmel (1897) divided the Newark Basin sequence into three formations: Stockton, Lockatong, and Brunswick. The Stockton Formation (maximum thickness ca. 1800 m) consists of thick beds of buff or cream colored conglomerate and sandstone and red siltstone and sandstone forming the basal formation of the Newark Basin. Throughout the exposed central portion of the Newark Basin, the Stockton Formation is overlain by the Lockatong Formation (maximum thickness 1150 m) which is made up of beds of gray and black siltstone. These siltstones are arranged, as Van Houten (1969) later showed, in distinctive sedimentary cycles. The youngest formation Kümmel recognized is the Brunswick. Throughout the Newark Basin, the lower half of this formation consists mostly of red siltstone, sandstone, and conglomerate with clusters of laterally persistent cycles of gray and black siltstone similar to that in the Lockatong Formation (Kümmel, 1897, 1898; McLaughlin, 1943; Van Houten, 1969). The upper Brunswick, on the other hand, is made up of three major, multiple-flow, basalt sheets (units Darton in 1890 called the Watchung Basalts), two major interbedded sedimentary units, and a thick overlying sedimentary unit. The latter sedimentary sequences have escaped even preliminary lithologic description.

Field work by myself and others (Olsen, in press) has shown that Kümmel's Brunswick Formation consists of a heterogeneous mix of major, mappable units of differing and distinctive lithology, each as distinct and perhaps originally as widespread as the Stockton or Lockatong; "Watchung Basalt" and the interbedded and overlying sedimentary beds are lithologically distinct from the stratigraphically older beds. In addition, Kümmel's upper Brunswick is Early Jurassic, rather than Late Triassic as most authors have assumed (Cornet, Traverse and McDonald, 1973; Cornet and Traverse, 1975; Cornet, 1977; Olsen and Galton, 1977; Olsen, McCune, and Thomson, in press). It now seems that these Jurassic rocks are in many ways different from the Late Triassic lower Brunswick Formation, Lockatong, or Stockton formations.

I have proposed elsewhere (Olsen, in press) that the terms Brunswick Formation (Kümmel, 1897) and Watchung Basalts (Darton, 1890) be dropped and their components subdivided to form seven new formations. Despite the wide (although inconsistent) use of those terms over the years, it is inappropriate to conserve them for the following reasons:

1. The division of the Brunswick Formation of Kümmel into four sedimentary formations constitutes a major redefinition of the unit. C.S.N. article 14b recommends that "When a unit is divided into two or more of the same rank as the original, the original name should not be employed for any of the revisions." Thus, while it could be argued that the term Brunswick Formation should be retained for the pre-basalt sediments of the Newark Basin, such use could be a source of confusion, and it seems better to establish a new term for the pre-basalt, post-Lockatong beds.

2. Darton's Watchung Basalt has been traditionally recognized as a single formation embracing the three major multiple flow units interbedded in Kümmel's upper Brunswick Formation (see, for example, Wilmarth, 1938, p. 896; Faust, 1975, 1978; Van Houten, 1969, p. 327). Since both the C.S.N. (article 10h) and the I.S.G. (chapter 5f, 1c) state that repetition of geographic names in formations is considered informal nomenclature, it is appropriate to drop the formal use of the term Watchung Basalt and recognize three basalt formations with individual names (Table 2).

The new formational names I have proposed to replace Kümmel's and Darton's formations are (from the bottom up): Passaic Formation, Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation. These new divisions of the Newark Basin section are similar in scale to Emerson's (1898) and Lehman's (1959) widely used divisions of the Hartford Basin and Klein's (1962) divisions of the Fundy Group, and are in accordance with the letter and intent of the C.S.N. and I.S.G. In this way, formal names are given to beds critical to the overall pattern of Newark Basin historical geology.

A NOTE ON THE CALCULATION OF STRATIGRAPHIC THICKNESS

The arguments which center on the accuracy of trigonometrically computed stratigraphic thicknesses of Newark Basin sections (Rogers, 1840, 1865; Kummel, 1898; Faill, 1973; Faust, 1975; Sanders, MS) concern two components. First, deposition along the stepfaulted northwest margin decreases the real thickness of beds preserved at any one place. This is a major concern, but the problem can be at least partially resolved by careful analysis of existing outcrops and geophysical data (see Faill, 1973, for a review and Dunleavy, 1975, and Olsen, in press, for particulars) (see Figure 5). Second, there are a large number of hidden strike faults with large dip-slip components. This problem has no clear quantitative solution in some important areas. In parts of the Newark Basin, such as the entire northern third of the basin, this is a substantial problem, as the following examples show (Figure 2).

1. A suite of faults has long been known to offset the northern segments of the Watchung ridges (Kümmel, 1897; Darton, et al., 1908; Olsen, in press). These series cut the type sections of both the Orange Mountain Basalt and the Preakness Basalt. 2. Another suite of faults cuts the Palisades ridge, especially in the area of Weehawken and Edgewater, New Jersey (Kümmel, 1898; Van Houten, 1969; Olsen, in press). 3. Faults duplicate 30 % of the exposed Lockatong Formation at Gwynned, Pennsylvania (Watson, 1958). Many other examples are know (Willard, et al., 1959; Rima, Meisler, and Longwill, 1962).

Most of these faults are visible because they cut ridges with topographically expressed offsets; in areas of low topography, they do not show up. In certain areas, such as the Passaic Formation type section (Figure 6), the distribution of such faults is essentially unknown. Those faults presently mapped which cut the Watchung ridges must continue and cut the Passaic Formation,though they may eventually die out. Thus, the trigonometrically computed thickness for the Passaic Formation in the northern third of the Newark Basin is certainly an overestimation.

In contrast, the field relationships of mapped gray and black siltstone and conglomerate beds in the Bucks-Hunterdon fault block (see Figure 2) show that these small strike faults are absent over broad areas. In these areas the trigonometrically computed thicknesses have been confirmed by some deep well records (Lesley, 1891; McLaughlin, 1943). This inconsistency over parts of the Newark Basin demonstrates that there can be no single constant to correct for "hidden faults." Rather, if a correction is attempted (as in Figure 6) it must be based on extrapolation of the local fault patterns. For thin units, such as the northern outcrops of the Lockatong or the basalt formations, these small faults usually do not present much of a problem since there are single outcrops covering much of each unit.

As a general guide, I place most confidence in thickness determinations in the Bucks-Hunterdon Block and the least confidence in the calculated thicknesses at the northeastern and southwestern portions of the

Newark Basin.

STOCKTON FORMATION

The Stockton Formation is the poorest known of all Newark Basin formations. It is also the oldest and most widespread deposit, forming the basal beds of the Newark Basin section everywhere except along portions of the northwest border.The Stockton is thickest near the Bucks-Montgomery county line in the Bucks-Hunterdon fault block (Figure 2), where it reaches a calculated stratigraphic thickness of 1830 m (Willard, *et al.*, 1959). Along its type section (Figure 3, Table 3) along the shores of the Delaware River near Stockton, New Jersey, the formation is 1500 m thick (McLaughlin, 1945). Measured from the base of the lowest continuous black siltstone unit of the overlying Lockatong Formation, the Stockton thins in all directions from this central area (Kümmel, 1897). Towards the south at Norristown, Pennsylvania it is 1221 m and at Phoenixville, Pennsylvania it is 700 m; to the north near Clinton, New Jersey it is 1350 m; to the east near Princeton, New Jersey it is 920 m; and to the northeast at Hoboken and Weehawken, New Jersey it is less than 250 m. The predeformational shape of the Stockton Formation lithosome is thus an asymmetrical lens with the thickest portion near the center of the Bucks-Hunterdon fault block (see Figure 4). McLaughlin (in Willard, *et al.*, 1959) presents evidence that the Stockton Formation in the southern Newark Basin thins by a progressive onlap of younger Stockton beds onto basement.

Stockton lithology is diverse. The dominant sediment types are gray and buff colored arkose and arkosic conglomerate, and red siltstone and arkosic sandstone. In broad view, the Stockton Formation fines upward with the coarsest sediments near the base. As noted by McLaughlin (In Willard, *et al.*, 1959) the Stockton coarsens in the same directions it thins; thus conglomerate bodies and coarse arkose are found high in the section along the eastern edge of the basin.

The belt of Stockton Formation which runs through the Bucks-Hunterdon fault block and through the Montgomery-Chester fault block (Figure 2) has been divided into members by McLaughlin (In Willard *et al.*, 1959) and by Rima, Meisler and Longwill (1962), primarily on the basis of texture (Table 3).They did not attempt to extend these member names into other parts of the Newark Basin. Upper Stockton fissile red sandstone and siltstone pass upwards into hard non-fissile red siltstones (argillite) in the Bucks-Hunterdon belt. These siltstones have been grouped with the overlying Lockatong Formation by a number of authors (McLaughlin, 1945; McLaughlin, In Willard et al., 1959; Van Houten, 1969). I believe the Stockton-Lockatong boundary should be defined at the base of the lowest continuous black siltstone bed. This is in accord with Kümmel's own definition which does not seem to include 30 m of red beds at the base of the Lockatong, although I think his definition is somewhat vague. I group these red siltstones with the Stockton.

While the predominant facies trend is clearly upward fining, important beds of different lithology occur throughout. Basal Stockton beds, where they are exposed, rest on a locally irregular surface. Where basal Stockton beds rest on Cambro-Ordovician limestones, red matrix limestone breccia and red siltstone fill apparent solution cavities. Elsewhere, there are basal red-matrix conglomerate and breccia composed of underlying basement rocks (Olsen, in press). The main masses of Stockton Formation conglomerate in the central part of the basin, however, are definitely not basal and rest some 100 m above the base of the formation. These conglomerates are gray and buff, but are never red (Rima, Miesler, and Longwill, 1962; McLaughlin in Willard, *et al.* 1959).

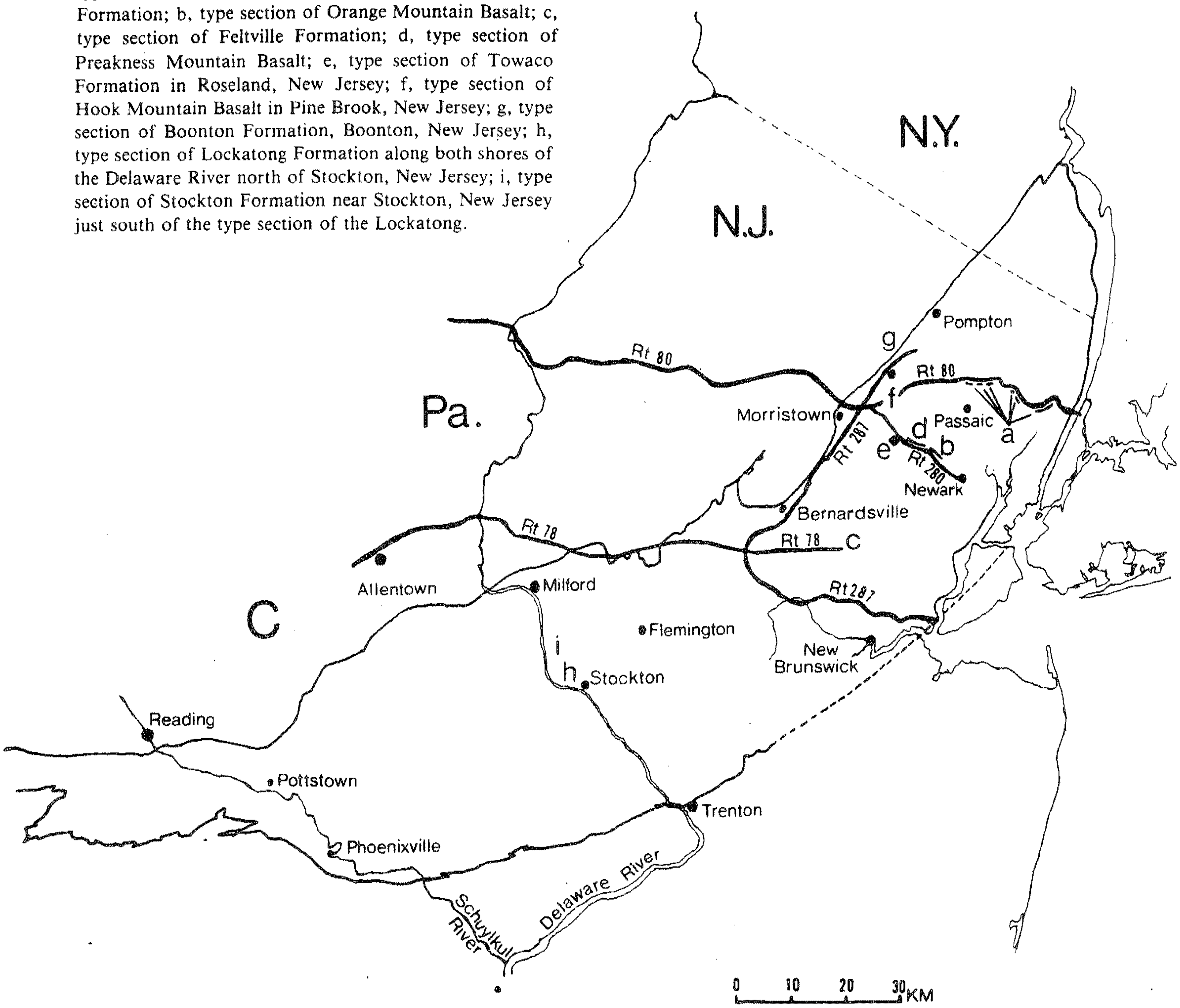
Red siltstones of the Stockton Formation are characteristically intensively bioturbated by roots and burrows, notably the arthropod burrow *Scoyenia* (see Olsen, 1977). Purple and mauve siltstone beds with a markedly disrupted fabric occur near the middle and top of the formation. These beds are usually densely penetrated by roots, but rarely burrowed by *Scoyenia.* Beds of greenish-gray and brown carbonate-rich pellets occur throughout the formation. These are often associated with bases of buff arkose beds. Well-bedded gray and gray-green siltstone beds are present locally in the upper Stockton, and these beds are the source of most of the Stockton fossils found so far. How these units, which are unusual compared to the bulk of the Stockton sequence, fit in the overall facies pattern remains obscure.

LOCKATONG FORMATION

The beds of the Lockatong Formation rest conformably on the Stockton Formation over most of the Newark Basin. The Lockatong is composed primarily of gray and black siltstones arranged, as shown by Van Houten (1962, 1964, 1965, 1969, 1977), in sedimentary cycles. In the Bucks-Hunterdon fault block, near the Lockatong's type section along Lockatong Creek, the formation reaches its maximum thickness of 1150 m (Figure 2, Table 4). The formation thins in all directions away from this central area, passing into Passaic and Stockton formations along exposed edges of the Newark Basin.

Van Houten (1962, 1964a,b, 1965, 1969, 1977) recognizes two end-members to the range of short cycle

Fig. 3 Geographic map of Newark Basin showing locations of type sections of formations: a, type section of Passaic Formation; b, type section of Orange Mountain Basalt; c, type section of Feltville Formation; d, type section of Preakness Mountain Basalt; e, type section of Towaco Formation in Roseland, New Jersey; f, type section of Hook Mountain Basalt in Pine Brook, New Jersey; g, type section of Boonton Formation, Boonton, New Jersey; h, type section of Lockatong Formation along both shores of the Delaware River north of Stockton, New Jersey; i, type section of Stockton Formation near Stockton, New Jersey just south of the type section of the Lockatong.



types present in the Lockatong; he terms these detrital and chemical. In the Delaware River section of the formation the detrital cycles are an average of 5.2 m thick and consist of a lower platy black calcareous siltstone succeeded upwards by beds of disrupted dark gray, calcareous siltstone, ripple-bedded siltstone, and fine sandstone. In the same area, chemical cycles average 3.2 m thick. Their lower beds consist of platy black and dark gray dolomitic siltstone, broken by shrinkage cracks, and containing lenses of pyritic limestone. The upper beds are massive gray or red analcime- and carbonate-rich siltstone, intensively and minutely disrupted. The massive beds often contain pseudomorphs after analcime and glauberite.

Detrital and chemical cycles are not distributed randomly through the Lockatong. In vertical section, in the central Newark Basin, the two cycle types occur in clusters; the center of each detrital cycle cluster is about 107 m from the next. Detrital cycle clusters are separated by clusters of chemical cycles. Again, in vertical section, there are more detrital cycles in the lower than in the upper Lockatong. Evidence gathered so far (Olsen, this Fieldbook) indicates that individual detrital cycles can be traced for over 20 km. Judging from the outcrop pattern of detrital cycle clusters in the upper Lockatong and lower Passaic Formation, it seems likely that individual detrital cycles can be traced basin-wide. Chemical cycles, on the other hand, are predominantly restricted to the central 97 km of the Newark Basin, passing laterally into beds indistinguishable from the Stockton and Passaic formations. At the southwestern end of the Newark Basin at Phoenixville, Pennsylvania, the Lockatong is 350 m thick; the formation consists of clusters of detrital cycles separated by red siltstone and some beds of gray sandstone. At the northeastern end of

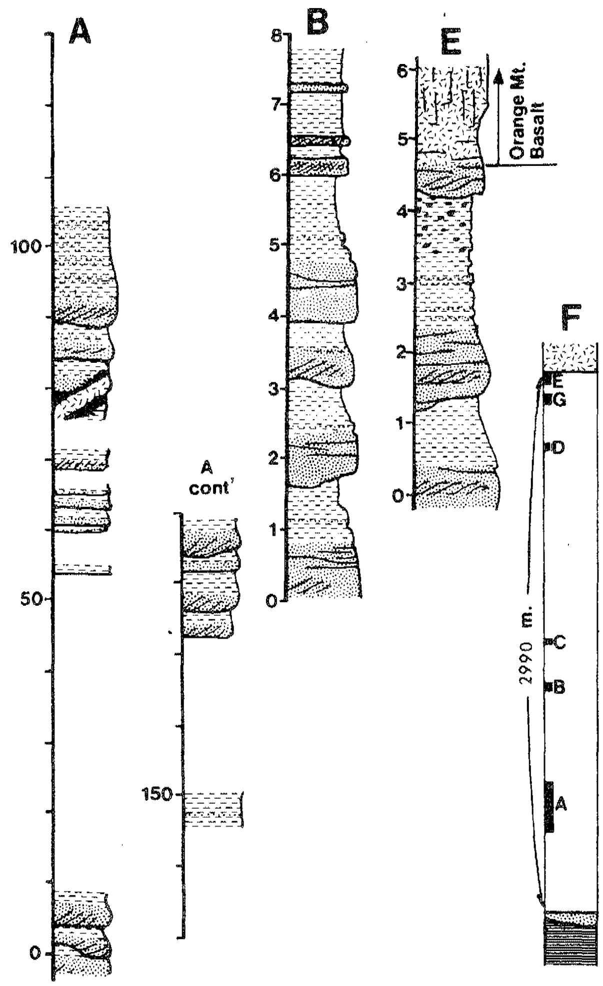


Fig. 4 A - E, type section of Passaic Formation (Table 5 for description); F, diagram showing positions of sections A - E in Passaic Formation. For key to units see Table 5.

the Newark Basin at Weehawken, the Lockatong is 150 m thick and consists of detrital cycle clusters separated by beds of buff arkosic sandstone. The large number of detrital cycles prevalent in the lower Lockatong in the central Newark Basin strongly suggests that the Lockatong outside of its thickest central portion comprises only the lower 500 m of the Lockatong or less (not including the lower 30 m of red siltstone grouped here in the Stockton).

The thickness of the Lockatong decreases away from the central Newark Basin not only by replacement of its upper beds by Passaic Formation but also by the thinning of individual detrital cycles. While the mean detrital cycle thickness is 5.2 m along the Delaware River, for example, it is 1.5 m along the Hudson River (see Olsen, this Fieldbook).

Beds along strike from the lower Lockatong at the northeastern, southeastern, and northwestern edges of the Newark Basin are indistinguishable from the Stockton Formation and are thus mapped (Figure 2).

PASSAIC FORMATION

The name Passaic Formation has recently been applied (Olsen, in press) to the predominantly red siltstones, sandstones, and conglomerate which conformably overlie the Lockatong Formation and which underlie the Orange Mountain and Jacksonwald Basalts. It is equivalent to the pre-basalt portion of Kümmel's Brunswick Formation (Table 2). The type section consists of intermittent exposures of red clastics along Interstate Route 80 near Passaic, New Jersey (Figure 3 and 7).

The Passaic Formation is the thickest coherent lithologic unit in the Newark Basin, reaching a maximum calculated thickness of over 6000 m (Jacksonwald Syncline — Figure 2). The formation outcrops throughout the Newark Basin, although its upper beds are preserved only in the Watchung Syncline (Figure 2), in the smaller synclines preserved along the eastern side of the Flemington Fault, and in the Jacksonwald Syncline (Figure 2). In all other areas, the upper Passaic has been removed by post-Newark erosion.

While in most areas the Passaic Formation rests conformably on Lockatong Formation or, where that is absent, Stockton Formation, in several areas on the western margin of the Newark Basin the Passaic directly overlaps the step-faulted basement without any intervening Stockton or Lockatong. In these areas (Figure 2) the thickness of Passaic Formation present below the Orange Mountain Basalt is comparatively slight.

Facies patterns of the Passaic Formation are a modified continuation of those of the Lockatong, and differ from all younger Newark Basin deposits. As in the Lockatong, periodically spaced clusters of detrital cycles occur through most of the thickness of Passaic Formation (Van Houten, 1969). The great majority of these non-red units, however, are not as laterally continuous as those of the Lockatong, and as a general trend, it is clear that the number of cycles involved in these clusters decrease in frequency upwards through the Passaic Formation (see Van Houten, this Fieldbook). The boundary between the Passaic Formation and the Lockatong can be operationally defined (both horizontally and vertically) as where the thicknesses of beds of red clastics dominate gray and black. It follows from this definition that where gray and black detrital cycles do not occur, as in Rockland County, New York, the Passaic Formation rests directly on Stockton Formation.

McLaughlin (1933, 1943, 1945, 1946, 1948) has succeeded in mapping out the distribution of Passaic Formation detrital cycle clusters over the Bucks-Hunterdon Fault Block and part of the Montgomery-Chester fault

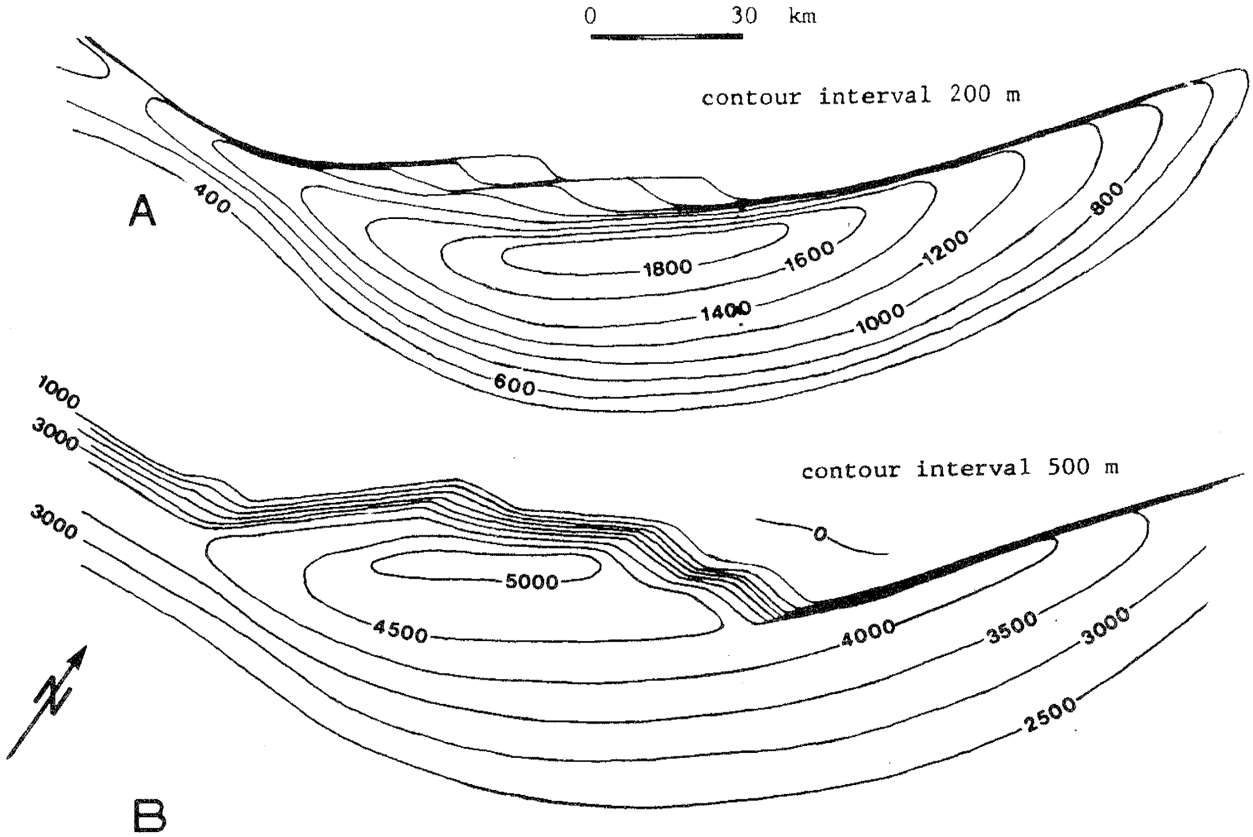
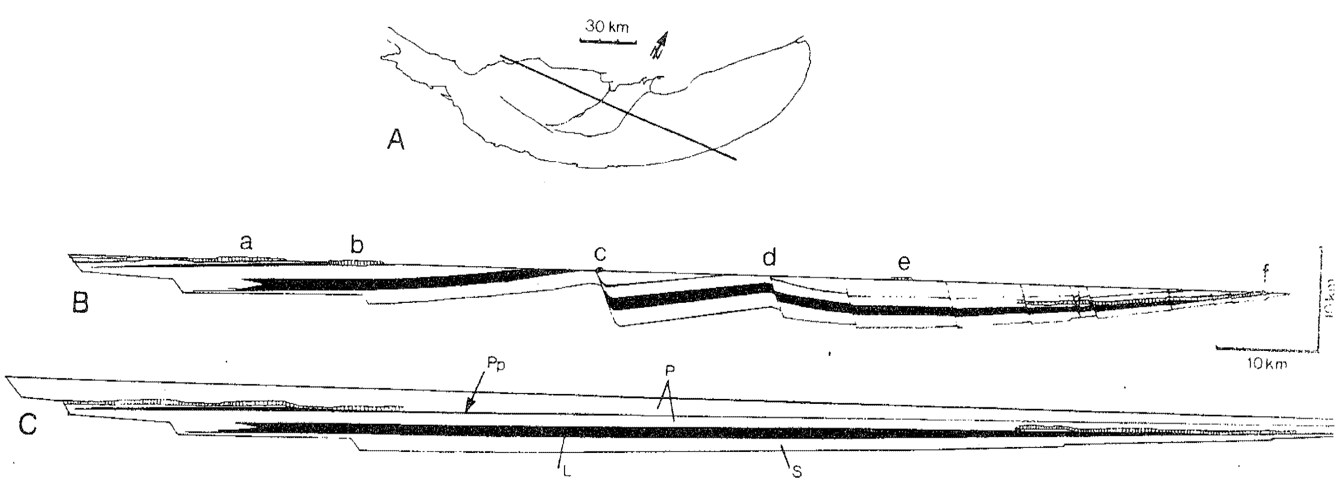


Fig. 5 Approximate predeformational shapes of Stockton Formation (A) and Lockatong-Passaic Formation (B) sediment bodies.

Fig. 6 Cross-section of the pre-Orange Mountain Basalt portion of the Newark Basin: A, position of section in Newark Basin; B, present cross section--note that the vertically ruled band represents diabase and gabbro sills and plutons; C, reconstructed section with Passaic Formation-Orange Mountain Basalt contact as horizontal--note thinning to east and ramping to west.
Abbreviations as follows: a, Haycock Mountain Pluton; b, Coffman Hill Pluton; c, Flemington syncline outlier of Orange Mountain Basalt and to the immediate left the Flemington Fault; d, Hopewell Fault; e, Orange Mountain Basalt of Watchung syncline; L, Lockatong Formation; P Passaic Formation; P;. Perkasie Member of Passaic Formation; S, Stockton Formation. Note that the trigonometrically calculated thickness of Passaic Formation east of the Watchung syncline has been reduced by 25% as a correction for dip slip faults.



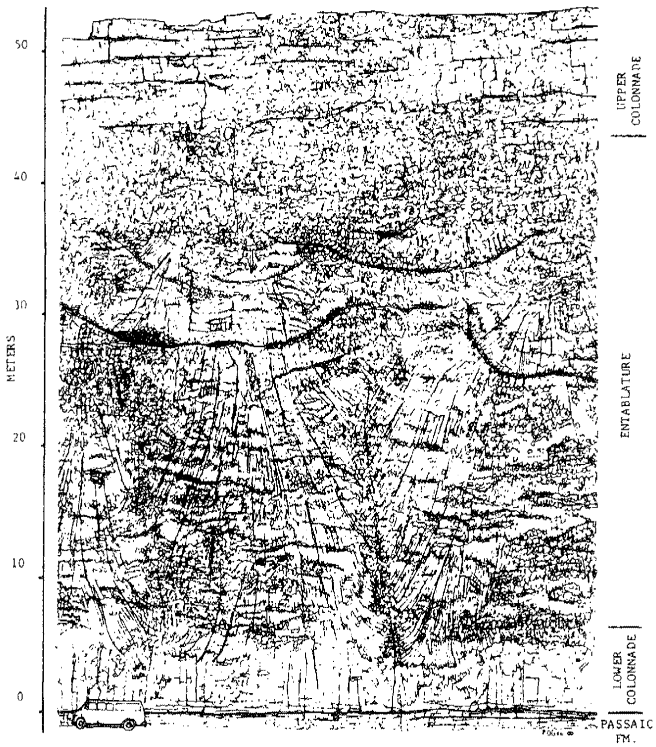


Fig. 7 Type section of the Orange Mountain Basalt; exposure along Interstate Route 280 in East Orange, New Jersey. Traced from a composite of a continuous series of photographs.

block. A detailed physical stratigraphy has developed around these mapped beds, each detrital cycle being designated by a letter (A,B,C,...). The extension of McLaughlin's units outside of the areas he mapped is a principal goal of ongoing field research (Figure 2). The highest of McLaughlin's mapped units (134 m above L and M) join with other cycles to the southwest to form a large body of black and gray siltstone called the Perkasie Member (McLaughlin, 1946). Unlike the Lockatong Formation, however, the thickest section of the Perkasie Member is in the southwestern portion of the Bucks-Hunterdon fault block. Due to repetition by the Hopewell, Flemington, and Chalfont Faults (Figure 2) and changes in strike along folds, the broader aspects of the three dimensional relationships of most Passaic dark clastic units can be observed. Looking over the bulk of the Passaic Formation (Figure 2), there is no evidence that the rest of the detrital cycle clusters of the Passaic (i.e., other than the lateral equivalents of the Lockatong or Perkasie Member) represent the remnants of a larger, now eroded, gray and black siltstone body as Glaeser (1963) has suggested.

There are major masses of red-matrix conglomerate at both the northern and southern ends of the Newark Basin (Figure 2). It is the southern body Glaeser (1966) has named the Hammer Creek Formation (= Robeson Conglomerate of McLaughlin, 1939). These masses of red conglomerate grade nearly imperceptively into the finer red clastics of the Passaic Formation. I would prefer to consider these units as facies of the Passaic. Other much smaller areas of conglomerate occur along the western border of the Newark Basin; these are especially prevalent where Passaic Formation onlaps basement rocks (Figure 2).

Because of the interfingering and inverse thickness relationships that are consequences of the definitions of the Passaic and Lockatong formations, the predeformational shape of each formation is very difficult to depict. Therefore, in Figure 5 the thicknesses of both formations are combined so that the lens shape of the Lockatong-Passaic lithosome is evident. Interestingly, the Lockatong-Passaic lithosome is thickest just to the west of the thickest portion of the Stockton. To the west and north of this thickest area, progressively higher Passaic beds lap onto a step-faulted basin margin, while to the east, the entire Lockatong-Passaic lithosome thins by the thinning of its individual components (see Figure 6).

ORANGE MOUNTAIN BASALT

Orange Mountain is the local name of the First Watchung Mountain in Essex County, New Jersey, long known for its spectacular exposures of columnar basalt (Cook, 1884). I have recently applied the name Orange Mountain Basalt to these multiple (at least two), tholeiitic, olivine-poor basalt flows and interbedded volcanoclastic units above the Passaic Formation and below the Feltville Formation (Olsen, in press). The type section (Figure 7), exposing about 40% (50 m) of the formation's total thickness, is along Interstate Route 280 at its cut through Orange Mountain in East Orange, New Jersey. The petrography and geochemistry of the Orange Mountain Basalt (as well as the two younger basalt formations of the Newark Basin) is reviewed by Faust (1975), and is therefore not discussed here.

The Orange Mountain Basalt is the oldest Newark Basin Formation thought to be wholly Early Jurassic in age, and like similarly aged beds in the Newark Basin, the main area in which the basalt is preserved is the Watchung Syncline (Figure 2). Smaller synclines preserve portions of the Orange Mountain Basalt in several other regions (Figure 2). In the New Germantown and Sand Brook Synclines, the overlying Feltville Formation is preserved above the basalt. Correlation by palynomorph assemblages and fossil fish of the overlying Feltville Formation (Cornet, 1977; Olsen, McCune, and Thomson, in press) demonstrate the identity of the underlying basalt. Between these two synclines is a newly identified, very small outlier of basalt, preserved in what can be called the Flemington Syncline (Figure 2). Unfortunately, the remnant is so small that no sedimentary rocks are preserved above the basalt. The simplest hypothesis identifies this basalt remnant as an additional portion of the Orange Mountain Basalt.The Jacksonwald Basalt crops out in a syncline near the southern terminus of the Newark Basin (Figure 2 and 3) over 100 km southwest of the Watchung Syncline. Palynomorph assemblages recovered from the overlying sediments indicate correlation with the Feltville Formation (Cornet, 1977). There is no evidence to contradict the hypothesis that this outlier too represents the Orange Mountain Basalt.Two other as yet poorly known probable outliers of Orange Mountain Basalt are the Union Hill and Ladentown basalts in Rockland County, New York (Ratcliffe, this Fieldbook), (Figure 2). Taken together, these remnants of Orange Mountain Basalt suggest that originally the basalt covered the entire Newark Basin, a minimum of over 7700 km². This is comparable to the extent of the Holyoke Basalt over the Hartford Basin and the North Mountain Basalt over the Fundy Basin.

The Orange Mountain Basalt appears thickest in the Watchung Syncline, varying between 100 and 200 m. At least 130 and 120 m are present in the New Germantown and Sand Brook Synclines, respectively, and + 100 m are present in the Jacksonwald Syncline. Potential error in measurement in these outliers is great. Existing exposures do not permit estimates of the thicknesses of the Flemington, Union Hill, or Ladentown outliers.

A minimum of two flows is evident in most sections of the Orange Mountain Basalt, at least in the Watchung, New Germantown, and Ladentown Synclines. The lower flow is exposed at the type section where it shows a nearly complete Tomkeieff structural sequence (Manspeizer, 1969). Other exposures of the lower flow are abundant. In most places the lower and upper flows are separated by a red volcanoclastic bed which is generally less than a meter thick (Bucher and Kerr, 1948; Johnson, 1957; Van Houten, 1969; Faust, 1975). In the New Germantown Syncline, however, the volcanoclastic bed is over 4 m thick and has numerous beds of purple, red, and gray ripple-bedded and mudcracked siltstone. The upper flow is extensively pillowed and pahoehoe-like near the type section (Fenner, 1908; Van Houten, 1969) and locally at isolated spots throughout the Watchung Syncline. Elsewhere, however, the upper flow resembles the lower in having a large columnar entablature. It is not clear whether these flows represent continuous sheets.

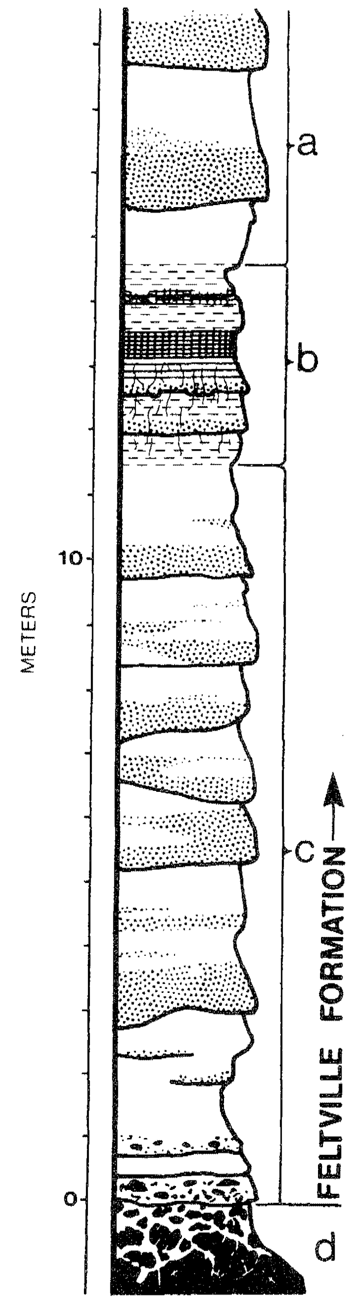


Fig. 8 Type section of the Feltville Formation; section exposed along ravine for Blue Brook about 1 km south of Lake Surprise in the Watchung Reservation. For key to individual units see Table 6.

FELTVILLE FORMATION

The sedimentary rocks above the Orange Mountain Basalt and below the Preakness Basalt are termed the Feltville Formation (Olsen, in press). The Feltville consists of red siltstone and sandstone, buff, gray, and white feldspathic sandstone, and a thick, laterally continous non-red unit containing a unique laminated limestone. This formation is named for the old village of Feltville, Union County, New Jersey, where the type section is located (Figure 8).

Like the underlying Orange Mountain Basalt, the Feltville Formation is preserved in the Watchung, New Germantown, Sand Brook, and possibly the Jacksonwald Synclines (Figure 2). The formation averages about 170 m in the Watchung Syncline, apparently thickening to 300 m in the Sand Brook and 600 m in the Germantown Syncline. More than 200 m seems to be present in the Jacksonwald Syncline.

The Feltville Formation is distinguished from the underlying Passaic Formation and the younger Jurassic formations of the Newark Basin by the presence of abundant beds of buff, gray, or white feldspathic sandstone interbedded with red siltstone in fining-upwards sequences (Olsen, in press); thus, much of the Feltville superficially resembles the Stockton Formation. The lower half of the Feltville contains a black to white laminated limestone, calcarenite, and graded siltstone bed (0.4 - 3 m) containing abundant fossil fish. This is sandwiched between two beds (each 1-7 m) of gray, small- to large-scale crossbedded siltstone and sandstone. As is true for the formation as a whole, these beds are thickest in the New Germantown Syncline (+ 14 m).

Conglomerate occurs in the Feltville Formation at Oakland, New Jersey, about 15 m below the Preakness Basalt (Faust, 1975). This conglomerate contains as much as 30 % vesicular basalt clasts, in addition to cobbles and pebbles of phyllite and limestone. Very little of the section below this unit is exposed and at this point it is impossible to say how much additional conglomerate is present. Other beds of conglomerate crop out in the New Germantown Syncline in association with the non-red laminated beds. The available evidence suggests that the Feltville Formation, like the Orange Mountain Basalt, originally occupied the whole of the area of the Newark Basin; the predeformational shape of the Feltville lithosome seems to have been a wedge thickest along the western border of the basin. The data are not conclusive, however.

PREAKNESS BASALT

Preakness Basalt consists of the extrusive, tholeiitic basalt flows and interbedded volcanoclastic beds above the Feltville Formation and below the Towaco Formation (Olsen, in press). Preakness Mountain is the local name of the second Watchung Mountain near Franklin Lakes, New Jersey. The type section is located along Interstate Route 280 (Figure 9) about 2.25 km west of the type section of the Orange Mountain Basalt.

The Preakness Basalt is the thickest extrusive unit in the Newark Basin. The calculated thickness is 215 m at its northernmost outcrops at Pompton and Oakland, New Jersey. Judging from outcrop width alone, the formation thickens to as much as 500 m near the type section. This figure is questionable since in the area where the formation seems to be the thickest, the strike of the beds parallels a series of small faults, many of which have a strong normal component. That a figure of more than 300 m may be nearer to the truth is suggested by the persistence of a large outcrop width around the southern curve of the Watchung Syncline. The

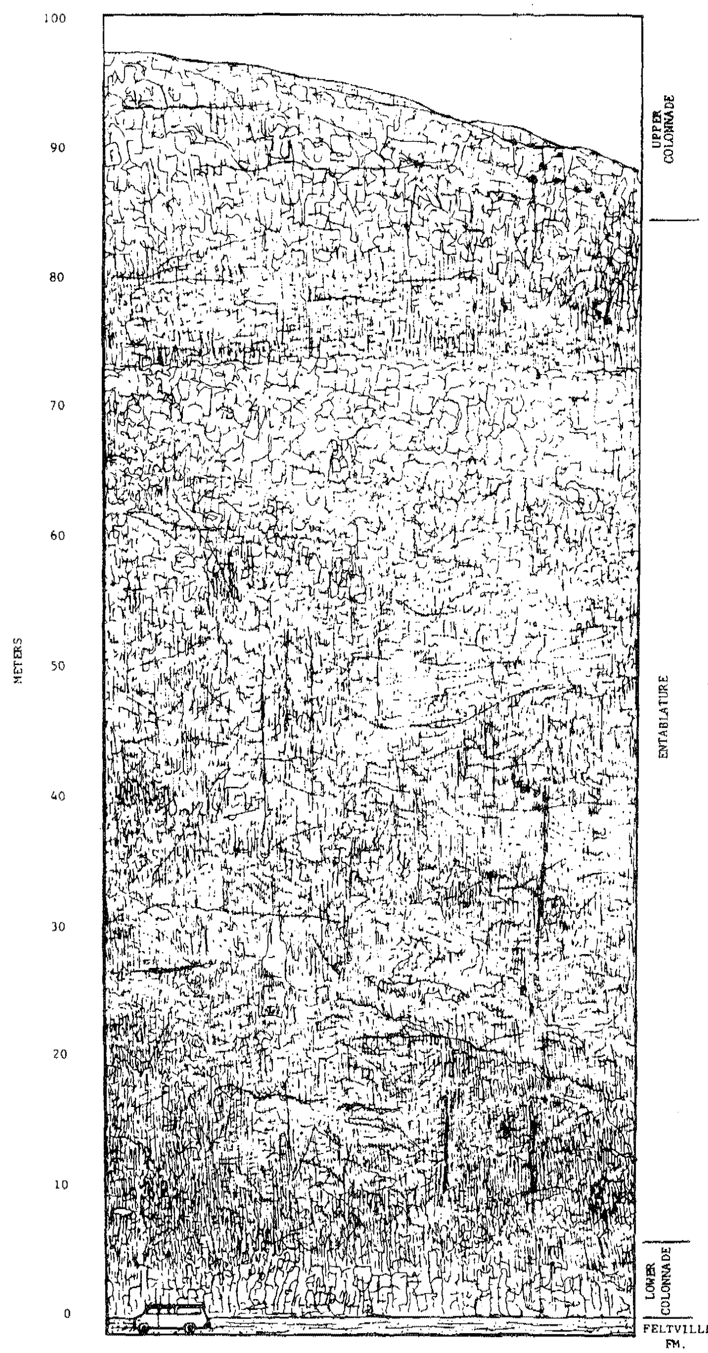


Fig. 9 Type section of the Preakness Mountain Basalt. Section located along Interstate 280, 2.25 km west of type section of the Orange Mountain Basalt. Section traced from composite of continuous photographs.

Preakness Basalt may be the youngest formation represented outside the Watchung Syncline. There are small masses of basalt at the northwestern edge of the New Germantown and Sand Brook Synclines, but it is unclear (because of poor exposure) whether these beds are lying stratigraphically above the Feltville or rare merely upthrown fault slices of the Orange Mountain Basalt (Olsen, in press). Some geochemical evidence supports the former hypothesis (Geiger, Puffer, and Lechler, 1980).

At its base, the Preakness Basalt is much more variable than the Orange Mountain Basalt. Locally, there are thick sequences of multiple basalt flows making up possible basalt foreset beds (Manspeizer, this Fieldbook). In other areas there are thick beds of angular and vesicular basalt breccia resembling aa. In still other areas the thick massive lower flow rests on the flat Feltville Formation surface (Lewis, 1908).

At least two or three thick individual flows make up the bulk of the Preakness Basalt. The lowest flow is the thickest (+100 m) and is exposed througout the Watchung Syncline usually showing a complete although modified Tomkeieff structural sequence (Figure 9). In most outcrops the entablature is coarsely grained and very densely jointed, forming high, irregularly jointed columns 0.1-1.0 m wide, in marked contrast to the hexagonally jointed Orange Mountain Basalt. This characteristic joint pattern, which Faust (1978) calls platy prismatic (in contrast to cooling joints), allows the Preakness Basalt to be identified at isolated outcrops (Olsen, in press). The first flow is separated from the second by a thin red siltstone, the distribution of which was mapped by Kümmel (1897) and Lewis (1907b) in the southern portion of the Watchung Syncline (but see Faust, 1975). The extent of the second flow outside this area is poorly known, although its extension into the northern Watchung Syncline is supported by some well data and known outcrop patterns (Darton, 1890;) Lewis, 1907b). There is at least one other flow present in the northern Watchung Syncline, separated by what I assume to be the second flow of the Preakness Basalt by a red and buff siltstone riddled with root casts. Faust, on the other hand (1975), feels this upper flow is the second. Darton (1890) presents evidence, partially confirmed by later field work (Olsen, in press), that the Preakness Basalt consists of three flows at Pompton, New Jersey. As with the Orange Mountain Basalt, more field work is required to clarify the number and distribution of flows in the Preakness Basalt.

TOWACO FORMATION

The name Towaco Formation is applied to the red, gray and black sedimentary (and minor volcanoclastic) rocks present below the Hook Mountain Basalt and above the Preakness Basalt in the Watchung Syncline (Olsen, in press). The type section is the Essex County Department of Park Recreation and Cultural Affairs, Walter Kidde Dinosaur Park (Roseland or Riker Hill Quarry), Roseland, New Jersey, where 50 m of the uppermost Towaco Formation is exposed, making up 15% of 340 m present in that area (Figure 10, Table 7).

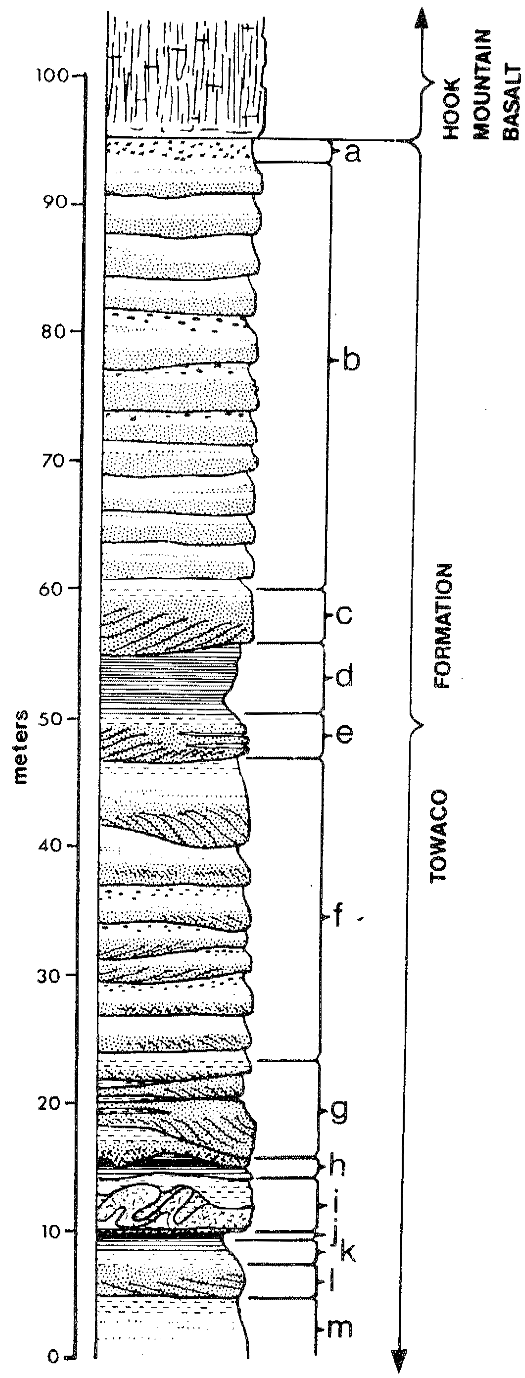


Fig. 10 Type section of the Towaco Formation in the Dinosaur Tract, Essex County Park Commission, Roseland, New Jersey. For key to individual units see Table 7.

Laterally continuous symmetrical sedimentary cycles characterize most of the Towaco Formation. These consist of a central black or gray microlaminated calcareous siltstone bounded above and below by gray sandstone and siltstone beds arrange in fining-upwards cycles. These symmetrical cycles are a mean of 35 m thick and bear a close resemblance to the East Berlin Formation (Hartford Basin) cycles described by Hubert, Reed, and Carey (1976). Towaco cycles are an order of magnitude thicker than Lockatong or Passaic Formation detrital cycles and differ from the otherwise similar Feltville Formation non-red unit in containing a predominantly clastic rather than carbonate laminated portion (Figure 13). In total, six such cycles have been identified in the upper half of the Towaco Formation and most of these have been traced through the Watchung Syncline.

Beds of conglomerate occur at numerous horizons through the Towaco Formation at Pompton, New Jersey. Not only is conglomerate present directly below the Hook Mountain Basalt in this area (Faust, 1975), but thick conglomerate beds also occur at intervals of about 120-150 m. 160-170 m, 185-195 m, 205-220 m, and 270-280 m below the Hook Mountain Basalt. As a general comment, I see no special relationship between the position of any Passaic-Boonton conglomerate beds and lava flows (*contra* Faust, 1975). Clast composition, especially the inclusion of basalt fragments, may be important, however.

There is a thin brown volcanoclastic unit at the top of the Towaco Formation. It is about 1 m thick and occurs at most exposures of the upper Towaco Formation. It is especially well exposed at the type exposure. This volcanoclastic unit is in the same position as the flow-breccia described by Faust (1978) at Pompton. Lewis (1908) has been the only worker to study unweathered sections of this volcanoclastic unit and he described it as consisting of altered volcanic glass with inclusions of feldspar and augite and pseudomorphs after olivine in a matrix of brown radial natrolite.

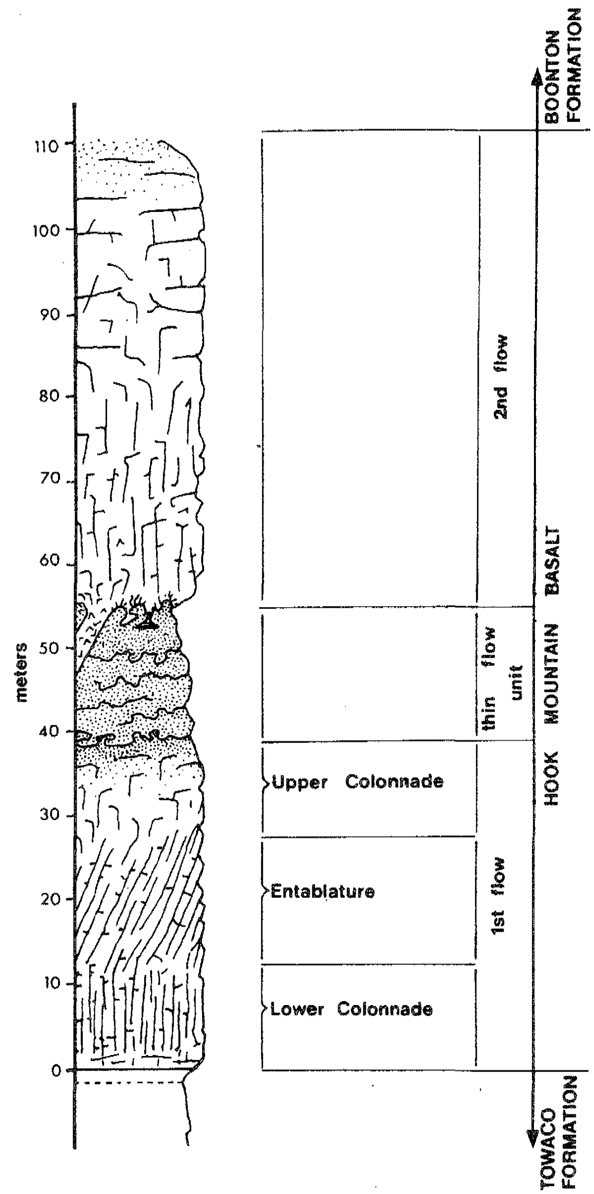


Fig. 11 Type section of the Hook Mountain Basalt. Note two major flow units and interbedded thin pahoehoe flows and possible feeder dike. Section exposed along Interstate 80 near Pine Brook, New Jersey.

HOOK MOUNTAIN BASALT

The uppermost extrusive unit in the Watchung Syncline is called the Hook Mountain Basalt (see Baird and Take, 1959). The name is taken from its type exposures (Figure 11) in cuts along Hook Mountain Road and Interstate Route 80 through the southern tip of Hook Mountain near Pine Brook, New Jersey. About 80% of the total formation is exposed there (Olsen, in press).

The Hook Mountain Basalt is the thinnest of the three major extrusive formations of the Newark Basin; at its type section, it is 110 m thick and it retains this thickness throughout the Watchung Syncline. That this basalt extends subsurface across the gaps between Hook Mountain and Riker Hill and between Riker Hill and Long Hill is shown by the bedrock topography maps of Nichols (1968) and the aeromagnetic data of Henderson, *et al.* (1966). In the area of Bernardsville, New Jersey, what has been mapped (Lewis and Kümmel, 1910-1912) as part of the Preakness Basalt is in fact Hook Mountain, as shown by unambiguous exposures of Towaco Formation between it and the underlying basalt. This portion of Hook Mountain Basalt I have traced nearly to the Long Hill portion. The remaining gap is probably due to a series of small faults.

Aeromagnetic data (Henderson, *et al.*, 1966) is no help in this area since the faults would probably run about N-S and thus be parallel with linears caused by errors in the alignment of flight paths. These newly mapped portions of the Hook Mountain Basalt are shown in Figure 2.

Two flows have been recognized through most of the Watchung Syncline. At the type section the lower flow is 57 m thick and shows a complete Tomkeieff structural sequence (Figure 11), while the upper flow is more massive, without clear columnar jointing. As is the case for the flows which make up the older two basalt formations of the Newark Basin, it is not definitely clear that the upper and lower flows of the Hook Mountain Basalt represent continuous sheets over the extent of the whole formation.

BOONTON FORMATION

Overlying the Hook Mountain Basalt are sedimentary rocks that Baird and Take (1959) termed the Boonton and Whitehall beds of the Brunswick Formation. I have proposed the formal name Boonton Formation for these beds, the type section being near Boonton, New Jersey along the Rockaway River (Figure 12) (Olsen, in press). The Boonton Formation is the youngest sedimentary unit in the Newark Supergroup sequence of the Newark Basin and consists of more than 500 m of red, brown, gray, and black fine to coarse clastics and minor evaporitic beds.

The stratigraphically lowest beds in the Boonton Formation are well exposed near Bernardsville, New Jersey. In this area, the formation consists of blocky to finely bedded red, gray, brown, and black, often dolomitic siltstone. Thin (1-4 m) beds riddled with hopper casts (pseudomorphs after gypsum, glauberite, and halite) are common in sequences of all colors. Similar beds are exposed along Packanack Brook, Wayne, New Jersey. The different colors or textures of these beds do not seem to be arranged in any obvious or consistent cyclic pattern and resemble no other units in the Newark Basin. Stratigraphically above these lower beds is a sequence of well-bedded red siltstones and sandstone beds (mean thickness 35 m) alternating with thinner beds of gray-green siltstones (mean thickness 2 m). The longest continuous section of these beds is the type section (Figure 13). The uppermost beds of the type section include a bearing fossil fish calcareous gray microlaminated siltstone at least one meter thick (Smith, 1900). This is the famous Boonton Fish Bed (Newberry, 1888; Schaeffer and McDonald, 1978). Also in this section are gray and brown conglomerate units up to 0.5 m thick. Along the western edge of the Watchung Syncline, northeast of Morristown, New Jersey are thick sequences of red-, gray-, and brown-matrix conglomerate and breccia. The relationships of these units to the finer portions of the formation are unclear.

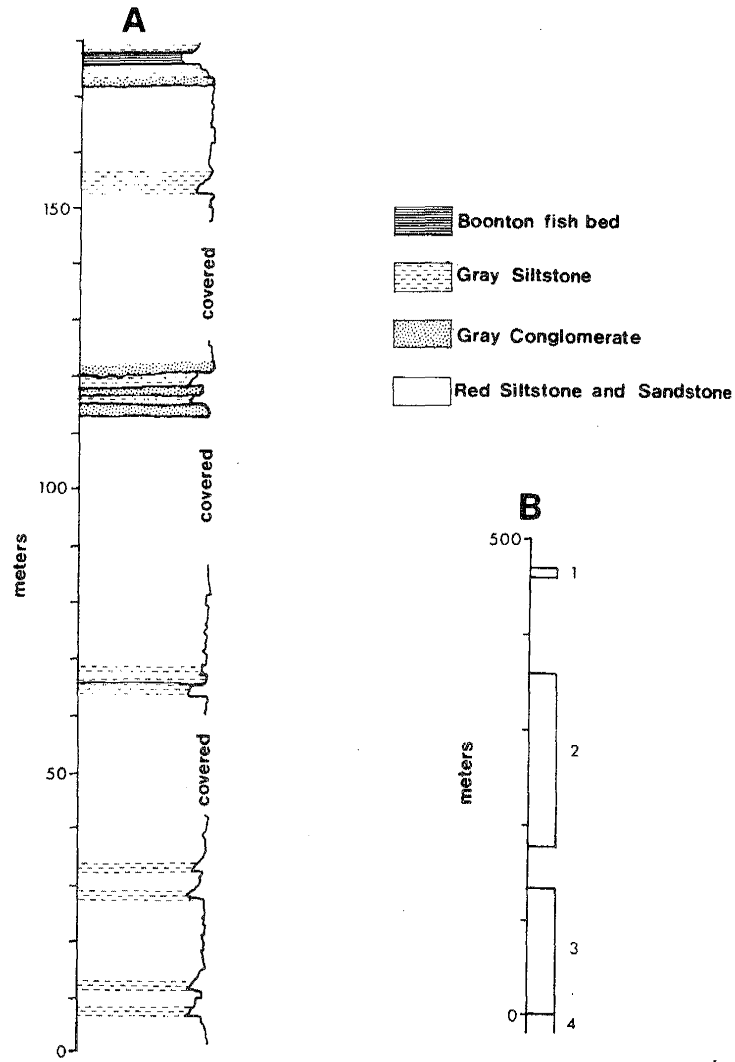


Fig. 12 Type section of the Boonton Formation: A, section exposed along Rockaway River in Boonton, New Jersey; B, composite section of entire preserved Boonton Formation; red matrix conglomerate exposed at Chestnut Hill, Morristown, New Jersey; 2, beds making up the type section; 3, gray, black, brown, and red siltstones exposed near Bernardsville, New Jersey; 4, Hook Mountain Basalt.

DIABASE INTRUSIONS

Large diabase and gabbro plutons and sills are emplaced through various portions of the pre-Orange Mountain Basalt section of the Newark Basin sequence. The areal extent, petrography, and contact relationships of these masses are, for the most part, well known (Darton, 1890; Kümmel, 1897, 1898; Lewis, 1908; Lewis and Kümmel, 1910-1912; Willard, *et al.*, 1959; Hotz, 1952) and will not be described in detail here. These bodies

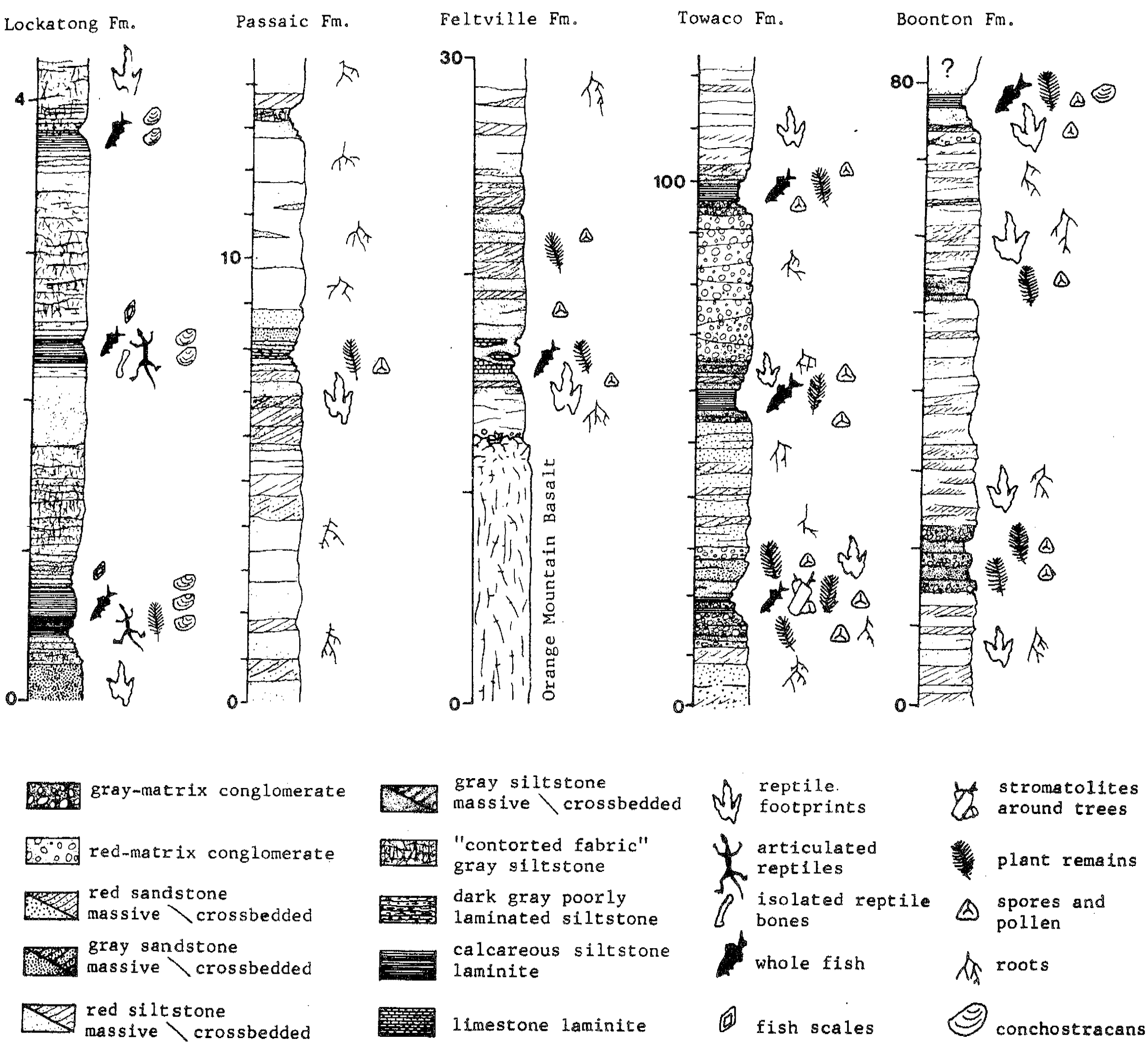


Fig. 13 Major types of sedimentary cycles of the formations of the Newark Basin. Note that the approximate center of the symbols for the major types of fossils found is placed about where they occur in the section to the left. Note the change in scale (in meters) from section to section.

Lockatong Formation section measured at Kings Bluff, Weehawken, New Jersey and represents three detrital cycles. The Passaic Formation section measured along Nishisakawick Creek and Little Nishisakawick Creek, northeast of Frenchtown, New Jersey; the two cycles shown represent the lower portion of McLaughlin's Graters Member (i.e., Member G) and are characteristic of most of the detrital cycles of the Passaic Formation. The upper cycle develops a dark gray siltstone a kilometer to the south. Feltville Formation section measured along East Branch of Middle Brook, Martinsville, New Jersey--there is only one such "cycle" in the Feltville Formation. Towaco Formation section measured along stream 2 km southwest of Oakland, New Jersey; three cycles are shown. Boonton Formation section is upper part of type section (see Figure 12); section not clearly cyclic.

generally parallel the distribution of major bodies of gray and black siltstones; thus the largest intrusives are broadly concordant (but locally discordant) to the Lockatong Formation (i.e., Palisade, Rocky Hill, and Sourland Mountain sills) or the Perkasie Member of the Passaic Formation (Haycock Mountain, Coffman Hill, and possibly the Cushetunk Plutons). The general pattern is for these intrusions to be emplaced progressively higher in the Newark Basin section viewed along an east to west section (Figure 6).

Like most Newark Supergroup deposits, Newark Basin beds are cut by a number of narrow, often straight and vertical diabase dikes which, in this area, trend north and northeast. The mapping of the distribution of these dikes is still very incomplete (see King, 1971, and May, 1971, for reviews).

PALEONTOLOGY AND BIOSTRATIGRAPHY

In contrast to the famous Triassic and Jurassic deposits of Europe, China, southern Africa, and southwestern United States, Newark Basin beds have been traditionally regarded as fossil-poor. Recently, however, this opinion has changed; it is now clear that every major sedimentary unit of the Newark Basin has its own suite of abundant fossils. Pollen and spores, megafossil plants, clams, arthropods, fish, reptile footprints, and even reptile skeletons are abundant in certain units through the Newark. Considering the very large number, high diversity, and excellent quality of Newark fossils and the very long (ca. 35 million years) time span represented by the fossiliferous beds, the Newark Basin section is certain to be a key factor in understanding the larger aspects of Early Mesozoic historical geology. Detailed descriptions of some individual sites are presented in Olsen, (this Fieldbook). Here the sediment-fossil relationships and the biostratigraphic framework of the Newark Basin section will be outlined.

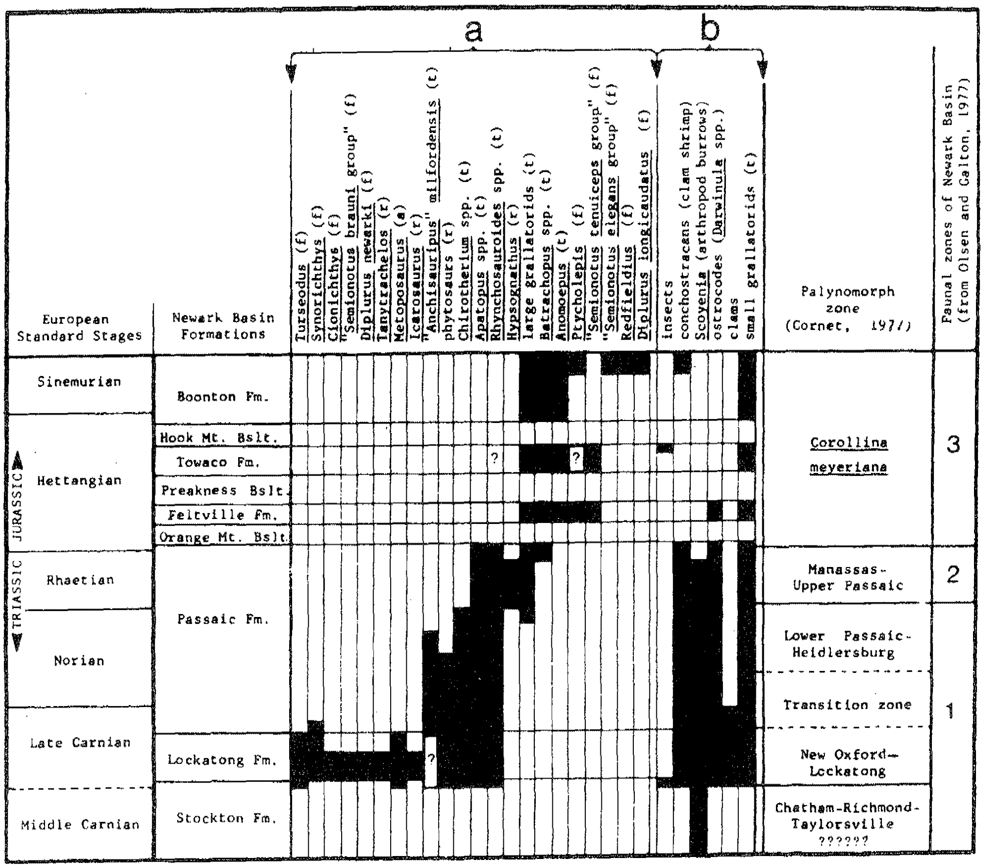
The bulk of Newark Basin sediments are red clastics. Throughout the basin, these beds are riddled with roots and burrows. As a general trend, bioturbation of all kinds is more intense in the older red beds (Stockton-Passaic) than in the younger. The arthropod burrow *Scoyenia* (see Olsen, 1977) is the most common trace of macro-bioturbation in the pre-basalt red clastics. Reptile footprints are abundant throughout the red beds in association with gray and black sedimentary cycles, and locally in red beds along the basin edge where bioturbation is not intense. Claystone-replaced megafossil plants occur in thin belts of red and purple siltstone near the base of the Stockton. Common plants include cycadeoids, conifers, and equisetalians. Newark Basin red sandstones have yielded a series of reptile skeletons, especially in the area of Passaic, New Jersey in the upper Passaic Formation (Colbert, 1946). Despite a notable lack of good exposures in this area, skulls and skeletons of the procolophonid reptile *Hypsognathus* show up at a rate of more than one per decade. Systematic collection in Newark Basin red beds would probably yield many more vertebrate remains. Most kinds of fossils, however, are more abundant in the gray and black facies of the Newark Basin, especially in the sedimentary cycles which characterize the Lockatong, Passaic, and Towaco formations. The distribution of characteristic fossils in these sequences is given in Figure 13. The discovery of large numbers of fossils in the Newark Basin (as well as throughout the Newark Supergroup) has prompted a restudy of the biostratigraphic relationships of the sequence as a whole.

The basic biostratigraphic framework for Newark Basin deposits has been outlined by Olsen and Galton (1977) and by Cornet (1977), and the details of this correlation will be given elsewhere (Olsen, McCune, Thomson, in press; Olsen, Baird, Salvia, MS; Colbert and Olsen, MS). Here I will simply outline the distribution of taxa within the Stockton through Boonton Formations and tie these in with the regional correlation (Table 8, Figure 14).

For regional correlation, relatively heavy emphasis has been placed on the distribution of palynomorph taxa (Cornet, 1977, and pers. comm.), especially for correlation between the upper Newark and the European type Early Jurassic (Figure 14). Tetrapod data, both in the form of skeletal remains and footprints, parallel the palynomorph data, and have been essential in correlating regions from which floral data is not available, such as the upper Stormberg (J.M. Anderson, pers. comm.). For fine internal correlation of the Early Jurassic portions of the Newark, however, the biostratigraphic subdivisions based on pollen and spores have proved too broad (Cornet, 1977). In these areas, fossil fish have provided a means of correlation (Olsen, McCune, and Thomson, in press).

The broad aspects of this biostratigraphic correlation agrees with most geophysical data, particularly the paleomagnetic work of McIntosh (1976) and Reeve and Helsley (1972) on the Newark Basin section and on the Chinle Formation (southwestern United States). In addition, radiometric dates of Newark Basin basalts suggest a Jurassic age for these units (Armstrong and Besancon, 1970; Dallmeyer, 1975; Sutter and Smith, 1979; K.K. Turekian, pers. comm.) It must be noted, however, that current geophysical techniques are too inconsistent for the data to be used in fine-scale correlation of individual formations of the Newark Supergroup.

A



B

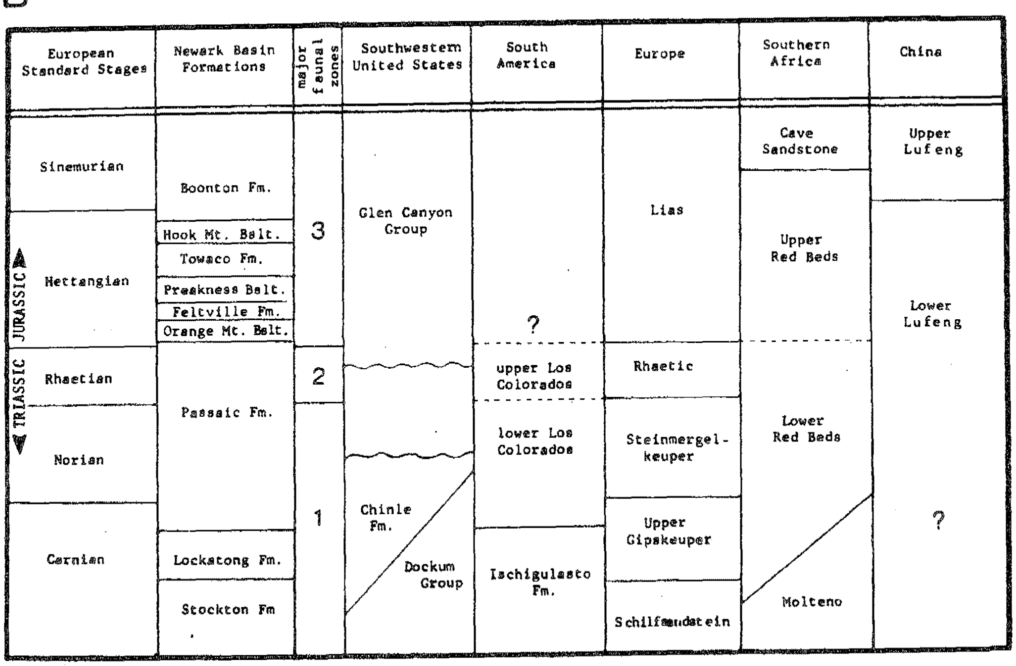


Fig. 14

A. Distribution of most abundant vertebrate and invertebrate fossils in the Newark Basin; a, taxa thought to be biostratigraphically important; b, taxa thought to be of little or no stratigraphic value. Letters in parenthesis--(f), (r), (a), (t)--indicate nature of fossils: (a) amphibians; (f) fish; (r) reptiles; (t) reptile footprints.

B. Correlation of the formations of the Newark Basin with other Mesozoic sequences.

Data for A and B from: Cornet (1977); Olsen (in press; Olsen and Galton (1977); Olsen, McCune, and Thomson (in press); Olsen, Baird, and Salvia (MS); and Olsen and Colbert (MS).

Table 3A. Type section of the Stockton Formation

Thickness (meters)	Description
30.5	purplish, gray, reddish brown, and red hard siltstone
250.0	red and brown siltstone and sandstone with minor beds of gray sandstone
46.3	RAVEN ROCK MEMBER, massive white, gray, and buff, medium and coarse arkose
298.9	white, gray, buff, and red sandstone, (soft) and medium to coarse arkose with minor beds of red siltstone
106.1	CUTALOSSA MEMBER, hard white, gray, buff, and red sandstone and medium and coarse arkose
95.8	poorly exposed red sandstone and siltstone
231.0	PRALLSVILLE MEMBER, white, gray, buff, yellow, and some red sandstone and medium and coarse arkose with some quartz complomerate
137.6	gray and red sandstone and medium arkose
172.8	SOLEBURY MEMBER, white and gray arkosic conglomerate with minor beds of red siltstone and sandstone
217.2	interbedded gray, white, and buff coarse arkose, quartz conglomeratem and red sandstone and siltstone

BASE OF NEWARK BASIN SECTION

Table 3, B

Bucks-Hunterdon fault block (McLaughlin, 1945, 1946)	Montgomery-Chester fault block (Rima, Meisler, and Longwill, 1962)
mostly red siltstone and sandstone above Raven Rock Member	Upper Shale Member
beds above Prallsville Member to top of Raven Rock Member also includes Cutalossa Member	Middle Arkose Member
beds from basement contact to top of Prallsville Member also includes Solebury Member	Lower Arkose Member

Table 3

A. composite type section of the Stockton Formation; adapted from McLaughlin (1945). Exposures occur in ravines, roadside exposures, and quarries on both shores of the Delaware River near Stockton, New Jersey.

B. equivalence of McLaughlin (1945) and Rima, Meisler, and Longwill's (1962) members of the Stockton Formation.

Designation of member	Thickness (meters)	Description
base of Passaic Formation		
"Transition"	7.6	interbedded red, gray, and brown hard siltstone
B	48.8	gray and black siltstone
"Double Red"	30.2	two beds of red hard siltstone sandwiching a bed of gray and black siltstone
A_2	81.2	black hard siltstone
"Smith's Corner"	3.4	red hard siltstone
A_1	87.2	black hard siltstone
"Triple Red"	45.5	three thick beds of hard red siltstone alternating with two beds of gray and black siltstone
no name	75.3	hard black siltstone
"First Big Red"	33.5	red hard siltstone
no name	84.1	hard black siltstone
"First Thin Red"	4.6	red hard siltstone
no name	305.0	black and gray hard siltstone
Byram Diabase	64.1	
no name	18.3	hornfels of hard black siltstone
no name	91.5	massive, hard, black siltstone with much interbedded light gray hard calcareous siltstone and impure limestone
no name	80.8	thick bedded hard black siltstone
no name	22.9	thick bedded hard black siltstone with interbedded hard brown siltstone
no name	33.6	interbedded red, purple, and black hard siltstone
base of Lockatong Formation		

Table 4

Composite type section of the Lockatong Formation, adapted from McLaughlin (1944, 1945). Measured sections exposed along the east and west banks of the Delaware River. The actual type section as designated by Kümmel is the bed of Lockatong Creek; these exposures have never been measured in detail.

Section E.

+10 m	massive basalt, base of Orange Mountain Basalt
.9 m	brown massive sandstone
4.2 m	red sandstone beds fining-upwards into beds of red siltstone with numerous carbonate nodules

Section D.

+ 3 m	red, cross-bedded sandstone

Section C.

3 m	2 fining-upwards sequences consisting of beds of red, irregularly cross-bedded sandstone grading upwards into beds of red siltstone. Laminated, carbonate-rich oblong chips and concentric carbonate accretions at base of sandstones.

Section B.

3.2 m	red, fissile siltstone beds sandwiching three beds of yellow-orange, coarse siltstone and sandstone.
2.6 m	red fissile to blocky siltstone
2.2 m	2 fining-upwards sequences of red sandstone and siltstone
+1.5 m	red blocky siltstone

Section A.

14.2 m	4 fining-upwards sequences of red feldspathic sandstone grading upwards into red blocky siltstone
26.0 m	covered
4.6 m	red siltstone
41.0 m	covered
16.4 m	fining-upwards sequences of red feldspathic sandstone grading into red fissile to blocky siltstone
2.0 m	diabase dike surrounded by .3 m zone of black hornfels
+3.0 m	red blocky siltstone
5.0 m	covered
1.7 m	red cross and planer bedded sandstone and siltstone
4.0 m	covered
4.6 m	red sandstone and siltstone beds
2.0 m	covered
1.2 m	red sandstone and siltstone, _Scoyenia_ abundant
48.0 m	covered
8.7 m	3 fining-upwards sequences of red feldspathic sandstone with strongly down cutting bases, grading up into red blocky siltstone.

Table 5

Type section of the Passaic Formation and key to Figure 4. Section exposed at intervals along Interstate Route 80, from Ridgefield to Paterson, New Jersey. Details of section in Olsen, in press. Sections measured from top down.

Unit a		
	+4.0	buff to red-purple feldspathic sandstone and siltstone
Unit b		
	.5 m	green and red ripple-bedded siltstone
	1.0 m	gray and red limestone and siltstone beds, laminated at the base. Fossil fish abundant. In other near-by sections, this unit is black.
	1.54m	beds of gray and red siltstone and fine ripple-bedded sandstone with abundant roots and reptile footprints.
Unit c		
	11.0 m	-1 m thick beds of buff and red sandstone grading up into beds of blocky red siltstone with roots. Lower beds contain breccia of upper Orange Mountain Basalt.

Table 6

Type section of the Feltville Formation and key to Figure 8. Section exposed in bluff on west side of Blue Brook about 1 km south of the dam for Lake Surprise in the Watchung Reservation, Union County, New Jersey (Details in Olsen, in press). Section measured from top down.

Table 7. Type section of the Towaco Formation

Unit a		
	.9	brown, badly weathered, palgonitic unit
Unit b		
	32.3	11 red fining-upwards cycles, each a mean of 2.9 m thick and composed of thick beds of red sandstone or coarse siltstone grading up into beds of red ripple-bedded or blocky siltstone. Uppermost cycle is lavender in color and the lowest cycle contains a buff intraformational breccia with scattered vertebrate remains. Dolomitic concretions, root casts, and reptile footprints common.
Unit c		
	3.4	Gray, buff, and lavender fining-upward sequences of sandstone and siltstone, plant fragments, reptile footprints, and roots common.
Unit d		
	2.6	fine gray to black siltstone base with prominent black, microlaminiated, calcareous siltstone. Upper parts of black unit contain chert nodules. Very fragmentary fish and insects present along with well preserved plant fragments.
Unit e		
	2.5	Gray-buff, well-bedded, upwards-fining siltstone and sandstone with dinosaur footprints and abundant roots.
Unit f		
	21.0	7 upwards-fining cycles similar to those of unit b. Upper-most cycle very thick (4.2 m) with extremely good reptile footprints. The uppermost beds of this cycle are gray-green.
Unit g		
	5.2	2 or 3 upward-fining cycles of gray sandstone and siltstone. Upper-most cycle grades into red siltstones. Plant fragments and reptile footprints locally abundant. Siltstones palyniferous.
Unit h		
	.8	black, microlaminated, calcareous siltstone grading upwards into gray, graded sandstones. Fossil fish and plant stems abundant.
	5.1	olive, massive, convoluted, poorly sorted siltstone grading up into beds of poorly sorted gray and black siltstone. Some recumbant folds over 1 m between limbs.
Unit j		
	.5	black laminated, calcareous siltstone similar to unit h, but without fossil fish.
Unit k		
	.6	very fine, gray siltstone grading upwards into j.
Unit l		
	3.0	gray fining-upwards sequence grading into fissile siltstone. Plant remains common.
Unit m		
	5.3	red, ripple-bedded siltstone, upper 1 m gray.

Table 7

Type section of the Towaco Formation in the Dinosaur Tract of the Essex County Park Commission, Roseland, New Jersey (key to Figure 10). Lower beds of unit f and all beds below are now covered. Details of section in Olsen, in press. Section measured from top down.

Table 8. Distribution of Taxa within the Stockton through Boonton Formations.

STOCKTON FORMATION		
Plants		
Equisetales (scouring rushes)		
Neocalamites sp.	lower - upper Stockton	Willard, *et al.*, 1959; Bascom, *et al.*, 1938; Brown, 1911, Bock, 1969
Coniferales (conifers)		
Pagiophyllum diffusum	upper Stockton	Cornet, 1977; Bock, 1969
P. simpsonii	" "	" " " "
Glyptolepis spp.+	" "	" " " "
Rotundolepis intermedia	" "	" " " "
Araucarioxylon spp.+	lower - ?upper Stockton	Wherry, 1912
Podozamites spp.	upper Stockton	Willard, *et al.*, 1959; Bascom, *et al.*, 1938
Bennettitales (cycad-like seed plants)		
Zamites spp.	lower - upper Stockton	Brown, 1911; Bascom, *et al.*, 1938; Willard, *et al.*, 1959
Pterophyllum spp.	" " "	Willard, et al., 1959; Bascom, *et al.*, 1938; Lyman, 1902
seed plants of uncertain affinities		
Eoginkoites	upper Stockton	Bock, 1969; Cornet, 1977
Invertebrates		
Mollusks		
Unionid clams		Lewis, 1884; Richards, 1944
Arthropods		
Darwinula spp.	" "	YPM (IP) 28805
Cyzicus	" "	Kummel, 1897; YPM (IP) 28804
Scoyenia (burrows)*	" "	YPM (IP) 28806
Koophichnium sp.* (limulid tracks)	" "	Caster, 1939

Table 8. (cont'd.)

Insects		
beetle elytron	" "	YPM (IP) 28803
Vertebrates		
Amphibians		
Calamops paludosus	lower Stockton	Sinclair, 1917; Olsen, et al., MS
Metoposaurus sp.	upper Stockton	Olsen, et al., MS.
Reptiles		
{cf. *Rutiodon* (*Phytosaurus*) *manhattanensis*}	" "	Von Huene, 1913
phytosaur teeth	" "	Olsen, et al., MS

LOCKATONG FORMATION AND STOCKTON LATERAL EQUIVALENT

Plants		
Equisetales (scouring rushes)		
Equisetites sp.	lower Lockatong	Bock, 1969
Coniferales (conifers)		
Pagiophyllum spp.	" "	" "
Glyptolepis spp.	" "	" "
Invertebrates		
Mollusks		
Unionid clams	lower Lockatong	Conrad, 1858, 1870

Table 8. (cont'd.)

Arthropods		
Darwinula spp.	through Lockatong	YPM (IP) 28809
Cyzicus spp.	" "	Jones, 1862; Bock, 1953
cf. *Palaeolimnadia*	" "	YPM (IP) 28802
*Scoyenia**	through Lockatong and Stockton lateral equivalent	YPM (IP) 28810, YPM 8262
Vertebrates		
Fishes		
Carinacanthus jepseni	lower Lockatong	Bryant, 1934
Turseodus spp.	through Lockatong	Schaeffer, 1952b; Olsen, McCune and Thomson, in press
Synorichthys sp.	" "	Schaeffer and Mangus, 1970; Olsen, McCune, and Thomson, in press
Cionichthys sp.	lower Lockatong	Bock, 1959; Olsen, McCune, and Thomson, in press
Semionotus brauni sp.	" "	Newberry, 1888; Olsen, McCune, and Thomson, in press
Diplurus newarki	" " "	Bryant, 1934; Schaeffer, 1952a; Olsen, McCune, and Thomson, in press
Amphibians		
Metoposaurus durus	" "	Cope, 1866; Colbert and Imbrie, 1956; Olsen, *et al.*, MS
Reptiles		
"deep tailed swimmer"	" "	Colbert and Olsen, MS.
Tanytrachelos ahynis	" "	Olsen, 1979
Icarosaurus seifkeri	" "	Colbert, 1966
Rutiodon spp.	through Lockatong	Cope, 1869; Colbert, 1965
phytosaur bones and teeth	through Lockatong and Stockton equivalent	Colbert, 1965; Olsen, *et al.*, MS.
Rhynchosauroides spp.*	" "	Bock, 1969; Olsen, *et al.*, MS.
*Gwyneddichnium**	lower Lockatong	Bock, 1969
*Apatopus lineatus**	through Lockatong and Stockton equivalent	Olsen, *et al.*, MS.

Table 8. (cont'd.)

Chirotherium cf. *eyermani**	Stockton equivalent	Olsen, *et al.*, MS.
"*Anchisauripus*" cf. *milfordensis**	lower Lockatong	Bock, 1969; Baird, 1957
Grallator spp.*	through Lockatong and Stockton equivalent	Bock, 1969; Olsen, *et al.*, MS.

PASSAIC FORMATION AND LOCKATONG LATERAL EQUIVALENT

Plants		
Equisetales (scouring rushes)		
Neocalamites sp.	lower to middle Passaic	Newberry, 1888
Filicales (ferns)		
Clathropteris sp.	middle Passaic	Newberry, 1888
Coniferales (conifers)		
Pagiophyllum spp.	lower to uppermost Passaic	Cornet, 1977; Bock, 1969
Brachyphyllum spp.	uppermost Passaic	Cornet, 1977
Glyptolepis platysperma+	middle Passaic	Cornet, 1977; Bock, 1969
G. keuperiana+	" "	" " " "
Bennettitales (cycad-like seed plants)		
?*Zamites* (*Dioötes*) sp.	" "	Newberry, 1888
?*Pterophyllum* (*Brunswickia dubium*)	" "	Wherry, 1959
Cycadales (cycads)		
Otozamites sp.	uppermost Passaic	Cornet, 1977
Invertebrates		
Arthropods		
Kouphichnium	lower Passaic	PU 22002

Cyzicus sp.	lower Passaic	Cornet, 1977; YPM
Scoyenia*	lower through upper Passaic	PU 21517
Vertebrates		
Fishes		
Semionotus sp.	lower Passaic	Olsen, McCune, and Thomson, in press
Synorichthys	" "	" " " "
Reptiles		
Hypsognathus fenneri	upper Passaic	Colbert, 1946
Sphodrosaurus pennsylvanicus	middle Passaic	Colbert, 1960
Stegomus arcuatus		Jepson, 1948
Clepsysaurus pennsylvanicus	upper Passaic	Lea, 1851; Colbert and Chaffee, 1941
phytosaur maxilla	middle Passaic	UPM 3772
Rhynchosauriodes brunswicki*	lower and middle Passaic	Ryan and Willard, 1947; PU 21520; Baird, 1957
R. hyperbates *	middle Passaic	Baird, 1957
cf. Rhynchosauroides sp.*	uppermost Passaic	PU 222140; 22204
Gwynnedichnium sp.*	lower Passaic	YPM 7556
Apatopus lineatus*	lower through upper Passaic	Baird, 1957
Apatopus lineatus*	upper Passaic	PU 21235
Chirotherium lulli*	middle Passaic	Baird, 1953
C. parvum*	" "	Baird, 1957
C. eyermani*	" "	" "
Chirotherium sp.*	lower Passaic	YPM 7555
"Grallator" sulcatus*	middle Passaic	Baird, 1957
"Anchisauripus" milfordensis	lower and middle Passaic	Baird, 1957; YPM 7554
small Grallator spp.*	lower through upper Passaic	Baird, 1957; PU21517
large Grallator spp.*	upper and uppermost Passaic	PU 21900; 21901; 21519
Batrachopus sp.*	uppermost Passaic	PU 22214b

FELTVILLE FORMATION

Plants		
Equisetales (scouring rushes)		
Equisetites spp.	lower Feltville	Cornet, 1977
Filicales (ferns)		
Clathropteris meniscoides	lower and middle Feltville	Newberry, 1888; Cornet, 1977
Coniferales (conifers)		
Brachyphyllum scottii	lower Feltville	Cornet, 1977
Brachyphyllum spp.	lower and middle Feltville	" "
Pagiophyllum spp.	lower Feltville	" "
Hirmerella cf. *muensteri*+	" "	" "
Masculostrobus spp.+	" "	" "
Cycadales (cycads)		
Otozamites sp.	" "	Cornet, 1977
Invertebrates		
Arthropods		
Darwinula sp.	" "	YPM (IP) 28807
Vertebrates		
Fishes		
Ptycholepis cf. marshi	" "	{Schaeffer, Dunkle, and McDonald, 1977}
"*Semionotus tenuiceps* group"	" "	{Olsen, McCune, and Thomson, in press}

Table 8 (cont'd.)

Reptiles		
small Grallator spp.	lower through upper Feltville	YPM 6636
large Grallator spp.	" " " "	YPM 8666
Anomoepus sp.	upper Feltville	AMNH 3639
Batrachopus cf. deweyi	" "	PU 18564
TOWACO FORMATION		
Plants		
Equisetales (scouring rushes)		
Equisetites sp.	through Towaco	Cornet, 1977
Filicales (ferns)		
cf. Phelbopteris sp.	middle Towaco	YPM (PB) 3771
Coniferales (conifers)		
Brachyphyllum spp.	through Towaco	Cornet, 1977
Pagiophyllum spp.	" "	" "
Invertebrates		
Insects		
beetle elytron	upper Towaco	YPM (IP) 28808
Vertebrates		
Fishes		
"Semionotus tenuiceps group"	through Towaco	{Olsen, McCune, and Thomson, in press}
Semionotus spp.	" "	" " " "

Reptiles		
cf. Rhynchosauroides sp.*	upper Towaco	PU 18563
Batrachopus sp.*	through Towaco	PU 19911
small Grallator spp.*	" "	RU main display slab
large Grallator spp.*	" "	RU " "
Anomoepus spp.*	" "	RU " "
BOONTON FORMATION		
Plants		
Equisetales (scouring rushes)		
Equisetites sp.	through Boonton	YPM (PB) 3769
Coniferales (conifers)		
Brachyphyllum spp.	" "	YPM (PB) 3770
Invertebrates		
Arthropods		
cf. Palaeolimnadia sp.	middle Boonton	YPM 6567
Vertebrates		
Fishes		
Ptycholepis sp.	" "	Schaeffer, Dunkle, and McDonald, 1977
Redfieldius cf. gracilis	" "	Schaeffer and McDonald, 1978
Redfieldius spp.	" "	Olsen, McCune, and Thomson, in press
"Semionotus elegans group"	" "	" " " "
Diplurus longicaudatus	" "	Newberry, 1888
Reptiles		
Batrachopus sp.*	" "	YPM 7558
small Grallator spp.*	" "	" "
large Grallator spp.*	" "	AMNH uncatalogued specimen in Cope collection
Anomoepus sp.*	" "	I. C. Russell (N.D.)

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ROAD LOG

This field trip is a traverse along Route 80 which intersects all of the sedimentary and extrusive formations of the Newark Basin portion of the Newark Supergroup (fig. 3). The road log commences at the Fort Lee entrance to Route 80 off Cross Street (see Olsen, this Fieldbook, for directions to this entrance).

Mileage

0.0 Entrance ramp for Route 95-80 off Cross Street, Fort Lee, New Jersey. Veer left onto entrance ramp, proceed on Route 95S.

To the east about one mile is the west portal of the George Washington Bridge, Fort Lee, New Jersey. The west abutments of the bridge rest on Stockton and Lockatong formations and Palisade Diabase. Roads along the east face of the Palisade Escarpment in the Fort Lee portion of Palisades Interstate Park have excellent exposures of nine individual detrital cycles of the lower Lockatong, each of which has been traced 15 km. to the south (Olsen, this Fieldbook). Three of these cycles are especially fossiliferous; the lowest of these (called cycle 6) has produced articulated remains of *Semionotus brauni* and disarticulated remains of the little reptile *Tanytrachelos*. The middle fossiliferous cycle (cycle 5) contains abundant disarticulated remains of *Diplurus newarki* and articulated remains of *Turseodus*. The upper cycle (cycle 2) has produced abundant articulated *Turseodus* and disarticulated large *Diplurus*. Clam shrimp (conchastracans) and ostracods are also common in cycles 5 and 2. These and other Lockatong cycles exposed here were deposited in shallower water than their more southern extensions.

In this area the trigonometrically computed thickness of both the Stockton Formation and the Lockatong Formation is less than 200 m. This is almost an order of magnitude thinner than the same formations along the Delaware River (Van Houten, this Fieldbook). While part of this thinning is due to the lateral replacement of Lockatong facies by Passaic Formation, most of the thinning is due to the thinning of individual cycles of the Lockatong Formation and thinning of the whole of the Stockton.

Numerous small, predominantly normal, faults striking north and northeast and down-dropping to the east characterize this portion of the Newark Basin. The reentrant in the Palisade Escarpment just south of here is an erosional result of some of the larger of these faults.

0.5 Crossing large normal fault cutting the Palisade Diabase and overlying the Lockatong Formation. This fault nearly doubles the outcrop width of the Palisade Diabase in this area. Just north of here the upper contact of the sill and the Lockatong is duplicated by this fault.

In marked contrast to faults is the northwestern portion of the Newark Basin, many of which have slickensides showing lateral (both synestral and dextral) movement, those examined to date in the area along the Palisades show only vertical slickensides (both those dropping down to the east and to the west) (personal observation and Manspeizer, pers. comm.).

1.0 Excellent outcrops of the Lockatong—Palisade Sill contact and overlying detrital cycles of the Lockatong. Here the upper surface of the Palisade Sill is smoothly concordant with the Lockatong. I believe the cycles exposed here tie in with those exposed in Granton Quarry to the south, although it is far from certain. Articulated *Turseodus* and conchostracans, at least, are common at this outcrop.

According to Van Houten (1969), these Lockatong hornfels include grossularite-andradite, prehnite, and diopside varieties.

1.5 Hill at this point is underlain by a tongue of Stockton Formation (Van Houten, 1969). Presumably this is the same unit exposed about 1 km. north of Granton Quarry. There good exposures reveal Stockton Formation with a thin bed of *Synorichthys* — bearing green and gray siltstone with overlying beds of gray-buff arkose containing what I interpret as very well-developed limestone caliche paleosols. Tongues of Stockton such as this may correspond to clusters of chemical cycles prevalent in similar positions in the central Newark Basin.

1.7 Approximate contact with Passaic Formation. Lowermost Passaic is very poorly exposed in the vicinity of Ridgefield and consists of mottled red-buff feldspathic sandstone and red siltstone.

2.3 Hackensack Meadows.

Broad belt of relatively soft red siltstone and minor gray siltstone and arkose correlating with upper Lockatong and lower Passaic Formation of Delaware River area (Van Houten, this Fieldbook).

2.6 Veer right onto exit for Route 80.

3.1 Beginning of the type section of the Passaic Formation (see Table 2, fig. 4, this paper) (Olsen, In Press). The type section of the Passaic consists of intermittent exposures along Route 80. These exposures show interbedded red feldspathic sandstone and siltstone with small-to-large-scale cross-bedding, abundant bioturbation structures (including roots and *Scoyenia*) and some beds of caliche. Section A (fig. 4) of the type section begins here.

6.2 Section B of the type section of the Passaic Formation.

7.3 Section C of the type section of the Passaic Formation.

11.1 Section D of the type section of the Passaic Formation.

12.8 Garrett Mountain is visible on left (south), Passaic Falls is on the right (north). The upper Passaic Formation of Rhaetic age (latest Triassic) has produced near here a series of well preserved skeletons of the highly specialized procolophonid reptile *Hypsognathus* (Colbert, 1946). About one skeleton or skull is found per decade.

Just south of this point, along Route 20 are exposures of Passaic Formation red conglomerates. The frequency of beds such as these increase to the northeast and decrease to the southwest. These conglomerate beds are crucial to tests of the "Broad Terrain Hypothesis" (Sanders, 1963, 1974). Cross beds consistently yield paleocurrent directions indicating transport from northeast to southwest (personal observation and Manspeizer, pers. comm.) in line with the mean paleocurrent vector for this portion of the Passaic Formation. Clasts consist primarily of Paleozoic sedimentary rocks, including quartzite, quartzite conglomerate, limestone, and minor phyllite. Such rocks are not known to be present to the east of the Newark Basin. Clast composition is very similar to beds found in the northernmost part of the Newark Basin, beds thought to have a northwestern provenance. The clasts are very different from those of the contemporary New Haven Arkose of the Hartford Basin. The "Broad Terrain Hypothesis" predicts that these beds of the Passaic should be western equivalents of the New Haven Arkose. Two alternative explanations come to mind.

1. The provenance of these Passaic conglomerates was to the east of the Newark Basin; presumably these source rocks are completely eroded. Either the Newark and Hartford Basins were with the Paleozoic sedimentary rocks intervening or the Paleozoic rocks were exposed to the east of a southern continuation of the Hartford Basin and contributed to New Haven Arkose bed no longer exposed.

2. The provenance of these Passaic conglomerates was to the west or north but the sediments were redeposited by southwest moving streams.

Detailed studies of these conglomerates are clearly needed.

15.3 Contact of Passaic Formation with overlying Orange Mountain Basalt on left (south). This is section E of the type section of the Passaic Formation (fig. 7). A series of faults cut the ridge made up of Orange Mountain Basalt here; some of these faults are visible in the cut on the left, just west of the Passaic-Orange Mountain contact.

Uppermost few meters of Passaic Formation, exposed to the south of here (Montclair State College) has produced a reptile footprint assemblage consisting of a mixture of taxa common to older beds of the Passaic and younger beds of the Feltville, Towaco, and Boonton Formations. The oldest North American occurences of *Batrachopus*, and grullatorid footprints of the *Anchisauripus minuscolus*-type have been discovered at this locality (Olsen and Galton, 1977).

This assemblage is nearly identical to a suite of footprints found in the Rhaeto-Liassic of France. It is unclear whether these uppermost Passaic beds are latest Triassic or earliest Jurassic (the French workers are unsure of their footprint bearing beds, as well). The Triassic-Jurassic boundary probably lies within a few meters of the Orange Mountain in the Route 80 area.

15.4 Exposures of Orange Mountain Basalt. Upper flow units of Orange Mountain Basalt are exposed in quarries near here. A diverse suite of zeolite minerals has made some of these quarries famous (Manspeizer, this Fieldbook; Van Houten, 1969).

16.9 Crossing the Passaic River, which here follows the Feltville-Orange Mountain Basalt contact.

The Feltville Formation is very poorly exposed in this area; the lower Feltville is not exposed at all.Exposures in bluffs just north and south of here consist of gray and buff arkose and sandstone, often cross-bedded and containing coalified plant remains, and red feldspathic siltstone and sandstone with roots and reptile footprints.

18.0 Position of Preakness Basalt: not exposed.

A confluence of a series of faults, densely spaced joint systems, and the low dip of the bedding are probably responsible for the low profile of the Preakness Basalt in this area. The outcrops of the main lower flow in this area (such as along Route 46 to the south) show the flow's characteristic splintery joint pattern.

18.9 Approximate position of Preakness Basalt — Towaco Formation contact.

The large outcrop width of Towaco Formation here is due to the Hook Mountain Anticline. Toward the west, along the axis of the anticline, the dip of the Towaco Formation steadily decreases.

24.2 About 4.4 miles north is the abandoned Vreeland Quarry which produced the superb reptile footprints on display at the Rutgers University Geological Museum. Just to the northeast is Tom's Point, an area which produced hundreds of reptile footprints in the 1960's. Exposures still extant include much of the non-red portion of the second-from-the-top Towaco Formation cycle. Exposures of the upper two Towaco Formation cycles occur sporadically in surrounding areas.

25.4 Type section of Hook Mountain Basalt.

Two flows and the contact between them are exposed along the highway (fig. 11). The entablature and lower colonnade of the lower flow are exposed on Hook Mountain Road just north of the Route 80 overpass.

25.6 Approximate position of Boonton-Hook Mountain Basalt contact.

29.1 The Boonton Formation is not exposed along Route 80 but 2 miles to the north are the excellent exposures along the Rockaway River (fig. 12). These exposures begin at the dam at the north end of Boonton (Jersey City) Reservoir and extend for over 1 mile along the river bluffs. The dam footing rests on the Boonton Fish Bed which during the

1800's and early 1900's produced thousands of fish of the "*Semionotus elegans* group," *Redfieldius* spp., several specimens of the large coelacanth *Diplurus longicaudadus*, and a single specimen of *Ptycholepis*.

Only the underlying beds are exposed now, by these beds produce abundant plant remains and reptile footprints.

31.1 Approximate position of the Ramapo Fault: end of the Newark Basin.

A prominent bluff of metamorphics marks the west wall of the fault (see Ratcliffe, this Fieldbook).

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PRECAMBRIAN ROCKS OF THE NEW JERSEY HIGHLANDS

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INTRODUCTION

Rocks exposed along Route 15 offer an excellent opportunity to observe most of the major metamorphic and igneous units that make up the New Jersey Highlands (Fig. 1). Rock is exposed along almost the entire twenty kilometers of Route 15 that traverse the strike of the rock units. The purpose of this field guide is to describe the rock units exposed along Route 15 and to report on the current status of recent efforts aimed at understanding the metamorphic and igneous environments that formed the rocks.

Most early descriptions of the New Jersey Highlands subdivide the Precambrian into four major units: These four units appear on the legend of Lewis and Kummel's (1910-1912) Geologic Map of New Jersey as:

1. Byram Gneiss "Gray granitoid gneiss composed of microcline, micro-perthite, quartz, hornblende or pyroxene, and sometimes mica".

2. Losee Gneiss "White granitoid gneiss composed of oligoclase, quartz, and occasionally orthoclase, pyroxene, hornblende, and biotite".

3. Pochuck Gneiss "Dark granular gneiss composed of pyroxene, hornblende, oligoclase, and magnetite".

4. Franklin Limestone "Coarse white marble...."

More recent works by Hotz (1952), Sims (1958), Drake (1969), Smith (1969), and Baker and Buddington (1970) have subdivided the Byram Gneiss into a "Hornblende Granite" and a "Pyroxene Granite" and a few minor units; have substituted rock names such as "Quartz-Oligoclase Gneiss" and "Hypersthene-Quartz-Oligoclase Gneiss" for portions of the Losee Gneiss; have subdivided the Pochuck Gneiss into "Amphibolite" and "Pyroxene Gneiss"; and have recognized several additional rock units such as "Quartz-Potassium Feldspar Gneiss and "Syenite Gneiss". Widmer (1964) has recognized twenty-four mappable Precambrian rock units in the New Jersey Highlands including marble, quartzite, skarn, pegmatite, quartz diorite, four kinds of granite, and fifteen kinds of gneiss. Because of the general reconnaissance nature of this field trip only the major units among the complex assortment of Highlands rock types will be described in this report.

STRUCTURAL SETTING

The igneous and metamorphic rocks of the New Jersey Highlands are divided into northern and southern structural blocks by the Paleozoic rocks of the Green Pond Mountain "Syncline" (Fig. 1). Drake (1969) has shown that the southwestern portion of the Highlands consists of a series of allochthonous slices that overly Paleozoic rocks. In the southwestern portion of the Highlands Drake (1969) reports cataclastic, mylonitic fabric, and retrograde metamorphism. These features, however, are absent from the northeastern portion of the Highlands. Dallmeyer (1974) accepts Drake's structural interpretation but uses a combination of geophysical (gravimetric) and more conventional structural data to show that the northeastern portion of the Highlands has not undergone similar large-scale lateral transport and is instead autochothonous basement.

PETROLOGY OF IGNEOUS AND METAMORPHIC ROCKS OF NEW JERSEY HIGHLANDS

The major rock units that make up the New Jersey Highlands include: 1. Granite; 2. Hypersthene-Quartz-Oligoclase Gneiss (or Quartz Diorite?); 3. Quartz-Oligoclase Gneiss (or Tonalite?); 4. Syenite Gneiss; 5. Amphibolite; 6. Pyroxene Gneiss; and 7. Marble. Each of these rock units, except for the Hypersthene-Quartz-Oligoclase Gneiss are exposed along Route 15.

1. Granites

Granites are the most abundant rock type in the New Jersey Highlands. Buddington (1959) uses the granites of the Highlands as an example of his "catazonal" level of granite emplacement. He also describes the granites as phacoliths, the most striking feature being the lack of large scale discordant features between the granites and

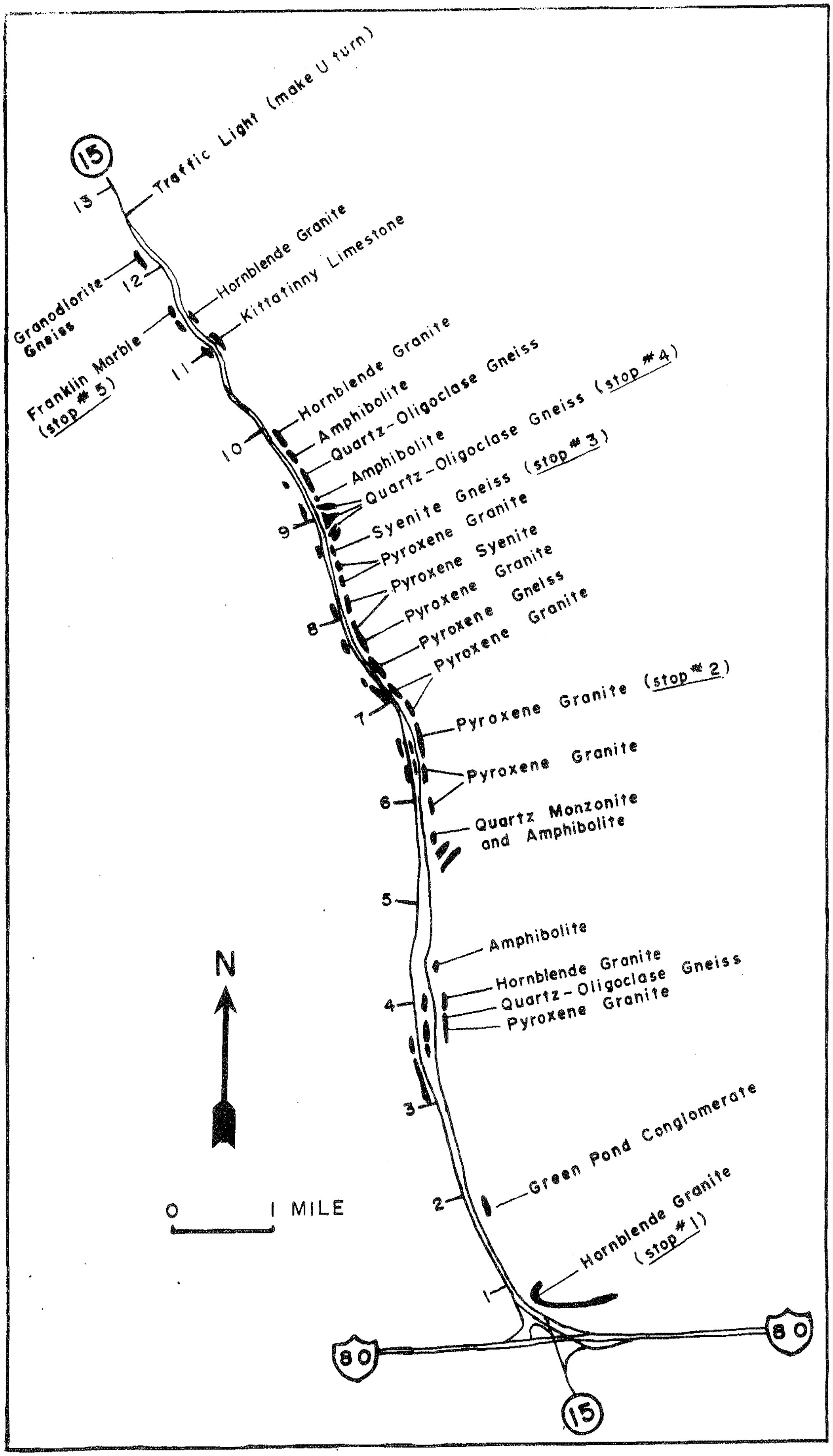

Fig. 1 Map showing road-cut locations with rock type identification, and field trip stop locations along New Jersey State Route 15.

the metamorphic rocks that contain them. Other catazonal characteristics displayed by the Highlands granites include: (1) the presence of gneissic foliation developed throughout the granite; (2) an association with high grade metamorphic rock (at least as high as amphibolite facies) and (3) a lack of chill zones. The two major granite types exposed in the Highlands are Hornblende Granite and Pyroxene Granite.

Hornblende Granite and Alaskite.

Hornblende Granite is found in both the northern and southern blocks of the New Jersey Highlands but is more common in the southern block. Drake (1969) has correlated the Hornblende Granite with the Storm King Granite of New York (Lowe, 1955) based on petrologic similarities. The granite is pinkish buff to greenish buff with a distinct gneissoid structure. It contains numerous xenoliths and large amphibolite schlieren and numerous pegmatites. The average composition of the granite is 46.5 percent microperthite and microcline, 26.9 percent quartz, 8.9 percent hornblende, 16.3 percent plagioclase with accessory and trace magnetite, ilmenite, apatite, zircon, sphene, biotite, and fluorite. (Table 1). The hornblende, biotite, and magnetite contents are highly variable (Table 1). The granite is mapped as an alaskite by Baker and Buddington (1970) and Sims (1958) where the mafic mineral content is less than five volume percent. The alaskite facies is closely associated with most of the magnetite ore deposits found in the New Jersey Highlands. The amphibole from hornblende granite sampled near Splitrock Pond is a hastingsitic variety (Collins, 1964) but the Fe^{3}/Fe^{2} ratio was not determined. Rhett (1977) has found traces of "relic" pyroxene commonly associated with the hornblende component of Hornblende Granite.

The microcline perthite component of the Hornblende Granite is a micro to mesoperthite variety. Baker and Buddington (1970) have suggested that it was originally an orthoclase before exsolution took place. Exsolution of plagioclase to grain boundaries creating an outer rim of plagioclase is commonly observed in thin sections but less extensive exsolution is more typical. The compositional range of the plagioclase is An_{22} to An_{35}, $Or_{2.4}$ to $Or_{6.8}$ with no antiperthitic exsolution (Vogel and others, 1968). The opaque oxides consist of subhedral grains of magnetite containing exsolution lamellae of ilmenite and independent grains of homogeneous ilmenite.

Pyroxene Granite and Pyroxene Syenite.

Pyroxene bearing granite is less common than hornblende granite and is restricted to the central portion of the northern structural block of the New Jersey Highlands, with minor exceptions. The Pyroxene Granite is light to dark green and displays a gneissoid structure that Baker and Buddington (1970) interpret as resulting from magmatic flowage. The granite contains numerous amphibolite schlierien and magnetite bearing pegmatites. The average composition of the granite (Table 1) is 61.6 percent perthite, 21.1 percent quartz,

Table 1.

Modes of New Jersey Highlands Rock Types

	Hb. Granite and alaskite		Pyrox. Granite and syenite		Quartz-Olig. Gneiss		Hyper.-Qtz. Olig. Gneiss		Amphibolite		Pyroxene Gneiss		Syenite Gneiss	
No. of samples	25	Range	15	Range	44	Range	48	Range	43	Range	34	Range	8	Range
Plagioclase and antiperthite	16.3	7.0-32.4	8.4	2.6-22.7	62.7	44.0-77.0	63.8	37.4-78.2	49.0	25.0-78.0	50.3	0-83.5	39.0	7.2-48.7
K-feldspar and perthite	46.5	34.0-57.1	61.6	41.0-70.4	0.1	0- 3.0	1.2	0-16.8	tr	0-tr	9.2	0-67.5	47.8	35.8-74.5
Quartz	26.9	12.8-34.2	21.1	7.8-34.9	29.7	17.5-37.5	17.8	0-30.8	0.3	0- 8.5	17.0	0-50.0	2.5	tr- 4.8
Hornblende	8.9	0-15.8	0.6	0- 2.0	1.5	0 - 6.5	1.7	0- 8.0	27.9	2-64.9	2.1	0-13.0	4.3	0-13.7
Pyroxene	tr	-	5.6	2.0-11.0	1.1	0 - 5.0	9.7	2.5-23.3	16.6	0-51.5	15.2	0.4-42.6	3.8	0-12.1
Biotite	0.1	0-1.7	0	-	2.1	0 -12.5	1.9	0-19.0	1.6	0-19.0	0.1	0- 1.5	0	-
Opaque oxides	0.9	0.2-2.2	1.9	0.2- 5.8	0.4	0 - 9.5	1.2	0- 5.0	1.3	0- 9.5	1.0	0-11.0	1.5	0.1- 3.7
Sphene	tr	0-0.1	0.2	0- 0.9	0	-	tr	-	tr	0- 1.0	0.7	0- 4.9	0.3	0- 1.5
Apatite	0.1	0-0.5	0.2	tr- 0.9	0.3	0 - 1.5	0.2	0- 0.6	0.2	0- 1.5	0.3	0- 1.0	0.3	0- 0.6
Zircon	tr	0-0.2	0.1	tr- 0.6	tr	0 - tr	tr	0- tr	-	-	-	-	0.1	0- 0.4
Other	0.3	-	0.3	-	2.1	-	2.5	-	3.2	-	4.1	-	0.4	-

8.4 percent plagioclase and antiperthite, 5.6 percent pyroxene, 0.6 percent hornblende with accessory opaque oxides, apatite, zircon, and sphene (Table 1).

The pyroxene is typically intergrown with opaque oxides and hornblende. Chlorite is a common alteration product of some of the pyroxene. Both clino- and ortho-pyroxenes occur in the granite but clino-pyroxene predominates. The ortho-pyroxene component has been identified as ferrohedenbergite by Baker and Buddington (1970) and as hypersthene by Rhett (1977). The clino-pyroxene component is probably calcic augite (Rhett, 1977). Rhett has observed that the clino-pyroxene typically displays varying degrees of replacement by hornblende. Rhett (1977) concludes that syn- and post-kinematic metamorphism reactions occurred in both the northern and southern blocks that produced hastingsitic amphibole and quartz from clino-pyroxene plus oxides plus feldspar plus water; but these reactions failed to convert all the pyroxene in the northern block because of a relatively low P_{O_2} and P_{H_2O} environment.

The perthite component is typically a microperthite to microantiperthite with the plagioclase portion of the intergrowths approximately equivalent to the K-spar portion. Mesoperthite with rims or "halos" of exsolved plagioclase on grain boundaries is also common. Some independent plagioclase also exists but is difficult to clearly distinguish in thin section from exsolved plagioclase. The opaque-oxide component includes magnetite with exsolved ilmenite lamellae and co-existing grains of ilmenite.

Where the mafic mineral content is less than five volume percent the rock is mapped by Baker and Buddington (1970), Sims (1958), and Smith (1969) as Pyroxene Alaskite; and where the quartz content of the granite is less than 10 volume percent, it is mapped as Pyroxene Syenite. Both Pyroxene Alaskite and Pyroxene Syenite are common varieties of the granite. Young (1979) has suggested that the syenite was generated at very deep crustal levels from partial melting of quartz-feldspathic and anorthositic rocks at higher temperatures and lower P_{H_2O} than the granites of the southern block.

Because of the catazonal setting it might be suspected that much of the Highlands granite formed in place and was not intruded from a still deeper source. Evidence that disagrees with this suspicion is the lack of a continuous envelope of rock surrounding the granite bodies that could be interpreted as refractory residual source rock. If the metasedimentary rocks of the Highlands underwent partial melting to yield granite magma then a partitioning of several elements probably occurred at the liquid-solid interface. The K_20 and $Si0_2$ content of the granite exceeds that of most of the metasedimentary host rocks (Table 2) and probably involved diffusion out of the metamorphic rocks into the granite magma. The FeO, CaO, MgO, and Al_2O_3 contents of the granite, however, are lower than in most of the common Highlands metamorphic rocks. These elements should be found concentrated in a refractory residue around the granites assuming that the granites formed in place. The Pyroxene Gneisses and perhaps some of the amphilbolite associated with the granites may have formed as just such a residue. But since the granites are found in contact with a variety of rock types in the Highlands area and display no consistent relationship with any mafic of migmatitic rock type it appears that at least some granite magma escaped from its residual envelope and intruded into overlying rocks.

2. HYPERSTHENE-QUARTZ-OLIGOCLASE GNEISS (OR QUARTZ DIORITE?)

About one-half of what is referred to as the Losee Gneiss on the Geologic Map of New Jersey (Lewis and Kummel, 1912) is mapped by Smith (1969) as a Hypersthene-Quartz-Andesine Gneiss; by Baker and Buddington (1970) and Dodd (1962) as a Hypersthene-Quartz-Oligoclase Gneiss; and by Sims (1958) and Drake (1969) as a Quartz Diorite. Minor portions of the "Byram Gneiss" are also remapped as Hypersthene-Quartz-Andesine Gneiss (Smith, 1969). The rock is foliated and is characterized by alternating light buff or light green and dark greenish gray or brownish gray bands. It contains numerous amphibolite schlieren and pegmatites. The average mineral composition is 63.8 percent plagioclase, 17.8 percent quartz, 8.2 percent orthopyroxene, 1.5 percent clinopyroxene, 1.9 percent biotite, 1.7 percent hornblende, 1.2 percent potassium feldspar, with accessory opaque oxides, zircon apatite, and graphite (Table 1). The dark layers contain more mafic minerals than the light layers. The clinopyroxene is a diopside (Smith, 1969) that is intergrown with hypersthene, and hornblende as mafic clusters. The plagioclase component is typically an antiperthitic andesine that ranges from An_{33} to An_{50}, $Or_{2.4}$ to $Or_{6.9}$ (Vogel and others, 1968).

There is very little agreement among petrologists concerning the origin of the Hypersthene-Quartz-Oligoclase Gneiss. Baker and Buddington (1969) and Collins (1969) suggest a metasedimentary origin in contrast to Sims (1958) and Drake (1969) who favor an igneous origin. Dodd (1962) suggests a metavolcanic origin. Vogel and other (1968) point out that the Gneiss is intimately interlayered with Hornblende Granite and suggest that both rocks formed under similar temperature and pressure conditions. Most authors recognize the charnokitic characteristics of the Gneiss and refer to long standing controversies pertaining to the origin of such rock.

Table 2.

Chemical Composition of Some Rock Types

	H.Q.O.[1] Gneiss	Q.O.[2] Gneiss	Hb[3] Granite	Pyrox.[4] Granite	Tonalite[5]	Quartz[6] Diorite	Dacite[7]	Gray-[8] wacke
SiO_2	67.69	71.69	74.89	72.43	66.15	61.54	63.58	66.7
TiO_2	0.48	0.43	0.21	0.24	0.62	0.66	0.64	0.6
Al_2O_3	15.99	14.88	12.33	12.94	15.56	16.21	16.67	13.5
Fe_2O_3	0.64	0.50	0.69	1.44	1.36	2.54	2.24	1.6
FeO	2.42	1.32	1.50	1.38	3.42	3.77	3.00	3.5
MnO	0.05	0.04	0.03	0.34	0.08	0.10	0.11	0.1
MgO	1.16	0.89	0.16	0.34	1.94	2.80	2.12	2.1
CaO	2.88	2.39	0.91	1.70	4.65	5.38	5.53	2.5
Na_2O	4.64	5.85	2.95	3.83	3.90	3.37	3.98	2.9
K_2O	2.86	1.39	5.38	4.74	1.42	2.10	1.40	2.0
H_2O+	0.35	0.51	0.35	0.37	0.69	1.22	0.56	2.4

[1]Hypersthene-Quartz-Oligoclase Gneiss collected from just north of the old road 0.5 mile northwest of where Pacock Brook enters Canistear Reservoir, Newfoundland quadrangle (Baker and Buddington, 1970).

[2]Average of four Quartz-Oligoclase Gneiss samples from the New Jersey Highlands after Drake, (1969), Sims (1968), and Baley (1941).

[3]Hornblende Granite collected from 0.75 miles east of upper end of Splitrock Pond, Boonton quadrangle, Dover District, (Sims, 1968).

[4]Pyroxene Granite collected 6200 ft. east of outlet of Sickel Pond, Stanhope quadrangle (Baker and Buddington, 1970).

[5]Average Tonalite (Nockolds, 1954).

[6]Average Quartz Diorite (Daly, 1942).

[7]Average Dacite (Nockolds, 1954).

[8]Average Graywacke (Pettijohn, 1963).

From a geochemical standpoint the chemical composition of the Hypersthene-Quartz Oligoclase Gneiss resembles an average graywacke more closely than an average quartz diorite (Table 1). If the chemical composition of the Hypersthene-Quartz-Oligoclase Gneiss appearing in Table 1 is typical (it has been described as typical by Buddington and Baker, (1970) there are no major elements with the exception of Na_20 and H_20 that deviate by more than a single percent from an average graywacke although $Si0_2$, total iron, Mg0, Ca0, and Na_20 all deviate by more than a percent from an average quartz diorite (Table 2).. Mineralogically the average Hypersthene-Quartz Oligoclase Gneiss (Table 1) qualifies as a quartz diorite but contains what would be an unusually low pyroxene plus amphibole content.

The chemical composition of the Hypersthene-Quartz-Oligoclase Gneiss also resembles some volcanic rock types such as dacite (Table 2). A metavolcanic origin as suggested by Dodd (1962) can not be ruled out but the very wide ranging mineral composition (Table 1) and banding is probably more typical of sedimentary and metasedimentary rock than relatively homogeneous igneous or metaigneous rock. In addition the accessory graphite content of the Hypersthene-Quartz-Oligoclase Gneiss is much more typical of metasedimentary rock than igneous or metaigneous rock.

3. QUARTZ OLIGOCLASE GNEISS (OR TONALITE?).

Quartz-Oligoclase Gneiss is widely distributed throughout both the northern and southern blocks of the New Jersey Highlands. On Smith's (1969) map of the Highlands, Quartz-Oligoclase Gneiss constitutes roughly one half of what is referred to as the Losee Gneiss on the Geologic Map of New Jersey (Lewis and Kummel, 1912). It is exposed along Route 15 (Stop # 4) near the type locality of the Losee Gneiss (Losee Pond renamed Beaver Lake,). It has been correlated with the Canada Hill Gneiss of New York State by Drake (1969). The Quartz-Oligoclase Gneiss appears white to light green, is medium grained and foliated. It contains numerous pegmatites some of which are conformable to the foliation of the gneiss and some of which are discordant. The mineral component of the Quartz-Oligoclase Gneiss averages 62.7 percent plagioclase, 29.7 percent quartz and 2.1 percent biotite with accessory garnet, hornblende, pyroxene, chlorite, epidote, orthoclase, apatite, zircon sillimanite and opaque oxides. (Table 1). The principal mafic mineral is biotite which is typically intergrown with chlorite, epidote, and opaque oxide. The plagioclase component is commonly clouded with epidote and chlorite.

The origin of the Quartz-Oligoclase Gneiss is at least as controversial as the origin of the Hypersthene-Quartz-Oligoclase Gneiss. Baker and Buddington (1970) include it in their petrographic description of "rocks of uncertain origin". They point out that Baker's (1955) and Hague and other's (1956) igneous interpretation is supported by discordant relations between the Gneiss and layers of metaquartzite and amphibolite. They also report a small amount of feldspathic pyroxene skarn at the contact between the amphibolite and the Quartz-Oligoclase Gneiss. But, in general, there is conformity between the Quartz-Oligoclase Gneiss and the amphibolite layers.

If the Quartz-Oligoclase Gneiss correlates with the Canada Hill Gneiss, additional support for an igneous origin is found. Mose (1978) has suggested that the Canada Hill Gneiss is younger than and discordant to the Storm King Granite and proposes that the Canada Hill Gneiss was derived by partial anatexis of paragneiss during late stage Grenville metamorphism.

The metasedimentary origin suggested by Sims (1958) is supported by the banded or layered nature of the rock, its garnet and sillimanite content, and its intimate concordant interlayering with obviously metasedimentary (or) metavolcanic rocks.

The chemical composition of the Quartz-Oligoclase Gneiss resembles an average graywacke (Table 2) except for the low potassium and iron content of the Quartz-Oligoclase-Gneiss. If the Quartz-Oligoclase Gneiss was an igneous intrusive rock it would be classified as a tonalite on the basis of its minerology. The chemical composition of an average tonolite, however, is approximately equivalent to an average graywacke (Table 2). Despite the ambigous chemical composition of the Quartz-Oligoclase Gneiss I tend to favor a metasedimentary origin largely on the basis of the same evidence as suggested by Sims (1958).

There is probably no way of determining exactly how much, if any, FeO and K_2O was removed from any sedimentary precursor of the Quartz-Oligoclase Gneiss. (Table 2) But since granite magma probably melted in close proximity to the Quartz-Oligoclase Gneiss it is logical to suspect that large quantites of K_2O diffused into the granite magma from the surrounding host rocks. According to Eskola (1932) the residuum from anatexis can be expected to be depleted in one or more of the three major minerals found in granite. This might explain the low K-spar content of the Gneiss.

Some iron may have also been mobilized during anatexis in a catazonal-granulite facies environment. Since the FeO/MgO ratios of the ferromagnesian components of the Gneiss were presumably decreasing in response to increasing temperatures and pressures during anatexis and since water is generally released during

DISTRIBUTION OF IGNEOUS AND METAMORPHIC ENVIRONMENTS

Radiometric data (Long and Kulp, 1962; Tilton and others, 1960; Mose and Helenk, 1976) suggest that the New Jersey Highlands underwent metamorphic recrystallization during the Grenville about 1100 Ma and was then invaded by Granites about 840 Ma. The metamorphic setting invaded by the granites was very deep seated and was within the hornblende granulite facies (Drake, 1969; Smith, 1969; and Young, 1971) or at least within the sillimanite-almandine-orthoclase subfacies of the amphibolite facies (Baker and Buddington, 1970) of Turner and Verhoogen (1960). Of particular interest are the charnockitic characteristics of much of the rock, as recognized by Sims (1958), Offield, (1967), and Drake (1969) particularly the Hypersthene-Quartz-Oligoclase Gneiss.

The natural division of the Highlands into two blocks has made it tempting to compare the igneous petrology of the two blocks. One such attempt was made by Rhett (1977) who applied the magneteite-ilmenite geothermometer and oxygen barometer to 13 granite samples from the southern block and 18 granite samples from the northern block. His data indicate considerable overlap of T-fO_2 conditions among the granites of the two blocks. The granites of the northern structural block equilibrated at temperatures ranging from 570° to 680 C°. Rhett suggested that probably all of the granitic magma initially contained pyroxene but that amphiboles plus quartz formed at the expense of clinopyroxene plus feldspar plus iron-titanium oxides during and after granite emplacement. Similar reactions occurred in the non-granites as a response to T, P_{H_2O}, Po_2 changes that accompained granite emplacement and deformation. The reactions did not go to completion in the case of the pyroxene granites of the northern block because of locally "dry" environments. Rhett's (1977) calculations agree with Young's (1978) suggestion that the pyroxene granites and syenites of the northern block probably equilibrated in a relatively low P_{H_2O} environment but do not agree with Young's suggestion that the pyroxene granites, and particularly the associated syenites of the northern block, equilibrated at higher temperatures than the granites of the southern block. Young (1978) has proposed that the syenites of the northern block formed through very deep-seated partial melting of quartz-feldspathic and anorthositic rocks.

There is also some evidence that eastern portions of the Highlands may have been more directly effected by Paleozoic igneous and metamorphic events than western portions. Long and Kulp (1962) described a "transition zone" that was effected by the "profound metamorphism of the Manhattan Prong in Paleozoic time". When the metamorphic grade of the Cambro-Ordovician rocks of the Manhattan Prong is compared to the virtually unmetamorphosed Cambro-Ordovician rocks associated with the western portion of the Highlands their suggestion seems valid. But the distribution of Paleozoic metamorphic effects on the Precambrian rock depends on the initial location of the allochthonous slices of Precambrian rock and the timing and extent of any overthrusting.

PETROGENESIS - DISCUSSION

There is general agreement among petrologists that have studied the New Jersey Highlands that it consists largely of metasedimentary rock that has been invaded by igneous magmas. But details concerning the sequence of geologic events that generated the Highlands are obscured by the high degree of tectonic activity and metamorphism that occurred there. The exact nature of the sedimentary precursors of the paragneisses, for example, may never be determined. Metaquartzites are, however, scarce in the Highlands and metabasalts (amphibolites) are common. In addition, much of the metasedimentary rock of the Highlands chemically resembles graywacke. The original sedimentary rocks, therefore, were probably more like a "flysch" sequence than a "molasse" or "orthoquartzitic" sequence. As an admittedly speculative working model a typical flysch sequence containing considerable graywacke may not be too far out of line as a starting point. Progressive regional metamorphism of graywackes presumably would have included intermediate grade metamorphic rocks containing hydrous ferromagnesian silicates (chlorite, mica, etc.). When the stability field of some of the hydrous potassium and iron bearing silicate assemblages was exceeded by prograde metamorphism approaching the granulite facies some iron, potassium, and aqueous fluid may have been mobilized and forced to diffuse along thermal and pressure gradients. Some of the iron may have precipitated in shear zones parallel to the foliation of the metasedimentary rocks to form magnetite concentrations common throughout the Highlands. Some potassium, silica, and other elements probably diffused into increasing quantities of granite magma that was forming during anatexis. The Quartz-Oligoclase Gneiss associated with the granites of the Highlands may have supplied a considerable portion of the potassium required to form granite. The most refractory, depleted, residual portions of the metasedimentary rock adjacent to newly formed granite magma were enriched in magnesium, calcium, aluminum, and other elements not required by the granite. These residual portions may be represented by the Pyroxene Gneiss of the Highlands and perhaps some of the other less common mafic rocks.

The fact that these mafic metasedimentary rocks no longer form a continuous envelope around the granite bodies probably indicates that some of the granite magma broke out of the site of origin and moved some distance through the metamorphic complex. Portions of the metagraywacke that were further removed from the zones of melting have become less involved in the chemical exchange that was going on. These less effected portions of the metasedimentary-igneous complex are probably represented by the Hypersthene-Quartz-Oligoclase Gneiss that chemically resemble graywacke more closely than the other rock types of the Highlands. The Hypersthene-Quartz-Oligoclase Gneiss may represent portions of the metasedimentary country rock that were simply too anhydrous to get involved in the melting process. Perhaps much of the water supply of this rock escaped before anatexis began, and at temperatures and pressures too low to dissolve much iron or potassium.

ROAD LOG

MILES

0.0 Exit north onto New Jersey Route 15 from westbound on Interstate Routh 80.

0.9 **STOP 1.** Hornblende Granite (sample 0.9, Table 3). Exit at the Picatinny Arsenal. The rock exposed along the hill to the right is Hornblende Granite. Exercise extreme caution when crossing the road to examine the granite. The granite here is quite homogeneous but on the other side of the hill contains less hornblende and becomes an alaskite. Note the well developed foliation. Busses will turn around and proceed north on Route 15.

1.0 Green Pond Fault.

1.8 Green Pond Conglomerate; silurian correlative of Shawangunk Conglomerate. Most of the pebbles are rounded milky quartz.

3.5 Very complex mixture of Pyroxene Granite near the south end of the roadcut (sample 3.6, Table 3). Quartz-Oligoclase Gneiss near the center, and Hornblende Granite near the north end (4.0 mile on log). Several disconnected xenoliths of amphibolite may be observed in the granite as well as numerous granite pegmatites implaced parallel to the foliation of the granite.

4.3 Amphibolite (sample 4.3, Table 3).

5.7 Fine grained quartz monzonite alaskite along end of roadcut; Amphibolite along the north end.

5.9 Pyroxene Granite (sample 5.9, Table 3).

6.5 **STOP 2.** Pyroxene Granite. Note the wide ranging quartz content, dark color, and well developed foliation. The pyroxene component of the rock here is deeply altered; the feldspar component ranges from a plagioclase rich perthite (as in sample 5.9, Table 3) to a K-spar rich antiperthite (as in sample 6.6, Table 3). Busses will part on breakdown lane. Watch out for loose rock on vertical face of road cut.

6.5 Pyroxene granite

7.3 Pyroxene Gneiss composed of approximately 50 percent antiperthite, 10 percent plagioclase, 15 percent quartz, 20 percent pyroxene-amphibole intergrowths, and 5 percent opaque oxides.

7.6 Pyroxene Granite

7.9 Pyroxene Syenite (sample 8.2, Table 3).

8.2 Pyroxene Granite including bands of syenite and various gneisses that have a similar general appearance but dissimilar mineralogies making up a virtually unmappable complex for 0.3 mile. Amphibolite bands are also found here.

8.7 **STOP 3.** Syenite Gneiss (sample 8.7, Table 3).

9.1 **STOP 4.** Quartz-Oligoclase Gneiss, (samples 9.1a and b, Table 3). Both white and pink varieties of Quartz-Oligoclase Gneiss occur here. Most of the rock here contains less biotite and is less foliated and banded than more typical Quartz-Oligoclase Gneiss. Amphibolite schliern are common. Busses park on abandoned entrance road to Route 15.

9.2 Amphibolite.

9.4 Quartz-Oligoclase Gneiss

9.6 Amphibolite

9.8 Hornblende Granite. Alternating plagioclase rich and K-spar rich bands make this rock less homogeneous than the granite at STOP 1.

11.0 Kittatinny Limestone. Cambro-Ordovician dolomitic limestone.

11.4 Hornblende Granite

12.7 Traffic light (make U-turn).

13.2 Granodiorite Gneiss. Highly foliated rock composed of 40 percent plagioclase, 30 percent quartz, 20 percent K-Spar, and 10 percent biotite.

13.8 **STOP 5.** Franklin Marble. The marble is intruded by granite pegmatites. If traffic is heavy it may be necessary to skip this stop. The road shoulder is quite narrow.

13.8 Continue south on Route 15.

25.4 Turn east on Interstate Route 80 and return to the Rutgers-Newark Campus.

Table 3.

Modes of Precambrian Rock Samples Collected Along New Jersey Route 15

Mileage*	0.9	3.6	4.0	4.3	5.9	6.3	6.6	7.8	8.2	8.7	9.1a	9.1b
Plagioclase and antiperthite	11	2	2	55	1	5	45	25	24	47	69	65
K-feldspar and perthite	44	60	66.5	tr	70.5	59.5	tr	27	64	38.5	0.5	2.5
Quartz	28	30	28	tr	24	30	49	23	4	5	28	30
Hornblende	15	tr	2	31.5	tr	tr	tr	10	tr	4	0.5	tr
Pyroxene	0	7	tr	8	2	1.5	1	6	4	3	0	tr
Biotite	0	tr	0	3	0	0	0	6	0	0	1.5	2.5
Opaque oxides	2	1	1.5	2	1.5	4	5	1	2	2	0.5	tr
Sphene	tr	tr	tr	tr	0	tr	0	0.5	1	0.5	0	0
Apatite	tr	tr	tr	0.5	tr	tr	tr	0.5	tr	tr	tr	tr
Zircon	tr	tr	tr	0	tr	tr	tr	0	tr	tr	tr	tr
Other	tr	tr	tr	tr	1	tr	tr	1	1	tr	tr	tr
Rock Type	H.G.	P.G.	H.G.	Amph.	P.G.	P.G.	P.G.	P.Gn.	P.Sy.	Sy.Gn.	Q.O.G.	Q.O.G.

*Mileage from New Jersey State Route 15 exit off Interstate Route 80 proceeding north (Fig. 1).

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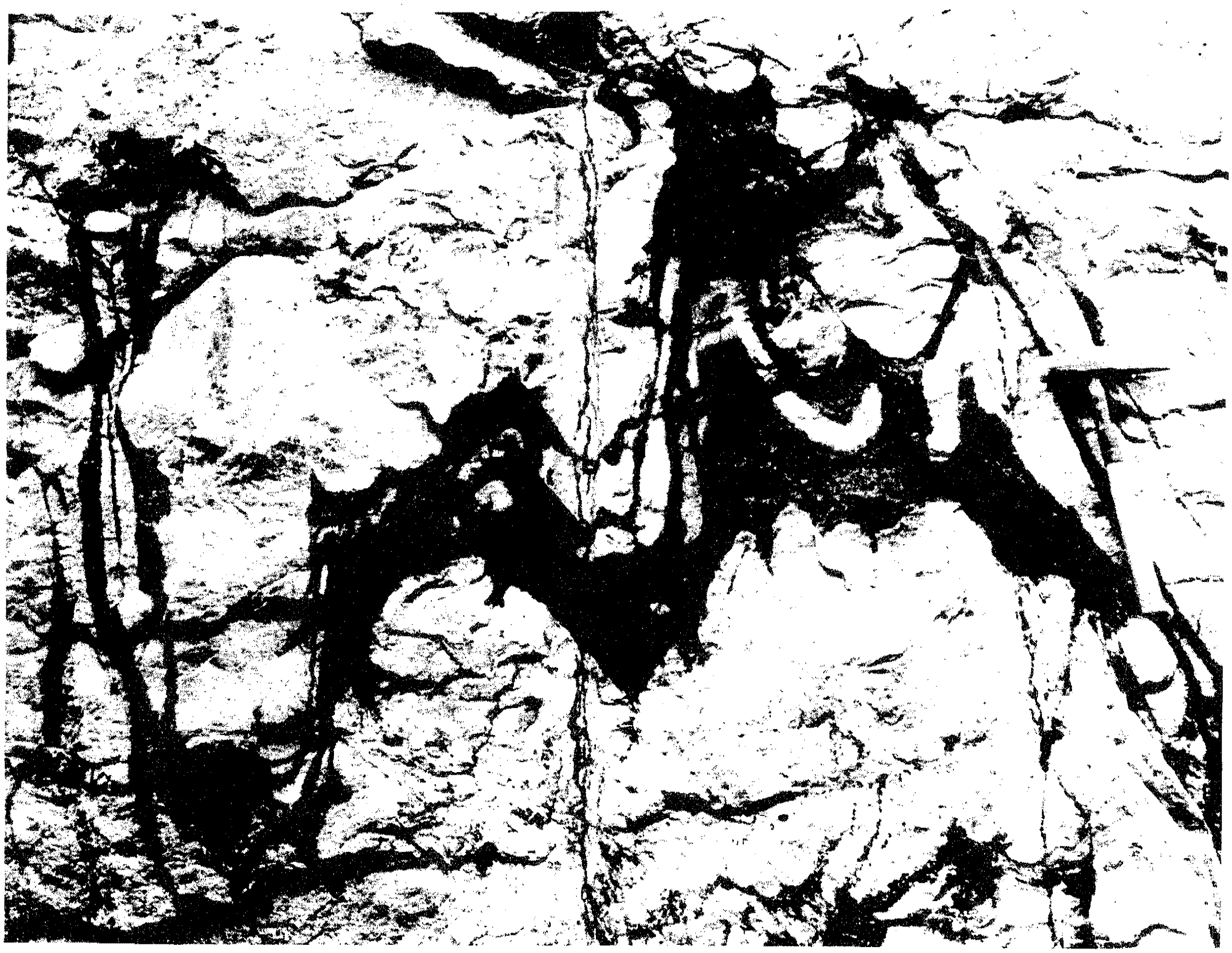
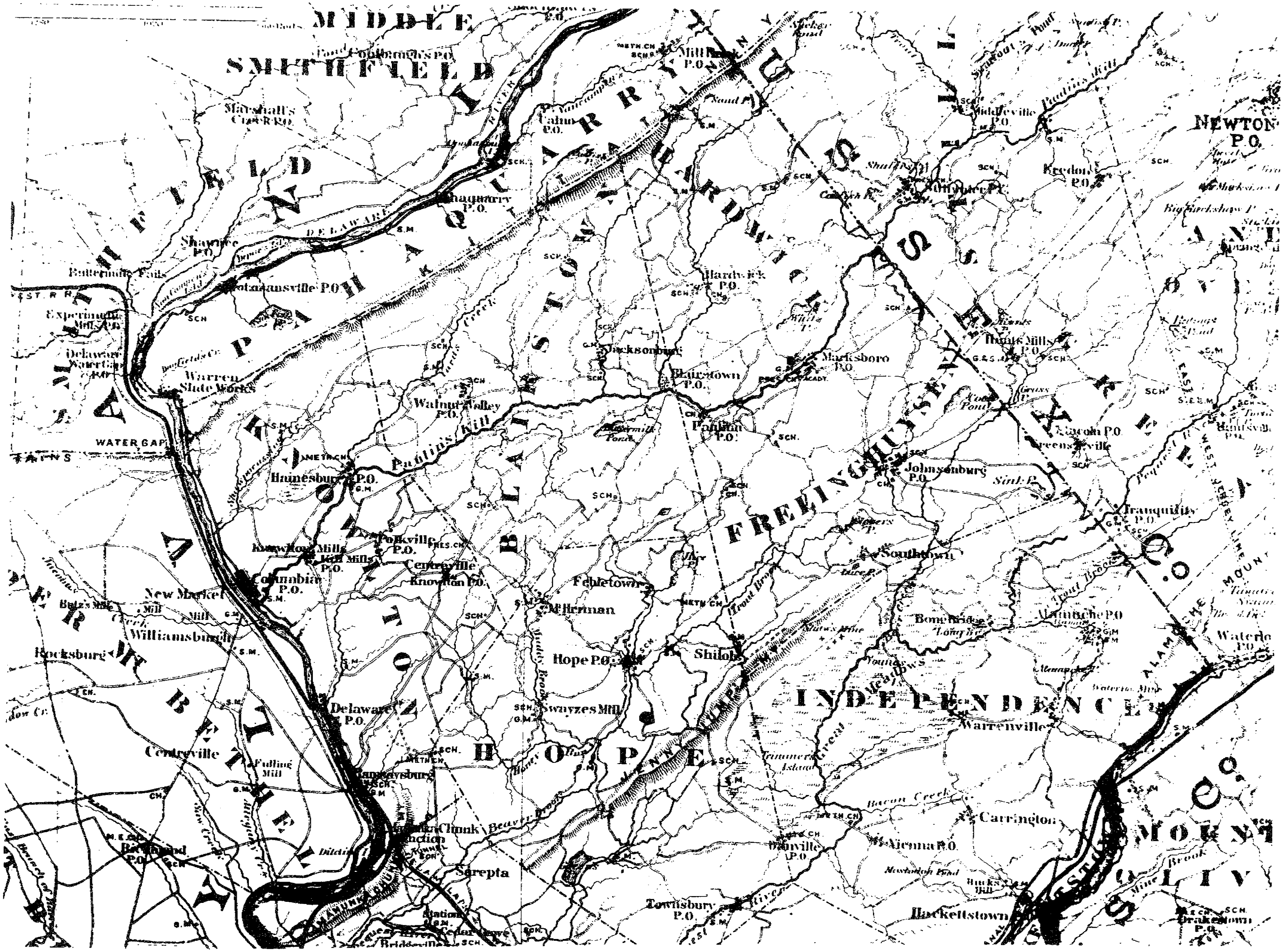


Fig. 2 Photograph of contorted amphibolite inclusion in Quartz-Oligoclase Gneiss located at field trip stop 4 (see Fig. 1)



Relief Map, Warren County, State Atlas, 1872

LOWER PALEOZOIC CARBONATES: GREAT VALLEY

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INTRODUCTION

The purpose of this field trip is to demonstrate the subdivision of the Cambro-Ordovician carbonate sequence as proposed by the field trip leaders. In addition, there will be discussions on environmental, hydrogeologic, and engineering problems in these carbonates and how this subdivision has "opened the doors" in understanding how everyday problems from man's activities can affect or be affected by certain lithic units within the carbonate sequence. This understanding of the interaction between man's activities and how it might affect or be affected by critical aquifers, thin or thick soil horizons, and specific lithologies by septic waste loads, ground water pollution, building foundation loading, landfills, etc., has become extremely important in the land development process.

We anticipate this field trip will not only relate the carbonate subdivision but will point out how important this breakdown is to applied geology.

"KITTATINNY LIMESTONE"

Weller (1900) used the general term "Kittatinny Limestone" for Cambro-Ordovician carbonate rocks of northern New Jersey and identified them with similar units in Virginia, Maryland, Pennsylvania and New York. In his "Annual Report of the State Geologist 1900," page 4, he states, "This limestone formation has a great thickness which is estimated at from 2,700 to 3,000 feet. It is designated the Kittatinny Limestone because it is the great limestone formation of the Kittatinny Valley..."

LEITHSVILLE FORMATION

Although there are no scheduled stops at Leithsville Formation outcrops (because of no exposures on or adjacent to Route 80) on the trip, a short description of the Leithsville Formation is included in order to better understand the Lower Paleozoic carbonate ("Kittatinny") group for this guidebook. (see Table 1)

The Lower Cambrian Leithsville Formation named by Wherry (1909) in Pennsylvania is the equivalent of the Tomstown Formation described by Miller and others (1939) in eastern Pennsylvania and New Jersey.

Avery Drake, (1961, 1967b) mapped the Leithsville Formation on the Frenchtown and Bloomsbury Quadrangles and Markewicz (1967) used the term Leithsville on the High Bridge Quadrangle. Wherry (1909) assigned a Lower-Middle Cambrian age to the Leithsville, whereas Willard (1961) infers that it is Middle Cambrian. No fossil evidence had been found to establish its age until the discovery of the Lower Cambrian fossil *Hyolithellus micans* in the early part of the 1960's, Markewicz (1964 unpublished), in rubbly dolomitic beds of the basal Leithsville at Califon, New Jersey and also near Monroe in southern New York State. In addition, the fossil *Archaeocyathus* occurs in basal Leithsville dolomite at Franklin, Califon and Wantage in New Jersey and at Easton, Pennsylvania. It is most prolific immediately above the Hardyston-Leithsville contact but has also been noted in the lower part of the Wallkill Member. A recent paper by Palmer and Rozanov (1976) describes the original *Archaeocyathus* found in New Jersey by George Banino at Franklin.

The Leithsville Formation is subdivided into three members, based upon field work by Markewicz 1964-68 and Markewicz and Dalton 1968-72. These members are in descending order:

Wallkill Member
Hamburg Member
Califon Member

Califon Member

The Califon Member is the basal Leithsville unit and is named after the *Hyolithellus micans* and *Archaeocyathus* bearing dolomite exposed in an abandoned

TABLE 1.

SUBDIVIDISION OF THE KITTATINNY LIMESTONE

	Formation Name Used on N.J. Geol. Map	Formations Recognized by H. B. Kummel and Others	Formations Recognized by A. A. Drake and F. J. Markewicz	Current Stratigraphy As Used by F. J. Markewicz and R. F. Dalton		
LOWER ORDOVICIAN	KITTATINNY LIMESTONE	Beekmantown	Epler	Ontelaunee Formation	Harmonyvale mbr.	
					Beaver Run mbr.	
				Epler Formation	Lafayette mbr.	
					Big Springs mbr.	
					Branchville mbr.	
			Rickenbach	Rickenbach Formation	Hope mbr.	Crooked Swamp Dolomite Facies
					Lower mbr.	
CAMBRIAN		Allentown	Allentown	Allentown Formation	Upper mbr.	
					Limeport mbr.	
		Tomstown	Leithsville	Leithsville Formation	Walkill mbr.	
					Hamburg mbr.	
					Califon mbr.	

The table indicates the present stratigraphy used in New Jersey and its correlation to those formational names used by earlier workers.

TABLE 1.

SUBDIVIDISION OF THE KITTATINNY LIMESTONE

<table>
<tr><th></th><th>Formation Name Used on N.J. Geol. Map</th><th>Formations Recognized by H. B. Kummel and Others</th><th>Formations Recognized by A. A. Drake and F. J. Markewicz</th><th colspan="3">Current Stratigraphy As Used by F. J. Markewicz and R. F. Dalton</th></tr>
<tr><td rowspan="7">LOWER ORDOVICIAN</td><td rowspan="12">KITTATINNY LIMESTONE</td><td rowspan="7">Beekmantown</td><td rowspan="5">Epler</td><td rowspan="2">Ontelaunee Formation</td><td colspan="2">Harmonyvale mbr.</td></tr>
<tr><td colspan="2">Beaver Run mbr.</td></tr>
<tr><td rowspan="3">Epler Formation</td><td colspan="2">Lafayette mbr.</td></tr>
<tr><td colspan="2">Big Springs mbr.</td></tr>
<tr><td colspan="2">Branchville mbr.</td></tr>
<tr><td rowspan="2">Rickenbach</td><td rowspan="2">Rickenbach Formation</td><td>Hope mbr.</td><td rowspan="2">Crooked Swamp Dolomite Facies</td></tr>
<tr><td>Lower mbr.</td></tr>
<tr><td rowspan="5">CAMBRIAN</td><td rowspan="2">Allentown</td><td rowspan="2">Allentown</td><td rowspan="2">Allentown Formation</td><td colspan="2">Upper mbr.</td></tr>
<tr><td colspan="2">Limeport mbr.</td></tr>
<tr><td rowspan="3">Tomstown</td><td rowspan="3">Leithsville</td><td rowspan="3">Leithsville Formation</td><td colspan="2">Walkill mbr.</td></tr>
<tr><td colspan="2">Hamburg mbr.</td></tr>
<tr><td colspan="2">Califon mbr.</td></tr>
</table>

The table indicates the present stratigraphy used in New Jersey and its correlation to those formational names used by earlier workers.

quarry near Califon, New Jersey. In New Jersey the member measures from 40 to 150 feet thick, but typically averages 100 feet thick.

It consists essentially of two distinct lithologies:

(1) The upper section, varying from 20 to 50 feet thick consists of: very fine to cryptogranular, light gray to locally light greenish gray, dense, sharp breaking, locally laminated dolomite, in beds 6″ to 20″ thick.

(2) The lower section can be 20 to 100 feet (thickness dependent on locality and depositional environment) and varies from gray to dark gray, sparkly to dull, fine to medium megacrystalline, strongly stylolitic, patchy textured dolomite.

Discontinuous pyritic seams, masses, lenses or clots are typically present, especially in the lower part of the section.

Hamburg Member

The type section for the Hamburg Member is located approximately one-half mile southwest of the town of Hamburg, where it forms a sharp, razorback hill. At this locality it is approximately 85 to 100 feet thick. The underlying Califon Member can be seen at several locations here. It is less than 40 ft. thick.

Typically, the member is best described as a rhythmically bedded sequence of sedimentary cycles, representative of mud flat to intertidal and lagoonal environments. The member is estimated to be from 35 to over 100 feet thick, depending upon locality and depositional environment. The overall lithology at any given exposure will generally consist of one of the following types:

(1) Dark, organic, ribbony to laminated to very thinly bedded, cryptogranular to very fine grained dense dolomite and shale with intercalated, thin siltstone and fine sandstone beds, lenses or stringers.

(2) Dark to light gray, locally brownish gray to green cyclical units of fine to coarse sandstone, (locally quartzitic) siltstone, shale and very fine grained to cryptogranular, dense, conchoidal-breaking dolomite. Lithology sequence is typically coarse to fine upward, and siliceous to calcareous upward.

(3) Thinly bedded to ribbony, brown to bright red, sometimes as or intercalated with green shales, siltstones and sandstones, or low grade orthoquartzites.

(4) Brownish weathering, thinly bedded, to strongly laminated siliceous to calcareous phyllite intercalated with local lense-like laminated dolomite and chert. This is the "damourite shale" unit as described in the early reports on the "Kittatinny" of New Jersey.

The contact with the overlying Wallkill Member, though rarely exposed is gradational upward from the Hamburg.

Wallkill Member

The Wallkill Member which overlies the Hamburg Member forms the upper part of the Leithsville Formation. It is poorly to rarely exposed, because it generally forms a topographic low in stream valleys or other low-lying areas.

The Wallkill Member is named after the dark gray, patchy dolomite that lies above the shaly, arenaceous Hamburg Member on the east side of the Wallkill Valley north of Hamburg. Here the lower part consists of fine to medium grained, rubbly to lumpy bedded, stylolitic, locally vuggy, mottled, patchy to ruditic textured, sparkly dolomite in beds from several inches to more than 1.5 feet thick. The lower part of the unit is similar in depositional environment and lithology to the lower Califon Member.

The upper part consisting of fine to medium-grained, locally coarse crystalline dolomite with some beds of algal like structures and large oolites and pisolites appears to be transitional into the lower part of the Limeport Member of the Allentown Formation. The Wallkill Member is estimated to be from 350 to 500 feet thick.

The lower part of the Wallkill, the entire Hamburg and Califon Members are considered to be potential sulfide-bearing horizons. Sphalerite, galena, fluorite, and some chalcopyrite have been found at several localities. The Austinville, Virginia zinc deposit probably occurs in the lower equivalent (?) of the Leithsville Formation.

ALLENTOWN FORMATION

The name Allentown was proposed by Wherry (1909) for the thick sequence of oolitic dolomite overlying the Leithsville in eastern Pennsylvania. B. L. Miller and others (1939) mapped the Allentown in the Lehigh Valley using the name Conococheague instead of Allentown. Later he reverted to the local name. Howell and others (1950) subdivided the Allentown into the Limeport and Allentown Formations.

Drake (1965) did not follow the twofold subdivision of the Allentown, instead he mapped the entire sequence as a single unit, the Allentown Formation.

In New Jersey, two mappable units are recognized within the Allentown. For the lower member, the name "Limeport" was reintroduced (1977) having been redefined on the basis of lithic and sedimentary features. The upper member is referred to as the Upper Allentown Member. Additional work is necessary to further define any lithic and fossil definitions.

Limeport Member

The Limeport Member lying above the Wallkill Member of the Leithsville Formation, consists of fine to medium crystalline, cyclically bedded, light to dark gray dolomite in beds from several inches to more than two feet thick. Oolites, crypotozoa, ripple marks, mud cracks, cross bedding and chip conglomerates predominate the member. Many forms of algal structures are present, ranging from thin mats to large thick colonies.

The Limeport Member varies from 300 to 700 feet thick through most of New Jersey. In the northwestern portion of the state, the unit thickens greatly at the expense of the upper member.

The transition zone between the upper member and the Limeport is gradational with oolites and cryptozoa becoming less abundant going upward. The field contact is placed at the last common appearance of cryptozoa and oolites and the appearance of uniformly textured, thick bedded dolomite.

Upper Allentown Member

The Upper Allentown Member is equivalent to the Allentown Formation as defined by Howell and others (1950). In the Hamburg area it is 1,000 to 1,200 feet thick. In northwestern New Jersey the upper member thins to less than 500 feet thick, due to a thickening of the Limeport Member.

The Upper Allentown is much more massive and thick-bedded than the Limeport Member. The beds, from one to six feet in thickness, vary from very fine to medium crystalline, light to dark gray dolomite with some beds being finely laminated. Chert and sandy units are much less frequent than in the Limeport. In contrast to the Limeport, stromatolites and oolite beds are infrequently found. The contact between the Allentown and the overlying Rickenbach is placed at an undulating scour and fill quartzitic conglomerate zone located about 75 feet above a distinct section of thin bedded, mottled dolomite containing local lenses or thin bands of oolites, cryptozoa, and silt beds.

RICKENBACH FORMATION

The Rickenbach Formation is subdivided into two members, an upper (Hope) member and a lower (unnamed) member along with a distinct lithic facies named the Crooked Swamp Dolomite.

Lower Member

The lower member consists of mostly thin to medium-beds, cream to dark gray weathering dolomite. Some are massive, mottled and weather to a raspy feeling surface. The texture is mostly fine to medium-grained with some coarse grained beds containing pits and clots. There are beds of chip conglomerate as well as sandy dolomites and local quartzites. Some beds consist of a purplish light gray dolomite. Lenses, knots and beds of chert can be present. Pyrite can be found throughout the section. The member varies in thickness from 75 to 150 feet and at the Rt. 80 section it is 125 feet thick.

The transition between the lower member and the Hope Member is gradational with the rock becoming darker and finer grained going upward from the lower member.

Hope Member

The Hope Member consists of light to gray, weathered, aphanitic to finely crystalline, medium-bedded dolomite which is interbedded with darker gray, weathered medium to coarsely crystalline, medium to massive-bedded dolomite. Many of the aphanitic beds contain a sandy zone at the base. The coarser beds can contain clots of quartz and white dolomite. At some locales a very distinctive internal brecciation or crackling is most probably related to the paleo-karstification of the Cambro-Ordovician sequence at the end of the Beekmantown.

Several chert beds and zones are found in this member one of which forms a distinctive marker horizon that can be traced from New York to Pennsylvania. This bed, which we have termed the "7 cherts" is a second higher or upper zone of knots and lenses of chert, some convex. Algal structures occur in and above this zone.

The contact between the Rickenbach and the Epler Formations is generally placed about 50 feet above the upper chert horizon. The Hope Member at its type locality on Route 80 is 167 feet thick.

Crooked Swamp Dolomite Facies

The Crooked Swamp Dolomite facies consists of a light to light gray, fine to coarse, euhedral grained dolomite and is best developed near Crooked Swamp, north of the town of Lafayette, Sussex County. The individual dolomite crystals can be surrounded by a fine clay-like material. Many of the beds contain clots and pits which are commonly filled with dolomite, quartz and kaolinite. The beds range from two to six feet in thickness and algal structures can be present.

At the type section this facies approaches 150 to 200 feet in thickness and it thins rapidly both north and south to less than 25 feet. As the unit thins a distinctive conglomerate is developed in the upper Rickenbach and lower Epler. The Crooked Swamp facies may represent a series of reef structures.

Samples of the Crooked Swamp Dolomite have been compared to the Kingsport Formation of eastern Tennessee and cannot be separated by visual examination. The basal part of the Epler where the conglomerate is developed is lithologically similar to the Mascot Dolomite of eastern Tennessee. The Mascot and Kingsport occupy a similar stratigraphic interval as the Epler and Rickenbach.

EPLER FORMATION

The Epler Formation as defined by Hobson (1963) consists of an interbedded sequence of dolomite and limestone with the contact between the Rickenbach and the Epler being placed at the lowest limestone bed. Drake (1965) places the upper contact at the unconformity with the Jacksonburg. Drake (1969, p. 87) states that "The Ontelaunee of Pennsylvania is absent in the Delaware Valley..." In the outcrop area northeast of where Drake worked the Epler is mainly a dolomite except for occasional limestone lenses which occur in the middle part of the formation.

The Epler Formation has been subdivided into three members (Markewicz and Dalton 1977). These are in descending order:

Lafayette Member
Big Springs Member
Branchville Member

Branchville Member

The contact between the Rickenbach and the Branchville Member is generally placed at a massive chert bed. This member usually will consist of two distinct lithic units. The lower one ranges from 0 to 50 feet in thickness and is a variable sequency of fine to coarse-grained, light to dark gray, medium to massive-bedded dolomite. Laminations may be present along with chert, shale, oolites and cryptozoa. At some localities, the lower most part consists of a reddish, pinkish and/or greenish cryptocrystalline sandy dolomite with some white porcelainite-like chert.

The upper part of the member is a 150 to 200 feet thick, very fine to fine grained, medium to dark gray, very massive, finely laminated dolomite with occasional thin siliceous to shaly interbeds. The rock generally weathers to a reddish brown to buff color.

Big Springs Member

The Big Springs Member is a 40 to 150 feet thick section of variable dolomites and limestones with very pronounced shaly to siliceous interbeds. In the type area, near Hamburg, the Big Springs generally consists of a light to medium gray, fine to medium grained dolomite with local green to pink beds, bands or lenses of siliceous dolomite, quartzite or shale. The dolomite beds are from one to three inches thick with the shaly and quartzitic interbeds being one-quarter to one inch thick. The siliceous beds weather in strong relief giving the rock a ribbed appearance. Cross bedding, chip conglomerates, cut and fill, oolites, chert and red and green argillitic dolomite can be present. The rock weathers with a distinctive bright red to yellow-orange rind and some of the interbeds weather to porous, siliceous ribs. This unit generally will show more evidence of deformation than the members above or below. Chevron folding is common as are torn and rolled beds.

In the northeastern portion of the outcrop at Hamburg there may be occasional limestone lenses of limited areal extent which may replace all or part of the unit although the distinctive sedimentary features are usually retained. The limestone weathers to a powder blue color with green or red-brown siliceous interbeds. From Newton, southwest toward the Delaware River, the Big Springs Member is predominantly a limestone which can change both laterally and vertically to a dolomite in many outcrops. The dolomite lenses are generally encased by a siliceous rind. In the Paulins Kill Valley west of Blairstown the limestone extends both above and below the Big Springs.

Lafayette Member

The Lafayette Member ranges from 50 to 250 feet in thickness and is almost identical to the Branchville Member. Two recognizable units occur within the member. The lower portion is generally a fine to medium grained, black, sparkly, massive-bedded dolomite that contains some beds of light to medium gray, fine grained dolomite with shaly laminations. The fine grained beds weather to an orange-gray color. Chert can be present along with some siliceous beds. The upper part of the member is a finely laminated, massive, light to medium gray, very fine to fine grained, cream to orange-gray weathering dolomite. The laminations stand out in relief on the weathered surface. Chert occurs in beds and clots. The Lafayette Member is transitional with the overlying Ontelaunee Formation through a sequence of medium gray, very fine grained, laminated dolomite to medium gray slightly sparkly, fetid dolomite. The Lafayette Member contains massive zones of breccia which will be discussed in the section on the paleosolution breccia.

ONTELAUNEE FORMATION

The Ontelaunee Formation was recognized in New Jersey by Dalton and Markewicz (1972), Markewicz and Dalton (1974 and 1976). Field work on the Ontelaunee in Pennsylvania by Markewicz during 1965-66 indicated that it is similar with the upper part of the "Kittatinny" in New Jersey. Hobson (1963, p. 75), in referring to the Ontelaunee, states that "A mappable unit of dolomite has not been recognized to date in the Lehigh River and Delaware River areas..." Drake (1969, p. 87), also, does not recognize the Ontelaunee in New Jersey.

The thickness of the formation is dependent on the amount of erosion during the Knox-Beekmantown Unconformity. At Sarepta Quarry, in Warren County there is evidence for over 200 feet of erosion in a very short distance. In the Phillipsburg area the Ontelaunee probably exceeds 800 feet in thickness. The formation has been divided into the following members:

Harmonyvale Member
Beaver Run Member

Beaver Run Member

The Beaver Run Member is 150 to 200 feet thick and contains three recognizable units. The lower part, about 50 feet thick, is a massive, medium to coarsely crystalline, black, sparkly, fetid dolomite. The individual euhedra are characteristically zoned.

Some laminated beds, along with a little chert, can be present. Above this is a 50 to 100 feet thick, massive dolomite similar to the lower part, except that there is a large amount of bedded, anastomosing, rugose, and knotted chert. Individual chert beds can be as much as ten feet thick. Many silicified fossils have been found in this section. The upper portion, which can be as much as 50 feet thick, is a massive, fine to medium grained, black, sparkly, fetid dolomite, generally with little chert.

Fossils found in the Beaver Run Member include straight nautiloids, brachiopods, gastropods, corals, bryozoa, and conularids. Typically they occur in the middle part of the member. Occasional fossils and an asphalt-like hydrocarbon can be found in the upper part of the member. The hydrocarbon occurs both as small masses or clots and as an interstitial material between the dolomite euhedra.

The transitional zone, with the overlying Harmonyvale Member, is an alternating sequence of thin, coarse-grained beds, alternating chert beds, and dense, fine-grained beds.

Harmonyvale Member

The Harmonyvale Member is the highest of the Lower Ordovician rocks present in New Jersey. Its thickness (in excess of 220 feet) is determined by the amount of erosion on the unconformity. At many localities, the Harmonyvale has been completely removed and the Jacksonburg is deposited directly on the Beaver Run. This member consists of a dense, fine-grained to cryptocrystalline, conchoidal-fracturing, styolitic dolomite in one to five foot beds that weather to a light cream gray color. Some of these beds will make a ringing sound when struck with a hammer. There are many medium crystalline mottled, fetid beds that weather with a silty gray surface. Floating frosted quartz grains, sometimes rutilated, as well as chert beds up to several feet thick may be present. Some beds weather with a strongly dissected crosshatch surface, referred to as elephant hide rock (Hobson, 1963). This surface is due to solutional action on a myriad of closely spaced fractures. The fractures are filled with a siliceous material that weathers with thin raised ribs on the rock surface. Many sets of thin, wispy, carbonaceous, filled microfractures or seams occur in some beds.

A zone of grayish chert occurs about 50 to 60 feet above the base. Along strike this chert grades into four-feet thick lenticular limestone beds at the type locality near Harmonyvale. The limestone contains fossils. About 20 feet above the limestone is a very fine-grained bed containing peculiar structures composed of ovoid concentric rings up to eight inches in length. These structures, termed oncolites, are found in most Harmonyvale sections at about the same distance above the Beaver Run-Harmonyvale contact. Fossils in the Harmonyvale include gastropods, brachiopods, and trilobites as well as the oncolites.

The reasons for correlating the Beaver Run and Harmonyvale members to the Ontelaunee of Pennsylvania (Figure 1) are as follows: (1) The Big Springs Member of the Epler can be correlated with Hobson's "60 foot fossil zone" by similar fossils that have been found in the Big Springs limestone facies and by similar lithologies; (2) Hobson (1963) places his Epler-Ontelaunee contact at the highest limestone bed and approximately 100 feet below a massive chert zone. This chert section is probably equivalent to the middle part of the Beaver Run. Hobson states that the cherts are characterized by rugose or colloform chert; and (3) he

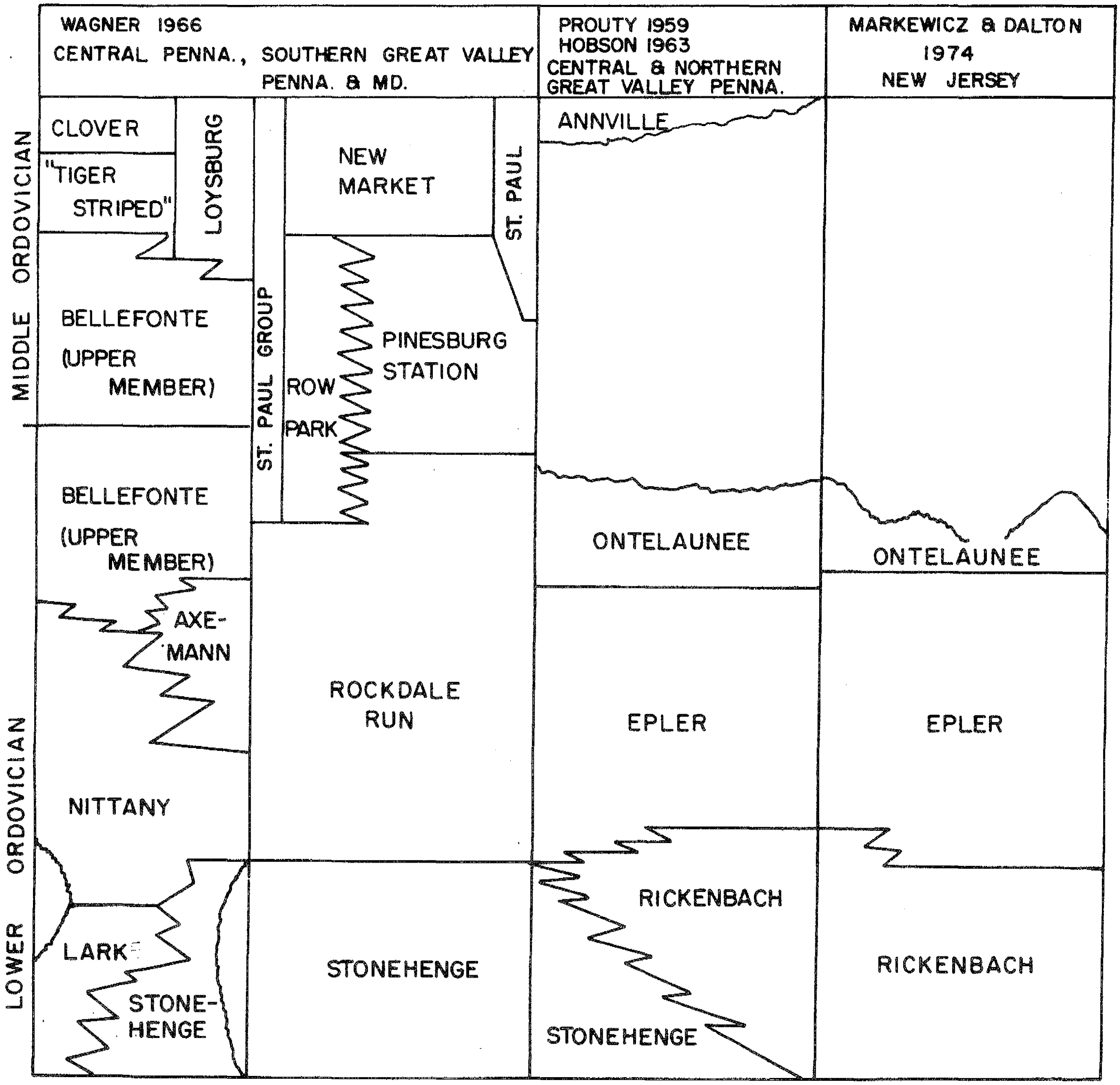


Fig. 1 Composite Correlation Chart

also states that nautiloids are *not* found in Epler. In the Beaver Run Member we have found many nautiloids, gastropods, and other fossils. In the Harmonyvale Member linguloid brachiopods, trilobites and gastropods have been found. The gastropods are similar to those seen high in the Ontelaunee of Pennsylvania by Markewicz. The base of the Ontelaunee, as we define it, does not coincide exactly with that of Hobson, since he places the contact at the change from limestone to dolomite and we place it at the change from the fine-grained laminated dolomites of Lafayette Member to the coarser-grained dolomites of Beaver Run Member. From the description of Hobson's measured sections, it appears that he includes a portion of what we call the Lafayette Member in the Ontelaunee.

Paleo-Solution Breccia

As mentioned under the description of the Lafayette Member, zones of paleo-solution breccia occur in the upper part of the "Kittatinny". These breccias have been interpreted as fault breccias by some workers and as intraformational conglomerates by others. Hobson (1963, p. 65) states that the massive breccia zones at Carpentersville are possibly fault related, although they do not look like fault breccias. They are commonly found in the Lafayette Member of the Epler Formation with similar breccias occurring in the Rickenbach and Ontelaunee as well. At some localities, the breccia has been traced from the lower part of the Beaver Run Member down through the Epler into the top of the Rickenbach, with a few short covered zones. The breccia may consist of angular blocks of laminated dolomite and rounded cobbles, very large slightly tilted blocks of laminated dolomite, or a zone of small fragments of slightly rotated laminated dolomite.

At some localities the breccia has filled tube-like channels in the rock. Generally, the breccia to wall rock contact shows no evidence of faulting. The clasts within the breccia, at many localities, consist of a heterogeneous assemblage derived from the overlying units as well as the unit containing the breccia. The interstitial material around the fragments is commonly a red to greenish silt, similar to the material found in present day karst deposits.

Some beds of dolomite contain a peculiar crackle breccia which consists of angular fragments measuring from one-quarter inch to greater than four inches in size, with the individual fragments showing little to no rotation. It is commonly found in a 50 to 200 feet thick zone, from the lower part of the Branchville Member of the Epler down into the Hope Member of the Rickenbach.

The crackling can disappear both vertically and horizontally in a few tens of feet. Within this zone of crackling, the breccia will be confined selectively to the dense, finely crystalline dark beds with little evidence of crackling in the coarser interbeds.

The filling material between the fragments typically consists of a white to light gray crystalline calcite and/or dolomite. In some areas such as Friedensville, Pennsylvania, the filling material is a light, honey colored sphalerite.

The crackle breccia is important because of its use as a possible ore (sphalerite) guide and, in some cases, for use in stratigraphic interpretation. At several localities in New Jersey, sphalerite has been found in association with the crackle breccia. Its similarity with the Friedensville crackle breccia is striking because it is difficult or impossible, even for the experienced geologist, to distinguish one from the other.

The origin of these breccias is related to the karstification of the upper portions of the Kittatinny during the erosional period prior to Jacksonburg deposition (the Knox-Beekmantown Unconformity). The relationship of the crackle breccia to the massive breccia (rubble breccia) is shown in Figure 2. The origin of the crackling is probably similar to the tension release fractures as found associated with present day cave passages.

The most important paleo-karst breccia occurrence is near Beaver Run, Sussex County. At this locality, 1.9 miles west of Route 94 on Beaver Run Road, a breccia body 300 to 400 feet wide can be traced downward for several hundred feet perpendicular to bedding. It is postulated that this breccia, before erosion, was more than 4,000 feet long. A few hundred feet to the south and higher on the hillside, one of the most unusual stratigraphic units present in the region is found. It occupies the interval between the Ontelaunee and Jacksonburg Formations (Fig. 3).

This unit consists of green siltstones with leached cavities and shards of chert, green siltstones, argillites, shales, and calcareous sandstones to pebble conglomerates. The green unit is about 200 feet thick and has a strike length of about 3,000 feet. It thins rapidly, both to the north and to the south, and is overlain by typical Jacksonburg. Based on the relationships observed at this locality, it is the opinion of the authors that the green unit fills a paleo-sinkhole. Figure 4 indicates the relationship between the development of the breccia and the downcutting during karstification.

The contact of the green unit with the dolomite was dug out at this locality. A very dark, manganese-rich, soft, earthy, soil-like zone occurs at the contact. The top of the Harmonyvale is irregular and the beds are parted

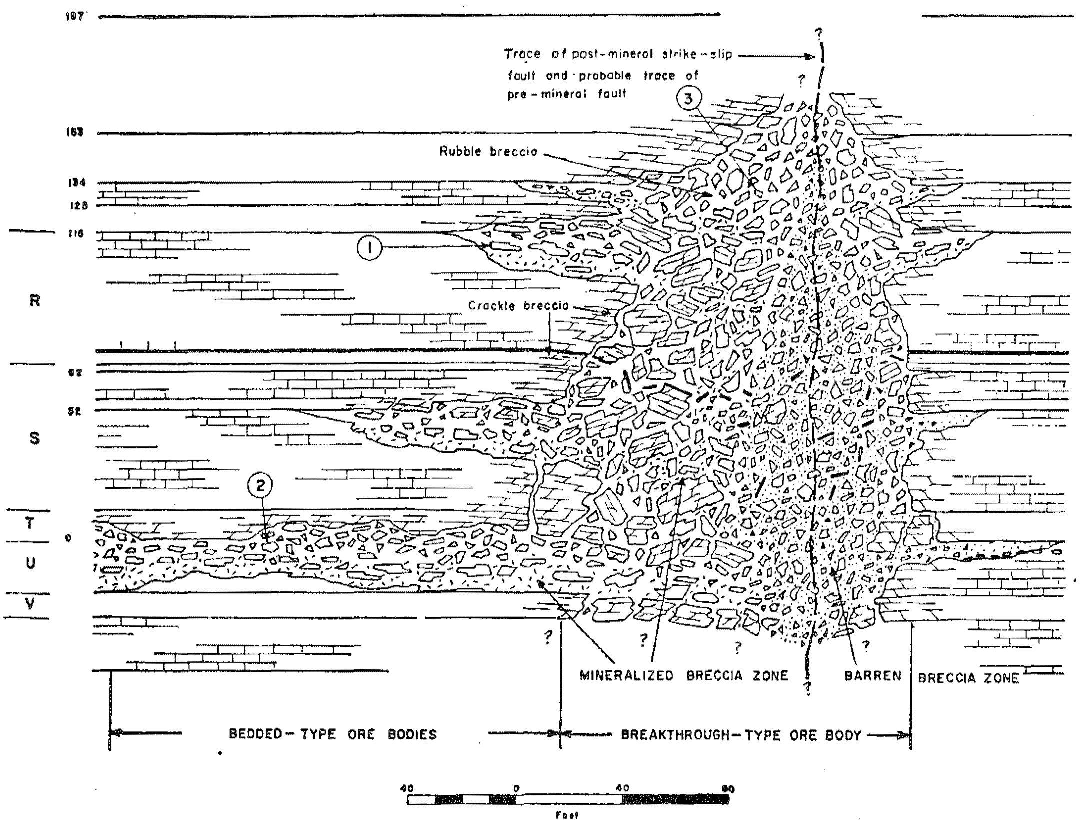


Fig. 2 Relationship between crackle breccia and rubble breccia (Fig. 4, Hardeman and others, 1969)

by a thin quartz-dolomite filled fracture system. Many of the filled fractures show a definite curving pattern with the top of the fractures bending in the same direction that the bedding is sagging, toward the center of the sinkhole.

This green unit has been found at several other localities. At one, near Swartzwood Lake, beds of massive conglomerate are interbedded with greenish argillaceous beds for a stratigraphic thickness of greater than 85 feet. The conglomerate beds are up to 25 feet thick with the intervening argillaceous beds up to 10 feet thick. This "pre" Jacksonburg unit represents the filling of some of the sinkholes developed on the paleokarst surface with the residual soil and rock fragments.

A similar unit known as the Dot Formation occurs at the top of the Knox unconformity in Tennessee. The following description is from Hardeman and others (1969, p. 41):

> "The basal facies of the Dot Formation is a series of argillaceous conglomerate, limestone, and shale units that fill irregularities on the Knox erosion surface. At the mine the basal beds of the Dot can be subdivided into four lithologic units (fig. 1). The lower unit (Ods) is greenish-gray shale with interbeds of argillaceous dolomitic limestone that contains abundant small chert fragments. This is directly overlain by a thin zone of lutite-textured grayish limestone (Odll). These units are present in the western part of the map area but pinch out against the unconformity in the central part of the mine (fig.1). Overlying the lower limestone (Odll) unit is a massively bedded, yellow-weathering argillite (Oda) which contains abundant angular chert and dolomite clasts as much as three inches in diameter. This unit is succeeded by massively bedded, bluish-gray limestone which contains very thin discontinuous lentils of fine-crystalline dolomite (Odul)."

The green unit is unique, not only because of its stratigraphic position and lithology, but also its relationship with major paleosolution breccia bodies for use as a guide in sulfide exploration.

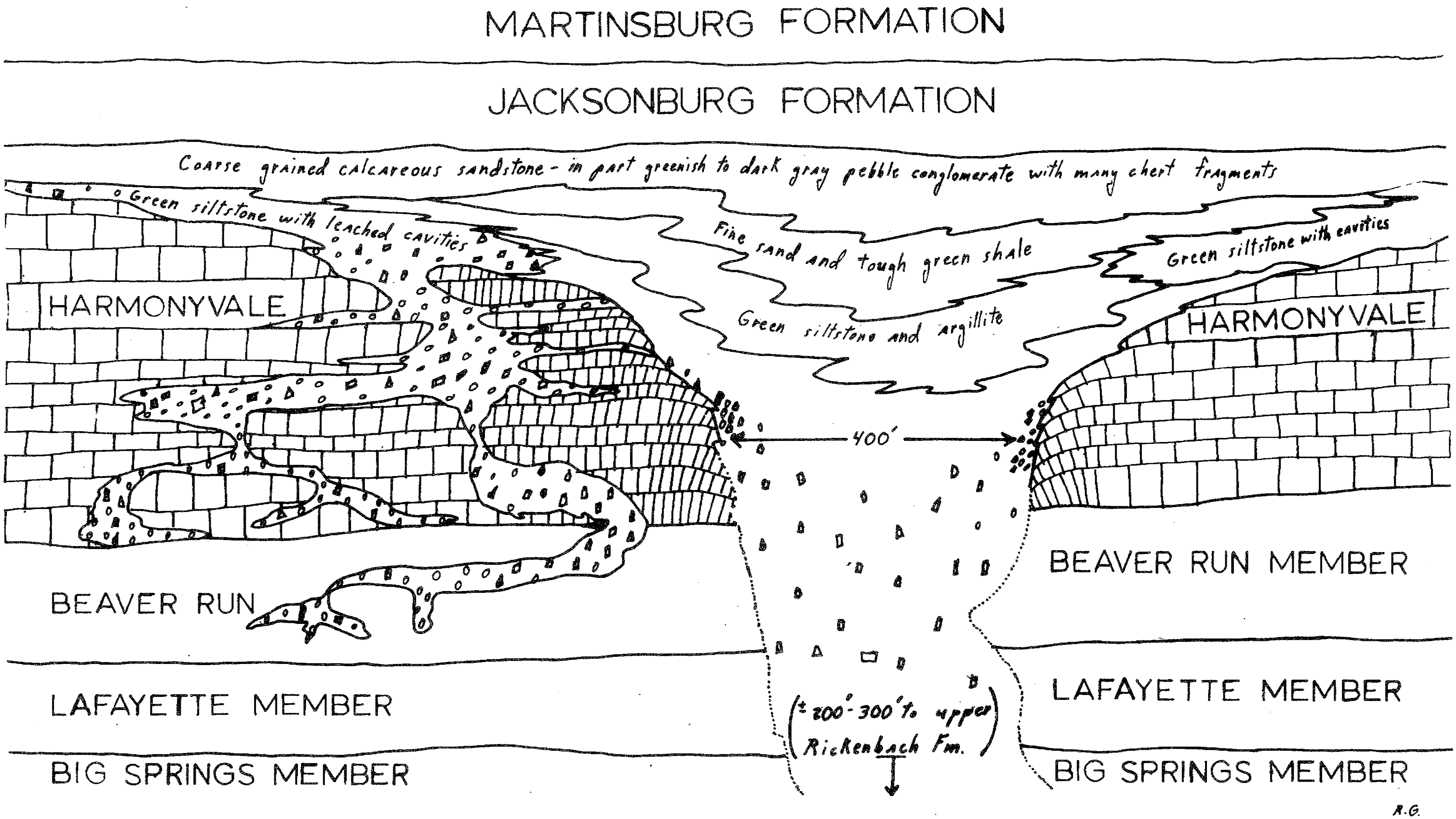
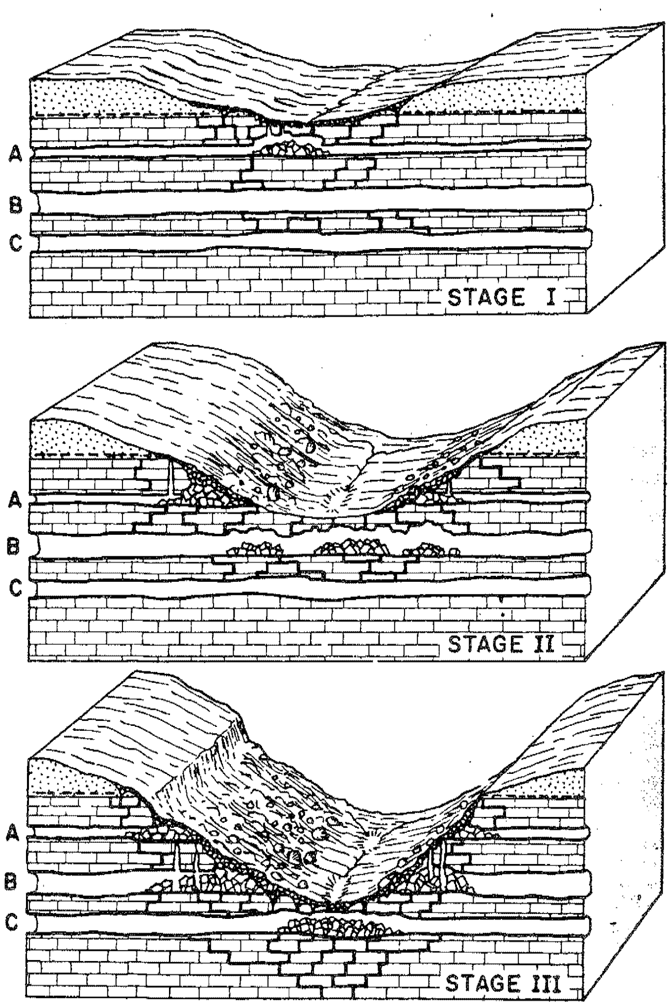


Fig. 3 Generalized Section of Paleosolution System South of Hamburg



Stages in cave passage truncation.

Fig. 4 Relationship between the downcutting during karstification and development of breccias (breakdown) (Fig. 2, Bruckner, 1966)

JACKSONBURG FORMATION

The Jacksonburg Formation was first named by Kummel (in Spencer and others, 1908) for the exposures at Jacksonburg, New Jersey. A systematic examination of the type section was done by Weller (1903). A trench was started at the Kittatinny-Jacksonburg contact and excavated uphill almost to the Martinsburg contact, a thickness of more than 122 feet.

The Jacksonburg was divided into a "cement rock" (upper) and the "cement limestone" (lower), by Kummel (1901). Prouty (1959) postulated a tentative correlation with the Hershey and Myerstown of central eastern Pennsylvania, with the "cement rock" and "cement limestone" in eastern Pennsylvania. It is likely that this correlation is valid for New Jersey.

The lower contact between the "cement limestone" with the "Kittatinny" is a pronounced karst unconformity. At the Sarpeta Quarry locality, the Jacksonburg has been deposited in a trough eroded at least 300 feet into the Ontelaunee Formation with the bottom of the trough not being exposed.

The "cement limestone" is medium to dark gray, fine to coarsely crystalline limestone which locally is a high calcium limestone. There are some light to medium gray calcarenite beds. At many localities, the basal part of the formation contains thin to thick beds of conglomerate. One of the thickest conglomerate sections is along Route 80 near Hope, where 275 ± feet of conglomerate has been measured. It is now possible, with the dolomite member subdivision, to recognize many of the individual cobbles in the conglomerate. The "cement limestone" has been estimated to be about 200 to 300 feet thick, Kummel (1900) and Drake (1969).

The "cement rock" consists of a dark gray to black, argillaceous limestone that has a pronounced cleavage. It contains some beds of coarsely crystalline limestone. Kummel (1900) and Drake (1969) estimate the "cement rock" to be in excess of 600 feet thick at some localities.

ROAD LOG

Mileage

0.0 Start at Rutgers-Newark assembly point. Proceed west via Interstate Routes 280 and 80 toward Allamuchy.

25.2 Intersection of Interstate Route 80 with State Route 15. Note: Precambrian rock cuts along Route 80. There will be some "on-bus" discussion of these igneous and metasedimentary rock units.

33.2 Intersection of Interstate Route 80 with Route 46 Exit ramp.

33.7 Mile marker 26 on Route 80

38.7 Entrance to scenic view of Delaware Water Gap

42.5 **STOP 1**

Geologic Setting

Limeport member of the Allentown Formation. Although less than 20 feet is exposed here it contains many of the sedimentary features found in the member.

In the Pequest Valley the highest stratigraphic rocks found by Markewicz and Dalton include units from Leithsville through the middle part of the Upper Allentown. Stop 1 is considered to be in the lower half of the Limeport Member.

The southeastern edge of the valley is underlain by a normal section of "Kittatinny" sediments lying above the Precambrian.

Along the southwestern border of the valley there are complex structural relationships just before the point where Route 80 enters the Jenny Jump Mountain Precambrian units. There have been various interpretations for this contact between the Precambrian and Paleozoic. These include nappe theories, normal contacts, and various fault interpretations such as an unrooted thrust block.

The Leithsville and Lower Allentown (Limeport) typically form a topographic lowland on the eastern border of the valleys in northern New Jersey. Leithsville rocks generally underlie the lowlands or river valleys and have a greater thickness of unconsolidated sediments - sand, gravel, clay, etc. overlying bedrock than any of the other formations of the "Kittatinny group." The Limeport, typically more resistant than the Leithsville forms a slighty higher pronounced bench. It is generally overlain by overburden that is thinner than the underlying Leithsville overburden, but thicker than overburden Upper Allentown.

Geologic Features

(a) algal units

(b) oolitic and local pisolitic units

(c) churned, lumpy, patchy bioturbidite facies

(d) intraformational conglomerate facies

(e) sandy facies

(f) ruditic, patchy textured clast conglomerate

(g) various dolomite facies, from dolomitic mudstones to medium coarse crystalline dolomite grainstone.

Many varied shallow water carbonate environments can be found at this stop. This is the type of outcrop that a geology professor likes to take his students to so that they can observe the many features that they hear about in the classroom.

44.6 Continue west on Route 80. Diabase dike within metasedimentary calc-silicates and various gneisses.

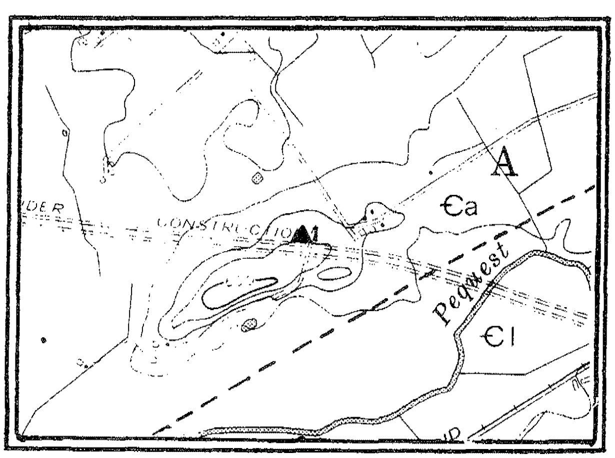


Fig. 5 Topography based on tranquility 7½ — quadrangle. (Geology by Markewicz and Dalton)

Legend [for fig. 5,6,7&8]

Δ Stop
Omb Martinsburg Formation
Ojb Jacksonburg Formation
Oo Ontelaunee Formation
Oe Epler Formation
Or Rickenbach Formation
Ꞓa Allentown Formation
Ꞓl Leithsville Formation
Pꞓ Precambrian

45.5 **STOP 2**

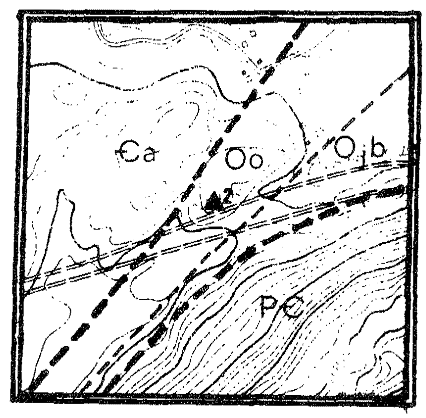


Fig. 6 Topography Blairstown 7½ — minute quadrangle. (Geology by Markewicz and Dalton)

Geologic Setting

Harmonyvale Member of the Ontelaunee Formation

This is the first exposure of dolomite on the west side of Jenny Jump Mountain.

During the construction of Rt. 80 the Jacksonburg Limestone was exposed at the east end of the exposure. On the west side of Jenny Jump, the first rock exposed is always the Jacksonburg along with the uppermost part of the Kittatinny sequence.

At Stop 2 exposures of the uppermost-lower Ordovician dolomite present in New Jersey can be observed; this is the Harmonyvale member of the Ontelaunee Formation.

Geologic Features

(a) dark to black wispy lines or streaks

(b) medium crystalline fetid beds

(c) massive paleo-solution breccia with silt (paleokast feature)

(d) possible fossils

(e) recent karst features

Black wispy lines are an important feature to be noted here. These seem to have been formed through some deformation process shortly after deposition of the dolomite since the Jacksonburg conglomerates in this region contain dolomite cobbles which have the wispy lines.

46.2 Exposures of the upper part of the Allentown Formation

46.8 **STOP 3**

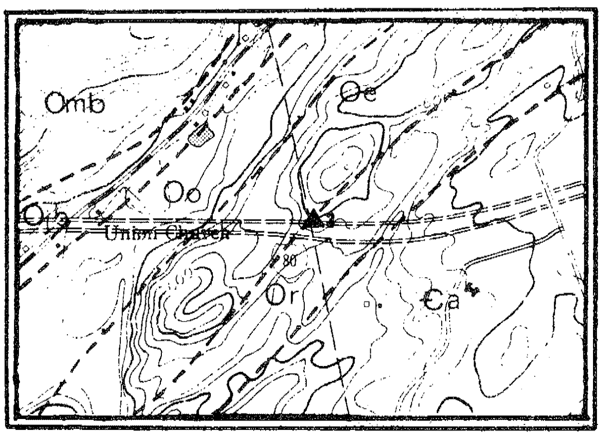


Fig. 7 Topography based on Blairstown 7½ — minute quadrangle. (Geology by Markewicz and Dalton

Geologic Setting

The Rickenbach and Epler Formations

This series of exposures which starts in the upper Allentown Formation and extends up to the Lafayette Member of the Epler forms one of the most complete sections in this area. Off the road, the section continues up into the Jacksonburg Limestone. We will be limiting discussion to the Rickenbach and Epler Formations at this stop.

A. The Rickenbach Formation at this locality measures approximately 290 feet and both the lower and the Hope Members are present. This stop is also the type section for the Hope Member. The features to note are:

a) compare lithologies of the lower member with the Hope Member.

b) clots of black botryoidal hydrocarbon? material -anthrazalite?

c) sand in the dark aphanitic beds

d) the "7 cherts" horizon

e) the upper chert horizon

f) algal structures

g) Trace amounts of sphalerite occur over a stratigraphic thickness of 225 feet.

B. The Epler at this stop has complete sections of the Branchville and Big Springs Members and a partial section of Lafayette Member. The features to note in the Epler are:

a) compare the alternating medium to massive bedded sequence of the Hope Member of the Rickenbach with very massive bedded laminated dolomites of the Branchville Member of the Epler.

b) the similarity of the Branchville with the Lafayette Member

c) note the siliceous ribbing (interbeds) as well as the distinctive reddish weathering characteristic of the dolomite.

d) the paleo-solution breccia in the Lafayette Member

e) fossils found in the Big Springs Member.

48.1 Route 521 exit ramp

50.1 **STOP 4**

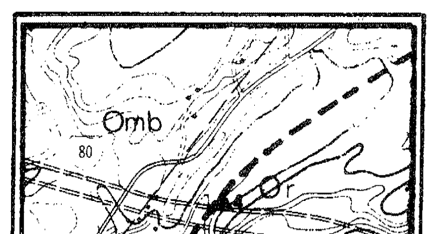


Fig. 8 Topography based on Blairstown 7½ — minute quadrangle. (Geology by Markewicz and Dalton)

Geologic Setting

Rickenbach Formation

From Stop 3 the highway cuts across the Jacksonburg and the Martinsburg Formations west of Route 521. As the highway ascends the large hill known as Mt. Herman a west dipping thrust fault is crossed. The first dolomite exposure is the Limeport Member of the Allentown Formation.

The west side of Mt. Herman is also bounded by a fault. This fault, based upon preliminary mapping is high angle.

Geologic Features

a) the changes in dip

b) the large amount of sulphides present in the rock

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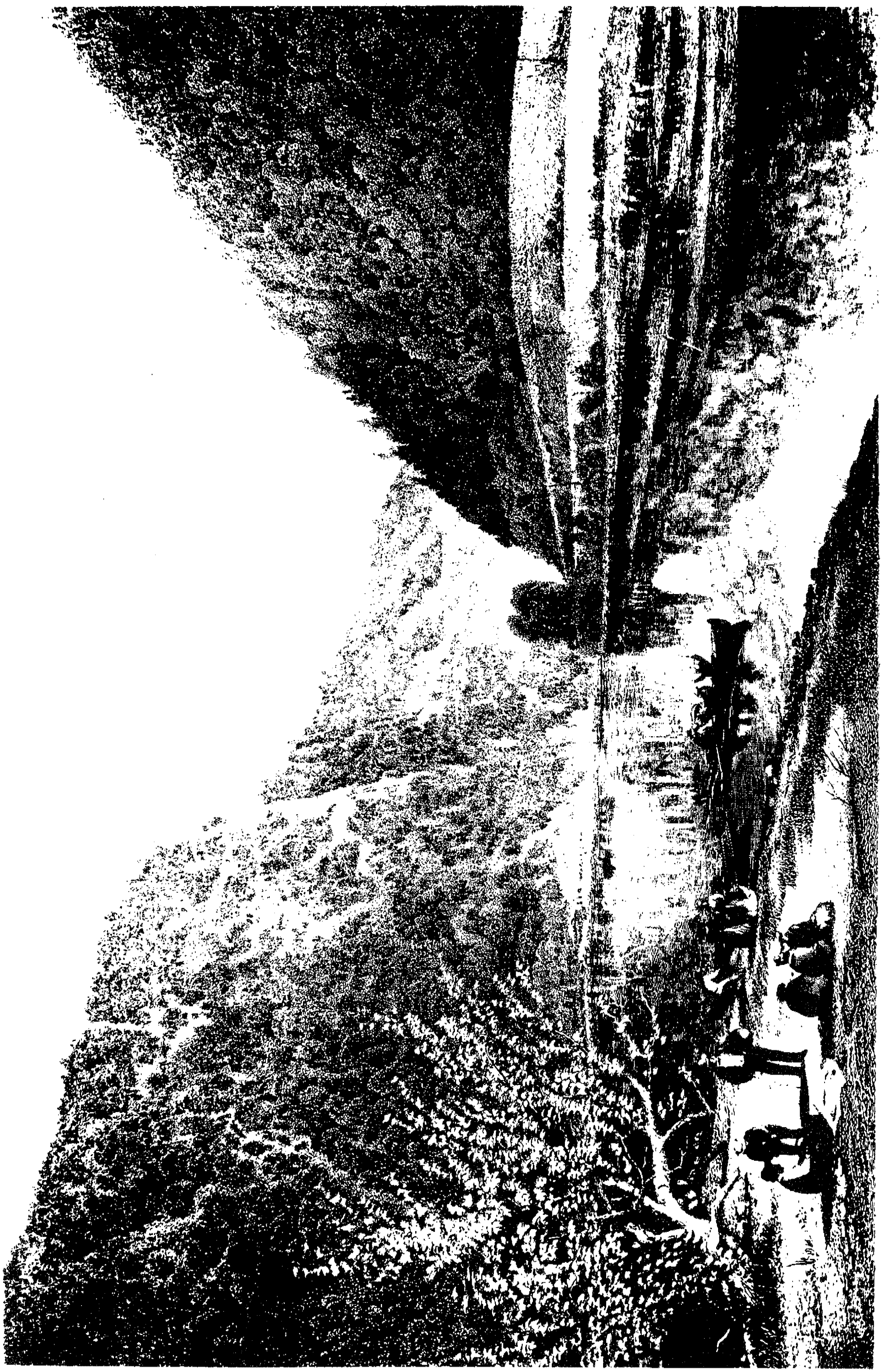

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GEOLOGY OF THE RIDGE AND VALLEY PROVINCE, NORTHWESTERN NEW JERSEY AND EASTERN PENNSYLVANIA

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INTRODUCTION

The rocks seen in this segment of the field trip range in age from Middle Ordovician to Middle Devonian and constitute a deep basin-continental-shallow shelf succession. Within this succession, three lithotectonic units, or sequences of rock that were deformed semi-independently of each other, have somewhat different structural characteristics. Both the Alleghenian and Taconic orogenies have left their imprint on the rocks. Wind and water gaps are structurally controlled, thus placing doubt upon the hypothesis of regional superposition. Wisconsinan deposits and erosion effects are common. We will examine these geologic features as well as some of the economic deposits in the area.

Figure 1 is an index map of the field-trip area, showing the trip route and quadrangle coverage. Figure 2 is a generalized geologic map.

STRATIGRAPHY AND ENVIRONMENTS OF DEPOSITION

The stratigraphic units seen on this trip are more than 15,000 feet (4,570m) thick. Their general characteristics are described in Table 1. More detail is given by Epstein and Epstein (1967, 1969, 1972; Epstein, 1973; and Epstein and others, 1967).

A thick sequence of rhythmically bedded shale (now slate) and graywacke was deposited during Middle and Late Ordovician basin deepening, forming the Martinsburg Formation which averages about 11,000 feet (3,350m) in thickness. The Martinsburg is divided into three members in this area--a middle graywacke-rich member (Ramseyburg) separating two distinct slate-dominated members (Bushkill and Pen Argyl). Taconic deformation and continental convergence peaked in the Late Ordovician when this area emerged. Uplands to the southeast shed nearly 3,000 feet (915 m) of braided stream deposits (Minsi and Tammany Members of the Shawangunk Formation), transitional continental-shallow marine sediments (Lizard Creek Member of the Shawangunk Formation), and meandering stream deposits (Bloomsburg Red Beds).

A general transgressive-shelf sequence followed characterized mainly by tidal sediments and barrier bars (Poxono Island, Bossardville, Decker, Rondout), succeeded by generally subtidal and bar deposits (Helderburg and Oriskany Groups), and then by deeper subtidal deposits (Esopus, Schoharie, and Buttermilk Falls), finally giving way to another deep-water to shoaling sequence (Marcellus Shale through the Catskill Formation). Rocks of the Marcellus through Catskill will not be seen on this trip.

This vertical stratigraphic sequence is complicated a bit because most Upper Silurian and Lower Devonian units are much thinner or are absent toward a paleopositive area a few tens of miles southwest of the field-trip area. Thus, the Palmerton Sandstone of Swartz (1939) for example, is a probable shallow-marine sand body correlative with parts of the Schoharie and the Buttermilk Falls. The Palmerton crops out near Bossardsville at Stop 3.

STRUCTURAL GEOLOGY

The rocks in the field-trip area are disharmonically folded. Four lithotectonic units have been mapped in eastern Pennsylvania (Epstein and Epstein, 1969), three of which will be seen (fig. 3). The folds in each unit differ, and there is evidence that the units are separated by detachment zones or décollements. The lithologic variations and descriptions of folds are given in Table 2. Rocks overlying lithotectonic unit 3 are more than 10,000 feet (3,050 m) thick and are in large folds that have wavelengths of several miles (e.g., Weir Mountain syncline and Lehighton anticline, fig. 2). We will compare the characteristics of each of the lithotectonic units at Stops 2-4.

Two mechanisms produced the folds: (1) flexural folding, in which bedding was active and movement was either by slip (flexural slip) or flow (flexural flow), and (2) passive folding, in which movement was along laminar flow planes (passive flow) or slip planes (passive

TABLE 1. GENERALIZED DESCRIPTION OF MIDDLE ORDOVICIAN TO MIDDLE DEVONIAN ROCKS IN THE DELAWARE WATER GAP AREA.

System	Series	Lithotectonic Unit	Group	Group, Formation, or Member	Average Thickness in Feet (m)	Description
DEVONIAN	Middle	3		Buttermilk Falls	270(82)	Medium-gray cherty limestone, argillaceous limestone, and calcareous argillite. Three members, from base upward: Foxtown, McMichaels, and Stroudsburg.
	Lower			Schoharie Formation	100(30m)	Medium-to-medium dark gray massive calcareous fossiliferous (including Taonurus) siltstone.
				Esopus Formation	180(55)	Medium-to-dark gray silty shale and siltstone containing Taonurus. Well developed cleavage
			Oriskany Group	Ridgely Sandstone and Shriver Chert	85(26)	Light-to-medium gray fine-to-coarse-grained conglomeratic fossiliferous sandstone grading down into medium-dark-gray siliceous calcareous and and cherty shale and siltstone.
			Helderburg Group	Port Ewen Shale	150(46)	Medium-dark-gray fossiliferous calcareous shale and siltstone that has well-developed cleavage.
				Minisink Limestone	15(5m)	Dark-to-medium-gray argillaceous limestone.
				New Scotland Formation	75(23)	Medium-to-dark gray cherty fossiliferous shale and limestone. Two members, from base upwards: Flatbrookville, Maskenozha.
				Coeymans Formation	55-110 (17-34)	Medium to dark-gray argillaceous arenaceous cherty fossiliferous partly biohermal limestone and light-medium to medium gray calcareous fossiliferous pebbly crossbedded sandstone and quartz pebble conglomerate. Four members, from base upwards: Depue Limestone, Peters Valley, Shawnee Island, Stormville.

	Upper Sil and Lower Devonian		Rondout Formation		30(9)	Light-to-dark-gray calcareous argillaceous fossiliferous mud-cracked limestone and medium dark-gray mud-cracked dolomite. Three members, from base upwards: Duttonville, Whiteport Dolomite, Mashipacong.
	Upper		Decker Formation		85(26m)	Calcareous quartz-pebble conglomerate, sandstone, and siltstone, argillaceous and arenaceous fossiliferous limestone and dolomite. Wallpack Center Member.
	Upper		Bossardville Limestone		100(30)	Medium-to dark-gray poorly fossiliferous mud cracked argillaceous laminated limestone.
	Upper		Poxono Island Formation		700±(213)	Light olive gray-to-green calcareous dolomitic shale, dolomite, sandstone, and siltstone.
	Middle and Upper		Bloomsburg Red Beds		1,500±(1457)	Red, green, and gray sandstone, siltstone, and shale partly in fining-upward sequences.
SILURIAN	Lower and Middle	2	Shawangunk Formation	Tammany Member	815(248)	Medium-to-medium-dark-gray fine to coarse-grained conglomeratic (quartz and argillite pebbles as much as 2 in. long) crossbedded and planar-bedded quartzite and minor argillite.
SILURIAN	Lower and Middle	2	Shawangunk Formation	Lizard Creek Member	275(84)	Medium-light-gray to medium-dark-gray and light-olive gray rippled and flaser-bedded sandstone containing burrows and trails, interbedded with medium-dark-gray to dark-gray burrowed siltstone and shale with rare fossils (euryptrids, Dipleurozoa, and Lingula).
SILURIAN ?	Lower and Middle ?	2	Shawangunk Formation	Minsi Member	300(91)	Light-gray to medium-dark-gray and light-olive-gray crossbedded and planar-bedded quartzite, conglomeratic quartzite, and quartz, chert, and shale-pebble conglomerate (pebbles as much as 2 in. long) and minor locally mud-cracked argillite.
ORDOVICIAN	Middle and Upper	1	Martinsburg Formation	Pen Argyl	3,000 - 6,000 (915-1820)	Dark-gray to grayish-black thick-to-thin bedded, evenly bedded claystone slate, rhythmically interbedded with quartzose slate or graywacke and carbonaceous slate.
ORDOVICIAN	Middle and Upper	1	Martinsburg Formation	Ramseyburg Member	2,800± (850)	Medium-to-dark gray claystone slate alternating with light-to-medium-gray thin-to-thick bedded graywacke and graywacke siltstone which makes up about 20-30 percent of the member.
ORDOVICIAN	Middle and Upper	1	Martinsburg Formation	Bushkill Member	4,000+ (1220)	Dark-to-medium gray thin-bedded claystone slate containing thin beds of quartzose siltstone and graywacke siltstone and carbonaceous slate.

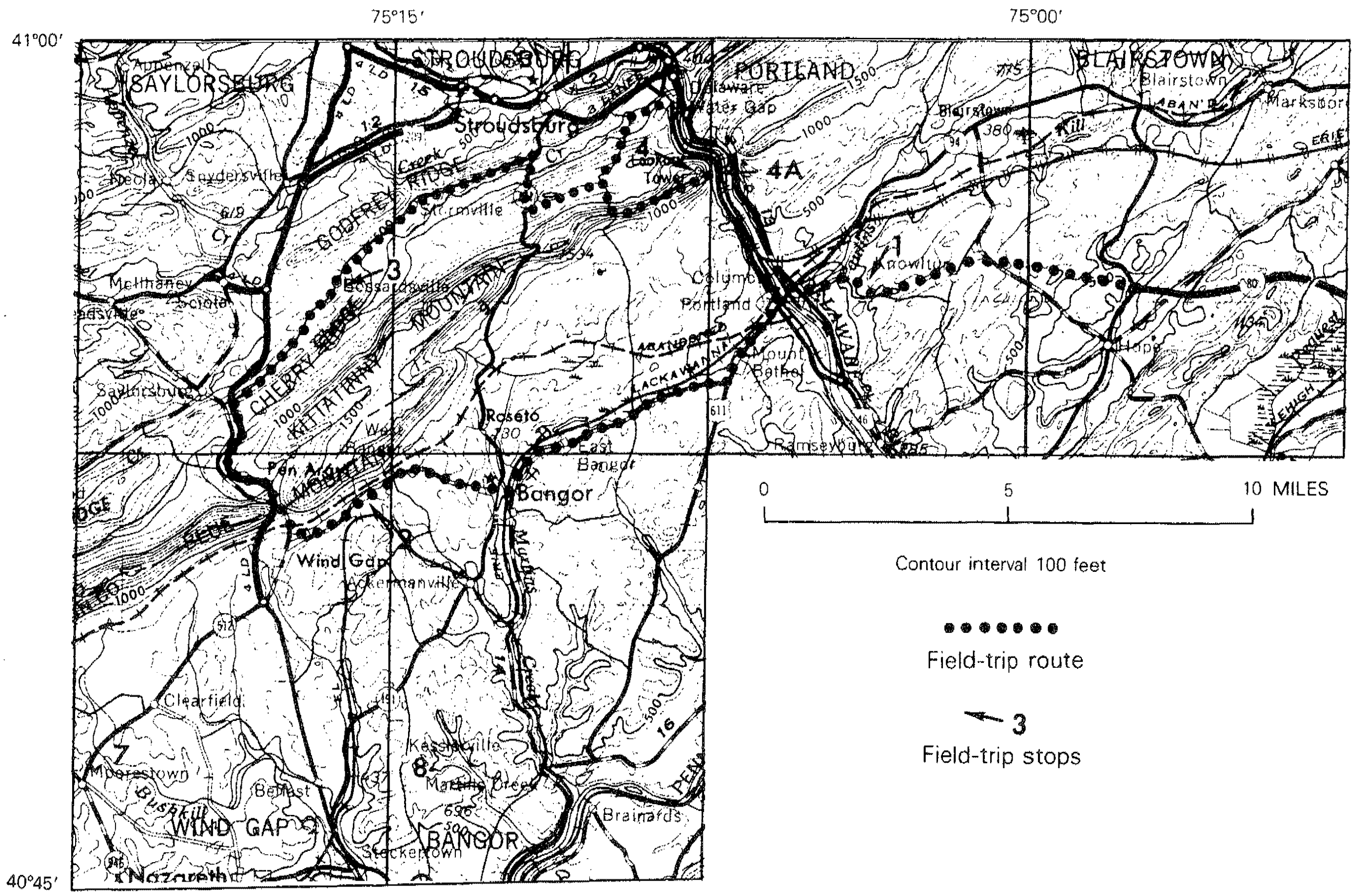


Figure 1

Index map of parts of northwestern New Jersey and eastern Pennsylvania showing the field-trip route, stops, and 7-1/2-minute-quadrangle coverage.

slip), and in which bedding was passive and merely documented deformation in the movement direction (see Donath and Parker, 1964). Flexural slip is indicated by bedding-plane slickensides and nearly constant orthogonal bedding thickness in all parts of the fold, whereas in flexural-flow folding thickness perpendicular to bedding need not be constant. Passive folds are similar and axial-plane thickness is generally constant (i.e., distance between beds measured along cleavage). Passive slip is defined where movement along cleavage is mascroscopically discontinuous (and the cleavage may be termed "slip" cleavage). The two types of cleavage are gradational. "Slaty" cleavage in this area is a descriptive term referring to the property whereby a rock can be split into very thin slabs; this property is dependent upon the laminar character of the rock produced by very thin alternating zones of aligned platy minerals (cleavage folia) and less well oriented quartz-rich interfolial areas. A second-generation slip cleavage is common in many rocks in all lithotectonic units.

For many years there has been controversy regarding the relative intensities of Taconic and Appalachian (Alleghenian) deformation in eastern Pennsylvania. There has also been disagreement on the age and genesis of slaty cleavage, particularly in the Martinsburg Formation (see Epstein and Epstein, 1969, p. 163-170, for a summary). There is still considerable discussion of these topics, and my conclusions are that the dominant cleavage in all rocks in the field-trip area, and most of the structural features we will see are Alleghenian in age. Vestiges of Taconic cleavage may be present in some areas. Taconic orogenesis and deformation is indicated by the coarse detritus in the Shawangunk Formation shed from Taconic highlands to the southeast, by the profound angular unconformity between the Martinsburg and the overlying Shawangunk, and by large regional nappes that have been mapped in the Great Valley to the south (Drake and Lyttle, this volume).

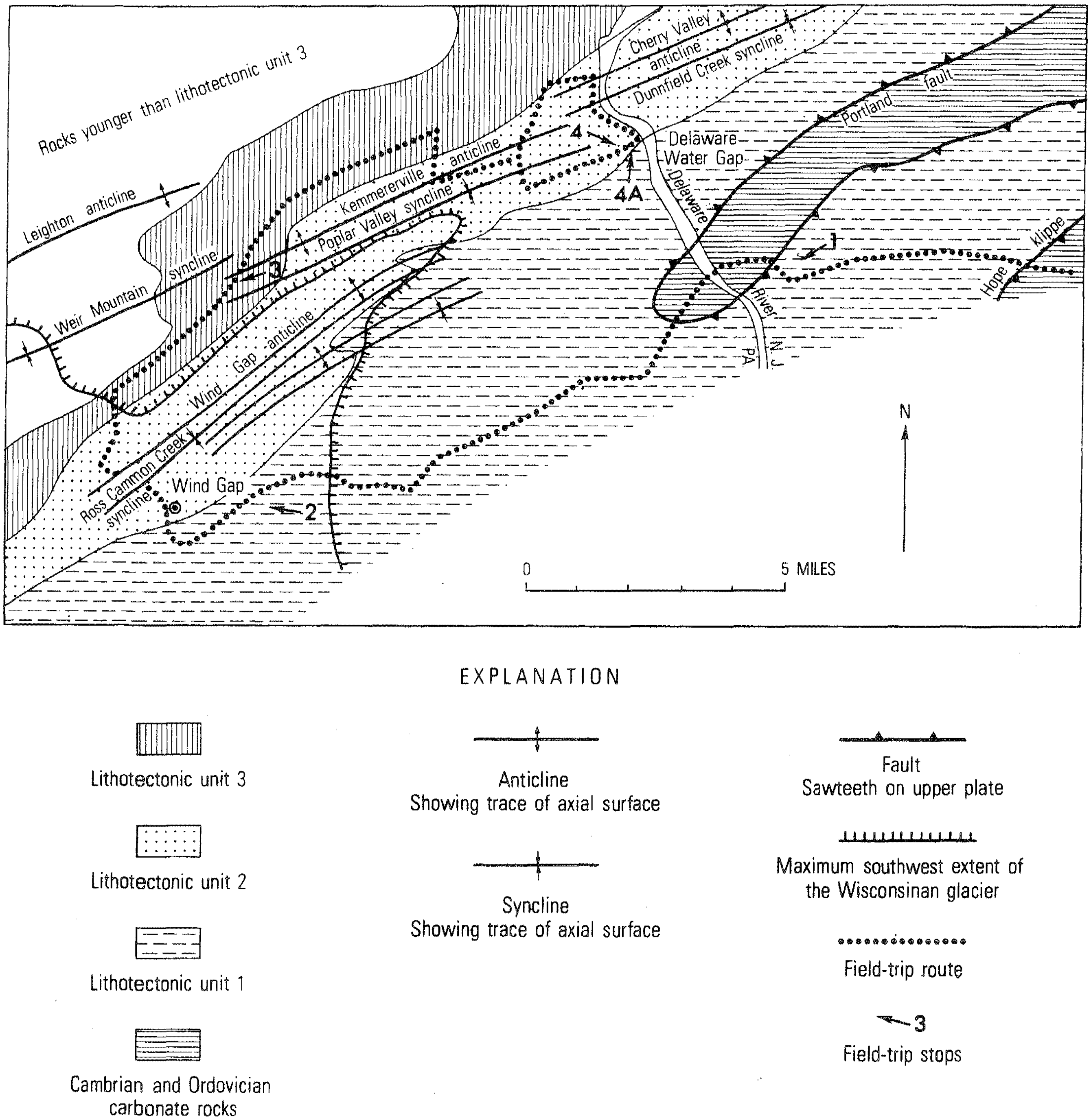


Figure 2.

Generalized geologic map of tahe Ridge and Valley province, Northwestern New Jersey and eastern Pennsylvania.

Table 2. Lithotectonic Units in the Ridge and Valley Province of Northwestern New Jersey and Eastern Pennsylvania

Litho-tectonic Unit	Age of Lithotectonic Unit and Stratigraphic Sequence (See Table 1)	Lithologic Characteristics	Style of Folding	Average Size of Folds
3	Middle Devonian to Late Silurian Buttermilk Falls Limestone to Poxono Island Formation	1,875 feet (570m) of limestone, shale, siltstone, sandstone, and dolomite; heterogeneous stratigraphic units between 3 and 180 feet (1 and 55 m) thick.	Asymmetric, concentric, and similar, flexural slip and flow.	Wavelengths 1,000 - 1,500 (305 to 455 m); amplitude about 250 feet (75 m).
2	Late to Early Silurian Bloomsburg Red Beds to Shawangunk Formation	2,900 feet (880m) of sandstone, siltstone, shale, and conglomerate; coarser toward base of sequence.	Asymmetric, concentric, flexural slip with minor passive slip and flow. Extensive bedding slip and wedging in the Bloomsburg Red Beds.	Wavelengths about 1 mile (1.6 Km); amplitudes 1500 - 5000 feet (455 to 1525 m).
1	Late and Middle Ordovician Martinsburg Formation	About 11,000 feet (3,350 m) of thick sequences of slate and graywacke.	Asymmetric, similar, nearly isoclinal and recumbent; mainly passive flow and slip; flexural slip near contact with Shawangunk Formation. Folds Superimposed on upright limb of regional nappe.	Wavelengths 1,000 to 3,000 feet (305 - 915 m); amplitudes 400 - 2,000 feet (120 - 610 m). Small-scale imbricate faults and major thrusts that have possible displacements in miles south of field-trip area.

GEOMORPHOLOGY

Eastern Pennsylvania and northwestern New Jersey, in the Ridge and Valley and Great Valley physiographic provinces, have long been a classic area for the study of Appalachian geomorphology. Because several major wind and water gaps are here, the origin of the gaps is of particular interest to this field conference. I conclude that the gaps are structurally controlled, adding fuel to the controversies regarding the hypotheses of superposition and drainage evolution. This subject is discussed at Stop 4.

GLACIAL GEOLOGY

No stops in glacial deposits are planned, but evidence for Wisconsinan and older glaciation is seen everywhere--in the varied stratified deposits and till, in the numerous landforms on the deposits, and in the common glacial striae, grooves, and erratics. Many of these features will be seen at all stops. Discussions of the glacial geology in the area are given by Epstein (1969), Epstein and Epstein (1969), Crowl (1972), Connally and Epstein (1973), Crowl and Stuckenrath (1977), and Connally and others (1979).

ROAD LOG

Mileage

0.0 Overpass; U.S. Interstate 80 and N.J. 521 (Blairstown-Hope Road).

0.3 Gently dipping Allentown Dolomite in the Hope klippe (see Drake and Lyttle, this volume).

1.3 Dolomite and cherty dolomite in the Allentown (?) Dolomite.

1.9 Small anticline in the Allentown (?) Dolomite.

2.0 Graywacke and slate in the Ramseyburg Member of the Martinsburg Formation. We have just crossed a major fault separating the Middle and Upper Ordovician Martinsburg from Cambrian carbonate rocks in the Hope klippe.

4.4 Kittatinny Mountain to the right (north) held up by quartzites in the Silurian Shawangunk Formation. The mountain is offset to the northeast by a syncline-anticline couplet near the site of the Yards Creek Pumped Storage Project north of Blairstown, N.J.

5.8 Bear right to scenic overlook

6.3 **STOP 1. DISCUSSION OF TRIP AND LUNCH.**

See Fig. 4 for stop description. After leaving Stop 1, we will travel down the Paulins Kill Valley, across the Delaware River, travel to the southwest to Pen Argyl, Pa., and stop at a slate quarry in the upper (Pen Argyl) member of the Martinsburg Formation. After crossing Blue Mountain at Wind Gap, we will visit a quarry at Bossardsville, Pa., in Silurian rocks. We will than attempt to drive to the top of Kittatinny Mountain to a vantage point overlooking Delaware Water Gap and examine the Shawangunk Formation and Bloomsburg Red Beds. After passing through the gap we will return to Newark, N.J.

Return to Interstate 80.

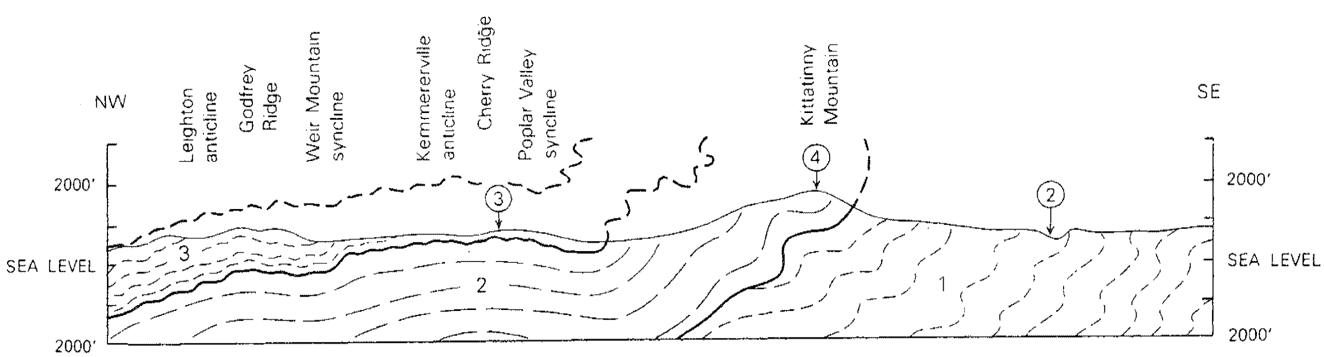


Figure 3

Composite cross section in the field-trip area showing disharmonic folding in the three lithotectonic units, 1, 2, 3, the Taconic unconformity between units 1 and 2, and the locations of stops 2, 3, and 4. Zones of detachment are believed to separate the lithotectonic units: the Blue Mountain decollement between units 1 and 2; Godfrey Ridge decollement between units 2 and 3; and Weir Mountain decollement between unit 3 and younger rocks.

6.6 Turn right on Interstate 80 heading west.

7.4 Laminated slates of the Bushkill Member of the Martinsburg Formation. Note the typical fine bedding in this member. You will not see similar laminations in slate of its Pen Argyl Member. This is one of the characteristics distinguishing the two predominantly slate-bearing members of the tripartite Martinsburg Formation.

7.7 Paulins Kill to right.

8.0 Junction with U.S. 46 and N.J. 94. Turn right following U.S. 46 east towards Columbia and Portland.

8.2 Junction of U.S. 46 and N.J. 94. Bear left on U.S. 46.

8.3 Southeast-dipping dolomite of the Epler Formation. We have crossed the Portland fault which separates the Epler from the Bushkill Member of the Martinsburg Formation.

8.5 Intersection of U.S. 80E and U.S. 46E. Bear left on U.S. 46.

8.6 Bear right on U.S. 611S heading towards Portland, Pa.

8.9 Crossing Delaware River. View of Delaware Water Gap to right (north). Tuscarora Power Plant smokestacks to left.

9.2 Toll Booth. Continue straight ahead on U.S. 611S. We will be driving on the Richenbach Dolomite of the Beekmantown Group for about 0.5 mile (0.8 km) and then on Wisconsinan kame deposits and till.

10.3 View of Kittatinny Mountain to right.

10.5 Mt. Bethel Post Office on left.

11.2 Turn right on Pa. 512S. The lowlands to the right are mostly underlain by Wisconsinan sand and gravel and some till.

13.3 Five Points. Glacial deposits are as much as 178 feet (54 m) thick in this area.

14.9 Follow Pa. 512 to right towards Bangor.

15.1 Crest of hill underlain by graywacke and slates of the Ramseyburg Member of the Martinsburg Formation. Note slate dumps ahead.

15.7 Slate dumps of the abandoned Capitol Slate quarry on right. Note the much thicker beds than in the Bushkill Member of the Martinsburg seen at mileage 7.4. We are in a slate "run" in the upper part of its Ramseyburg Member. Graywackes are found higher in the sequence and the contact with its overlying Pen Argyl Member is placed where graywacke beds become less dominant.

15.9 Flooded New Bangor and Columbia Bangor quarries on left, with nearly recumbent folds.

16.2 The Bangor Excelsior quarry on the left has been filled in, partly with fly ash. It was at least 140 (43 m) feet deep.

16.35 Pennsylvania Historical and Museum Commission sign on right: "Slate Industry—Robert M. Jones of Wales, who came here in 1848 as an immigrant, began the slate quarrying industry. The region became a major world center for slate. From here came slate roofs and old-time school slates and pencils."

To the right of the sign are the remains of an old kiln that used to fire the slate for lightweight aggregate (see Epstein, 1974a, for a discussion of the slate industry and potential uses for waste slate).

16.5 The Old Bangor slate quarry is over the dumps to the left. The nearly flat Old Bangor syncline is exposed in the quarry and can be traced for several miles in the area. The quarry also lends its name to the "Old Bangor run", a series of beds that include important commercial slate beds.

16.9 Railroad crossing, Town of Bangor. Follow Pa. 512S to right.

17.0 Follow Pa. 512 to left toward Pen Argyl.

18.0 Crest of Wisconsinan terminal moraine. Poor exposures of till may be seen in cuts to the right.

18.5 Contact between the Wisconsinan till to east and Illinoian(?) till to west. Note slate dumps from quarry in the Pen Argyl Member of the Martinsburg Formation straight ahead.

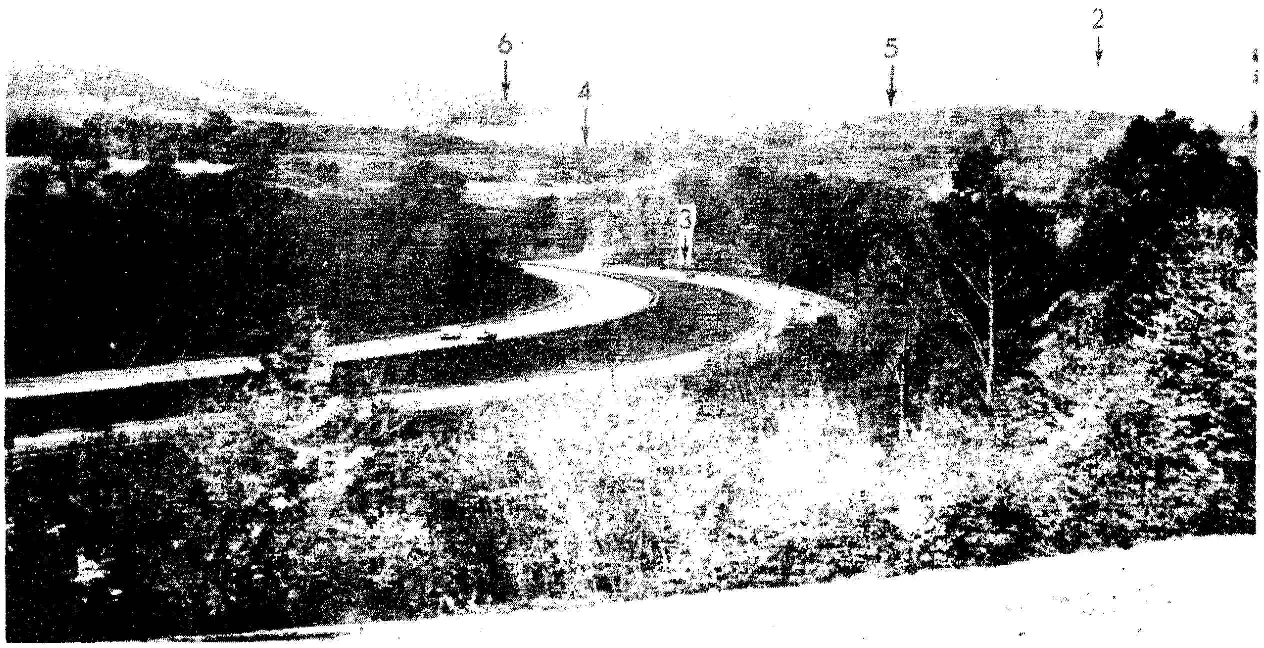


Figure 4

View northwest from Stop 1. Major small ridge (1) is Kittatinny Mountain underlain by resistant quartzite and lesser siltsone and shale of the Shawangunk Formation. The Shawangunk generally dips moderately to the northwest, such as at Delaware Water Gap (2), but is overturned to the southeast in places. The dark laminated slates exposed along Interstate 80 below (3) are in the lower (Bushkill) member of the Martinsburg Formation. Paulins Kill Valley (4) is underlain by carbonate rocks of the Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone that are in a window and are separated from the Martinsburg by the Portland Fault. The hills in the middleground beyond the Paulins Kill (5) are underlain by the Bushkill and Ramseyburg Members of the Martinsburg Formation. The upper (Pen Argyl) Member of the Martinsburg first appears across the Delaware River in Pennsylvania, coming out from under the Taconic unconformity with the overlying Shawangunk Formation (6) (also see Fig. 10).

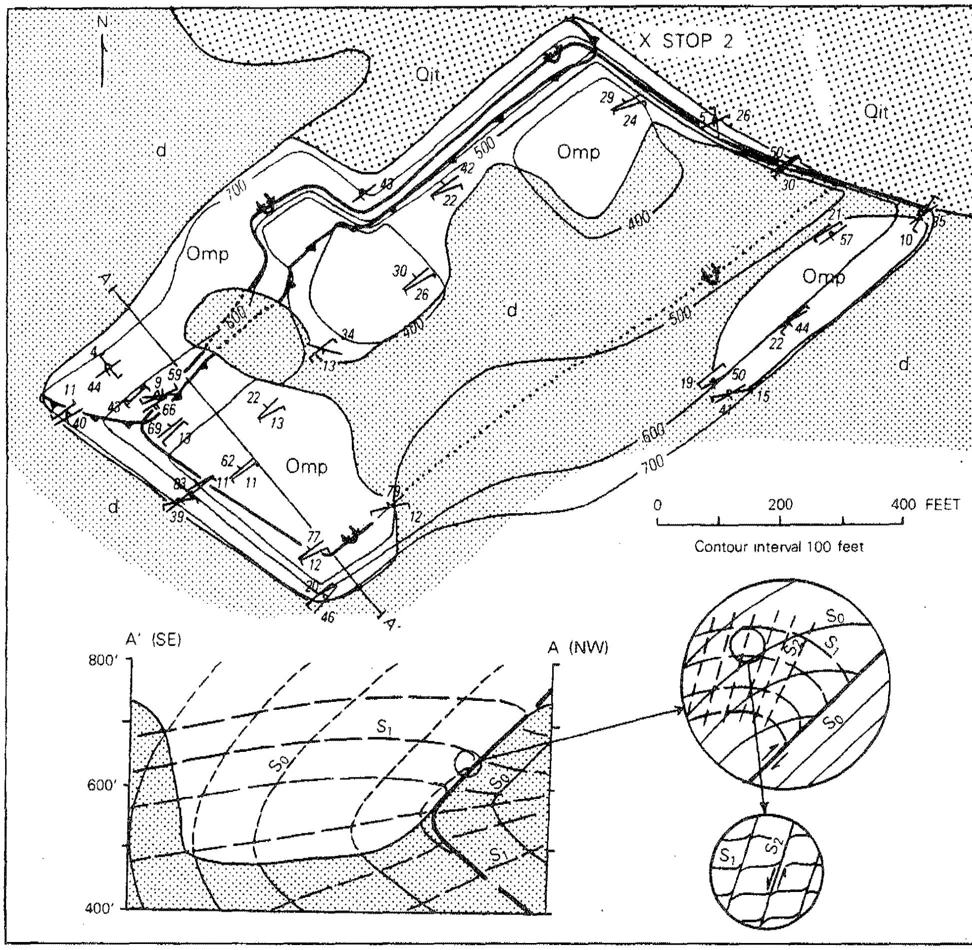
19.8 Stop at traffic light. Do not turn right towards Wind Gap. Continue straight on East Main Street which merges into West Main Street.

20.3 Turn left into unnamed street just before two gasoline pumps and one block after (east of) Broad Street. Follow black top and gravel road to Stop 2.

20.5 **STOP 2.** STEPHANS JACKSON SLATE QUARRY; STRUCTURE AND STRATIGRAPHY OF THE MARTINSBURG FORMATION; SLATY CLEAVAGE; QUARRYING OPERATION.
DANGER—STEEP QUARRY WALLS, DO NOT BE TOO BOLD!

The Stephans Jackson Slate Quarry is one of only a few that remain active in the slate belt of Pennsylvania which extends for about 45 miles (72 km) west of the Delaware River. The belt is dotted with more than 400 abandoned slate quarries and prospects. The quarry is currently about 350 feet (110 m) deep. Quarrying and milling methods have changed little for the last 50 years, and are still much the same as described by Behre (1933). The slate is used for roofing, blackboards, flagging, aquaria bottoms, sills and treads, and billiard-table tops. Immediately southwest over the dumps is the abandoned Parsons quarry, which reportedly was more than 900 feet (274 m) deep, the deepest slate quarry in the United States.

The Stephans Jackson Slate Quarry is in an overturned syncline whose axial plane dips gently to the southeast (fig. 5). A bedding-slip fault forms much of the northwest wall of the quarry. Slaty cleavage and bedding in the overiding block are dragged into the fault and a slip cleavage that shows antithetic movement to the fault, has developed in the drag fold (see inset, fig. 5). In general, slaty cleavage



EXPLANATION

69 Upright — 40 Overturned — 9 Rotated more than 180°

Strike and dip of beds

Overturned syncline
Showing trace of axial surface, dotted where concealed

12 Upright — 43 Rotated more than 180°

Strike and dip of cleavage

Bedding slip fault
Dotted where concealed

66 Strike and dip of slip cleavage

d, slate dumps

Qit, till of Illinoin(?) age

Omp, Pen Argyl Member of the Martinsburg Formation of Ordovician age

S_0, bedding

S_1, slaty cleavage

S_2, slip cleavage

Figure 5.

Geologic map and section of the Stephans Jackson Slate Quarry. Section is drawn looking to the southwest, as seen from Stop 2.

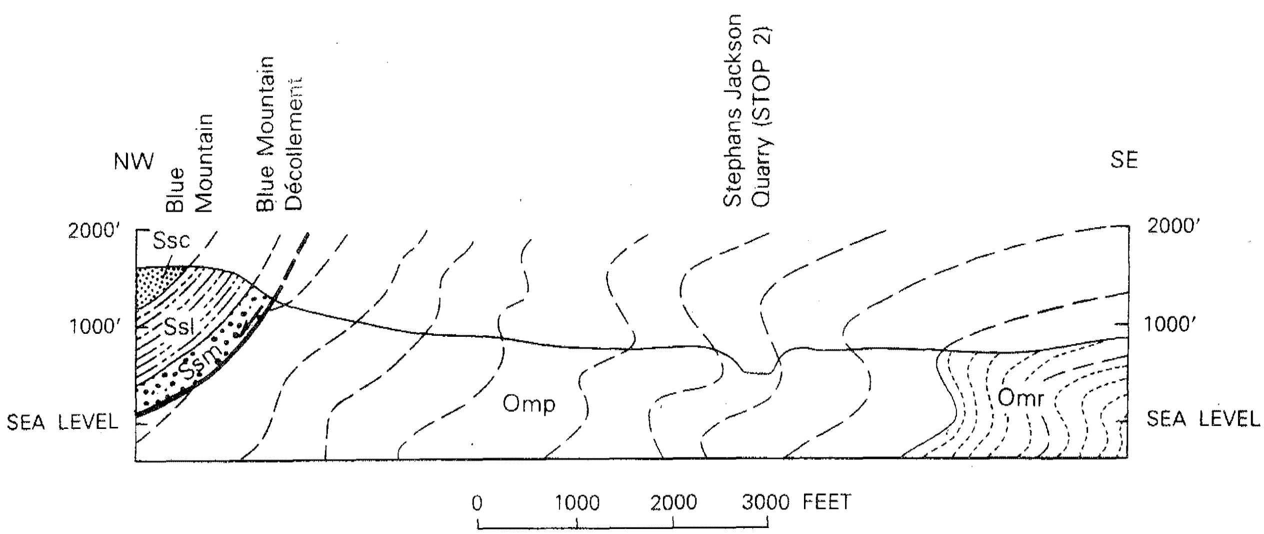


Figure 6.

Cross section showing the regional structural position of the Pen Argyl Member of the Martinsburg Formation (Omp) in the Stephans Jackson Quarry (Stop 2). Omr, Ramseyburg Member of the Martinsburg Formation; Ssm, Ssl, and Sst, Minsi, Lizard Creek, and Tammany Members of the Shawangunk Formation, respectively. Note that the Pen Argyl Member overlies the Ramseyburg Member and cannot be the lowest (Bushkill) member repeated by folding. This is evidence for three members in the Martinsburg, not two.

forms a gentle arch and fans the fold by about 14°. The fault is marked by a gouge or "spar zone" that is as much as 2 feet thick and filled with quartz and calcite.

The fault zone is a marked zone of weakness in the rock. In 1948, the northeast section of the quarry was being worked when a large mass of rock slipped down into the quarry along the zone, killing two workers below. That part of the quarry was abandoned, and the presently active section was started. Note the pins that were bent by the sliding mass in the northern corner.

The sequence of deformation was complex. Bedding-plane slickensides that are offset by cleavage indicate that initial flexural-slip folding was followed by passive folding (fig. 46, Epstein and Epstein, 1969). As the folds continued to tighten, failure was again along bedding, producing the bedding-slip fault, warping of slaty cleavage, and formation of crenulation cleavage parallel to the axial plane of the cleavage fold. Movement along the bedding-slip fault was up to the northwest, as indicated by the drag, but steps on one of two slickensided surfaces in the fault zone indicate an opposite sense of movement, perhaps due to earlier flexural slip.

The origin of slaty cleavage in the Martinsburg Formation, as well as in rocks above and below, has been a focus of considerable attention during the last two decades. Did it form by tectonic dewatering or did it form under conditions of low-grade metamorphism? Mapped relationships and petrologic considerations led me to conclude that it formed as a product of metamorphism (Epstein, 1974b) by a combination of the following processes: mechanical rotation of detrital grains parallel to the cleavage, corrosion of quartz by pressure solution and migration of silica, intrusion and flow of pelitic material, grain diminution by granulation, and by recrystallization and neocrystallization.

The Stephans Jackson Slate Quarry is in the Pen Argyl Member (upper) of the Martinsburg Formation and is about 1500 feet (457 m) above the contact with its Ramseyburg Member (middle) (fig. 6). The Pen Argyl is typically thick bedded, containing some beds of gray slate more than 10 feet (3 m) thick. The member is cyclically bedded, each cycle consisting of medium-gray slate grading up into grayish-black carbonaceous slate. Graywacke may form the base of some of the cycles.

For more than 70 years there has been controversy regarding the number of members in the Martinsburg (see Drake and Epstein, 1967). On the basis of the very characteristic difference in bedding thickness between the lower (Bushkill) and upper (Pen Argyl) members, and as proved by detailed mapping (fig. 6), I have mapped three members in this area, nearly in the same manner as Behre (1933). The Pen Argyl cannot be the Bushkill repeated by folding as earlier suggested by Stose (1930), for example. Recently, Stephens and others (1979) argued for a two-fold division based on fossil collections in the Schoharie Ridge area, about 35 miles (56 km) to the southwest. This bipartite interpretation, however, is presently clouded by structural complications that may be present in that area (Epstein and others, 1972; Lyttle, 1979).

Return to West Main Street.

20.7 Turn left on West Main Street.

20.9 Stop sign. Turn right on E Street and continue to top of hill.

21.1 Stop sign. Turn left on Pa. 512. We will be riding on gentle slopes underlain by colluvium and Illinoian(?) till which cover the Pen Argyl Member of the Martinsburg. Quartzites in the Shawangunk Formation are seen in cliffs in Blue Mountain to the right.

22.75 Junction with Alpha Road. Turn right at Arco station.

23.2 Stop sign. Junction with North Broadway in town of Wind Gap. Turn right.

23.5 Exposures of the lower (Minsi) member of the Shawangunk Formation in woods on left. The low col straight ahead is Wind Gap, underlain by nearly vertical quarzites and veneered with weathered colluvium.

23.6 Appalachian Trail. Bear right on Pa. 33 towards Stroudsburg.

24.4 Red shale, siltstone, and sandstone of the Bloomsburg Red Beds. For about 1.5 miles (2.4 km) along Pa. 33, the Bloomsburg is thrown into many small folds that are superimposed on the Ross Common Creek syncline and Wind Gap anticline. Note the well-developed cleavage in the Bloomsburg.

25.4 Chestnut Ridge to the left, underlain by complexly folded rocks of Late Silurian and Early Devonian age.

25.8 Bloomsburg Red Beds to right. Cherry Ridge straight ahead held up by sandstones in the Ridgeley and Palmerton Sandstones.

26.2 Wisconsinan till in road cut to right.

26.7 Cut through Cherry Ridge in South-dipping overturned Esopus and Schoharie Formations and Palmerton Sandstones.

26.9 Turn right off Pa. 33.

27.0 Stop sign at Cherry Valley Road. Turn left towards Bossardsville.

27.1 Many abandoned clay pits in deeply weathered Buttermilk Falls Limestone are in woods to right. These are in saprolites as much as 250 feet (76 m) deep. The clay is used as whitener in cement.

27.5 Panoramic view to left (see fig. 7).

27.8 Junction with road to Snydersville; continue straight.

29.7 Hill to right underlain by Decker Formation and Bossardville Limestone.

30.1 Village of Bossardsville. Turn right into Hamilton Stone Company quarry. Drive to upper working level of quarry.

30.8 **STOP 3.** HAMILTON STONE COMPANY QUARRY. STRATIGRAPHY AND STRUCTURE OF UPPER SILURIAN ROCKS IN CHERRY RIDGE.

Three Upper Silurian units are well exposed in the quarry in a series of upright to tight and slightly overturned folds (fig. 8). The units are, from top to bottom:

Wallpack Center Member of the Decker Formation: Medium-bedded and lenticular medium-gray to medium-light-gray, fine-to coarse-grained, quartzose limestone, medium-gray, fine-to coarse-grained calcareous sandstone, siltstone, and conglomeratic sandstone, containing brachiopods, rugose and colonial corals, bryozoans, and crinoid columnals. Leperditiid ostracodes are abundant near basal mud-cracked dolomite. Upper contact concealed. About 70 feet (21 m) exposed. Forms cap rock. Useful for crushed stone.

Bossardville Limestone: Graded laminated to very thin-bedded, dark-gray, fine-to very fine grained pyritic argillaceous mud-cracked limestone with scour-and-fill at base of graded units and leperditiid ostracodes. Uppermost beds very finely laminated limestone and smaller amounts of dolomite. About 95 feet (29 m) thick. Quarry rock useful for crushed stone.

Poxono Island Formation: Interbedded and interlaminated medium-gray, calcareous dolomite, medium-gray and mottled pinkish-gray-green to medium-greenish-gray to gray, very fine grained dolomite, grayish-red limestone, and light-grayish-yellow-green shale and calcareous shale; contains several mud-crack intervals. Uppermost dolomite contains color contortions. About 40 feet (12 m) exposed.

These rocks are interpreted to have been deposited in a complex and generally transgressive tidal-flat barrier-bar

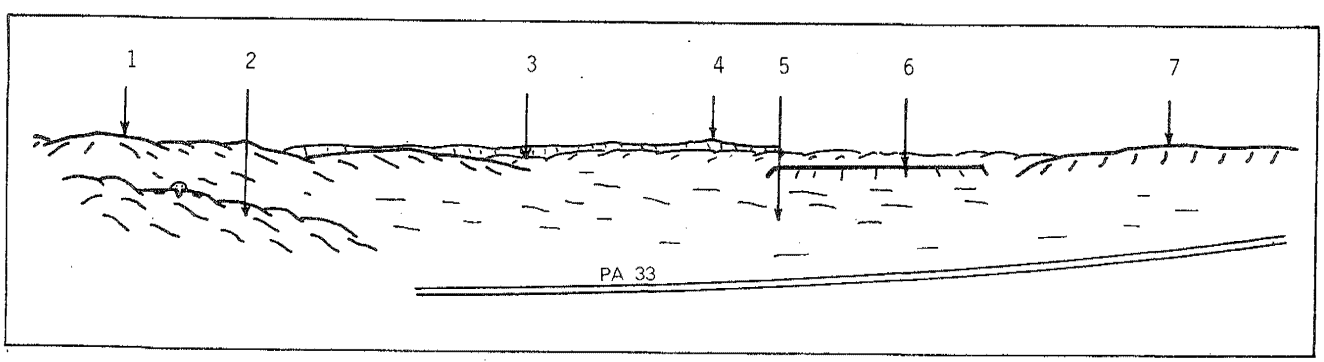


Figure 7.

Sketch of view looking north from Cherry Ridge at mileage 27.5. 1, Weir Mountain, held up by rocks in the Marcellus Shale, Mahantango Formation, and Trimmers Rock Formation. 2, Wisconsinan terminal moraine. 3, Trimmers Rock Formation in the northwest limb of the Lehighton anticline. 4, Camelback Mountain in the Pocono Plateau underlain by sandstones in the Catskill Formation. 5, Lake Creek valley underlain by varved lake beds, site of glacial Lake Sciota. 6, Flat-topped glacial delta which was deposited in Lake Sciota. 7, Southwest termination of Godfrey Ridge, underlain by complexly folded Lower and Middle Devonian rocks.

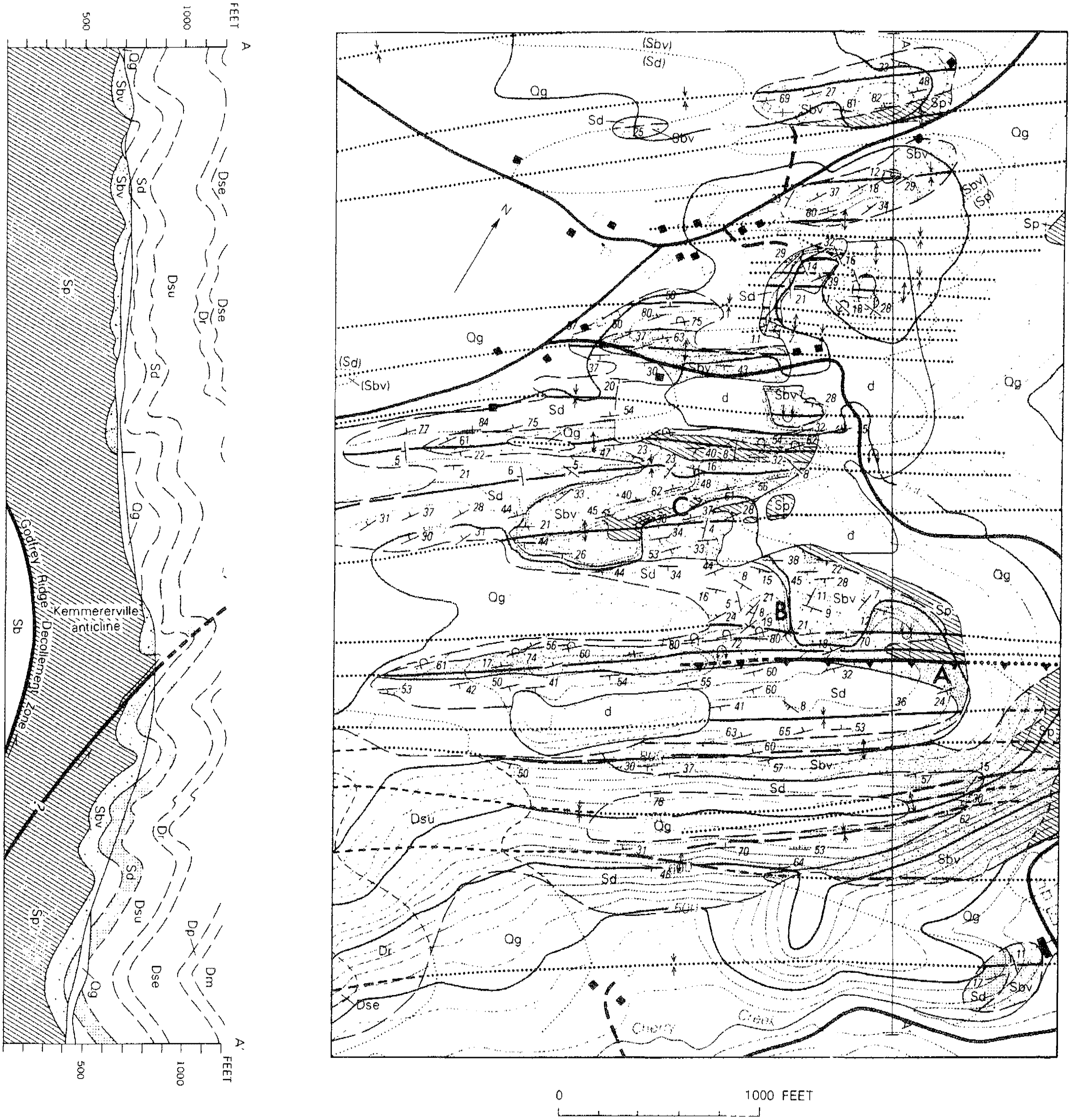


Figure 8.

Geologic map and section of the quarry area at Bossardsville, Pa. Letters represent localities discussed in text. The Poxono Island Formation, Bossardville Limestone, and Decker Formation are the only units shown with a pattern.

EXPLANATION

d
Dump

Pleistocene

Qg
Wisconsinan glacial deposit
Till in the quarry area; stratified drift in Cherry Valley

DEVONIAN

Middle Devonian

Dm
Marcellus Shale
Shown in section only

Dp
Palmerton Sandstone
Shown in section only

Lower Devonian

Dse
Schoharie and Esopus Formations, undivided

Oriskany Group

Dr
Ridgeley Sandstone

Helderburg Group

Dsu
Shriver Chert of the Oriskany Group and Helderburg Group, undivided

SILURIAN

Upper Silurian

Sd
Decker Formation

Sbv
Bossardville Limestone

Sp
Poxono Island Formation

Middle and Upper Silurian

Sb
Bloomsburg Red Beds

Contact
Long dashed where approximately located. Short dashed where inferred. Dotted where concealed

FOLDS

Anticline

Syncline

Overturned anticline

Overturned syncline
Showing trace of axial surface. Long dashed where approximately located. Short dashed where inferred. Dotted where concealed

27
Inclined

80
Overturned

Strike and dip of beds

Thrust fault
Sawteeth on upper plate. Dashed where inferred

U D
High-angle fault
U, upthrown side. D, downthrown side

shallow subtidal environment on the basis of lithology, sedimentary structures, texture, bedding characteristics, fossils, and lateral facies (see Epstein and others, 1967, and Epstein and Epstein, 1969, p. 192-196).

The structure in the quarry area is dominated by about 25 folds whose axial planes strike N. 50°-60°E. and whose axes plunge about 5°SW. These folds are disharmonic on the Kemmererville anticline in the Bloomsburg Red Beds in the underlying lithotectonic unit. The Poxono Island Formation is believed to be separated from the Bloomsburg by a decollement (see cross section, fig. 8). The anticlinal ridge underlain by the Bloomsburg rises as we travel to the northeast after leaving the quarry.

Folding was initiated by flexural slip followed by passive folding and development of cleavage. This is indicated by cleavage that wrinkles bedding-plane slickensides. In a few places, such as in the 10 foot-(3 m) wide fault zone in the east corner of the quarry, a slip cleavage cuts the earlier cleavage.

The stratigraphic units behaved differently during deformation. The more pelitic rocks failed passively, with development of prominent cleavage, whereas the more competent carbonate rocks and sandstones in the Decker and the Bossardville were concentrically folded and in places formed fold mullions. This small-scale folding is somewhat disharmonic and folds in the Poxono Island are generally tighter than in overlying rocks. This disharmonic folding is similar to the structure on a regional scale.

Places that we may visit in the quarry depend on the whims of the shovel, but we will probably go to three localities shown in figure 8: (A) A very tight anticline in the Poxono Island Formation and a fault that cuts out about 50 feet (15 m) of the Bossardville Limestone are conspicuous in outcrop here (fig. 9). As we look to the west from a high point we can see the Trimmers Rock and Catskill Formations in the southwest-plunging Weir Mountain syncline. To the north, the Pocono Plateau, Godfrey Ridge, and glacial lake deposits are seen. A well-developed ice-contact delta and esker marks a recessional position of the Wisconsinan glacier and the northeastern ice-defended boundary of glacial Lake Sciota. (B) Fold mullions and many sedimentary features are present in the Decker Formation in this overturned syncline. (C) Well-developed mudcracks, edgewise conglomerate, and other structures suggestive of supratidal deposition are of interest in the Poxono Island Formation. Cleavage that warps bedding slickensides is common in the Bossardville.

Return to Cherry Valley Road.

31.5 Stop sign. Turn right on Cherry Valley Road.

31.8 Abandoned quarries in the Bossardville Limestone to right and left.

32.0 View to right of Cherry Valley; Godfrey Ridge on left; rounded ridge in the middleground is underlain by the Bloomsburg Red Beds in the southwest-plunging Kemmererville anticline; northwest-dipping quartzites in the Shawangunk Formation hold up Kittatinny Mountain on the skyline.

32.35 Poxono Island Formation exposed in creek to right.

32.4 Near-vertical Bossardville Limestone on left.

32.9 Flat floor of Cherry Valley on right partly underlain by glacial lake clays, silts, and sands. Kittatinny Mountain forms skyline to right.

33.2 Near-vertical Bossardville Limestone on left.

34.2 Village of Stormville, type locality of the Stormville Member of the Coeymans Formation. Continue right on Cherry Valley Road towards Delaware Water Gap at fork in road.

34.6 Very well developed columnar mudcracks in the Whiteport Dolomite Member of the Rondout Formation on left.

34.8 Low hill ahead is a kame containing Wisconsinan sand and gravel.

35.0 Coeymans Formation on left in slump block.

35.2 Ridgeley Sandstone, which caps Godfrey Ridge, in float on left.

35.9 The Bloomsburg Red Beds in Kemmererville anticline to right rises up-plunge.

36.9 Junction with Pa. 191. Turn right towards Bangor. Good exposures of the Stormville Member of the Coeymans Formation in steep slope beyond farm house on right. If we cannot drive to the top of Kittatinny Mountain to Stop 4, we will turn *left* here and proceed to Stop 4a. See route to Stop 4a later in the road log.

37.1 Cross Cherry Creek.

37.6 Entering Wildcat Hollow. Exposures of northwest-dipping red and green clastic rocks of the Bloomsburg Red Beds in the northwest limb of the Kemmererville anticline.

38.0 Crest of Kemmererville anticline. South of here the rocks dip gently southeast.

38.15 Turn left on Poplar Valley Road.

39.7 Crest of Kemmererville anticline.

40.0 Stop sign. Junction with Totts Gap Road. Turn right and descend southeast limb of Kemmererville anticline.

40.3 Trough of Poplar Valley Syncline. Note ten foot long (3 m) long glacial erratics of Buttermilk Falls Limestone in creek to right.

40.8 Contact between the Shawangunk Formation and Bloomsburg Red Beds. Ascend (we hope) steep dirt road to crest of Kittatinny Mountain.

41.0 Crest of Kittatinny Mountain. Proceed east (to left) along dirt road to Stop 4. The quartzites of the Shawangunk Formation here are overturned to the southeast, dipping about 50°. As we proceed eastward, the rocks become vertical and then dip moderately northwest at Delaware Water Gap.

41.1 Microwave Tower of AT&T on right.

41.3 Good view of Kemmererville anticline, Godfrey Ridge, and

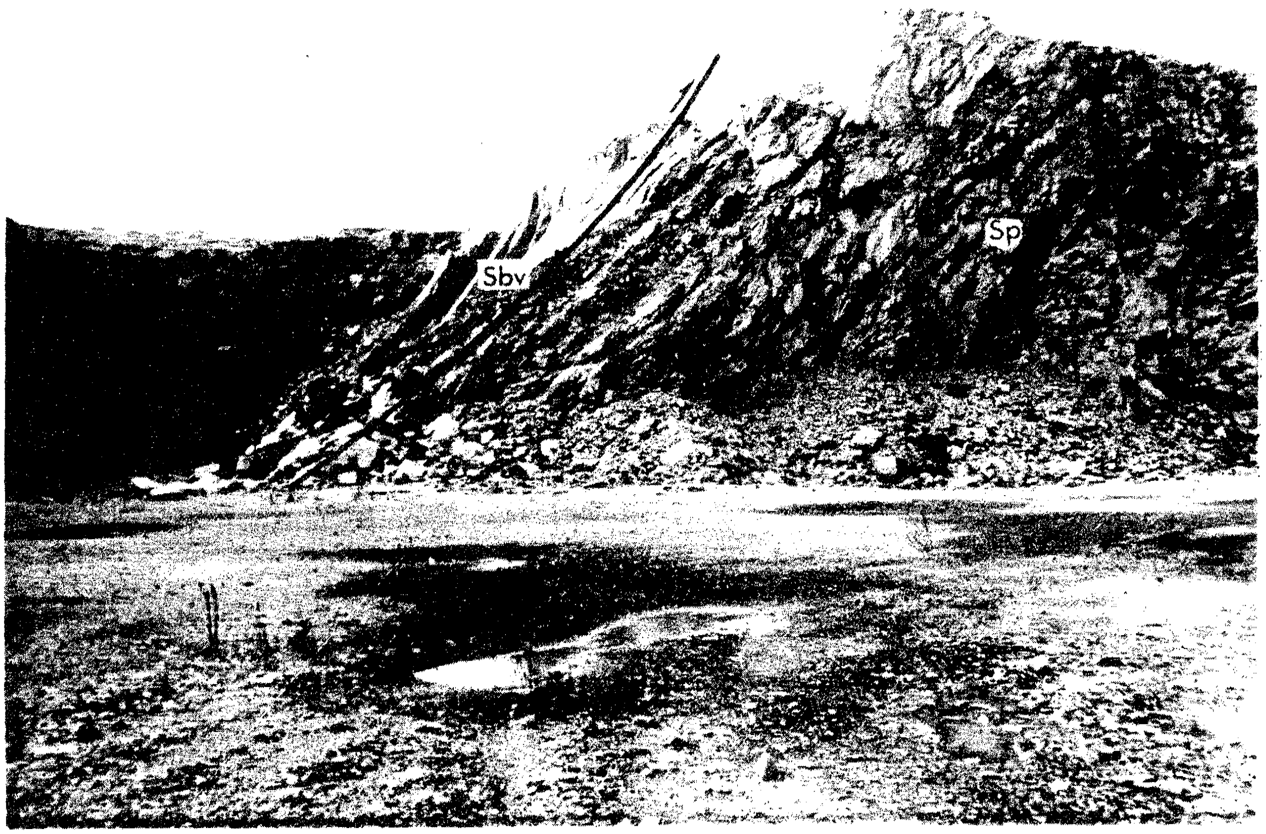


Figure 9.

Fault cutting out about 50 feet (15 m) of the Bossardville Limestone (Sbv) and traced of tight fold in the Poxono Island Formation (Sp), quarry of Herbert R. Imbt, Inc., Bossardsville, Pa., locality A in fig. 8.

the Pocono Mountains to the north (left).

41.35 National Park Service gate.

43.1 **STOP 4.** DELAWARE WATER GAP OVERLOOK. STRATIGRAPHY AND STRUCTURE OF THE SHAWANGUNK FORMATION: ORIGIN OF WIND AND WATER GAPS; NATURE OF THE ORDOVICIAN-SILURIAN CONTACT; SUMMARY OF TRIP.

Park at end of road. Disembark and follow Appalachian Trail to edge of Delaware Water Gap.

The three members of the Shawangunk Formation, basically two conglomeratic quartzite units separated by a sequence of argillites and quartzites, and the lower part of the Bloomsburg Red Beds, are well exposed in the gap. The Minsi and Tammany Members of the Shawangunk are interpreted to have been deposited by braided streams flowing off highlands uplifted during the Taconic orogeny, whereas the Lizard Creek Member of the Shawangunk represents a complex transitional continental-marine environment (Epstein and Epstein, 1967, 1969, 1972). Fining-upward sequences in the Bloomsburg are indicative of meandering streams. The contact between the Shawangunk and the Bloomsburg, based on an upward change from gray to red rocks, is extremely irregular, particularly near the village of Delaware Water Gap, 1.5 miles (2.4 km) to the northwest (see fig. 10 and Epstein, 1973).

The Shawangunk in the gap dips moderately to the northwest (figs. 10 and 11) and contains many small satellitic folds. The beds reverse their dip in the Dunnfield Creek syncline, and do so again in the Cherry Valley anticline. We will see the northwest limb of the Cherry Valley anticline at the toll booth on Interstate 80 in the village of Delaware Water Gap. Many small undulations, wedges, and bedding slips in the Bloomsburg are superimposed on the larger Dunnfield Creek syncline. Movement of these structures suggests sliding to the northwest.

The regional strike between the Martinsburg and the Shawangunk in this area differs by about 15°, and the Ramseyburg-Pen Argyl contact in the Martinsburg is buried beneath the Shawangunk 1.2 miles (2 km) southwest of the gap. The difference in structural trends is very apparent in the field, on aerial photographs, and high-altitude imagery. This regional Taconic unconformity is well documented. On the basis of several lines of reasoning, however, I believe the cleavage in the Martinsburg at the gap to be Alleghenian in age. Note that the cleavage in the

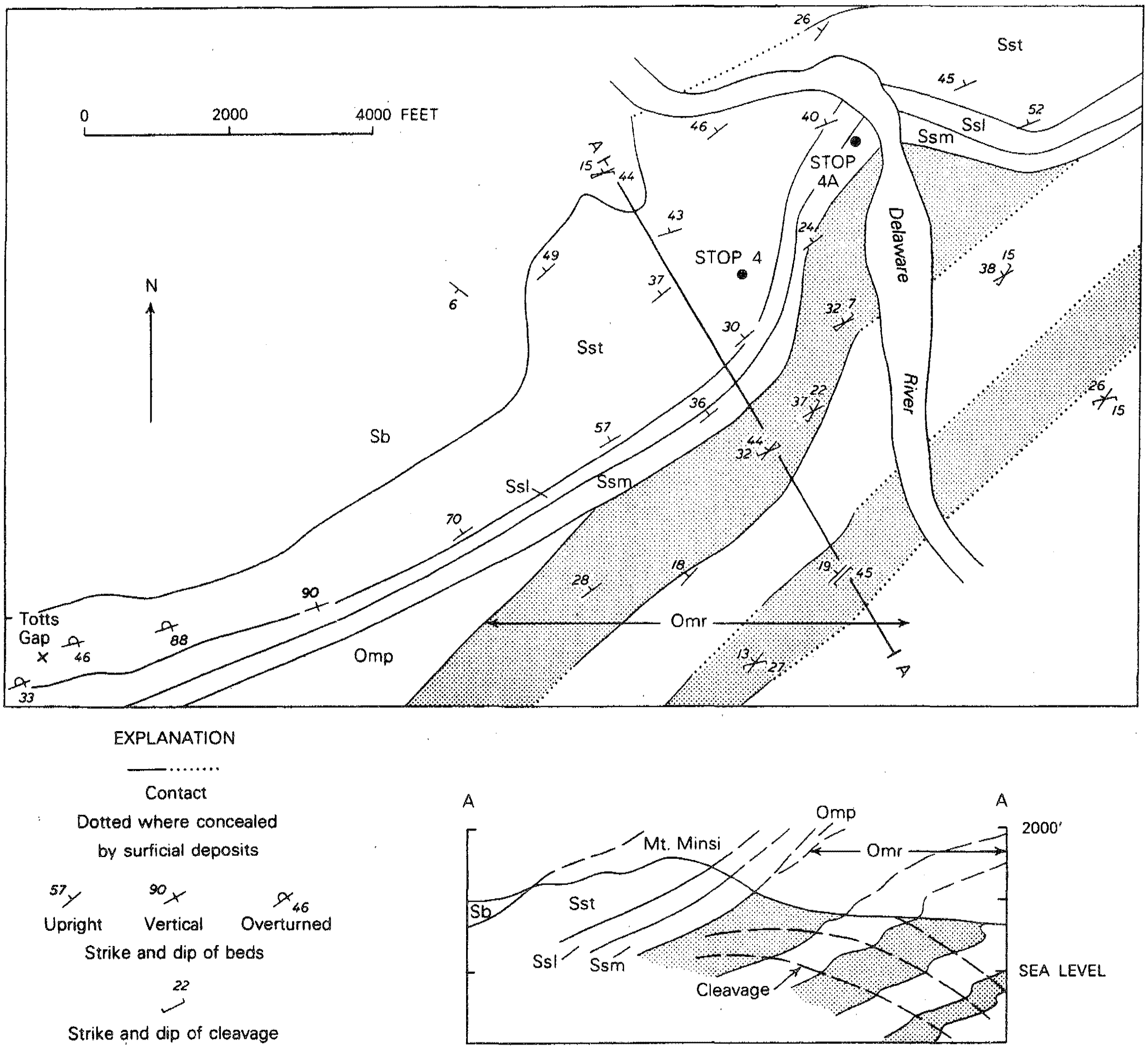


Figure 10.

Generalized geologic map and section at Delaware Water Gap showing the angular unconformity between the Martinsburg and Shawangunk Formations (also believed to be a zone of movement, the Blue Mountain Decollement) and the "arching" of cleavage in the Martinsburg. The cleavage is generally steeper in the graywacke beds than shown. Sb, Bloomsburg Red Beds; Sst, Ssl, and Ssm, Tammany, Lizard Creek, and Minsi Members of the Shawangunk Formation; Omp and Omr, Pen Argyl and Ramseyburg Members of the Martinsburg Formation. Stippled areas are grayacke-bearing intervals in Omr. Surficial deposits not shown. Positions of Stops 4 and 4A are shown.

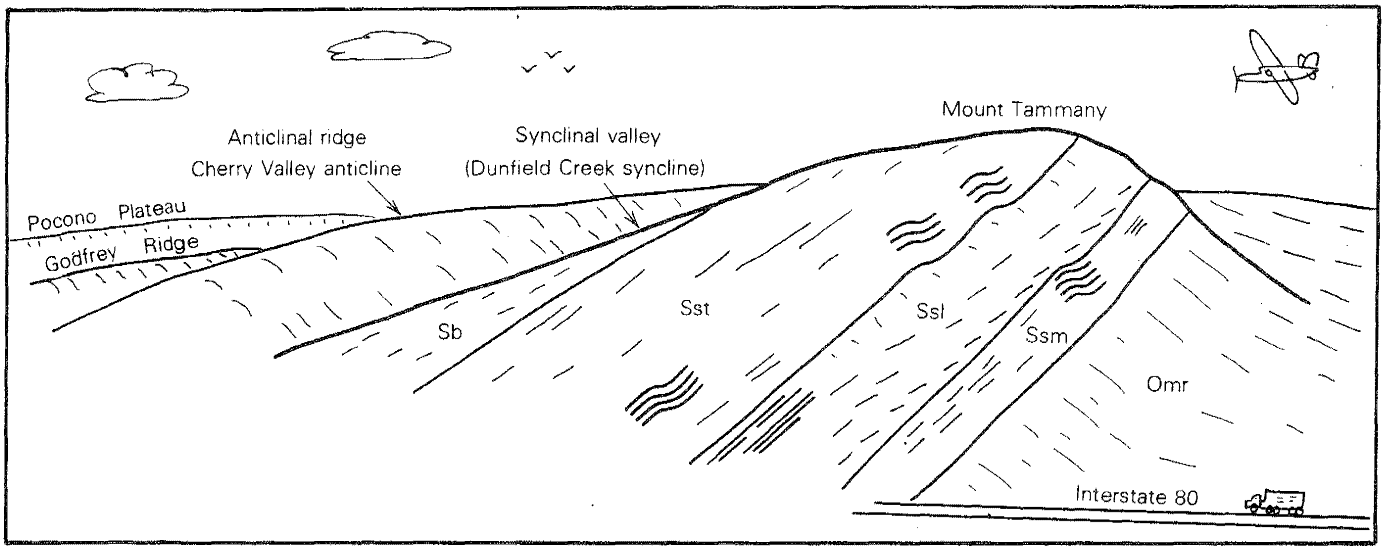


Figure 11.

Sketch from photograph looking northeastward into New Jersey from Stop 4 showing the geology at Delaware Water Gap. A few satellitic folds in the Shawangunk Formation are indicated. Relief between the Delaware River and Mt. Tammany is 1260 feet (384 m). Sb, Bloomsburg Red Beds; Sst, Ssl, and Ssm, Tammany, Lizard Creek, and Minsi Members of the Shawangunk Formation; Omr, Ramseyburg Member of the Martinsburg Formation, which is talus covered in the area of the sketch.

Martinsburg arches, whereas bedding maintains its general northwest dip (fig. 10), indicating that the arching was not caused by external rotation during post-Taconic deformation. Rather, I believe that the arching is due to a pressure-shallow mechanism whereby cleavage in pelitic rocks adjacent to more competent rocks fans away from the axis of a syncline (see Epstein and Epstein, 1969, p. 166-167). The upper limb of the syncline in the Shawangunk is eroded away, of course, but it can be seen down-plunge to the southwest where the beds are overturned, such as at Totts Gap.

Glacial striae and roches moutonnees are common on top of Kittatinny Mountain. They trend about due south, but the Wisconsinan glacier was deflected more to the southwest on the slopes and in the valleys, following the trend of the topography.

For many years there have been numerous discussions on the origin of wind and water gaps and how that origin relates to Appalachian geomorphic development. Basically, two contrasting viewpoints have been presented. One favors coincidental location of the gaps due to superposition from a coastal-plain cover (e.g., Johnson, 1931). The other argues for northwestward headward erosion from the original drainage divide to the southeast along lines or points of structural weakness. The test of superposition, according to Strahler (1945), was to show lack of structural control for the location of the gaps.

For 40 miles (64 km) along Kittatinny and Blue Mountains and the ridges to the north, I have mapped the geology at 12 major gaps in Pennsylvania and New Jersey. The gaps are located where one or more of the following geologic conditions exist: (1) folds die out within short distances, (2) beds dip steeply and resistant units have narrow outcrop widths, and (3) there is more intense local folding or shearing than nearby (see Epstein, 1966).

At Delaware Water Gap the crest of Kittatinny Mountain in Pennsylvania is offset 800 feet (245 m) to the southeast from the trend of the crest in New Jersey. However, a transverse fault is not present through the gap (as has been suggested by several workers), because the contacts of the three members within the Shawangunk are not displaced at river level (fig. 10). The offset of the ridge crest is due to downward flexing of the rocks on the Pennsylvania side whereas the rocks maintain a constant dip on the New Jersey side (fig. 12). The flexure can be seen by looking west from the New Jersey bank. The abrupt change in strike at the gap site must have resulted in extensive fracturing in the brittle Shawangunk. Structural control is therefore thought to have determined the location of the gap. Also, the Bloomsburg Red Beds just north of the gap are involved in about 15 folds that die out rapidly to the southwest, including the large Dunnfield Creek syncline and Cherry Valley anticline. This structural situation is present at other large gaps, such as Wind Gap and Lehigh Gap. The rocks were probably more highly sheared here, and resistance to erosion was less than in the areas between gaps where similar folds were not observed.

Thus, data supporting structural control for location of the gaps does not favor the concept of regional superposition. Rather, it favors those hypotheses that maintain that gaps are located in zones of structural weakness where erosion was most effective during the course of stream competition along the ancestral drainage divide.

Time permitting, we will sumarize the themes of this trip: structural comparisons of the several lithotectonic units, ages of deformation, regional stratigraphic framework, history of sedimentation, and Quaternary history. Return to bus on Totts Gap Road. Proceed west.

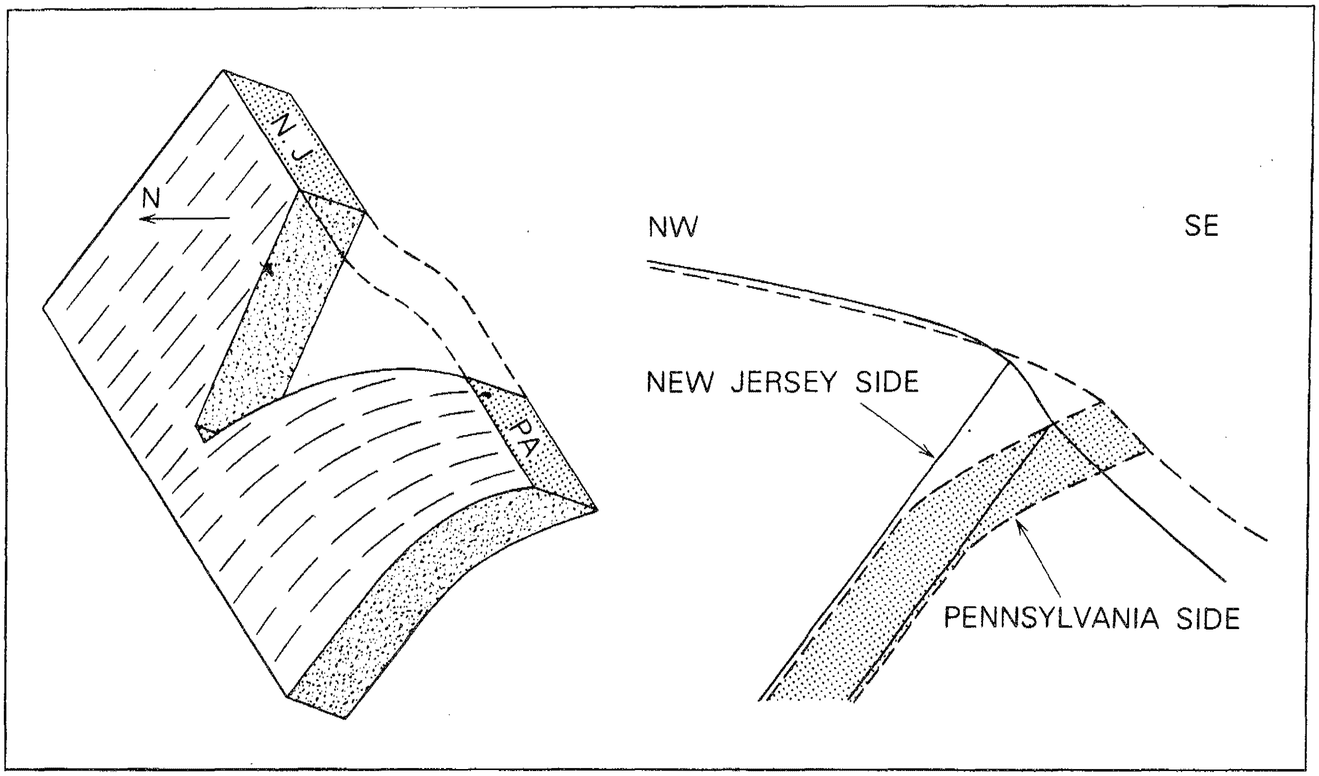


Figure 12.

Cross section and reconstructed flexure at Delaware Water Gap showing topographic offset of Kittatinny Mountain due to downwarping of the Shawangunk Formation in Pennsylvania, suggesting extensive fracturing at the gap site.

45.2 Turn right at Totts Gap and proceed down mountain.

46.2 Turn right at intersection of Totts Gap Road and Poplar Valley Road.

46.3 Crest of Kemmererville anticline. Descend northwest limb of anticline. A thin layer of till caps bedrock in most of this area.

47.4 Stratified Wisconsinan sand and gravel in kames underlying golf course on left. Godfrey Ridge, underlain by complexly folded Upper Silurian and Lower Devonian rocks, forms the ridge beyond Cherry Valley.

47.8 Intersection with Cherry Valley Road. Turn right.

48.7 Village of Delaware Water Gap. Intersection with U.S. 611. Continue straight ahead.

49.0 Stop sign. Continue straight to Interstate 80E.

49.1 Stop sign. Enter Interstate 80. Proceed to toll booth. Exposures are northwest-dipping rocks in the Shawangunk Formation on the northwest limb of the Cherry Valley anticline.

49.3 Exposures of Shawangunk Formation on right dip to south on the southeast limb of the Cherry Valley anticline.

49.6 Crossing Delaware River.

49.8 Undulations in the Bloomsburg Red Beds on left are superimposed on the northwest limb of the Dunnfield Creek syncline. Many wedges and bedding-plane slips are exposed in these rocks. Note the well-developed cleavage.

50.2 Water-worn and glacially striated Bloomsburg on left.

50.5 Kame terrace on left.

50.6 Contact between Shawangunk Formation and Bloomsburg Red Beds covered on left.

50.8 Massive conglomeratic quartzites of the upper (Tammany) member of the Shawangunk Formation on left.

50.9 Interbedded quartzite, siltstone, and shale in the middle (Lizard Creek) member of the Shawangunk Formation on left.

51.0 Quartzites of the lower (Minsi) member of the Shawangunk Formation on left. Note to the right that the Shawangunk dips about 45° at river level and is warped to lesser dips halfway up the mountain (fig. 12). Note gabions retaining the colluvium on left. The contact of the Martinsburg and Shawangunk is buried here but was discussed by Beerbower (1956).

Continue south and then east on Interstate 80 back to Newark.

In case we do not go to Stop 4, follow this road log to alternate Stop 4, picking up at mileage 36.9.

36.9 Turn left on Pa. 191 North.

37.1 Bear left at "Y" heading towards Stroudsburg.

37.2 Steeply dipping Port Ewen Shale of the Helderburg Group, Shriver Chert and Ridgeley Sandstone of the Oriskany Group, and Esopus Formation on left. Note well-developed cleavage in the Esopus.

37.6 Crest of Godfrey Ridge supported by siliceous siltstones in the Esopus Formation. The road descends through several folds in the Esopus and Schoharie Formations and Buttermilk Falls Limestone.

38.1 Stop sign. Turn right on U.S. 611 S. Slightly overturned Buttermilk Falls Limestone on right.

38.3 Overturned Schoharie Formation on right. The road ascends through several folds.

38.9 Crest of Godfrey Ridge, underlain by the Esopus Formation seen on left with well-developed cleavage. View to right of Cherry Valley, the Kemmererville anticline underlain by the Bloomsburg Red Beds in the middleground, and Kittatinny Mountain, underlain by Shawangunk quartzites, in the skyline.

39.0 Esopus Formation on left.

39.1 Ridgeley Sandstone on left underlain by Shriver Chert.

39.2 Port Ewen Shale on left. The road descends through various Wisconsinan deposits.

40.5 Bear right on U.S. 611 S. in the village of Delaware Water Gap.

40.9 Traffic light. Continue south on U.S. 611.

41.3 Northwest-dipping gray sandstone and siltstone in the Shawangunk Formation on right.

41.5 Crest of Cherry Valley anticline. Note the lateral gradation of red, green, and gray beds at this contact between the Shawangunk Formation and Bloomsburg Red Beds.

41.7 Resort Point Overlook on left. Note the undulations in the Bloomsburg across the river which are superimposed on the northwest limb of the Dunnfield Creek syncline. Cleavage is well developed and wedges and bedding slips are common.

42.0 Note "Indian Head" in cliffs of the Shawangunk on the left side of the gap.

42.6 Shawangunk-Bloomsburg contact on right.

43.2 Turn right into Point-of-Gap Overlook and park in parking lot.

ALTERNATE STOP 4. See Stop 4 for discussion.

Leave parking lot and continue south on U.S. 611.

43.5 Cold Air Cave on right. Cave is formed by a large slab of quartzite float resting on smaller stones. Cold air stored in the colluvium flows down through the rocks and into the cave. It was used for storage of soft drinks more than 50 years ago (Stone, 1932).

43.7 Outcrop of the middle (Ramseyburg) member of the Martinsburg Formation on right. Beds dip 32°NW and cleavage dips 7°NW.

44.3 Very coarse kame-terrace deposits on right. These deposits flank both sides of Delaware Valley for more than 1 mile downstream.

45.4 Two quarries hidden in narrow valleys on right are in the lower (Bushkill) member of the Martinsburg Formation.

46.9 Traffic light in town of Portland. Continue straight ahead.

46.95 Intersection with U.S. 611 S. Continue straight under bridge.

47.1 Turn right to toll bridge. Cross Delaware River and follow Interstate 80 back to Newark.

End of trip.

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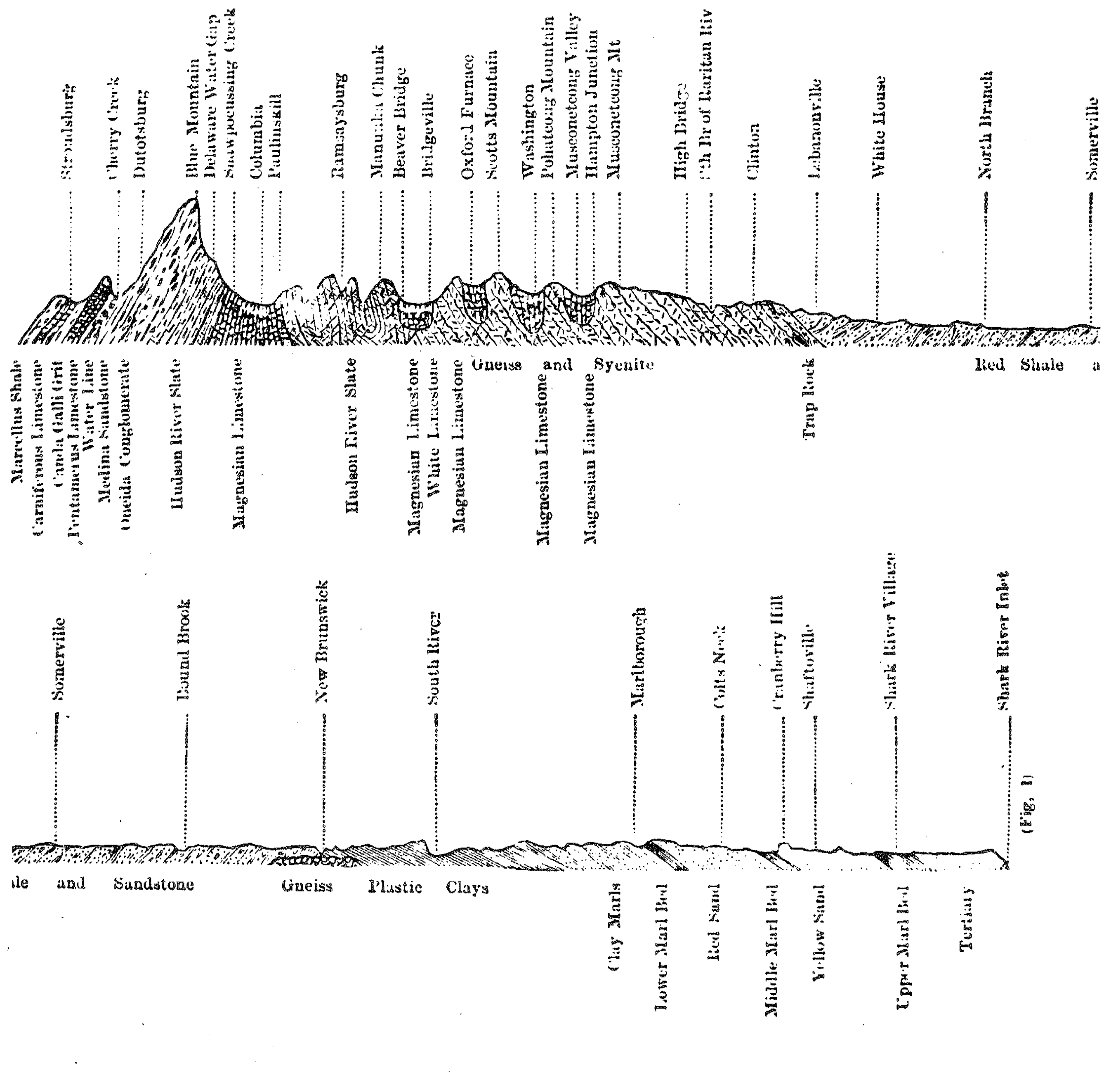

Cross Section from the Delaware Water Gap to the Shark River Inlet by G.H. Cook, State Atlas of New Jersey, 1872.

ALLEGHANIAN THRUST FAULTS IN THE KITTATINNY VALLEY, NEW JERSEY

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Introduction

Major thrust faults involving both Proterozoic basement and Cambrian and Ordovician sedimentary rocks have been known in the Kittatinny Valley at least since the geologic mapping that resulted in the New Jersey State Geologic Map (Lewis and Kummel, 1910-12) and the Raritan Folio (Bayley and others, 1914). Three important thrust faults, the Jenny Jump, Portland, and Federal Springs, display quite different tectonic styles at the present level of erosion and, thereby, serve as showpieces of thrust fault tectonics for this part of the central Appalachian orogen. The purpose of this field trip is to demonstrate these three thrust faults and to present evidence for their late, probably Alleghanian age. In addition, attendant structural features such as autoclastic mélange and chert mylonite will be shown.

Stratigraphy

Rocks pertinent to this study include Proterozoic Y gneisses and foliated granitoids and sedimentary rocks of Cambrian and Ordovician age. The pre-upper Middle Ordovician rocks of the Kittatinny Valley belong to the orthoquartzite-carbonate facies and were deposited on the great east-facing shelf of the North American craton. Subsequent to the foundering of that shelf, upper Middle and lower Upper Ordovician graywacke-shale flysch was deposited.

Proterozoic Y Rocks

Proterozoic Y rocks form the nappe cores within the Musconetcong nappe system of the Reading Prong nappe megasystem. On this field trip, these rocks will be seen in the very large Jenny Jump and small Silver Lake I klippen of the Jenny Jump thrust sheet (fig. 1). In this part of New Jersey, the Proterozoic Y rocks consist of a sequence of metasedimentary and metavolcanic rocks and three suites of intrusive rocks (Drake, 1969).

Metasedimentary and Metavolcanic Rocks

The metasedimentary-metavolcanic sequence consists of amphibolite and pyroxene amphibolite much of which is migmatized, pyroxene gneiss, dolomite and calcite marble, oligoclase-quartz, gneiss and quartzo-feldspathic gneiss which has potassic feldpar, biotite-quartz-plagioclase, and sillimanite-bearing end member variants. The sequence originally consisted of interbedded limestone and dolomite (marble, pyroxene gneiss, and some amphibolite), semipelitic and psammitic sedimentary rocks (quartzo-feldspathic gneisses), and felsic and mafic volcaniclastic rocks and related mafic flows (oligoclase-quartz gneiss and some amphibolite). Some amphibolite in New Jersey may have been intrusive, but there is no evidence for this in areas we have studied. These rocks were metamorphosed in the granulite facies during the Grenville orogeny.

The most abundant intrusive rocks in this part of northern New Jersey are hornblende granite, alaskite, and related pegmatite which are characterized by microperthite. Because of their close petrographic, petrochemical, and spatial relations, these rocks are thought to have stemmed from the same magma, and thereby, constitute an intrusive suite (Drake, 1969). Rocks of this suite occur in conformable sheets, pods, and hook-shaped refolded bodies which, in the past, were described as phacoliths. These granitic rocks have all the features usually ascribed to syntectonic intrusions. They are foliated and many bodies are gneissoid. Where they have enjoyed more intense Paleozoic deformation, they are auger, flaser, or mylonite gneiss, mylonite, or brecciated mylonite. Practically all the geologists who have worked in the Reading Prong have found that the bulk of the microperthite-bearing granitic rocks have intruded the metasedimentary-metavolcanic sequence although there is some evidence of granitization of amphibolite on the margins of some plutons (Drake, 1969). These rocks were intruded during the Grenville orogeny (Rankin and others, in press).

Smaller bodies of two other suites of intrusive rock occur sporadically in this part of northern New Jersey. One of these suites consists of alaskites and granites which are characterized by the presence of microantiperthite. Many of these rocks contain clinopyroxene and it is likely that they are related to the clinopyroxene- and microantiperthite-bearing granites and syenites so abundant in areas farther east in New Jersey (Baker and Buddington, 1970). The microantiperthite-bearing rocks are foliated and in most exposures have a strong lineation marked by lenticulated quartz. To our

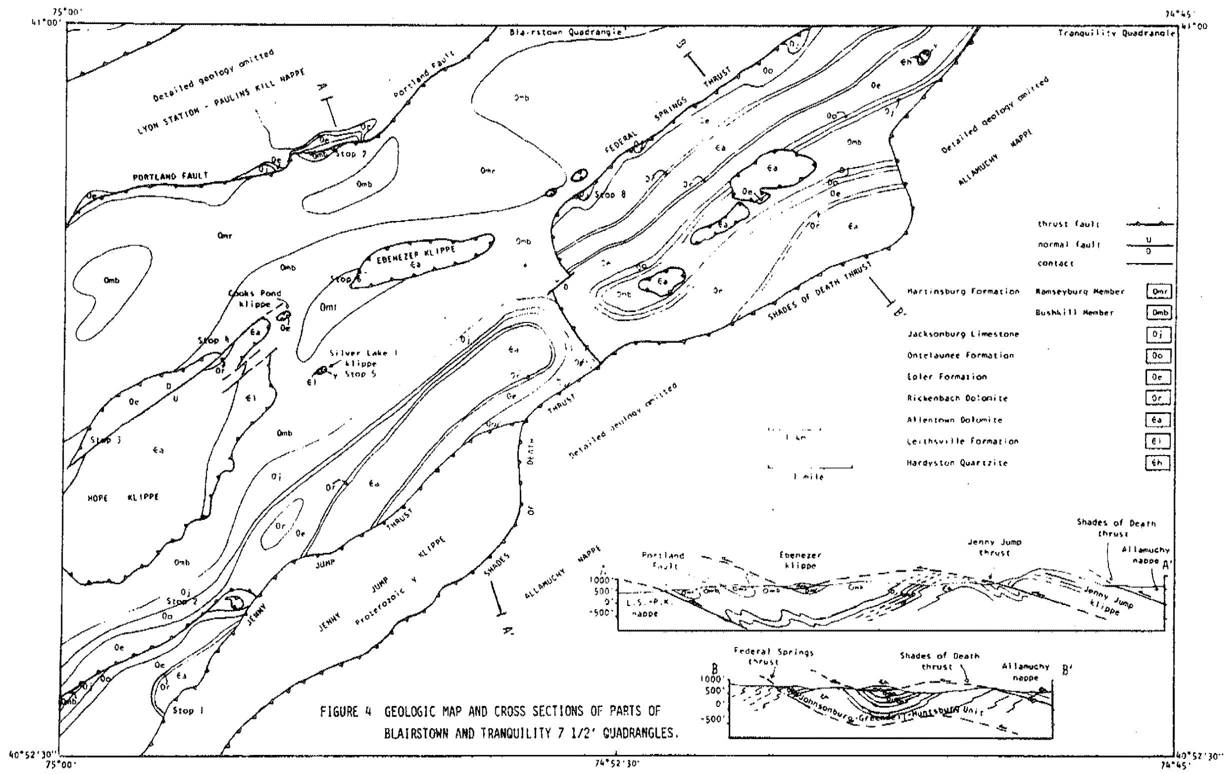


Figure 1. A. Geologic map and cross sections of parts of Blairstown and Tranquility 7½ minute quadrangles, New Jersey.

knowledge, these rocks have not been dated, but there is no reason to suspect that they are other than Grenvillian in age.

The third suite consists of bodies of sodic granite rocks that are fairly common throughout northern New Jersey. These rocks are thought to result from the anatectic remobilization of the metavolcanic oligoclase-quartz gneiss (Drake, 1969) during the Grenville orogeny.

Cambrian and Ordovician Rocks

The Cambrian and Ordovician rocks of the Kittatinny Valley belong stratigraphically to the Lehigh Valley sequence as first defined by MacLachlan (1967) and tectonically to the Musconetcong nappe system (Drake, 1978). A brief description of the stratigraphy of the Lehigh Valley sequence is given in Table 1. The carbonate rocks between the Hardyston Quartzite and Jacksonburg Limestone, that is the Leithsville Formation, Allentown Dolomite, and Beekmantown Group have been termed the Kittatinny Limestone since the work of H. D. Rogers (1840). In New Jersey, the Kittatinny was first subdivided by Drake (1965) during his systematic geologic study of the Delaware Valley. Kittatinny is an old and honored stratigraphic name and is quite useful in describing the carbonate-rock terrane of Cambrian to earliest Middle Ordovician age in eastern Pennsylvania and New Jersey. We, therefore, introduce the term Kittatinny Supergroup to include the Leithsville Formation, Allentown Dolomite, and Beekmantown Group consisting of Stonehenge Limestone (not known in New Jersey), Rickenbach Dolomite, Epler Formation, and Ontelaunee Formation. It overlies the basal Hardyston Quartzite. The Hardyston has a facies relation with the overlying carbonate rocks as aptly shown by Aaron (1969). Inclusion of the Hardyston with the Supergroup of predominantly carbonate rocks follows the lead of Fisher (1977) who included the basal Poughquag Quartzite with the carbonate rocks in the Wappinger Group of Cambrian and Early Ordovician age in New York.

The Kittatinny Supergroup, as defined above, together with the Hardyston Quartzite, forms a part of the Lehigh Valley sequence which constitutes the cover rocks of the Musconetcong nappe system in the Reading Prong and Great Valley of New Jersey and eastern Pennsylvania. Its western limit is in the Reading, Pa. area where the rocks of the Musconetcong nappe system pass beneath the Lebanon Valley sequence of the Lebanon Valley nappe (MacLachlan, 1979b; MacLachlan and others, 1975). In addition, the quartzite-carbonate sequence of Cambrian to Early Ordovician age in the Buckingham Valley of eastern Pennsylvania likely belongs to the Kittatinny Supergroup although these rocks have not been studied in any detail. The Kittatinny Supergroup is directly on strike with the Wappinger Group in New York and is a correlative unit, although internal subdivisions may not be the same. The application of modern conodont biostratigraphic techniques should result in more exact correlations.

Table 1.--Lehigh Valley sequence of eastern Pennsylvania and New Jersey

Supergroup	Group	Formation	Member	Description	Thickness (meters)
		Martinsburg, upper Middle and lower Upper Ordovician (Geiger and Keith, 1891)	Pen Argyl (Behre, 1927	Dark-gray to grayish-black, thick- to thin-bedded, evenly bedded slate; rhythmically interlayered with beds of quartzose slate or subgraywacke and carbonaceous slate. Upper contact is unconformable and site of a décollement. Contains mineral assemblage muscovite-chlorite-albite-quartz. Not present in northwestern N. J.	1,000-2000
			Ramseyburg (Drake and Epstein, 1967)	Medium- to dark-gray slate that alternates with beds of light- to medium-gray, thin- to thick-bedded graywacke and graywacke siltstone. Graywacke composes 20-30 percent of unit. Upper contact gradational. Pelitic elements contain mineral assemblage muscovite-chlorite-albite-quartz.	About 930
			Bushkill (Drake and Epstein, 1967)	Dark- to medium-gray thin-bedded slate containing thin beds of quartzose slate, graywacke siltstone, and carbonaceous slate. Upper contact gradational. Contains mineral assemblage muscovite-chlorite-albite-quartz.	About 1350
		Jacksonburg Limestone, Middle Ordovician (Spencer and others, 1908)	Cement-rock facies (Miller, 1937)	Dark-gray, almost black, fine-grained, thin-bedded argillaceous limestone. Contains beds of crystalline limestone at places. Upper contact gradational. Contains mineral assemblage calcite-chlorite-muscovite-albite-quartz.	100-330
			Cement-limestone facies (Miller, 1937)	Light- to medium-gray, medium- to coarse-grained, largely well-bedded calcarenite and fine- to medium-crystalline high-calcium limestone. Upper contact is gradational in main outcrop belt but is apparently unconformable and marked by a conglomerate in the Paulins Kill lowland. Lower contact is marked by beds of dolomite-pebble to boulder-conglomerate in main outcrop belt.	20-130
Kittatinny (here named)	Beekmantown Clark and Schuchert, 1899)	Ontelaunee, upper Lower and lowest Middle Ordovician (Hobson, 1957)		Medium- to thick-bedded medium dark-gray, fine-to coarse crystalline dolomite, that is very cherty at the base, passing up into medium- to thick-bedded, medium-gray, fine- to medium-crystalline dolomite that contains beds of medium crystalline calcilutite at the top in some places. Upper contact is sharp and unconformable. Unit only sporadically present east of Northampton, Pa., because of extreme erosion on the Middle Ordovician unconformity.	0-200
do	do	Epler, Lower Ordovician (Hobson, 1957)		Interbedded very-fine-grained to cryptogranular, light- to medium-gray limestone and fine- to medium-grained light-gray to dark-medium-gray dolomite. Upper contact sharp and unconformable except where Ontelaunee is present. At those places it is gradational.	About 270
do.	do	Rickenbach Dolomite, Lower Ordovician (Hobson, 1957)		Fine- to coarse-grained, light-medium to medium-dark-gray dololutite, dolarenite, and dolorudite. Lower part characteristically thick bedded, upper part generally thin bedded and laminated. Upper contact gradational.	About 220
do	do	Stonehenge Limestone, Lower Ordovician (Stose, 1908)		Medium-light-gray to medium gray, finely crystalline limestone marked by silty or sandy laminae. Easternmost exposures contain a fair amount of dolomite. Unit has a facies relation with the Rickenbach Dolomite. Upper contact gradational. Unit not known in easternmost Pa. or N. J.	0-75
do		Allentown Dolomite, Upper Cambrian and probably lowest Lower Ordovician		Very fine- to medium-grained, light-gray to medium-dark gray, alternating light- and dark-gray weathering, rhythmically bedded dolomite containing abundant algal stromatolites, oolite beds, and scattered beds and lenses of orthoquartzite. Upper contact gradational.	About 575
do		Leithsville Formation, Lower and Middle Cambrian (Wherry, 1909)		Interbedded light-medium-gray to dark-gray, fine- to coarse-grained dolomite and calcitic dolomite, light-gray to tan phyllite, and very thin beds and stringers of quartz and dolomite sandstone. Upper contact is gradational. Phyllite contains mineral assemblage muscovite-chlorite-albite-quartz.	About 350
		Hardyston Quartzite, Lower Cambrian (Wolff and Brooks, 1898)		Gray quartzite, feldspathic quartzite, arkose, quartz pebble conglomerate, and silty shale or phyllite. Upper contact is gradational. Phyllite contains mineral assemblage muscovite-chlorite-albite-quartz.	Maximum about 30

Structural Geology

In the period between 1959 and 1970, a nappe theory has been devised to explain the highly complicated structural geology of the Great Valley-Reading Prong segment of the Taconides (Drake, 1980) in east-central and eastern Pennsylvania and New Jersey (Gray, 1959; MacLachlan, 1964; Drake, 1969, 1970). More recent work, however, has shown that the structural geology is even more complex and that the Proterozoic Y and lower Paleozoic rocks are involved in a nappe megasystem of Taconic age that was later deformed, during the Alleghanian orogeny, into a system of décollements at different tectonic levels that are linked by steep ramp faults like those of the Valley and Ridge (Drake, 1978, 1980; Faill and MacLachlan, 1980; MacLachlan, 1979a, 1979b; MacLachlan and others, 1975). This linked décollement style of deformation is beautifully illustrated by a long outcrop of Ramseyburg on the east-bound lane of interstate 80 about 2 miles west of the Hope exit (fig. 2). The structures in this outcrop, which is immediately adjacent to the Hope klippe, are typical of the décollement terrane of the Valley and Ridge; see for instance Harris and Milici (1977) and Perry (1978).

Three phases of folds have been recognized in this part of the Taconides in northern New Jersey: An eastnortheast-trending set of early folds and northeast- and nearby east-trending sets of later folds (Drake, 1978). Major thrust faulting occurred subsequent to the northeast fold phase and prior to the northeast-trending fold phase which, in turn, predated the nearly east-trending fold phase (Drake, 1978).

Rock fabric related to these deformations is best shown by rocks of the Martinsburg Formation. Penetrative slaty cleavage (fig. 3) is the dominant planar structure in most of these rocks. It essentially parallels axial surfaces of what appear to be the earliest eastnortheast-trending folds. The age of this cleavage is one of the more controversial problems in central Appalachian geology. Many workers (Drake and others, 1960; Maxwell, 1962) believe that this cleavage formed during the Taconic orogeny. Other geologists (Epstein and Epstein, 1969; Lash, 1978) have found strong evidence supporting an Alleghanian age for the slaty cleavage of the Pen Argyl Member of the Martinsburg rocks in the eastern Pennsylvanian slate belt. More recently, David Rowlands (written communication, 1979) and Nicholas Ratcliffe (personal communication, 1980) have independently found inclusions of cleaved Martinsburg within rocks of the Upper Ordovician Beemerville carbonatite-alkalic rock intrusive complex in northern New Jersey. This cleavage may predate the regional slaty cleavage in the Martinsburg and must date from the Taconic orogeny. We suggest that the dichotomy of cleavage age may be resolved by applying the concepts of Mitra and Elliott (1980) who found that the formation of penetrative cleavage may migrate in time progressively toward the foreland. If this is true for the Taconides of eastern Pennsylvania and New Jersey, what appears to be the same cleavage may date from the Ordovician in the older and tectonically lower parts of the Martinsburg and be of Alleghanian age in the younger and tectonically higher parts. In the Pennsylvania part of the Great Valley the upper Pen Argyl Member of the Martinsburg and perhaps parts of the middle Ramseyburg Member appear to be at a tectonically higher level than the lower Bushkill Member. This may help explain the differences in age assignment for the slaty cleavage in this region by various workers (Drake and others, 1960; Epstein and Epstein, 1969; Lash, 1978). Most of the New Jersey part of the Great Valley mapped by us is interpreted to be at a tectonically higher level than the Pennsylvania part.

For the above speculation to apply, the Taconic through Alleghanian deformational events must be considered as major pulses of one more or less continuous Paleozoic orogenic event. Such a concept receives some support from the recently gained seismic reflection profiles across the Appalachian orogen (Harris and Bayer, 1979). As a matter of fact, these data can be interpreted to define an orogenic period starting in the Later Proterozoic time and continuing until the present.

Superposed on this slaty cleavage is a less pervasive but locally penetrative strain-slip fabric (Drake and others, 1960, Drake, 1978). This strain-slip cleavage formed during the northeast-trending fold phase and roughly parallels the axial surface of folds in both cleavage and bedding. This cleavage is thought to be an Alleghanian feature (Drake and others, 1960; Drake, 1969, 1970, 1978; Epstein and Epstein, 1969). The latest, nearly east-trending fold phase has a poorly developed cleavage at only a few places (Drake, 1978).

Lineations related to the above deformation includes axes of small folds in both bedding and slaty cleavage, the intersection of bedding and slaty cleavage (a characteristic feature of the Bushkill Member; (see figure 3), and crenulated cleavage. Fabric data for the Martinsburg Formation in the Blairstown quadrangle are given in figure 4. The widespread of the plot of axes of small folds and bedding--slaty cleavage intersections (fig. 4A) reflects the polyphase deformation although the statistical maximum results from the early eastnortheast-trending folding. The plot of axes of small folds in cleavage (fig. 4B) reflects mostly the northeast-trending fold phase although there is some spread.

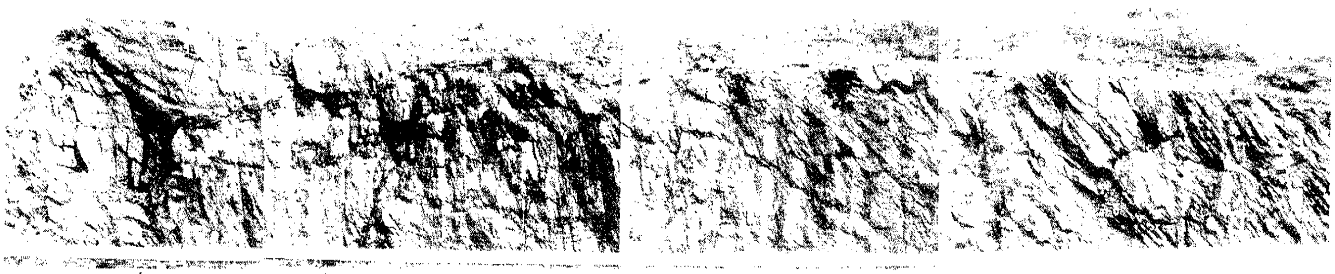


Figure 2. Outcrop of Ramseyburg Member of Martinsburg Formation illustrating linked décollement deformation. Note particularly, the fault-bonded phacoids in the left part of the photograph and the sharp-peaked "tepee fold" at the bottom center. Road cut ranges in height from about 4 to 6 meters.

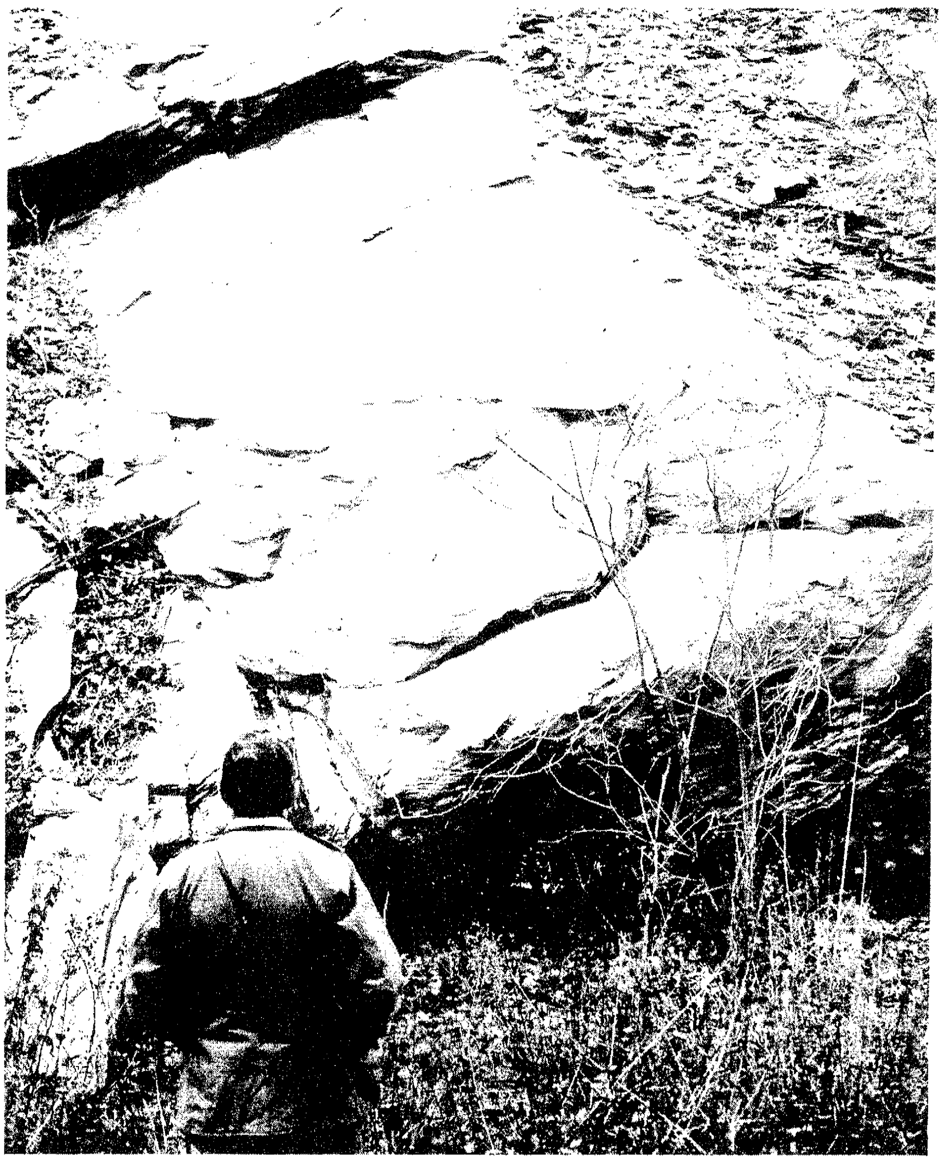


Figure 3. Typical ribbon slate of the Bushkill Member of the Martinsburg Formation. Bedding (inverted) dips to right and the slaty cleavage dips more gently to the right. The bedding-slaty cleavage intersection plunges southeast (toward the viewer) about parallel with the direction of transport on the nearby Federal Springs thrust fault.

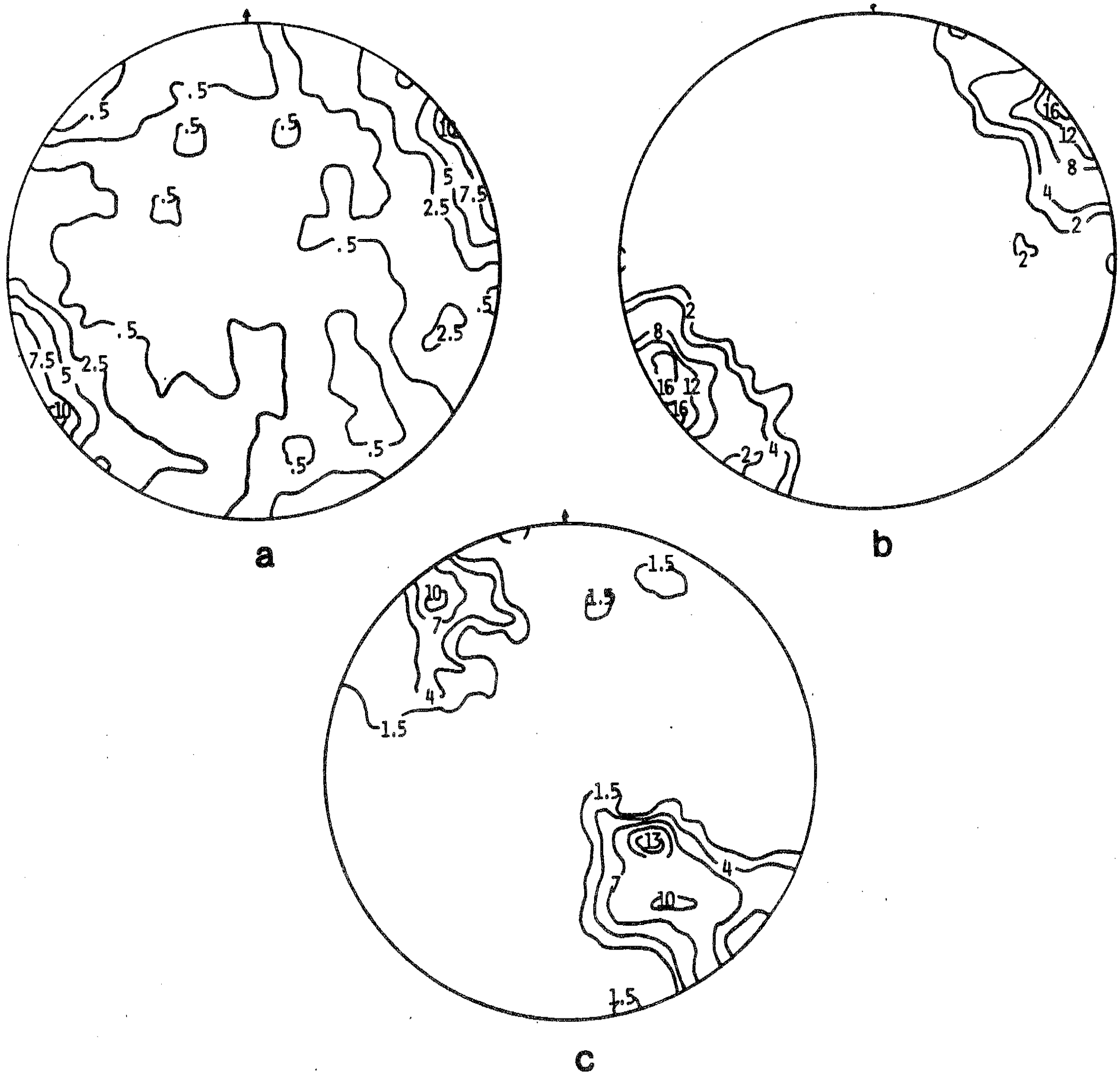


Figure 4. Fabric diagrams of rocks of Martinsburg Formation in the Blairstown quadrangle.

A . Equal-area plot (lower hemisphere) of 206 axes of small folds in bedding and bedding-slaty cleavage intersections. Contours at 10, 7.5, 5, 2.5, and .5 percent per 1-percent area.

B . Equal-area plot (lower hemisphere) of 52 axes of small folds in cleavage and crenulations. Contours at 16, 12, 8, 4, and 2 percent per 1-percent area.

C . Equal area plot (lower hemisphere) of 63 extension lineations. Contours at 13, 10, 7, 4, and 1.5 percent per 1-percent area.

A characteristic feature of the Taconides of eastern Pennsylvania and New Jersey is the rotation of small fold axes and attendant lineation toward the direction of transport near major thrust faults. This was particularly well documented for the Portland fault where it frames the Whitehall window near Catasauqua, Pennsylvania (Drake, 1978, fig. 11A). The rotation of fold axes toward the transport direction is an important clue to the recognition of major thrust faults. The phenomena can be seen at many places in northwestern New Jersey and is reflected by a weak maximum in the southeast and northwest quadrants of figure 4A.

The slaty cleavage at many places in northwestern New Jersey is marked by an extension lineation (smearing and stretching phenomena). These lineations were first recognized by Broughton (1947) who correctly related them to the emplacement of the Jenny Jump thrust sheet. A plot of these lineations (fig. 4C) shows that they fall on a girdle about an inferred axis essentially colinear with that of the northeast-trending fold hinges. The Jenny Jump thrust event then postdates the early eastnortheast-trending folds and related slaty cleavage and predates the northeast-trending folds.

The major tectonic units in this part of northwestern New Jersey are the Allamuchy nappe and Lyon Station-Paulins Kill nappe, which is exposed in the large Paulins Kill window, of the Musconetcong nappe system, the fragmented Jenny Jump thrust sheet, and the poorly understood Johnsonburg-Greendell-Huntsburg unit (fig. 1).

Allamuchy Nappe

The Allamuchy nappe is typical of the other crystalline-cored nappes de recouvrement of the Reading Prong nappe megasystem as described to the west (Drake, 1969, 1970; MacLachlan, 1979b; MacLachlan and others, 1975). It has not been studied in any detail as yet, but parts of both its upper and lower limbs appear to be exposed at the present level of erosion. This nappe was proved by diamond drilling by the New Jersey Zinc Company (Baum, 1967). Rocks of this nappe are brought above those of the Jenny Jump klippe of the Jenny Jump thrust sheet and Johnsonburg-Greendell-Huntsburg unit on the major Shades Of Death thrust fault (see fig. 1). This fault is probably the northeast continuation of the Lower Harmony fault (Drake, 1967a, 1967b; Drake and others, 1969). The Allamuchy nappe is not critical to the theme of this paper and will not be discussed further.

Lyon Station-Paulins Kill Nappe

The Lyon Station-Paulins Kill nappe is the frontal structure of the Musconetcong nappe system and has been described at some length by Drake (1978). The upper limb of the nappe is exposed in the Paulins Kill window, the crystalline core being blind. This nappe is separated from the other overlying structures of the Musconetcong nappe system by the Portland thrust fault which was first recognized by Drake and others (1969). It brings younger rocks over older and is strongly folded into the "snakehead" geometric form (Drake and others, 1969; Drake, 1978) typical of the décollement terrane of the Valley and Ridge. This fault clearly post-dates the slaty cleavage in the Martinsburg and is deformed by both the northeast- and nearly east-trending fold phases (Drake, 1978). Therefore, it is thought to be an Alleghanian structure. This fault is exposed at a deeper tectonic level than the others which are the subject of this paper and field trip.

Jenny Jump Thrust Sheet

The Jenny Jump thrust fault is the most obvious of such structures in northern New Jersey. It was recognized in the early geologic mapping of that state (Lewis and Kummel, 1910-12; Bayley and others, 1914). Geologic sections drawn at that time show the important fact that a very large thrust sheet has been fragmented into several different, essentially flatlying, klippen of both Proterozoic Y and Lower Paleozoic rocks, and that the thrust fault itself was folded. In 1929, George Stose, H. B. Kummel, and M. E. Johnson made a more thorough study of the thrust which led to an exellent manuscript which, for some reason, was never published. A copy of this manuscript which contained the important conclusion that the Jenny Jump thrust was somehow related to the Reading overthrust of Stose and Jonas (1935), came into Drake's hands upon the death of Anna Jonas Stose.

The litter of klippen which constitute erosional remnants of this thrust sheet in the Kittatinny Valley led Drake (1969, 1970) to the recognition that tectonism had operated at a higher level here than in eastern Pennsylvania and, because of the characteristic Musconetcong aeromagnetic signature along the leading edge of the Jenny Jump klippe (fig. 5), to the erroneous belief that the thrust sheet was the result of the core of the Musconetcong nappe shearing through its cover. This thrusting was considered at that time to be of Taconic age. This seems highly unlikely, however, as the largest klippe of Proterozoic Y rocks, the Jenny Jump, transects several folds in the Kittatinny Supergroup and lies on a variety of carbonate rocks of Ordovician Age as well as Martinsburg Formation (Fig. 4). The carbonate rocks beneath the klippe do not have a penetrative thrust fabric; however, they contain abundant subsidiary thrust faults which are marked by zones of ductile deformation (fig. 6), selectively occurring along layers of chert and(or) metabentonite within the

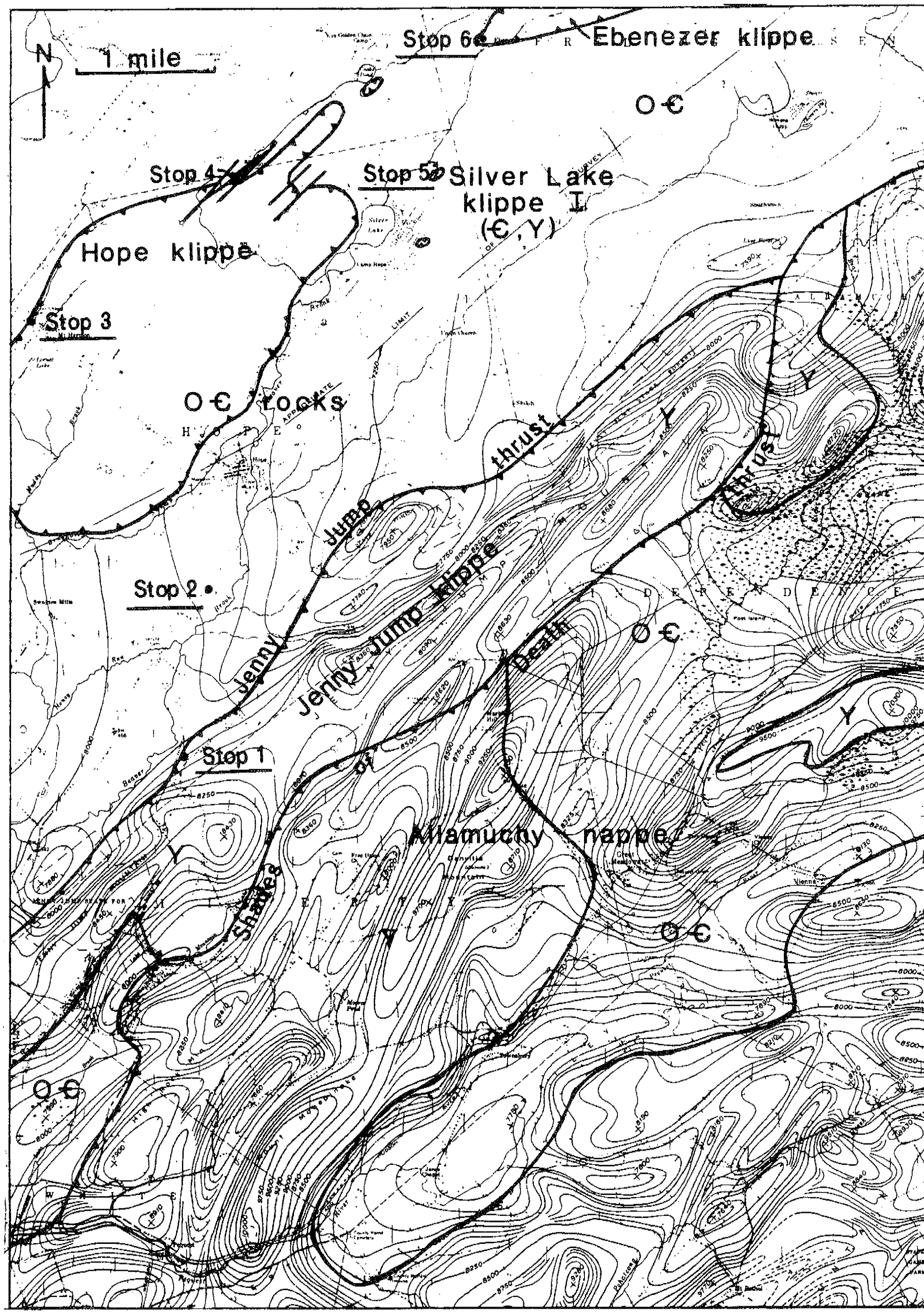


Figure 5. Aeromagnetic map of the south half of the Blairstown 7½-minute quadrangle and north half of the Washington 7½-minute quadrangle, New Jersey. Superimposed on it is a simplified geologic map emphasizing the following structural features:

a. the Jenny Jump thrust that brings the magnetic Proterozoic gneisses (Y) over the Cambrian and Ordovician carbonates and clastic rocks (C-O). Note the abrupt break in magnetic signature at the thrust fault clearly demonstrating that the Proterozoic gneisses do not extend under the lower Paleozoic rocks in the valley north of Jenny Jump Mountain. See Stop 1.

b. the Shades of Death thrust that brings the Allamuchy nappe (containing both Proterozoic gneisses and Lower Paleozoic rocks) over the Jenny Jump thrust sheet.

c. the Hope klippe containing Cambrian and Lower Ordovician dolomites that structurally overlie the Middle Ordovician Martinsburg Formation. See Stops 3 and 4.

d. the Silver Lake I klippe containing Proterozoic gneisses and Cambrian(?) dolomite structurally overlying the Martinsburg Formation. See Stop 5.

e. the Ebenezer klippe of Cambrian Allentown Dolomite structurally overlying the Martinsburg Formation. See Stop 6.

carbonate rock, a phenomenon recognized some years ago by Stevens (1962). At many places the mylonitic foliation was folded during the northeast-trending fold phase (fig. 7). The Proterozoic Y rocks of the klippe show the effects of two Paleozoic deformation phases, in which a mylonite fabric is overprinted by a more brittle fabric.

The other klippen of the thrust sheet lie in troughs in the slaty cleavage within the Martinsburg Formation, and therefore, obviously were emplaced subsequent to the early folding and attendent cleavage formation. Some of these klippen transect contacts between the Bushkill and Ramseyburg Members. The slaty cleavage in klippen areas is marked by an extreme extension lineation (see above) and the rock below klippen soles is severely smeared and tectonically disrupted into autoclastic mélange (fig. 8). The carbonate klippen are reminiscent of those of the southern Appalachians in their general lack of obvious body deformation. The Proterozoic Y rocks of the small Silver Lake-I klippe show the effect of both ductile mylonitic and brittle deformation (fig. 9). This klippe is likely polykinematic, as the Proterozoic Y rocks appear to be in thrust contact with rocks of the Leithsville Formation.

If the various fragments of the Jenny Jump thrust sheet were reconstituted, they would likely form the crystalline core and upper limb of a nappe as the various klippen contain right-side-up, northwest-dipping rocks of the Kittatinny Supergroup from Hardyston Quartzite through Epler Formation. The thrust sheet probably stemmed from a nappe intermediate between the Allamuchy and Lyon Station-Paulins Kill nappes. This is far from certain, however, as the south end of the thrust sheet is cut off by the Shades Of Death thrust (fig. 4) and too little work has been done in New Jersey as yet to allow reasonable palinspastic reconstructions.

We believe that the Jenny Jump thrust sheet was emplaced during the Alleghanian orogeny, perhaps as a phase 1 feature (Drake, 1980) as it is deformed by two fold phases. It clearly post-dates Alpine-type nappe tectonism and the regional slaty cleavage. The problems of the cleavage age have been treated above, but we believe that the dichotomy in age noted by many workers may be real. That is, we may not be dealing with a Taconic *versus* an Alleghanian age for the regional slaty cleavage, but with Taconic *and* Alleghanian age for that cleavage.

Johnsonburg-Greendell-Huntsburg Tectonic Unit

The Johnsonburg-Greendell-Huntsburg tectonic unit is not fully understood. On the basis of rock distribution, it appears to be a Martinsburg-cored syncline within Kittatinny Supergroup rocks. Klippen of Allentown Dolomite lie on the Martinsburg in the apparent synclinal core. The northwest margin of the unit is marked by the Federal Springs thrust fault and the Shades Of Death thrust fault brings rocks of the Allamuchy nappe above it on the southeast. It may be that this tectonic unit is exactly what it appears to be, but more than 20 years experience in this part of the Taconides teaches one caution.

Be that as it may, the Federal Springs represents yet another type of thrust fault. Where shown on this field trip, it stands quite steeply and clearly post-dates major early folding in rocks of the Kittatinny Supergroup and the slaty cleavage in the Bushkill Member of the Martinsburg. Its steep altitude combined with the fact that it separates tectonic units suggest that it may be a major ramping splay fault which has reached the surface. The field evidence cited above suggests that it too is an Alleghanian structure.

Conclusions

Three thrust faults of different aspect have been described above, and will be examined on this field trip. All these faults post-date major early folds and the regional slaty cleavage in the Martinburg Formation. They serve as structural boundaries between and telescope major tectonic units which owe their major structural features to the Taconic orogeny. We think, therefore, that these thrust faults result from the Alleghanian orogeny.

ROAD LOG

THE FIELD TRIP BEGINS IN THE PARKING LOT AT RUTGERS-NEWARK AND REACHES THE KITTATINNY VALLEY BY THE GARDEN STATE PARKWAY AND INTERSTATE 280 AND 80. SUBSEQUENT TO STOP 9, THE TRIP RETURNS TO RUTGERS-NEWARK BY ROUTE 206, INTERSTATES 80 AND 280, AND THE GARDEN STATE PARKWAY. GEOLOGIC NOTES ARE PROVIDED FOR THE ROUTE 206 SEGMENT OF THE RETURN. FIELD TRIP STOPS 1-8 ARE IN THE BLAIRSTOWN 7 ½-MINUTE QUARDRANGLE AND STOP 9 IS IN THE NEWTON EAST QUADRANGLE. (A COPY OF THESE TWO QUADRANGLES WILL BE PROVIDED TO EACH PARTICIPANT.) THE TRIP ROUTE ALSO TRAVERSES THE TRANQUILITY, NEWTON EAST, AND STANHOPE QUADRANGLES.

Mileage

0.0	Turn right onto Warren Street, leaving the parking lot.
0.1	Right turn at traffic light onto High Street. Continue for 0.5 mile north on High Street.
0.6	Left turn at traffic light onto Orange Street.

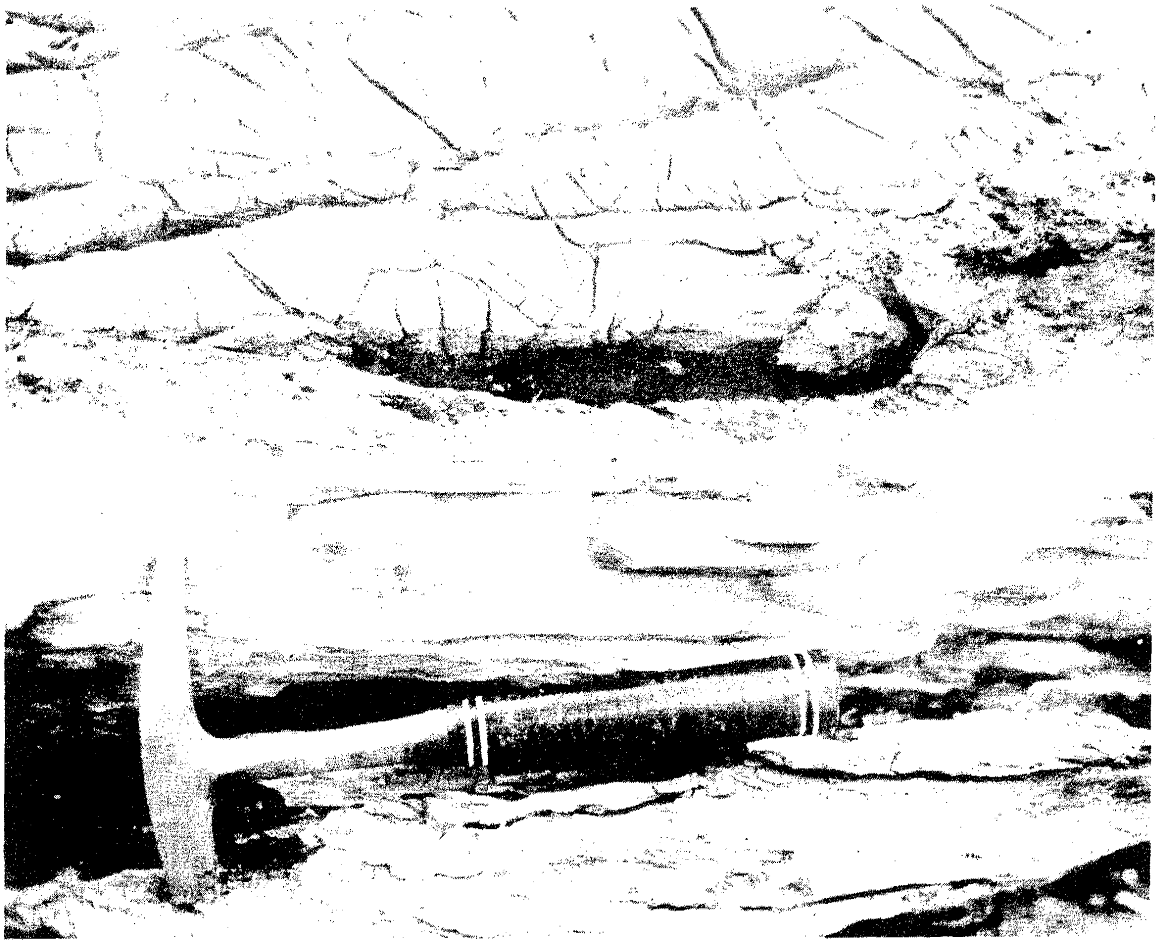


Figure 6. Chert mylonite in the Ontelaunee Formation. Undeformed dolomite at top of photograph, chert mylonite above the hammer, and dolomite autoclastic mélange beneath the hammer.

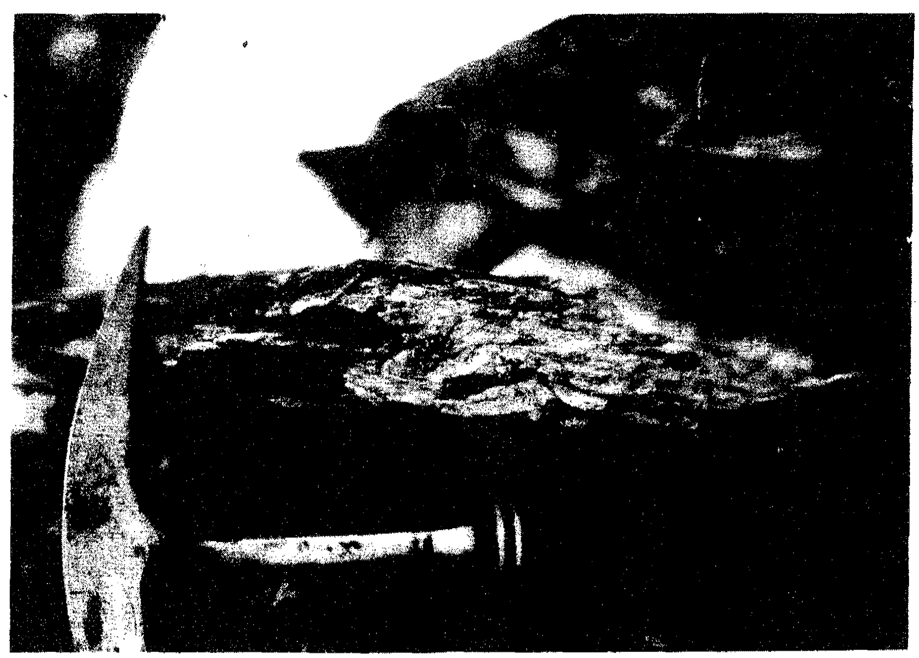
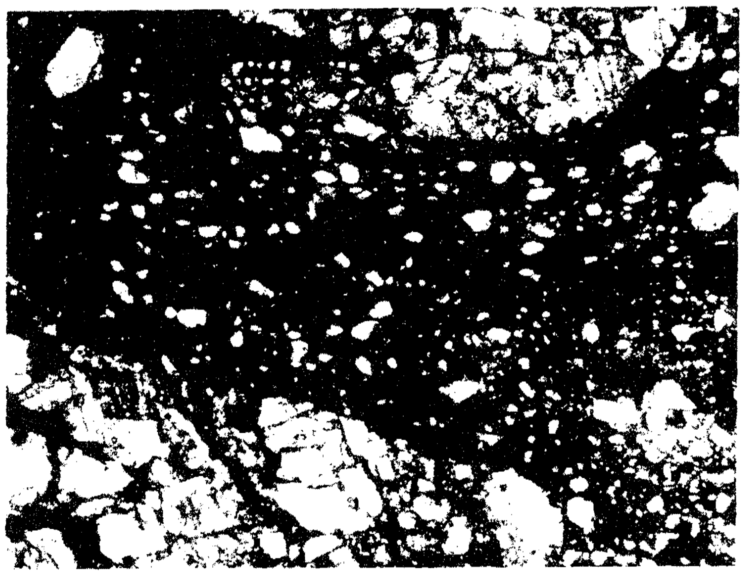


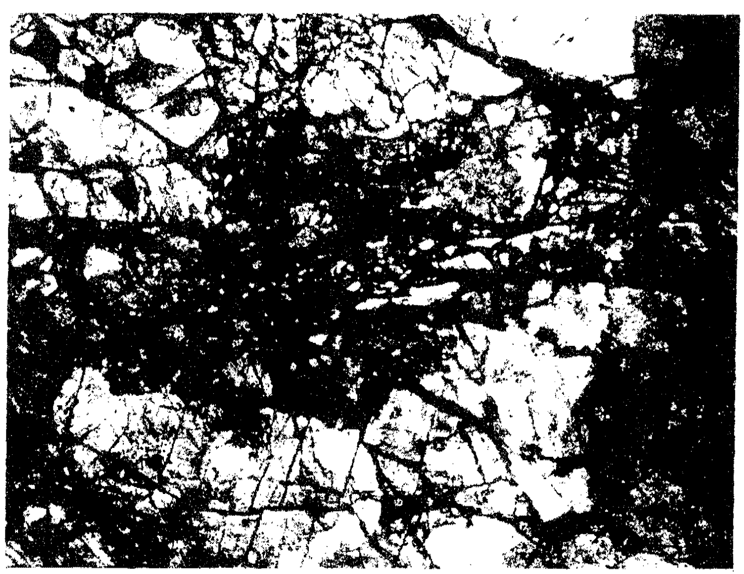
Figure 7. Small fold in mylonitic foliation in chert of Ontelaunee Formation. Axis plunges 15° N. 45° E.

Figure 8. Autoclastic mélange in Bushkill Member of Martinsburg Formation directly beneath the Hope klippe of the Jenny Jump thrust sheet. Note detached fold hinges and phacoids (tectonic fish) of graywacke swimming in the pelite sea.

Figure 9. Photomicrographs of Proterozoic Y mylonitized and brecciated granite—Silver Lake klippe I.



a . Large perthite and quartz crystals that have been severely strained, locally mylonitized (dark areas and stringers), and later brecciated. Scale: 1 cm on photo equals 0.5 cm.



Close up of mylonite stringer (dark band) between two large perthite crystals. The crystals and mylonite together have been brecciated. Note incipient break up of large crystal at bottom of photo. Scale: 1 cm on photo equals 0.5 cm.

0.7 Right turn at first traffic light onto Nesbit Street.

0.8 Left turn at "T" intersection (glass apartment building directly to north). Proceed straight across the intersection, going west, onto the ramp leading to the Interstate Highway 280 and the Garden State Parkway.

1.4 Alternating beds of red sandstone and mudstone with a few thin interbeds of gray siltstone and dark gray to black micaceous shale, occurring below the first overpass. These siltstones yield a probable late Norian palynoflora and occur about 1100 m below the First Watchung Mountain Basalt (Cornet and Traverse, 1975, p. 27). Sporadic exposures of sandstones and mudstones with fining-upward sequences, characteristic of meandering streams, occur along Interstate 280 for the next 4.4 miles.

2.1 Bear right for the Garden State Parkway.

2.1 Bear left for Interstate Highway 280.

5.8 Basalt of the First Watchung Mountain; contact with the underlying red beds is concealed. Note: characteristic radial columnar joint pattern.

7.3 Basalt of the Second Watchung Mountain; contact with the underlying beds is concealed.

10.3 Basalt of the Third Watchung Mountain is exposed to the south of the highway.

10.8 Passaic River Valley; the valley is underlain with glacial clays and silt that were deposited in Glacial Lake Passaic. The lake formed as glacial meltwaters were impounded betwen the New Jersey Highlands to the west and the Watchung Mountains to the south and east (see Kummel, 1940).

14.0 Termination of Interstate Highway 280. Bear left as Interstate 280 merges with Interstate 80 west.

17.0 Check point, Exit 42, Route 202 Parsippany and Morris Plains. Water tower on right is on Proterozoic (Precambrian Y) rocks of the N.J. Highlands.

17.9 Begin climb from Jurassic-Triassic Basin into the Highlands.

18.7 First roadcuts of Highlands rocks, here steeply dipping amphibolites.

23.1 Outcrops of very rusty metasedimentary biotite-quartz-plagioclase gneiss.

24.8 Exit 35 interchange to Mt. Hope and Dover. This was field area of famous Precambrian geologist Paul Sims. The ridge to right front is held up by the Silurian Green Pond Conglomerate.

26.9 Cruddy outcrops of Proterozoic gneiss.

28.0 Exit to rest area.

30.7 Lots of glacial till on left.

30.9 Large outcrop of strongly layered biotite-quartz-plagioclase gneiss of Proterozoic age on right.

32.5 Outcrops of hornblende granite of Proterozoic age.

32.8 More of same.

33.4 Exit to Route 206 South to Sommerville.

34.0 Outcrops of Proterozoic rocks.

35.0 Exit to Route 206 North. This is place where field trip route will rejoin Interstate 80 for return to Newark.

35.9 Outcrops of Proterozoic rocks.

37.3 Musconetcong River, formerly a great trout stream, now a temporary habitat for fish between hatchery and skillet.

37.8 Continuous outcrops of Proterozoic rocks on Allamuchy Mountain. These rocks are in the core of the Allamuchy nappe of the Musconetcong nappe system of the Reading Prong nappe megasystem. The rocks cropping out at the rest stop to the left and above the highway are severely deformed and contain several flat thrust faults.

39.5 Scenic overlook. If weather is fine, bus will pull off here and we will give a short briefing on the regional geology and this field trip. Looking north from this place, one has an excellent view of the Kittatinny Valley and Jenny Jump Mountain.

40.9 Allamuchy Interchange. Bold outcrops of Proterozoic rocks.

41.9 This outcrop of granite gneiss contains mafic segregations of plagioclase, epidote, garnet and magnetite surrounded by a rind of almandine garnet in a more felsic matrix of potassium feldspar, quartz, plagioclase, epidote, and accessories. Foliation appears to parallel gneissic layering and is oriented N. 45° E., 39° SE. Pegmatites are roughly parallel to foliation, but upon close inspection are seen to cut it.

42.3 Entering Bear Swamp. Rocks in this area are Allentown Dolomite of Late Cambrian age.

43.2 Nice outcrop of Allentown Dolomite. Beds strike N. 82° W., and dip 15° NE, cleavage strikes N. 55° W. and dips 22° NE, their intersection, roughly parallel to axes of small folds, plunges 14° N. 18° W. The beds face up and are probably in the upper limb of the Allamuchy nappe.

44.9 Begin the ascent of Jenny Jump Mountain, here we are crossing the trace of the Shades of Death thrust which brings rocks of the Allamuchy nappe onto rocks of the Jenny Jump klippe of the Jenny Jump thrust sheet. The Proterozoic rocks here are dominated by a sequence of marble, amphibolite, and lesser calcsilicate rock.

46.1 We have passed through the Proterozoic rocks of the Jenny Jump klippe and here enter a sequence of lower Paleozoic rocks beneath the thrust fault. Here the outcrops are Epler Formation of the Beekmantown Group of Early Ordovician age. These outcrops contain fairly abundant solution collapse breccia. Many bedding surfaces in these rocks are also thrust faults and a fair amount of carbonate mylonite has been formed. Axes of small folds plunge 5°S. 25° E. beneath the Proterozoic rocks of the Jenny Jump klippe.

46.9 Nice outcrops of Allentown Dolomite. Here we are about on the crest of an anticline which plunges 5° N. 45° E. Beds face up as shown by good algal stromatolites.

47.4 Long continuous outcrop beginning in Allentown Dolomite, Rickenbach Dolomite, Epler Formation, and Ontelaunee Formation. (See Markewicz and Dalton, this Guidebook.)

47.7 Large outcrop of sandy, mottled, laminated dolomite of the Epler Formation. The contact with the Rickenbach Dolomite is about in middle of this cut. It is placed at the contact of laminated, burrowed, mottled, finely crystalline dolomite (Epler) with thick-bedded, dark-medium-gray, medium crystalline dolomite (Rickenbach). Rock contains abundant cascade-type folds which plunge 5°-10° N. 25° E.

47.7 Crossing over N.J. Route 519.

47.9 Outcrops of Jacksonburg Limestone. Most of rock here is crystalline limestone but some beds are dark-gray, more argillaceous cement rock. Axes of small folds here plunge 20° N. 5° W. Slickensides on bedding surfaces plunge down the dip.

48.1 More outcrops of Jacksonburg Limestone.

48.4 More outcrops of Jacksonburg Limestone. A lot of conglomerate here. Outcrops to south of Interstate are Bushkill Member of the Martinsburg Formation. Slaty cleavage, which strikes N. 60° E. and dips 20° NW., is principal planar element in these rocks. The cleavage surfaces are marked by a strong extension lineation which plunges 5° N. 35° W. and crenulations which are nearly horizontal N. 70° E. Strong crenulation cleavage strikes N. 70° E. and dips 75° SE.

48.6 Leave Interstate 80 at Hope-Blairstown exit. Keep to left and turn left (south) on Route 521 toward Hope. We are driving on Bushkill Member of Martinsburg Formation. Outcrops to right are Allentown Dolomite in the large Hope klippe of the Jenny Jump thrust sheet. The dolomite beds face up, dip gently northwest, and contain abundant algal stromatolites and oolite.

49.4 Here we are at the base of the Hope klippe. The outcrop to the right is oolitic, shaly, Allentown Dolomite, probably the lowest beds of that unit. The beds dip gently to the northwest and face up.

50.1 Entering the town of Hope which is a pre-revolutionary Moravian settlement.

50.2 Outcrop on right is Leithsville Formation of Early and Middle Cambrian age. The gently northwest dipping rocks are right at the sole of the Hope klippe. They dip gently northwest, have a vague mylonitic foliation which strikes N. 45° E. and dips 18° NW., and a general mangled appearance.

50.6 Blinking light in center of Hope, continue straight on to the south. The road is now Route 519.

51.1 Outcrops on right are Jacksonburg Limestone. The rock here is well-bedded, calcarenite grainstone that contains abundant fossil hash and small scattered pebbles of dolomite. The beds strike N. 75° W. and dip 25° NE. They have a cleavage which strikes N. 55°E. and dips 15° SE.; this cleavage is marked by an extension lineation which plunges approximately down the dip. The intersection of the cleavage with the bedding plunges 7° N. 88° E. These rocks are *autochthonous to the Jenny Jump thrust sheet* and belong to an as yet unnamed tectonic element of the Musconetcong nappe system of the Reading Prong nappe megasystem.

51.5 Outcrop on right is Ontelaunee Formation of Beekmantown Group. This is Field Trip Stop 2 to which we will return.

52.0 Swayze Cemetery on right.

52.1 Turn left on Lake Just-It Road.

52.3 Bridge (6-ton limit) over Beaver Brook.

52.4 Poor outcrop of Allentown Dolomite on lawn on the right. Abundant, excellent outcrops of Allentown on wooded knoll to to the east.

52.9 **STOP 1:** Jenny Jump klippe of Jenny Jump thrust sheet; speaker, Peter Lyttle. (Field trippers will disembark, bus driver will take bus to top of hill to Hissim Road to turn around. He should wait there for 30 minutes, and return down the hill to pick up the field trip in front of the house at the base of hill.)

We are on the northwest edge of the main mass of the Jenny Jump thrust sheet on the northwest side of Jenny Jump Mountain. The Proterozoic rocks we will be looking at here are primarily hornblende granite gneisses with minor fine-grained mafic dikes. These rocks structurally overlie the lower Paleozoic rocks of the valley that we have just driven through. Although the Jenny Jump thrust is nowhere exposed, there are several locations along the north side of Jenny Jump Mountain where outcrops of Paleozoic carbonate with structures dipping to the southeast occur within a few tens of meters of the Proterozoid gneisses. It is clear in map pattern (see Figure 4) that the Jenny Jump thrust truncates both contacts and structures in Paleozoic rocks.

In order to see all of the structures mentioned below, it is necessary to hike a hundred meters or so along the side of Jenny Jump Mountain in this area of semi-continuous outcrop. Almost all of the structures can be seen in several places and the diligent tripper should be able to find them all on his/her own. The most important structure to note at this outcrop is well-developed foliation that is, in most places, parallel to compositional layering and is axial planar to the rarely observed earliest isoclinal folds that are presumably Grenville in age. This foliation is seen in both the gneiss and mafic dikes. The orientation of the dikes appears to roughly parallel the foliation, but can by at an angle to compositional layering, indicating that the dikes intruded either during or before this early folding episode. This foliation is folded by a later event interpreted to be the emplacement of the Jenny Jump thrust sheet. Over most of Jenny Jump Mountain the foliation strikes roughly N. 60°E. and dips 30-40° to the southeast. However, at several places along the northwest edge of Jenny Jump Mountain, it is common to find the foliation folded by large, open, upright to slightly overturned folds.

There has been considerable slip on many foliation planes (evidenced by slickensides) and if the rocks at this outcrop are not wet or in the shade, the field tripper will note many narrow zones of mylonite that are roughly parallel to the foliation. Locally, these zones of mylonite are brecciated. These outcrops are very near the sole of the Jenny Jump thrust sheet and it is likely that the mylonitization and brecciation are related to the emplacement of the thrust sheet.

In one area of these outcrops, a thin mafic dike is cut by numerous small-scale thrusts spaced 3-10 cm apart. The sense of movement is always toward the NNW.

The gneisses here are quite magnetic, the magnetite probably being produced with chlorite at the expense of hornblende. Very little fresh hornblende is seen in thin section. Quartz, microcline oligoclase, minor hornblende and magnetite, and accessory zircon and apatite make up the bulk of the gneisses. The oligoclase and hornblende are commonly altered, and the quartz is highly strained and occurs in long sheared out stringers.

53.5 Bridge over Beaver Brook

53.7 Turn right on Route 519

54.2 **Stop 2:** Bedding-parallel faults in the Ontalaunee Formation; speaker, Peter Lyttle. (Driver pull bus onto turnout on left side of road.)

This will be a very quick stop to illustrate bedding-parallel shear and mylonitization in the Lower Ordovician Ontalaunee Formation. Other outcrops show this more extensively, but this outcrop is logistically more feasible for this field trip. Although pressure solution is the dominate deformation mechanism producing tectonic shortening in the carbonate rocks of the Great Valley, both the rocks within and tectonically beneath the Jenny Jump thrust sheet exhibit extensive faulting parallel to bedding. This shearing is commonly, though not exclusively, concentrated in chert-rich zones within dolomites. The chert need not be in continuous beds. Zones of nodular chert and very thin stringers appear sufficient to provide a contrast or inhomogeneity in rock strength sufficient to concentrate shearing within these areas.

Although this stop has well-developed zones of mylonite concentrated along chert zones that have behaved ductilely and show small drag folds (see fig. 7), other outcrops show a transition from brittle to ductile structures in these zones. This transition is achieved through a continual change in the mechanical properties of the rock probably because of the reduced grain size, water weakening or localized frictional heating rather than changes in external parameters such as external temperature and confining pressure. Initially, the dolomite and chert together form a breccia with pieces of dolomite ranging in size from 1-15 cm and pieces of chert ranging in size from 1 mm to 5 cm. Continued shearing pulverizes the chert which then acts as a fine-grained matrix surrounding pieces of dolomite which are still angular and recognizable, yet smaller, pieces of dolomite. At this stage the rock has a "frothy" appearance and the chert has lost its black translucence. More shearing produces a mylonite, such as the example at this stop (see fig. 6), and there are no longer any recognizable pieces of dolomite. Everything has been finely comminuted and the rock has a fluxion structure. At this outcrop the fluxion structure is folded into small drag folds.

It is important to realize that the fluxion structure or "cleavage" developed in these zones does not represent regional cleavage. The orientation of the "cleavage" or mylonitic foliation in these shear zones is related to the original attitude of the chert zones and is parallel to the shear zones. Regionally, this "cleavage" is best developed in narrow shear zones in and immediately beneath the large scale thrusts and is essentially parallel to these thrusts. The Jenny Jump thrust was slightly above the present erosional surface at this stop and may have caused the subsidiary thrusting and mylonization at this locality.

The Ontelaunee Formation at this stop is very finely to finely crystalline, light to medium gray, medium- to thick-bedded dolomite with thin beds of chert. Fabric information: bedding N. 67° W. 15° NE; extension lineation 13° S. 38° E; fold axis in mylonite 14° N. 48° E.; joints N. 85° E. 67° SE. and N. 15° E. 15° SE.

54.7 Outcrop at Jacksonburg Limestone on left.

55.0 Entering town of Hope.

55.3 Turn left on Union Street at flashing light and pass St. Luke's Episcopal Church on the left.

55.45 Turn right on Mt. Hermon Road toward Mt. Hermon and Vale (Methodist and Moravian Churches on left mark turn).

55.6 Bridge across Brookaloo Swamp.

55.8 Sole of Hope Klippe. Outcrops of Allentown Dolomite on the left. Beds strike N. 75°., and dip 25° NW. Rocks face up as shown by abundant algal stromatolites.

56.05 Outcrops of Allentown Dolomite on left. Here there are dolorudite beds and orthoquartzite lenses. Big, rounded bedding surfaces suggest algal stromatolites but internal ornamentation is not obvious.

56.6 Outcrops of Allentown Dolomite on right. Rock here is mostly oolite with some oolite matrix conglomerate.

56.7 Outcrops of oolitic Allentown Dolomite on right. Rock has strongly developed extension fractures which strike N.48° E. and dip 65° NW.

57.0 Enter town of Mt. Hermon.

57.13 Cross small stream which follows a steep normal fault which fragments the Hope klippe in this area.

57.25 Cross small stream which marks the northwest border of Hope klippe.

57.2 **STOP 3:** Hope klipppe of Jenny Jump thrust sheet; speaker, Avery Drake. (Park in Methodist Church parking lot on right, unless church services are being held; if services are being held, park on left side of street near Honeywell Hall.)

Here we are on the Bushkill member of the Martinsburg Formation at the northwest border of the Hope klippe. The bounding thrust fault lies in the stream a short distance to the southeast, and carbonate rocks of the klippe crop out on the ridge to the southeast of the streams. The klippe here has been fragmented by a later normal fault which has brought rocks of the Epler Formation into contact with the Bushkill. We will first observe rocks of the Bushkill on the slope to the southeast of Green Chapel Cemetery. The Bushkill here is very disturbed. In the fall of 1978 the following fabric elements could be measured: bedding, N. 30° E., 65°SE. (inverted); slaty-cleavage, N. 20° E., 40° SE.; and pseudo-slaty cleavage, N.38°E. 52°SE.; strainslip cleavage, N. 50°. 45° NW.; intersection of bedding and slaty cleavage and pseudo-slaty cleavage, 20° S.55° W., crenulations, 16° N. 36° E.; extension lineation on slaty cleavage,38°S. 50° E.; and a joint, N. 60° W. 60° SW. There are many folds in bedding, but the details have not been worked out. The pseudo-slaty cleavage is thought to result from the emplacement of the Jenny Jump thrust sheet. At this place the planar elements, save the strain-slip cleavage which results from post-klippe emplacement folding, dip beneath the carbonate rocks and the extension lineation plunges beneath them. Bushkill is also exposed in pavement outcrops in the secondary road to the southwest of the Mt. Hermon Road.

After observing the Bushkill, we will examine the outcrops of Epler on the ridge to the southeast. The rock there is finely crystalline to medium crystalline, light gray to medium-gray dolomite which contains thin partings, lenses, and very thin beds of orthoquartzite. The outcrop contains abundant solution collapse breccia. Many of the blocks in the breccia are quite large. Bedding in the outcrop is N. 45° E. 38° NW. A poor fracture cleavage has the altitude N. 10° E. 55° SE. Return to bus and continue northwest on Mt. Hermon road.

57.5 Turn right on Union Brick Road.

57.75 Outcrop of Ramseyburg Member of Martinsburg Formation on the left.

57.90 Overpass above Interstate 80.

58.1 Poor outcrops of Ramseyburg on the right.

58.3 More poor outcrops of Ramseyburg on the right.

58.5 Small pond on right. Geology along here is obscured by ground moraine.

59.2 Continue straight on to northeast, avoid left turn.

59.8 Small pond and Union Brick Cemetery on the left.

59.85 Turn right on Heller Hill Road.

60.3 Outcrops of Ramseyburg on left.

60.5 Continue straight on to south, avoid right turn onto Turpin Road.

60.65 Bridge over small brook.

60.75 Stop sign at T-intersection. Turn left on Hope Road. Mangled outcrops of Allentown dolomite of Hope klippe on the left. Continue north .15 mile distance and pull into turn-off on right.

60.90 **STOP 4:** Northwest boundary of Hope klippe; speaker, Avery Drake.

Here rocks of the Bushkill Member crop out in a cut at road level and carbonate rocks of the klippe crop out on the hill above. This is not a good exposure of the Bushkill, but it is extremely important as the rock here is an autoclastic tectonic mélange. Careful observation will reveal phacoids, "tectonic fish" of graywacke and slate, some of which are fold hinges, within the mangled slate matrix (see fig. 8). PLEASE NO HAMMERING OR PLUCKING OF "TECTONIC FISH." There are at least two flat cleavages interlacing within this outcrop, presumably the slaty and pseudo-slaty cleavages viewed elsewhere. The prominent foliation in this outcrop is due E. 10° S.

Here the carbonate rock of the klippe is Allentown Dolomite. The outcrop has a jumbled appearance and bedding is difficult to determine but seems to be about N 10° W., 10° NE. Most of the rock is rather nondescript crystalline dolomite, but there is a fair amount of dolarenite and some oolite, desiccation dolorudite, and dark-gray chert lenses and skims. In addition, some curved forms without internal ornamentation are suggestive of algal stromatolites. It is quite clear at this stop that the carbonate rocks of the klippe lie above the Bushkill. Reboard the bus and continue northeast on Hope Road.

61.05 Turn right on Mud Pond Road (10,000 pound limit). This road essentially follows a normal fault which has fragmented the Hope klippe in this area, carbonate rocks of the klippe on the right, Martinsburg on the left. Carbonate rock for first .2 mile along road is Rickenbach Dolomite.

61.35 Mangled outcrops of Allentown Dolomite on right.

61.40 Outcrops of severely mangled Martinsburg. Rock here is an autoclastic mélange consisting of phacoids and lenses of graywacke and slate "swimming" in slate. Extension lineation plunges essentially down the dip of the principal foliation. The klippe sole here lies a few feet up the hill to the right.

61.5 Small pond on left.

62.6 Good pavement outcrop of Bushkill on the left.

62.8 T-intersection. Turn left.

62.9 Ramseyburg outcrop on the left.

63.0 T-intersection. Turn right on Ridgeway Avenue. Outcrops of slate containing a few thin graywacke beds at intersection.

63.05 Bridge over small stream. Bus will go a short distance farther and disembark the field trippers. It will then continue south on Ridgeway Road and turn around wherever possible, and return for the field trip in about 1/2 hour.

62.0 Cooks Pond on the left. Outcrop of cherty, laminated, finely crystalline medium-dark-gray dolomite of the Epler Formation on the right. This carbonate rock constitutes the small Cooks Pond klippe.

62.2 Turn right on Cook Road. Outcrops of Bushkill slate at intersection.

63.2 **STOP 5:** Silver Lake I klippe; speaker, Peter Lyttle.

The Silver Lake I klippe is a tiny erosional remnant of the Jenny Jump thrust sheet that contains a strongly deformed and perhaps highly telescoped section of Proterozoic granite and Lower paleozoic dolomite (probably Cambrian Leithsville Formation). Although the two or three outcrops that we will examine at this stop may at first glance be a little disappointing, this single locality records much of the tectonic history that we are trying to present on this field trip. We will look at a small ledge of Proterozoic granite that records an early tectonic event of high strain, local mylonitization, and retrograde metamorphism. This first event is interpreted to have occurred during the Taconic orogeny. Later, these same rocks were severely brecciated and comminuted, but not recrystallized (see fig. 9) photomicrograph. Although most of the rock consists of quartz, perthite, and plagioclase, there are minor amounts of magnetite and chlorite that appear to be alteration products of a mafic mineral, probably hornblende. All the minerals, particularly the perthite and quartz are highly strained, brecciated and rotated and severely reduced in grain size. These later structures are interpreted to have been produced during emplacement of the Silver Lake I klippe as part of the much larger Jenny Jump thrust sheet in Alleghanian times.

This small klippe structurally overlies the Middle Ordovician Bushkill Member of the Martinsburg Formation. After the bus picks us up we will head back north along this road passing an outcrop of the Bushkill at the first intersection. At this locality the slaty cleavage dips southeast under the Silver Lake I klippe. South of Stop 5 near Camp Hope (approximately 1/2 mile) the slaty cleavage in the Bushkill dips consistently to the northwest. Therefore, the klippe is sitting in a broad synfromal trough of the slaty cleavage. Although it is impossible to prove at this stop, the emplacement of the klippe postdates the formation of the slaty cleavage. We will establish this to the satisfaction of the sceptical field tripper at the last stop of the day, the Grand Union klippe.

The only structures recorded at this stop are a fairly flat mylonitic foliation, N. 16° E. 18° NW. and a steeper and later cleavage N. 78° E. 50° SE. These were both measured (with difficulty) in the highly weathered Proterozoic granite. The pervasive rusty weathering was probably facilitated by the extensive brecciation along the later fracture cleavage. The tiny outcrop of dolomite fractures in a rectilinear fashion no matter how small the pieces become. This may be related to the late fracture sets.

63.4 T-intersection. Turn right.

63.9 Small outcrops of Ramseyburg on left.

64.1 House with small pond on left.

64.25 **STOP 6:** Ebenezer klippe; speaker, Avery Drake (At about the Ebenezer sign, the bus will pull off to the right and allow field trippers to disembark. The bus will continue up hill to intersection with Lake Wasigan Road and park. Field trippers will walk up hill examining the outcrops. This will be the lunch stop.).

The first outcrop to examine is just to the north of the small stream. The rock here is Ramseyburg Member of the Martinsburg Formation. Fabric elements measured here in the fall of 1978 include: bedding, N.52° E. 25° NW.; slaty cleavage, N. 48° W. 5° NE.; strain-slip cleavage, N. 25° E. 20° SE,; a joint, N. 44° W. 70° SW.; intersection of bedding and slaty cleavage, 7° N. 48° E.; and extension lineation, 3° N. 35° W. The reader will note that here the bedding, slaty cleavage, and extension lineation have been rotated from their normal southeast dips and plunge so as to dip and plunge beneath the carbonate rocks to the north.

The last outcrop of Ramseyburg is about 400 feet to the north and the first outcrop of the carbonate rock of the klippe is about 375 feet north of there. The rock of the klippe is Allentown Dolomite. There is a particularly good outcrop of Allentown about 225 feet farther north which contains all the characteristic rock types of that unit: algal stromatolites, oolites, dessication dolorudites, etc. The sedimentary structures show that the carbonate rocks face up. The subtle field trippers will have noted that Ramseyburg crops out about 30 feet to the south of this Allentown outcrop for a length of about 20 feet showing that the klippe here, like the Hope klippe, is fragmented by later normal faults. The beds in the Ramseyburg clearly dip beneath the carbonate rocks of the klippe. There are additional good outcrops of Allentown along the road to the east of Lake Wasigan.

We plan to have lunch around Lake Wasigan. This is far from a perfect place, but our choices are limited. Following lunch, board the bus.

64.65 Turn left on Lake Wasigan Road. Lake Wasigan is to the front.

64.9 Continue straight, avoid left turn. Inverted Bushkill slate crops out on the left.

65.3 Pass under tracks of Erie-Lackawana Railroad. Excellent outcrop of Ramseyburg on the left. Some beds here are more than 1 m thick.

66.2 Turn left on Route 94 toward Blairstown. Outcrops of Ramseyburg on left.

66.55 Village of Paulina. Rocks here are Martinsburg Formation in the Musconetcong nappe system.

66.75 Crossing small stream. We will cross the trace of the Portland thrust fault within a few feet. Here the slaty cleavage in the Martinsburg is marked by a strong extension lineation which plunges down the dip. The Portland thrust fault frames the very large Paulins Kill window.

66.85 Large outcrops of Allentown Dolomite. These rocks are in the Lyon Station-Paulins Kill nappe which is exposed in the Paulins Kill window.

67.0 Intersection with Hope Road. Avoid left turn and continue west on Route 94. Allentown Dolomite crops out up Hope Road to the Left.

67.1 Route 602 joins Route 94. Avoid left turn and continue west on Route 94.

67.27 Bridge over Paulins Kill.

67.3 Very sharp right turn onto Route 521 North (Stillwater Road). Here Route 521 roughly parallels the Paulins Kill. The Blairstown Ambulance Corps is on the right.

67.5 Blairstown School on the right.

67.75 Outcrops of Allentown Dolomite in Lyon Station-Paulins Kill nappe on right. Rock is severely deformed, most bedding surfaces have served as fault surfaces. Outcrop is characterized by very abundant filled, northeast-trending extension fractures.

68.0 Continue straight on Route 521 (Stillwater Road), avoidvery sharp left turn.

68.15 Turn right on unnamed road and proceed down steep hill. Small outcrop of Allentown Dolomite on knoll to right.

68.2 Small pond to left front.

68.45 Bridge over small stream. Small pond on left.

68.65 Small pond on left. Small outcrop of Allentown Dolomite on right.

68.8 Outcrop of very sandy Allentown Dolomite on right. There are abundant orthoquartzite beds here.

68.9 Large outcrops of Epler Formation on the left. Rocks here include laminated sandy dolomite, laminated dark-gray dololutite, chert-ribbed finely crystalline dolomite, sandy medium to medium-coarse crystalline limestone, and excellent examples of solution collapse breccia. Axes of small folds here plunge 70° S. 15° W., down the dip of the beds.

69.1 **STOP 7** Portland thrust fault; speaker Avery Drake (Field trippers will disembark and examine outcrops along road to left. Bus will have to find some means of turning around. There is a small parking area along road to left. This stop is just above the abandoned grade of the New York Susquehanna and Western Railroad. This is a very narrow road and field trippers must use extreme caution.)

The first outcrop to observe is 500 feet along the road to the east. Here are slate outcrops of the uppermost Bushkill Member of the Martinsburg Formation. The slate contains abundant thin beds of graywacke. Fabric elements include: bedding, N. 85° E. 48° SE.; slaty cleavage, N. 72° E. 68° SE.; and intersection of bedding and slaty cleavage, 35° S. 55° W.

The Portland thrust fault crops out about 375 feet farther to the east. The observations recorded here were made in October 1978 shortly after the road was widened. Winters are particularly hard on exposures in this area and no guarantee can be made as to what the quality of the exposure will be at the time of the field trip. In any case, the Portland fault was found to have the attitude of N. 78° E. 48° SE. and the slate above the fault to the east an attitude of N. 80° E. 55° SE. The carbonate rock beneath the fault is thoroughly tectonized. It is mostly medium crystalline, medium-gray dolomite that contains some solution collapse breccia, flat-pebble conglomerate, and dark gray sparr calcite. Judging from stratigraphically lower outcrops of extremely cherty dolomite up the hill to the north, this rock probably belongs to the Ontelaunee Formation. The dolomite contains several movement zones beneath the major thrust which are marked by carbonate mylonite. Extension lineations on the thrust surface plunge 45° S. 38° E. Post-thrust strain-slip cleavage has the attitudes of N. 80° E. 40° NW., and post-thrust crenulations plunge 10° S. 70° E. There are outcrops of both Ontelaunee and Epler along the road to the east and excellent outcrops of Epler up the hill to the north. We may examine some of these rocks depending on available time. (Board buses and follow unnamed road back up the hill to the north.)

70.1 Turn left on Route 521 (Stillwater Road) to return to Blairstown.

70.25 Keep to left on Route 521. Avoid right fork.

71.0 At flashing red light make very sharp left turn onto Route 94 and follow to east toward Newton.

71.6 Crossing the trace at the Portland thrust fault, the frame of Paulins Kill window.

72.2 Junction with Wasigan Road, continue east on Route 94.

72.4 Outcrop of inverted Bushkill slate at road intersection on the right.

72.9 Nice outcrops at Ramseyburg on the right.

73.2 More nice outcrops at Ramseyburg. Sedimentation sequences in these rocks begin with a cross-laminated interval which pass up into a planar laminated interval which is overlain by pelite. They are, then T_{cde} turbidites and belong to turbidite Facies D of Walker and Mutti (1973). The cleavage in these rocks is marked by an extension lineation which plunges 35° S. 15° E.

73.9 Entering Village at Marksboro.

74.4 Very small pond on left.

80.0 Turn right up hill toward Johnsonburg. Outcrops of Bushkill slate on left past intersection. Cleavage here is marked by an extension lineation which plunges 20° S. 48° E.

80.3 Outcrops of Bushkill slate on the right. Extention lineation on cleavage here plunges 34° S. 25° E.

80.7 Farm with three small fish ponds on the right.

81.1 Rickenbach Dolomite in the small Alpha Klippe crops out to the left. Allentown Dolomite in the even smaller Beta Klippe crops out in the woods about .25 miles to the east-northeast. Both these klippen rest on Ramseyburg and are shown but not labeled on figure 1.

81.3 Stop sign at crossroads. Continue on to south. Just to south at crossroads there is a small dammed stream and pretty house. Rock is Bushkill.

81.5 Underpass beneath Erie-Lackawanna Railroad. (Immediately south of this underpass bus will pull off to right and field trippers will disembark. Bus will have to continue south to Johnsonburg and turn around. This will be an hour stop.)

STOP 8: Federal Springs thrust fault; speaker, Avery Drake. (Follow path to left of stop to reach the grade of the Erie-Lackawanna Railroad. Be extremely careful on the railroad grade, there are occasional trains. Follow railroad grade about 600 feet to west.

Here are beautiful outcrops of interbedded slate and thin graywacke of the upper Bushkill member of the Martinsburg Formation (see fig. 2). The Ramseyburg Member crops out along the road about 700 feet north of these outcrops. The rock in this outcrop is inverted as shown by sedimentary structures. Fabric elements are: bedding, 50° W. 45° SW.; slaty cleavage, N 70° W, 35° SW.; intersection of bedding and slaty cleavage, 20° S, 35° E., and extension lineation, 28° S. 38° E. Here, the bedding-cleavage intersections which are roughly parallel to the local fold axes plunge southeast beneath the Federal Springs klippe about parallel to the direction of transport as shown by the extension lineations.

Next, the field trip will turn around and follow the railroad tracks to the east. About 400 feet east of the overpass there are horribly mangled outcrops of Bushkill not very far beneath the Federal Springs thrust fault. The field trippers can sort out structures here at their pleasure. The Federal Springs thrust fault crops out about 500 feet farther to the east. The geologic relations at this site are quite complex as it is essentially a quadruple point between Epler Formation, Ontelaunee Formation, Jacksonburg Limestone, and Bushkill Member of the Martinsburg Formation. The Federal Springs thrust fault brings rocks of the Beekmantown Group and Jacksonburg Limestone onto the Bushkill. Two units occur within the Beekmantown here. The lower unit, the Epler Formation consists of very earthy, silty, finely crystalline dolomite that has silty partings, limey dolomite, and some limestone. The Elper is overlain by a unit of medium-gray, medium- to coarsely-crystalline dolomite which based on our experience in Pennsylvania, we assign to the Ontelaunee Formation.

The Jacksonburg Limestone appears to uncomformably overlie both Beekmantown units in these exposures. The Jacksonburg here is a small tectonic sliver of dark gray, shaly cement rock. A sample of this rock contained a poor conodont fauna which, according to John Repetski (written commun., 1979) included the following:

2 drepanodonti form elements, indeterminate, deformed
1 paltodonti form element A
1 paltodonti form element B

Another tectonic sliver of Jacksonburg crops out along the Federal Springs fault about 1100 feet N. 63° E. from this site. The Jacksonburg here is a radically different rock type, being medium-grained calcarenite grainstone. A sample from this site contained as, identified by John Repetski (written commun., 1979) the following conodont fauna:

PANDERODUS
PHRAGMODUS UNDATUS Branson and Mehl
dichognathiform elements
oistodonitform elements
phragmodontiform elements
PLECTODINA
cyrtoniodontiform (N) element

This rather nondiagnostic microfauna ranges from the Rocklandian to upper Richmondian. The conodont color alteration index (CAI) of the elements in this sample is 5, indicating host rock temperatures greater than about 290°C.

The structure above the Federal Springs thrust is quite complex. At the end of the railroad cut about 550 feet to the east of the fault, Epler crops out at track level. About 65 feet west of this point Ontelaunee is at track level, and about 250 feet farther west Epler comes back down to track level. This rock distribution defines a very tight fold which plunges about 35° N. 70° E. Small early folds within this part of the outcrop plunge 35° S. 47° E., essentially parallel to the extension lineation within the Epler. These folds have an S rotation sense when viewed in profile showing that this is an inverted limb. Other fabric elements here include: steep fracture cleavage, due N., N. 80° E.; pressure solution veins which plunge 40° S., 20° E., and opens buckle folds in bedding which plunge 10° N. 75° E.

Just at the Federal Springs thrust which trends northeast and at these places dips rather steeply, the Jacksonburg Limestone is transposed and the transposition foliation is folded with the rocks of the Beekmantown Group. The fabric elements within the Jacksonburg include: the transposition foliation, N. 25° E., 52°NW.; intersection of bedding and slaty cleavage 40° N. 20° W., extension lineation on the transposition foliation, 48° N. 40° W.; and axes of small folds in the transportation foliation 10° S. 45°W. The lineation formed by the intersection of bedding and cleavage streams around the fold hinge directly above the thrust.

Folds such as those above the thrust are not obvious in the slates of the Bushkill beneath the thrust. The fabric elements in the slate include: bedding, N. 75° E. 35NW. (sedimentary structures show that the rock faces up); slaty cleavage, N. 5° W. 35° SW.; fracture cleavage, N. 75° W. 40° SW.; and axes of small folds in slaty cleavage 12° S. 60° W. A wide variety of structures can be observed in the Bushkill to the west of the thrust and the interested observer can observe these at his/her leisure.

(Following the observations of the Federal Springs thrust, the field trip will return to the bus, board it, and retrace the field trip route north along the unnamed road toward Route 94.)

81.7 Stop sign at crossroads. Continue north.

83.0 Turn right and follow Route 94 to the east. Immediately on the right are outcrops of Bushkill.

83.2 More outcrops of Bushkill on right.

83.9 Entering Tranquility 7 1/2-minute quadrangle.

84.0 Junction with Johnsonburg Road. Continue east on Route 94. Small outcrop of Bushkill on left.

84.95 Junction with Yellow Frame Road. Yellow Frame Cemetery on right. We have just crossed Sussex County line.

85.25 Enter Newton West 7 1/2-minute quadrangle. There is a good view of Hunts Pond to the right front. We have done no geologic mapping in this area.

85.85 Pavement outcrops of Bushkill on the left.

86.2 Excellent Bushkill outcrop on the left.

86.6 Bushkill outcrop to right, small pond to left.

87.0 Road junction. Continue following Route 94 to the east. Bushkill outcrops on the left.

87.5 Outcrops of Bushkill on the left. Here, the slaty cleavage has been rotated past the horizontal and dips northwest. Route 94 is roughly paralleling the geologic strike in this area.

88.6 Fredon Township School. Continue east on Route 94.

89.1 Paulins Kill Lake Road on left. Continue east on Route 94.

89.5 Springdale Road on right. Continue east on Route 94.

91.3 Entering town of Newton.

91.6 Entrance to Newton Memorial Hospital on the left.

91.7 Scattered outcrops of Bushkill along here. Slaty cleavage dips to the northwest.

92.2 Keep to the left staying on Route 94.

92.4 At the Sussex County Courthouse begin going around the town square.

92.45 Turn left. This is combined Route 206 North and Route 94. From this point, follow signs for Route 206 North toward Vernon and Milford.

92.5 Turn left again at red light and continue around the square.

92.55 Back at Sussex County Courthouse. Turn right and follow Route 206 North.

92.85 Enter Newton East 7 1/2-minute quadrangle.

93.00 Outcrops of Martinsburg Formation on the left.

93.6 Turn left into Newton County Mall and drive to northeast end and park to right at Shepards Family Fashions. Field trip stop is to rear of this building.

STOP 9: Grand Union klippe; speaker Avery Drake.

This klippe is a relatively small slab of Allentown dolomite which lies on rocks of the Ramseyburg Member of the Martinsburg

Figure 10. Grand Union klippe of Allentown Dolomite (light-colored rock) overlying Ramseyburg Member of Martinsburg Formation. The Jenny Jump thrust (middle of photograph) about parallels bedding in the Allentown and is marked by gouge and crushed dolomite. Note the essentially vertical bedding in the Ramseyburg in the right part of the photograph and the gently northwest (left) dipping slaty cleavage.

Formation. The thrust fault beneath it (fig. 10) was well exposed during excavation for this shopping center. The thrust fault, thought to be the Jenny Jump thrust fault, is roughly parallel to the bedding in the Allentown N. 50°, E. 40° NW., and is marked by 1 to 3 inches of gouge as well as by a fair amount of crushed dolomite. The rocks of the klippe face up as is clearly shown by abundant algal stromatolites.

The rocks of the Ramseyburg beneath the thrust are isoclinally folded. The fold trains have a (zigzag) "M" pattern suggesting that the rocks occur in a fold hinge. Bedding immediately adjacent to the thrust is N. 35° E. 65° NW., and it approaches vertical several feet to the southeast (Fig. 10). Slaty cleavage is N. 20° E. 35° NW., has been rotated past the horizontal, and is truncated by the thrust. These data and their geometric relations suggest that the Ramseyburg here is in the brow and upper limb of a northwest-closing recumbent fold. The slaty cleavage is marked by an extension lineation which plunges 39° N. 55°W. and extension fractures are N. 38° E. 85° SE.

Close examination of the Ramseyburg shows that it, like other Martinsburg we have seen in exposures beneath the Jenny Jump thrust, is an autoclastic mélange. Here, most of the graywacke beds have been pulled apart and fragmented and swim as autoclasts in a more slaty matrix.

Two sets of small faults can be seen in the Ramseyburg. One set is N. 52° E., 40° NW. and has pressure solution veins which show left-separation. The other set is N. 50° E. 80° NW. and shows normal-separations.

This exposure is extremely important as it clearly shows that a klippe of the Jenny Jump thrust sheet was emplaced subsequent to major deformation and slaty cleavage development in rocks of the Martinsburg Formation. This klippe, like the others we have seen, lies in a synform in the slaty cleavage of the Martinsburg. (Following this stop, board the bus, and return to Newton on Route 206. As the town square is reached (marked) by Sussex County Courthouse, stay in left lane.)

95.05 Directly in front of Courthouse turn left sharply following Route 206 signs. Immediately get into right lane.

95.1 At stop light, turn right toward Netcong (an Armed Forces Recruiting Center is dead ahead when at stop light).

95.3 First Baptist Church at Newton on right. Veer slightly left staying on Route 206 South.

96.3 Large outcrops of Allentown dolomite on right. This rock is in the Allamuchy nappe.

98.1 Village of Springdale. Junction of Route 206 with Greendell-Tranquility Road. Veer left and continue south on Route 206.

98.6 Good outcrops of Allentown Dolomite on left.

98.8 Outcrops of Allentown Dolomite on the right.

99.4 Whites Pond on left.

99.6 Approximate common corner of Newton West, Newton East, tranquility and Stanhope 7 1/2-minute quadrangles.

100.0 Outcrops of Allentown Dolomite behind the Rustic Wine Cellar. This is in the Stanhope 7 1/2-minute quadrangle.

100.1 Outcrops of Allentown Dolomite on both sides of road.

100.25 Crossing tracks at Lehigh and Hudson Railroad.

101.0 Stop light at junction of Route 206 and Route 517. Continue south on Route 206. This is in village of Andover. Andover Ponds are to left front.

101.4 Tranquility - Hackettstown Road (Route 517 South) goes off to right. Keep left and follow Route 206 to the south.

101.8 Pass under tracks of Delaware, Lackawanna, and Western Railroad.

102.2 Proterozoic rocks at the Allamuchy nappe crop out to the right. The allochthonous nappe-nature of the tectonic unit was confirmed in this area by diamond drilling by the New Jersey Zinc Company (Baum, 1967).

102.25 More outcrops of Proterozoic rocks on the left. We will remain in these rocks until we rejoin Interstate 80.

102.6 Outcrops of hornblende granite. This is Bryam Township, the type area of the so-called Bryam Gneiss.

103.5 Cranberry Lake on the right.

105.9 Stoplight. Junction of Route 206 with road to Waterloo. Continue south on Route 206.

106.7 Keep right on Route 206. Avoid going left on Route 46. Begin to watch for Interstate 80 signs.

107.5 Pass under Interstate 80. Route 206 merges with Interstate 80. End of field trip. Continue east on Interstate 80 and return to Rutgers-Newark parking lot via Interstate 80, Interstate 280, Garden State Parkway, Nesbit Street, Orange Street, High Street, and Warren Street.

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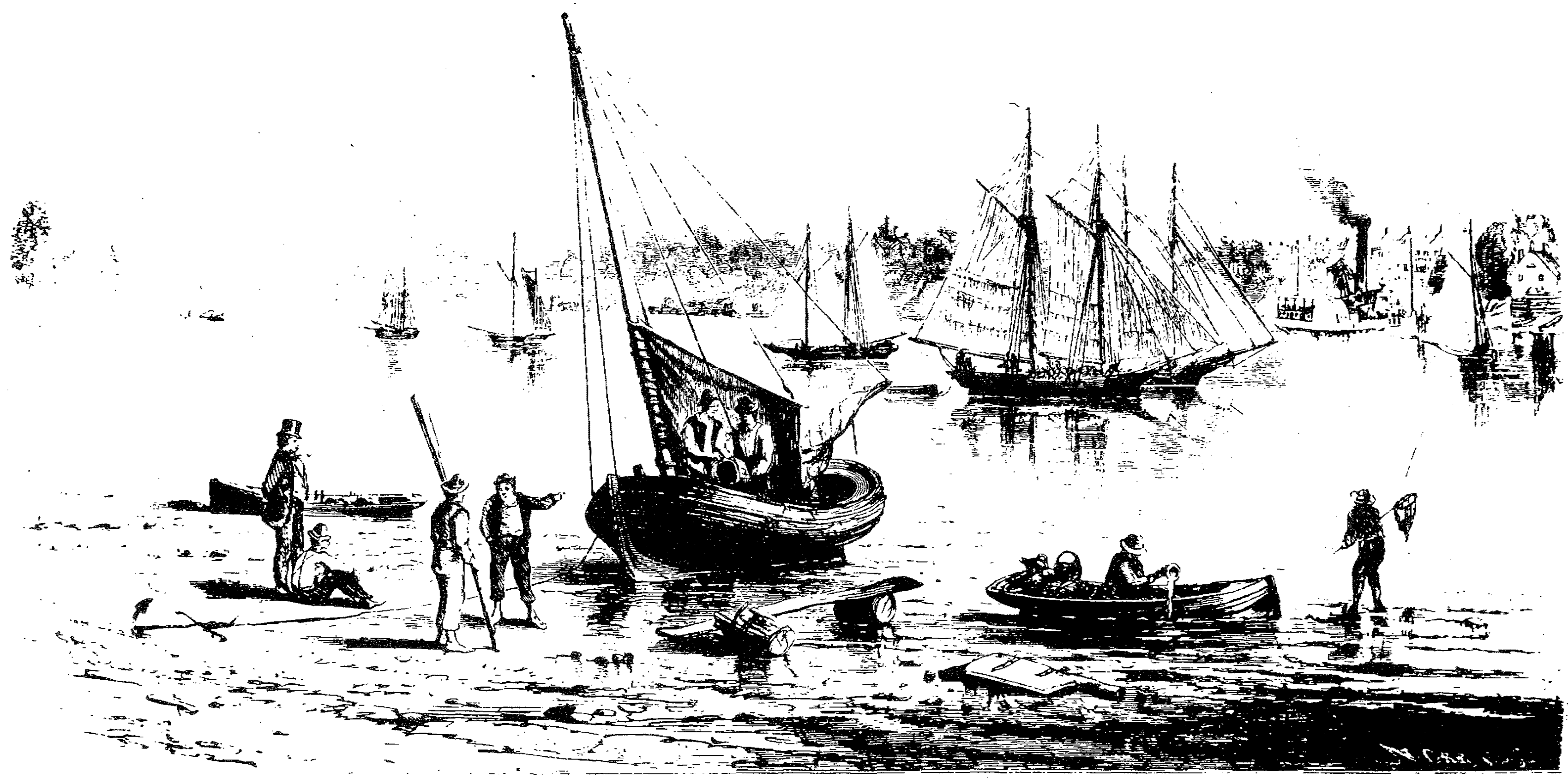

AT RED BANK.

AT RED BANK by Granville Perkins
from
1872, *Picturesque America,* Vol I

THE NEW JERSEY COASTAL PLAIN AND ITS RELATIONSHIP WITH THE BALTIMORE CANYON TROUGH

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Introduction

The coastal plain of New Jersey lies along the western edge of the Baltimore Canyon Trough, a large sedimentary basin which extends along the United States Middle Atlantic states (Fig. 1). The Baltimore Canyon Trough extends seaward beneath the continental shelf to the upper continental slope. A westward extension of the trough forms the Salisbury Embayment of New Jersey, Delaware, Maryland and eastern Virginia. The Raritan Embayment of northern New Jersey and Long Island is a shallow embayment. The South Jersey High separates these two embayments of the trough. The Baltimore Canyon Trough is composed of a seaward-thickening wedge of Mesozoic and Cenozoic sedimentary rocks which overlie a warped and faulted crystalline basement. The sediments that lie within the New Jersey Coastal Plain were deposited west of the main hinge line of deposition. Seaward of the hinge line the sedimentary rocks of the Baltimore Canyon Trough thicken to at least 14 km (Poag, 1979). In contrast the maximum thickness of sediments in the New Jersey Coastal Plain is less than 2 km in the Salisbury Embayment.

The sediments in the Baltimore Canyon Trough were initially deposited when North America and Africa separated during early Mesozoic time. The sediments (Figs. 2,3) that accumulated in the Baltimore Canyon Trough consist of limestones, sandstones, sands, shales, and clays (Poag, 1979). Diapir structures noted in geophysical profiles (Grow, 1980; Schlee and Grow, 1980) along the continental slope suggest evaporite deposition occurred in the early phases of continental separation. A deeply buried thick sequence of limestone of Jurassic and Early Cretaceous age is identified in multi-channel seismic reflection profiles of the trough and a carbonate bank or reef thought to represent the lower Cretaceous shelf edge is postulated to lie beneath the present day upper continental slope. Limestones of late Jurassic and early Cretaceous age were penetrated in the basal portion of the COST B-3 well which was drilled on the continental slope off New Jersey. The limestone sequence is confined to the deeper portions of the trough and does not extend beneath New Jersey.

Overlying the limestone sequence (Figs. 2,3) are upper Jurassic and lower Cretaceous nonmarine and shallow marine sandstones and shales (Poag, 1979). These sediments thin beneath New Jersey and lie upon crystalline basement rock. Where penetrated in wells they appear to be nonmarine in character although they

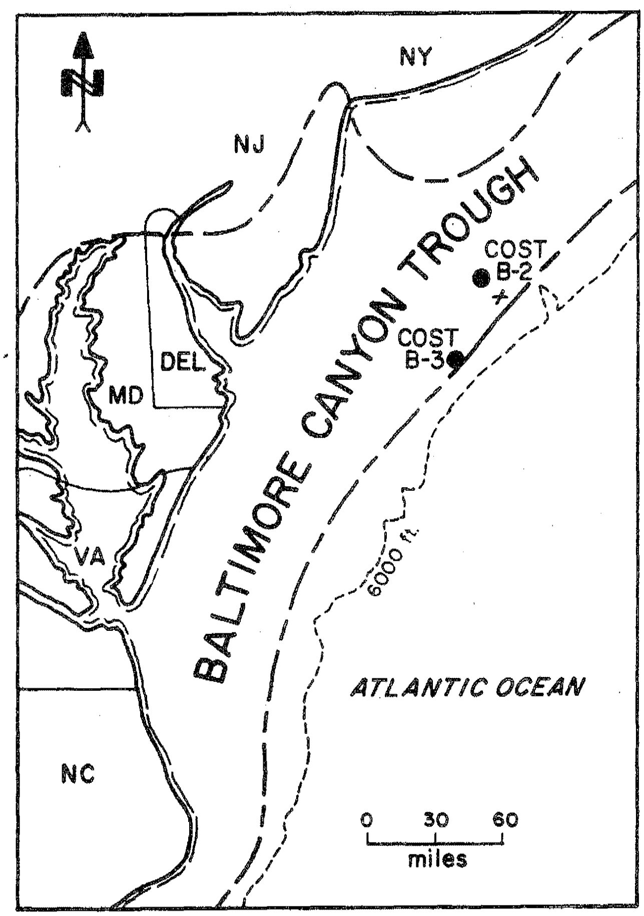

Fig. 1 Outline map of the Baltimore Canyon Trough and its relationship to the New Jersey Coastal Plain. Location of COST B-2 and B-3 wells is shown. The hatchered mark shows location of natural gas discoveries.

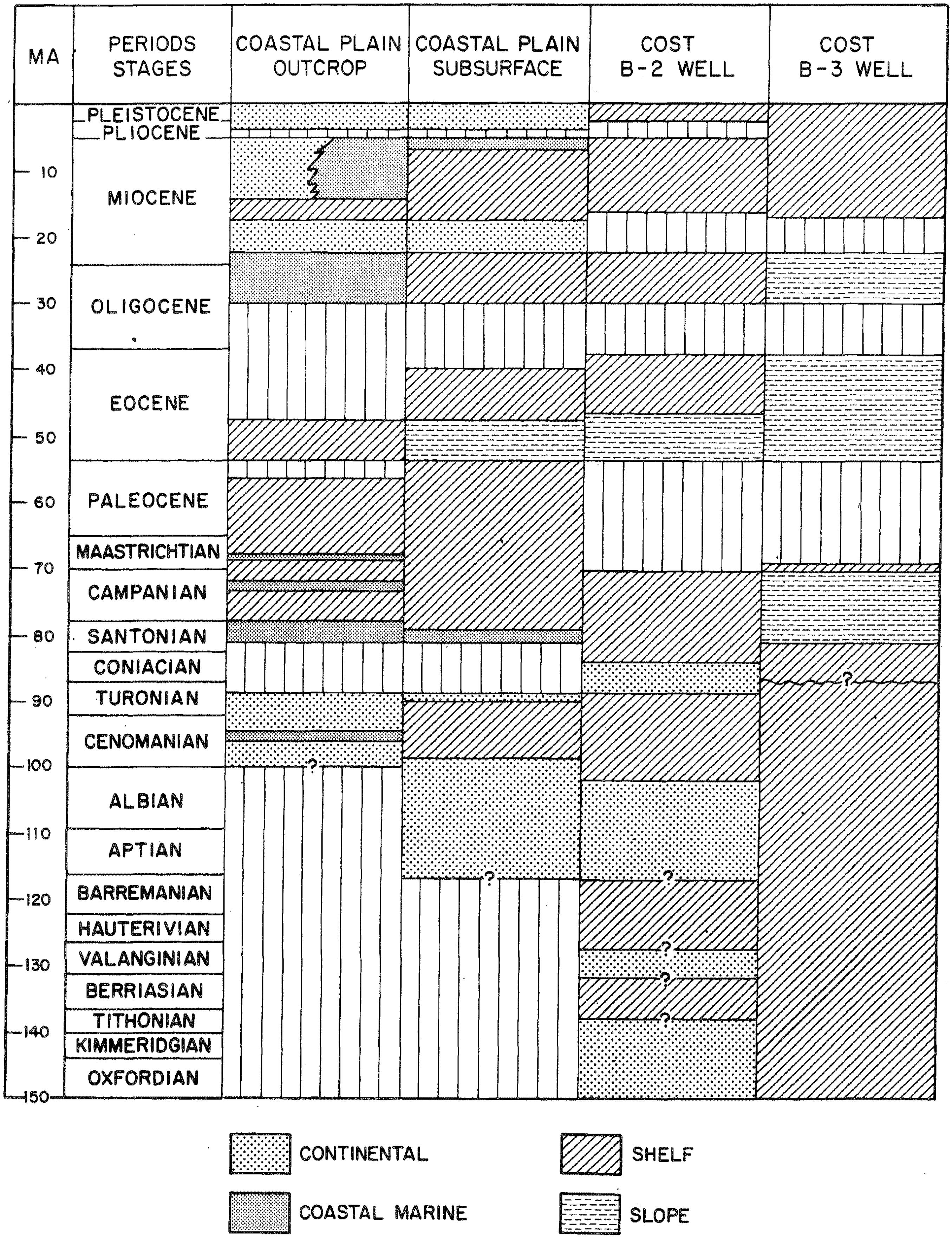

Fig. 2 Diagram showing distribution of the continental, coastal marine, shelf, and slope facies in time. Data on COST B-3 well is taken from Poag, 1980.

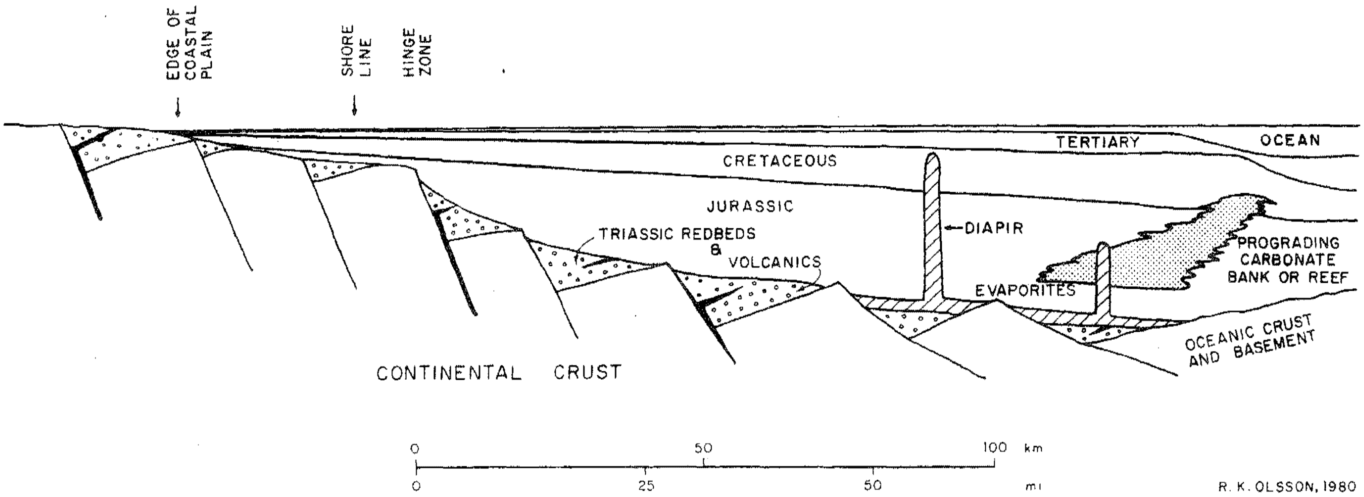

Fig. 3 Cross-section through Coastal Plain and Baltimore Canyon Trough modified after Schlee and Grow, 1980.

have not been thoroughly studied. The upper Cretaceous and Tertiary marine sequence that forms the major part of the New Jersey coastal plain belongs to a marine cycle that began during Aptian time and transgressed over the Atlantic margin, bringing sea level over the New Jersey area for the first time since the Atlantic began to open.

The sediments that were deposited in the coastal plain of New Jersey consist of fluvial sands, gravels, and varigated clays; coastal deposits of beach, lagoon, marsh, and related deposits; inner shelf sediments consisting of shore face sands with characteristic *Ophiomorpha* trace fossil assemblages and offshore micaceous clay and silty thinly bedded fine sands; mid and outer shelf clay glauconite sands and glauconitic clays, often extensively burrowed; and slope deposits composed of calcareous clays and silts. The formations of these various facies were deposited during major cycles of sea level change and are genetically related to sedimentary units that have been penetrated in the COST B-2 and B-3 wells in the Baltimore Canyon Trough. The relationship of the New Jersey formations to the units penetrated in these wells will be discussed in the section on lithologic units.

Geological History of Coastal Plain and Baltimore Canyon Trough

A general sequence of events based upon subsurface studies (Figs. 2,3) in the New Jersey coastal plain, data from the COST B-2 and B-3 wells, seismic reflection profiles, and seismic refraction studies can be constructed for the Baltimore Canyon Trough and the adjacent New Jersey coastal plain (Grow, 1980; Poag, 1979, 1980; Schlee and Grow, 1980; Sheridan, 1979).

The separation of North America and Africa began during the Triassic with extensive drifting and formation of faulted basins in which continental sediments accumulated. As continental separation began and the initial opening of the Atlantic occurred evaporite environments formed during the Late Triassic and Early Jurassic. Some of the rifted basins continued to receive continental sediments during Early Jurassic time. This early stage of development was accompanied by extensive volcanism consisting of intrusive and extrusive placement of basaltic and dioritic rocks.

As circulation within the developing Atlantic Ocean became less restricted during Jurassic time carbonate environments developed with bank and reef growth. Fluvial sediments were deposited over the Triassic rifted basins landward of the carbonates. During Jurassic to Early Cretaceous time as the Atlantic continued to widen the carbonate bank and reef complex prograded seaward over the oceanic basement (Fig.3). In the coastal plain area extensions of the Baltimore Canyon Trough developed as embayments. These embayments, the Salisbury and Raritan embayments, which are probably fault bounded, received thicker sequences of Jurassic and Lower Cretaceous fluvial sediments. In Late Jurassic and Early Cretaceous time shallow marine incursions began to extend landward of the carbonate complex (Fig. 3).

A major cycle of sea level rise began during Albian time and in the Cenomanian seas spread into the coastal plain area for the first time (Fig. 3). This cycle of sea level rise ended the deposition of carbonate sediments along the Lower Cretaceous shelf edge. The carbonates now lie beneath the present upper continental slope. The rise of sea level which began during Albian time lasted until the Turonian before being interrupted by a moderate fall in sea level. Nevertheless, renewed rise in sea level continued during the latter part of Late Cretaceous time. The Late Cretaceous stratigraphy of the coastal plain was controlled by individual cycles within this major rise of sea level. The deposition of marine sand, silt, and clay sifted with each sea level cycle.

Changes in sea level continued to influence deposition during the Paleocene and Eocene. During the Late Cretaceous and Paleocene sediments accumulated in shelf environments of deposition in the coastal plain and for the most part in the Baltimore Canyon Trough except in its most distal part. During the Early Eocene, however, bathyal environments of deposition extended into the coastal plain (Fig. 3). The Eocene shelf and slope profile appears to have been very gradual with no distinct shelf edge. Shelf deposition was reestablished in the coastal plain during the middle Eocene time and bathyal conditions retreated further out in the Baltimore Canyon Trough. Late Eocene shelf deposition occurred over most of the Baltimore Canyon Trough and may have extended into the coastal plain, although upper Eocene sediments are missing there.

At the end of Eocene time a major lowering of sea level occurred and the entire Baltimore Canyon Trough was subjected to erosion. Sea level rose during Late Oligocene time and the sea transgressed across an eroded and beveled surface into the coastal plain area.

During Miocene time clastics prograded over the Baltimore Canyon Trough and constructed the present shelf and edge profile (Fig. 3).

Sea Level Cycles

Sea level change has had an important influence on the stratigraphic development of the New Jersey coastal plain and the Baltimore Canyon Trough. Perhaps the two most important events are the Albian-Turonian rise in sea level which first established marine processes in the coastal plain and ended carbonate depositions in the Baltimore Canyon Trough, and the Oligocene lowering of sea level which may have exposed the entire Atlantic margin. In post Oligocene time progradation formed the present shelf profile and brought an end to the unique environment of glauconite formation that characterized the Late Cretaceous and Early Tertiary.

Vail and others (1977) have shown in their study of stratigraphic onlap and offlap sequences in seismic reflection profiles that major cycles of sea level change can be recognized and correlated from basin to basin. These changes which they believe to be eustatic in origin are the basis of the well known Vail curve of relative sea level change. Of interest to many geologists is the magnitude of sea level rise or fall. The magnitude of change shown on the Vail curve is derived from the extent of onlap and offlap sequences as viewed in seismic records and not from direct means of paleoenvironmental analysis. As such the Vail curve should be regarded as a first approximation in achieving a universal curve of sea level change in the geologic record.

Figures 4, 5, and 6 show the record of sea level change in the coastal plain and the Baltimore Canyon Trough. The magnitude of sea level rise and fall is estimated on paleontologic criteria, chiefly foraminifera. It can be observed that in many places there is general agreement with the timing of sea level cycles shown on the Vail curve but not necessarily with the magnitude or character of each cycle. Of note (Fig. 6) is the record of the upper Eocene and Oligocene which differs significantly from that of Vail and others in that the major lowering of sea level occurs in the lower Oligocene where they show a major rise in sea level.

Lithologic Units

Jurassic

Nonmarine coarse sandstone and red and green shale of probable Jurassic age lie upon crystalline basement beneath New Jersey. Similar rocks intercalated with marine shale were penetrated in the COST B-2 well where a thick Jurassic section is present. Carbonate sediments are present further to the east in the COST B-3 well and in lower intervals in the Baltimore Canyon Trough.

Potomac Group (Lower Cretaceous)

The Potomac Group consists of three formations of continental origin, the Patuxent, Arundel and Patapsco. These formations are well-developed south of New Jersey but they have not been recognized in New Jersey. However, palynological data indicates that small remnants of sediments of equivalent age are present in southern and central New Jersey. In the subsurface thick section of Lower Cretaceous continental sediments have been encountered. In the COST B-2 well the Lower Cretaceous rocks are mostly nonmarine in origin and contain thin coal seams. Thin shallow marine intervals are present in the lower and uppermost parts of the Lower Cretaceous section in this well. Further east in the COST B-3 well the Lower Cretaceous is a marine sequence of sand, shales, and thin beds of limestone and dolomite. Multichannel reflection profiles along the upper continental slope indicate the presence of a carbonate bank or reef which may represent the Lower Cretaceous shelf edge.

Raritan Formation

The Upper Cretaceous stratigraphic sequence in New Jersey begins with the nonmarine Raritan Formation

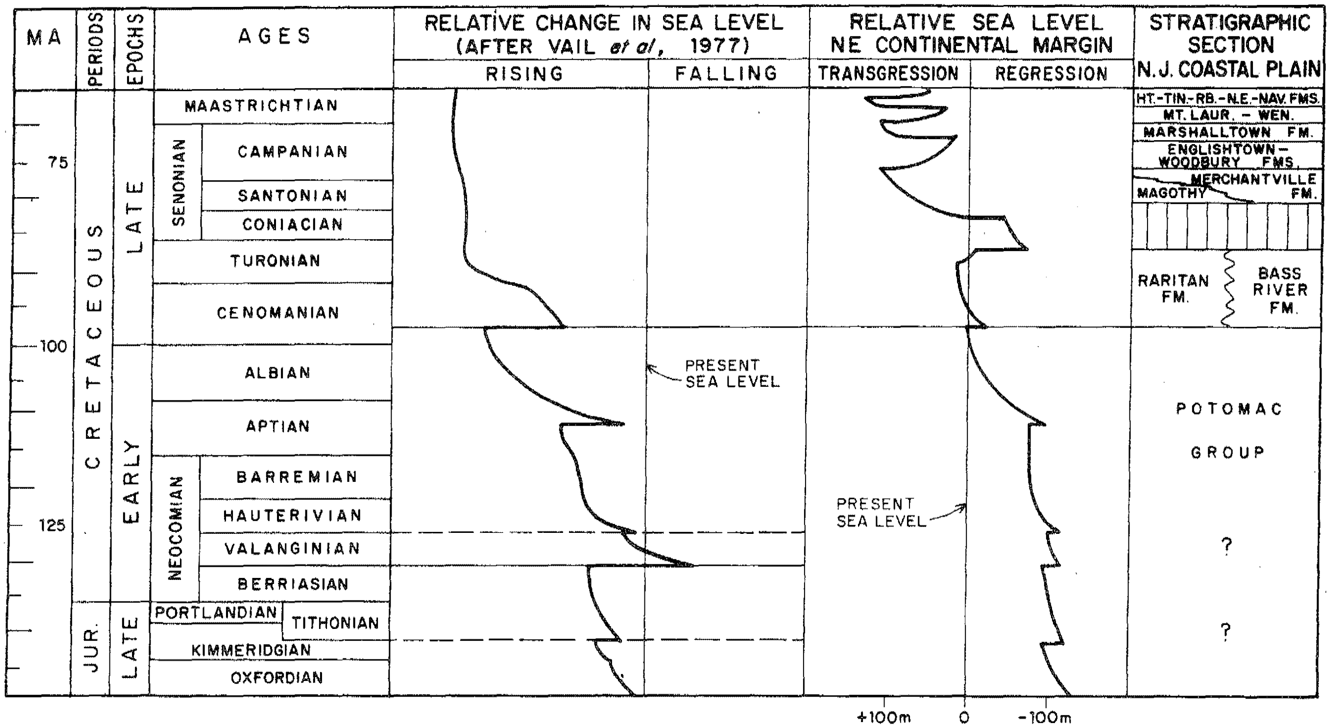

Fig. 4 Stratigraphy and sea-level changes for the Upper Jurassic and Cretaceous of the New Jersey Coastal Plain showing estimated Paleobathymetry. Comparison is made with the curve of Vail *et. al.*, 1977.

which consists of light-colored sands and variegated clays. Several members which vary greatly in thickness and lateral extent have been recognized in the Raritan. One of these units, the Woodbridge Clay, contains marine fossils, thus indicating the first marine deposition in the New Jersey Cretaceous. The coastal sediments of the Woodbridge are limited in extent and are overlain by other continental deposits of the Raritan. The indication of marine deposition in outcrop is more fully expressed in the New Jersey subsurface where the Raritan is replaced by the marine Bass River Formation.

Bass River Formation

This subsurface formation is composed of an olive-gray to olive-black, chloritic, glauconitic, clayey silt which in places contains a considerable amount of shell material. The Bass River reaches a maximum thickness of 400 feet in its downdip extent but pinches out some 15 miles or so from outcroppings of the Raritan. Undoubtedly, the Woodbridge Clay represents coastal deposition marginal to Bass River shelf deposition.

The Bass River is a time-transgressive unit; its age spans the lowermost Cenomanian (Upper Washitan) to lower Turonian (Eagle Fordan). In the farthest downdip wells the formation encompasses this entire interval whereas in updip wells only the Turonian is present. Palynological studies (Doyle, 1969; Wolfe and Pakiser, 1971) show that the Raritan Formation in its type locality ranges in age from late Cenomanian to early Turonian, whereas the upper part of the Patapsco Formation (Potomac Group) is equated with the lower Cenomanian. Thus, the Bass River is not only a marine equivalent of the Raritan but also of the uppermost part of the Potomac Group. The Bass River which is one of the most extensive units in the subsurface of the New Jersey Coastal Plain was deposited during a world-wide transgression that began in Albian time. This transgression which brough marine processes into New Jersey for the first time is clearly observed in the Baltimore Canyon Trough in the shoreward overlapping of the nonmarine Lower Cretaceous sediments by Albian marine sandstone and shales. The transgression ended during Turonian time.

Magothy Formation

The Magothy Formation is separated from the underlying Raritan Formation by an upper Turonian-Coniacian (Lower Austin) disconformity. The disconformity persists in most of the subsurface of New Jersey except in the Salisbury Embayment. The disconformity disappears eastward in the Baltimore Canyon Trough where nonmarine (B-2) and marine (B-3) sediments are present. Palynologic data indicate that the Magothy is Santonian (Late Austin) in age.

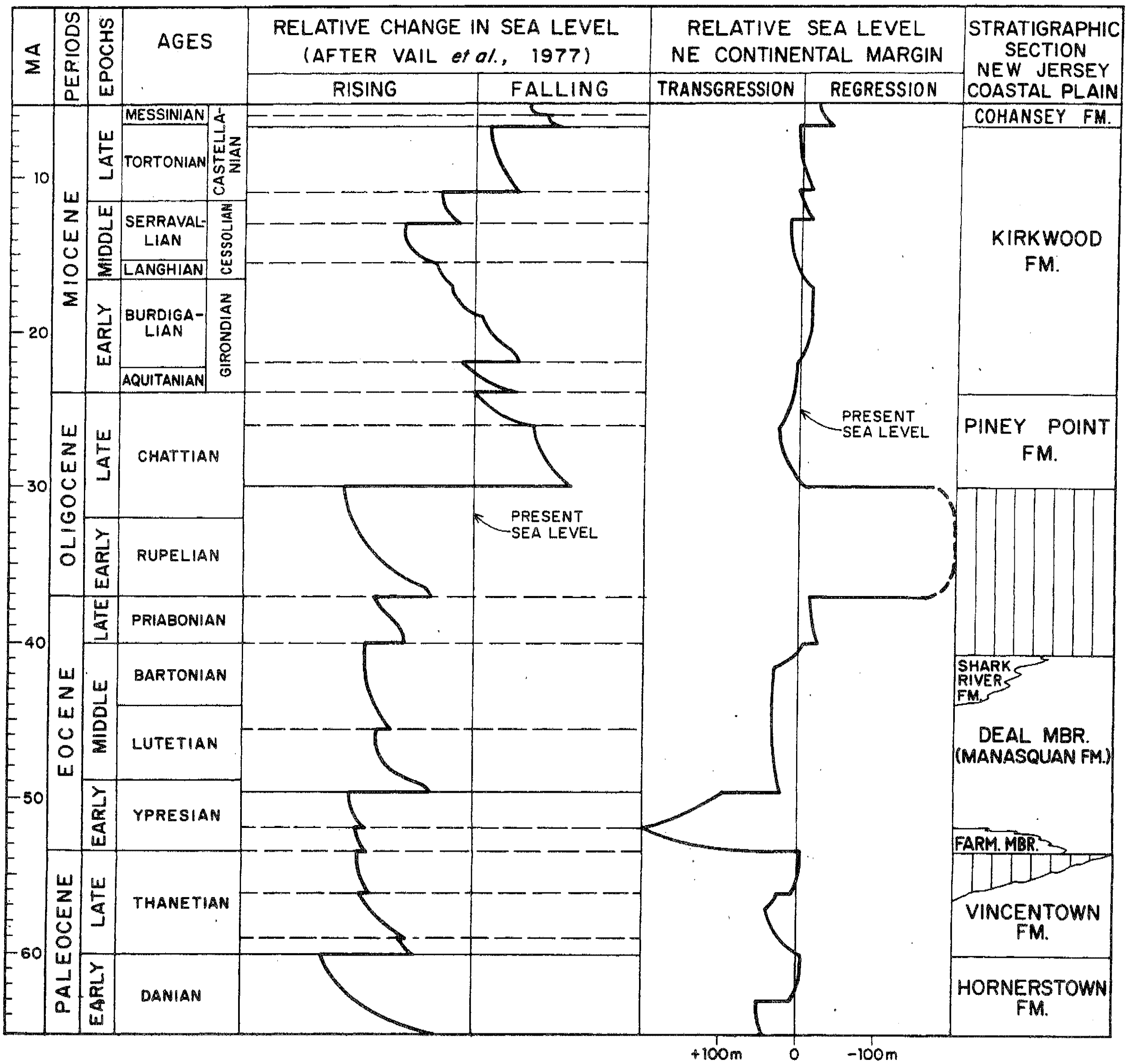

Fig. 5 Stratigraphy and sea-level changes for the Paleocene to Miocene of the New Jersey Coastal Plain showing estimated Paleobathymetry. Comparison is made with the curve of Vail *et al.*, 1977.

The interstratified dark carbonaceous-rich silty clays and light-colored sands and laminated clays of the Magothy were deposited in a coastal environment. In the subsurface the Magothy thins and is partly replaced by the marine Merchantville Formation, thus indicating that the Magothy is a coastal facies associated with a transgressing sea.

Merchantville Formation

The glauconitic, micaceous clays and clayey silts of the Merchantville Formation are the first massive shelf deposited sediments to be exposed in the Upper Cretaceous section of New Jersey. They contain a diverse assemblage of megafossils which are preserved mostly as molds; calcium carbonate has been leached from outcroppings of the Merchantville. The formation can be recognized in outcrop southward into Delaware.

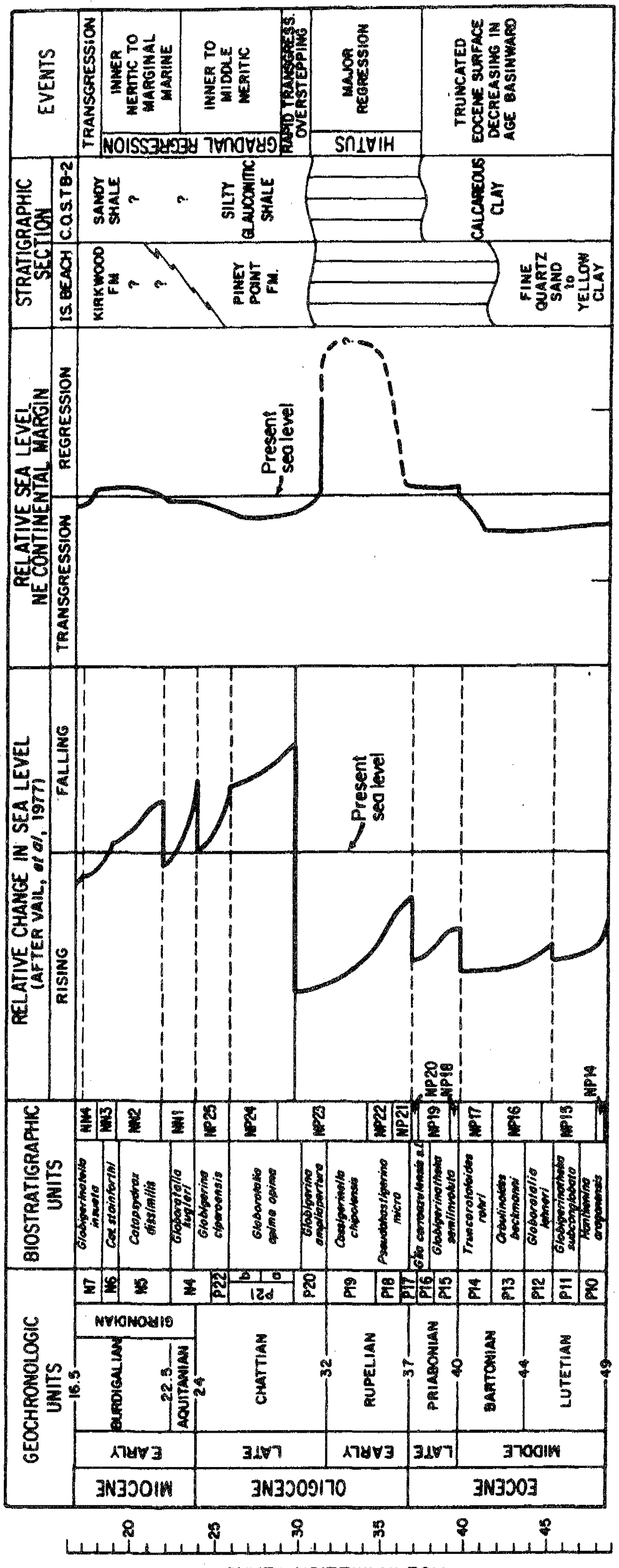

Fig. 6 Stratigraphy and sea-level changes of the Oligocene event showing estimated Paleobathymetry and Biostratigraphic framework. Comparison is made with the curve of Vail *et. al.*, 1977.

In downdip sections it thickens and is partially equivalent to the Magothy Formation. In outcrop the Merchantville contains a lower Campanian (lower Taylor) molluscan fauna. In the subsurface the lower part of the Merchantville is Santonian in age and the upper part lies within the lower Campanian. It thus becomes clear that the Merchantville is transgressive with respect to the Magothy. The Merchantville was deposited during the second major transgression of the Late Cretaceous. Dark gray micaceous silty mudstone and calcareous mudstone penetrated in the COST B-2 and B-3 wells, respectively, were deposited during the Merchantville transgression.

Woodbury Formation

The Merchantville Formation grades upward into a light to dark gray, micaceous, chloritic, silty clay with minor amounts of glauconite, siderite, and lignite. This lithology is typical of the Woodbury Formation. Although it is sometimes difficult to place a lithologic boundary between these two formations, the Woodbury represents sediments depositied under shoaler inner shelf conditions. This is evident in subsurface sections where well-preserved foraminiferal assemblages record this change.

In downdip sections there is a pronounced thickening of the Woodbury as it interfingers and replaces the sands of the overlying Englishtown Formation. In the Salisbury Embayment the Campanian interval occupied by the Woodbury up-structure consists of clays and chalks. To the east in the Baltimore Canyon Trough the Woodbury regressive trend is evident in correlative mudstone and sandstone in the B-2 well.

Englishtown Formation

The Englishtown Formation consists of quartz sands, silty sands, and silts which are thickest on the northeast and gradually thin and disappear along strike on the southeast. It also thins downdip where it is replaced by the Woodbury Formation. Thus, the Englishtown occupies a stratigraphic position landward of the inner shelf Woodbury. The presence in places of cross-stratified sands and the trace fossil *Ophiomorpha* indicate a coastal to shoreface environment. It appears to mark the maximum phase of a regression that began during deposition of the Woodbury.

Marshalltown Formation

In outcrop the Marshalltown is a very thin unit which consists of a burrowed (mottled), clayey, to silty, micaceous, quartz glauconite sand. Although thin, it is remarkably persistant along strike and can be recognized from northern New Jersey into Delaware. The

Marshalltown sediments which were deposited under mid-shelf conditions overlie the Englishtown and signal a renewed transgression of the sea during latest Campanian time. This transgressive cycle is also evident in the calcareous mudstones in the uppermost Campanian in the COST B-2 and B-3 wells.

The formation thickens somewhat in the New Jersey subsurface where it overlies first the Englishtown and then the Woodbury. It loses lithologic identity in the far subsurface in the Salisbury Embayment.

At certain localities shell beds of the oyster *Exogyra ponderosa* contain well-preserved microfossils whereas at other localities only molds of megafossils occur.

Wenonah Formation

The Wenonah Formation consists of a gray, clayey, silty, slightly glauconitic, micaceous, fine quartz sand. It is gradational with the Marshalltown Formation and with the overlying Mt. Laurel Formation. It contains molds of marine fossils and various types of trace fossil burrows. The formation is best developed in outcrop in the central and northern parts of the coastal plain. It thins and disappears in the southern part.

A regressive facies relationship exists between the Wenonah and the Mt. Laurel. The fine-grained Wenonah was deposited under inner shelf conditions adjacent to coarser-grained shoreface deposition of the Mt. Laurel. The thinning and replacement of the Wenonah in outcrop, thus, is related to its replacement by the Mt. Laurel. In the subsurface the formation is replaced by clays, sandy silts and silts.

Mt. Laurel Formation

The Mt. Laurel Formation is more variable in lithology than the Wenonah Formation. Lithology consists of gray, massive, medium-grained sands to thin-bedded light gray to white, fine to medium sands with thin chocolate brown silt and clay layers. Cross-bedding is common in the thin-bedded sequences. The upper 6 feet or so is bioturbated with glauconite infilling of burrows and is a poorly sorted clayey sand containing rounded pebbles and abraded fossil molds. This part may be a lag deposit related to the overlying transgressive Navesink.

The thin-bedded sections contain abundant burrows of the trace fossil *Ophiomorpha* and others. The trace fossils and associated sedimentary features indicate shoreface to transitional offshore deposition for the Mt. Laurel. Shell layers are present in the uppermost portion of the formation in the central part of the outcrop belt. They may be related, however, to deposition of the Navesink mid-shelf facies.

In the subsurface the Mt. Laurel becomes finer-grained and merges into the Wenonah, its offshore counterpart.

Navesink Formation

A return to mid-shelf conditions following deposition of the Mt. Laurel and Wenonah formations resulted in accumulation of the light to dark gray clayey glauconite sands of the transgressive Navesink Formation. The Navesink is a burrow-mottled unit that is rich in skeletal fossil content. The most prominent megafossils are the oysters *Exogyra, Pycnodonte, Ostrea;* the brachiopod *Choristothyris*; and the belemnite *Belemnitella*. In addition to these, molds of various molluscs are common, microfossils (foraminifera, ostracodes, coccoliths, dinoflagellates, epibiont bryozoans) are abundant, and fish and reptilian remains are present.

The Navesink is recognized only in New Jersey; it thins along strike on the south and disappears north of Delaware. In the subsurface the Navesink glauconites blend with similar younger sediments and it becomes difficult to separate the Navesink as a formation. The glauconite content of this stratigraphic interval diminishes in the far downdip.

Redbank Formation

In the northern part of the coastal plain, thick, micaceous, feldspathic quartz sands lie above the Navesink. These sands comprise the Redbank Formation. They are of limited geographic extent, thin rapidly, and disappear north of the central part of the outcrop belt as well as in the shallow subsurface. On the south and downdip the Redbank is replaced by the dark gray-brown, clayey glauconite sands of the New Egypt Formation.

The Redbank is composed of two members, a lower Sandy Hook Member and an upper Shrewsbury Member. The Sandy Hook Member is a dark gray, micaceous, silty, fine to medium, feldspathic quartz sand. In places it contains well-preserved microfossils and small megafossils. The Sandy Hook represents mid to inner shelf deposition related to a regressive phase following the Navesink transgression.

Continued shoaling resulted in deposition of the light gray to white, micaceous, fine to medium feldspathic quartz sands of the Shrewsbury. Large scale cross-bedding and the trace fossil *Ophiomorpha* indicate deposition in an inner shelf environment.

New Egypt Formation

The New Egypt Formation is a clayey glauconite facies that was deposited peripherally to the Redbank sands. It has been considered as a more glauconitic facies of the lower Redbank but paleontological data (Koch and Olsson, 1977) show that it is equivalent to the entire Redbank and to the Tinton Formation as well. The New Egypt is a shelf facies marginal to these formations. It lies above the Navesink Formation and in turn is overlain by the Hornerstown Formation.

Tinton Formation

The Tinton Formation is the only indurated unit in the Upper Cretaceous section of New Jersey. It is very thin and is more limited in extent than the Redbank Formation upon which it lies. It is a brownish-green, argillaceous, medium to coarse, quartz and glauconite sandstone interbedded with layers and lenses of gray claystone. Molds of molluscs, crab claws, and the trace fossil *Ophiomorpha* are common in places.

The formation is interpreted as an inner shelf facies related to the regressive Redbank facies. In fact, it was once regarded as an upper member of the Redbank.

Maestrichtian-Paleocene Hiatus

The Maestrichtian-Paleocene section in the New Jersey coastal plain disappears eastward in the Baltimore Canyon Trough. Paleocene rocks are missing in the B-2 and B-3 wells. Only lower Maestrichtian rocks are present in the B-3 well. Thus curiously, a significant unconformity which appears unrelated to the coastal plain occurs in the Baltimore Canyon Trough.

Hornerstown Formation

The Hornerstown Formation is unusual in several ways, that is, in regards to its lithology and to its age. It is almost a pure glauconite sand, containing little fine-grained matrix. This gives it a distinctive deep-green color. It is a very persistent unit that can be traced along the entire outcrop belt in New Jersey and southward into Maryland. This massive and extensively burrowed facies originated in an inner to mid shelf environment. In the subsurface increasing amounts of clay matrix are present and it gradually loses its lithologic characteristics in the far downdip.

The Hornerstown has been regarded as the basal formation in the Tertiary of New Jersey. However, recent paleontological data (Baird, 1964; Richards, *et al.*, 1973; Richards and Gallagher, 1974; Koch and Olsson, 1974, 1975; Koch, 1975) indicate that the basal beds are Cretaceous in age (*ie*. the top of the Cretaceous System in New Jersey lies within the Hornerstown). A varied assortment of fossil remains of invertebrate megafossils, microfossils (foraminifera, ostracods, coccoliths, dinoflagellates), and vertebrates (fish, reptiles, birds) are found in the formation. A five foot shell bed consisting of the brachiopod *Oleneothyris* and the oyster *Pycnodonte* occurs at the top of the formation. The age of the Hornerstown thus ranges from latest Maestrichtian to mid-Paleocene.

The Hornerstown also plays prominently in a stratigraphic argument at the Cretaceous-Tertiary boundary. The successive stratigraphic overlap along strike from north to south of the Hornerstown over the Tinton, Redbank and New Egypt (basal Redbank and on the far south Navesink of others) has been interpreted as an angular unconformity (Clark, 1897; Cooke and Stephenson, 1928; Minard, *et al.*, 1969). However, paleontological criteria (Koch and Olsson, 1977) demonstrates a facies relationship below the Hornerstown. The Hornerstown is transgressive over the regressively related formations below.

Vincentown Formation

The Vincentown Formation contains two prominent facies, a massive quartz sand facies and a quartz calcarenite facies rich in bryozoans and foraminifera. It lies upon the Hornerstown Formation along the entire outcrop belt. Although it is up to 100 feet thick in outcrop, it thins rapidly in the shallow subsurface where it is replaced by a silt facies. Thus it is regressive over the Hornerstown.

The paleontologic content of the Vincentown places it as an upper Paleocene inner to mid-shelf facies.

Manasquan Formation

Eocene deposits in New Jersey begin with the Manasquan Formation which is separated from the Vincentown Formation below by a slight disconformity. The disconformity seems to be limited to the outcrop area and the shallow subsurface; no evidence of its presence has been found in the deeper subsurface where silts and clays have replaced the Vincentown.

The Manasquan has been divided into two members by Enright (1969), a lower Farmingdale Member and an upper Deal Member. The Farmingdale Member is a mottled, slightly clayey, medium to coarse, quartzose glauconite sand. It is characteristic and persistent along the outcrop strike but loses its distinctive lithology in the subsurface and disappears some 20 miles downdip where it is replaced by the Deal Member. The Farmingdale is a mid shelf facies transgressive over the Vincentown.

The Deal Member is a very distinctive unit, especially in the subsurface where it thickens considerably as it replaces the Farmingdale and the Shark River above. It is a slightly glauconitic, clayey, fine-grained quartz sand to clayey, sandy silt. It becomes more clayey as it extends into the subsurface where it ranges from the lower to mid Eocene.

The Deal is very rich in microfossils; in places it is composed largely of microfossil remains. In addition to foraminifera, coccoliths, and dinoflagellates, it also contains abundant siliceous microfossils (radiolarians, diatoms, sponge spicules), the first known occurence of these fossils in New Jersey. This assemblage of fossils indicates shelf and upper slope conditions for the deposition of this unit which is transgressive over the Farmingdale.

Eastward in the Baltimore Canyon Trough the Deal interval becomes more clayey and calcareous and contains very fossiliferous limestones. In places almost pure calcareous ooze is present. These sediments accumulated under bathyal environments of deposition.

The Shark River Formation contains two members, the Squankum Member and the Toms River Member. The Squankum Member is limited to the northern part of the outcrop belt. The argillaceous, glauconite sands and quartzose glauconitic mudstones of the Squankum are rapidly replaced in the subsurface by the clays and silts of the Deal. Sharks teeth and various molluscan molds are present in the Squankum.

The Toms River Member is recognized only in the subsurface where it reaches a thickness of approximately 80 feet. It, however, decreases rapidly in thickness downdip and is replaced by the Deal. The micaceous slightly clayey and glauconitic, fine to medium grained quartz sand of the Toms River was deposited under inner shelf conditions.

UPPER EOCENE-LOWER OLIGOCENE UNCONFORMITY

An extensive beveled erosional surface on Eocene rocks can be traced from the subsurface of New Jersey into the Baltimore Canyon Trough (Olsson and Miller, 1979). This surface which transgresses lower to middle Eocene rocks in New Jersey to upper Eocene rocks in the COST B-2 and B-3 wells is overlain by upper Oligocene rocks which in New Jersey are called the Piney Point Formation. The unconformity which can be traced southward in the coastal plain (Olsson, Miller and Ungrady, 1980) resulted from a major lowstand of sea level during early Oligocene time.

Piney Point Formation

The Piney Point Formation, a subsurface unit of Maryland and Delaware, was first identified in southern New Jersey by Richards (1967). The formation occurs throughout the subsurface of New Jersey where it ranges from 0 to 400+ feet in thickness (Olsson and Miller, 1979; Olsson, Miller, and Ungrady, 1980). The Piney Point consists of olive-gray to brownish-yellow glauconitic silt and medium to coarse quartz and glauconite sand, which in places becomes very coarse and shelly. Although some of the glauconite is unweathered much of it is well rounded and polished. In addition, weathered Eocene lithoclasts and reworked, recrystallized Eocene foraminifera are present, especially in the lower sections.

Foraminiferal studies (Olsson and Miller, 1979; Olsson, Miller and Ungrady, 1980) show that the Piney Point is late Oligocene in age and that it was deposited as a transgressive deposit upon an eroded and beveled Eocene surface. Seaward in the Baltimore Canyon Trough in the B-2 and B-3 wells upper Oligocene olive-gray silt, clay, and glauconite rest upon upper Eocene calcareous claystones.

Kirkwood Formation

Gray-brown sand, silt, and clay overlie the Piney Point in the subsurface whereas updip along the outcrop belt they lie upon Cretaceous to Eocene formations. These sediments which belong to the Kirkwood formation consist of a complex of coastal and inner shelf facies. The basal portion of the Kirkwood is regressive over the Piney Point and the updip portions of the formation appear to interfinger with the Piney Point (Olsson, Miller, and Ungrady, 1980).

In the subsurface of New Jersey three marine intervals are recognizable in the Kirkwood, an uppermost Oligocene?-lower Miocene interval, a middle Miocene interval and an upper interval of uncertain age.

The Kirkwood was deposited during the progradation and buildup of the present continental shelf and edge which began in the Miocene (Grow, 1980; Schlee and Grow, 1980). Seismic profiles of the Baltimore Canyon Trough clearly show prograding sand beds which define the present shelf and slope.

ROAD LOG

Log of trip begins at Turnpike entrance off of Route 18. Stay on 18.

Mileage

0.0 Head East on Route 18

1.0 Turn right at jughandle to South River. Cross Route 18 and immediately bear right onto Turnpike St.

1.9 At traffic light turn left on West Prospect St.

2.5 Bear left at light. Follow Reid St.

2.8 South River, Junction with Highway 535. Turn left and follow 535 over bridge. Also known as Washington Rd.

5.5 Washington Rd. crosses R.R. track in Sayreville.

5.9 Debark from buses and cross road to Sayreville Pit.

STOP 1 Raritan Formation overlain by the Pensauken Formation (Pleistocene?). The sands and clays of the Raritan represent continental and coastal marine sediments deposited adjacent to a transgressing sea. The marine facies of the transgression is encountered in coastal plain wells. The subsurface marine unit is called the Bass River Formation.

Pensauken Formation 5-10 feet
dark yellowish-brown sand and gravel. Large scale steeply dipping cross-beds represent slip faces of fluvial bars. Approximately 50 yds. to the west a fining upward sequence is present. Gravel and lithic fragments are present at contact with Raritan Formation.

Raritan Formation (Woodbridge Member) 65 feet
interbedded sand and clay with numerous siderite and iron oxide cemented sand layers. Two directions of planar cross-bedding can be observed. The cross-bedding probably represents sand waves of a meandering stream or of intertidal currents. Marine fossils are present in some of the sand layers. 30-40 feet.

sand and clay containing abundant carbonized wood. 5 feet.

dark-gray clay and silt, sharp contact with overlying unit. Fine bedding (0.5 mm) composed of clay-silt laminations. 20 feet.

Correlation: Plant fossils and palynological remains in the Raritan indicate a Cenomanian to Turonian (Washita to Eagle Ford) age. Marine fossils (planktonic foraminifera) of a similar age occur in the Bass River marine facies in N.J. coastal plain wells.

6.1 Walk along Washington Rd. to Sayreville Jr. High where buses are parked. Trip continues along Washington Rd.

6.4 Turn right on Ernston Rd.

7.5 Cross Route 9. Continue straight on Ernston Rd.

8.1 Turn sharp right onto dirt road leading into excavation area. Follow road to area bearing left at first fork.

8.8 Park and walk to ravine. Exposure is off Garden State Parkway.

STOP 2 Magothy Formation overlain by Pleistocene? sediments. The Magothy represents estuarine sediments deposited in front of the advancing Merchantville sea. This exposure represents an intertidal sequence of tidal delta sands and lagoonal clays.

Pleistocene? 1 ½ feet
Sand and gravel

Magothy Formation 45 feet
dark gray sands and clays with carbonaceous rich layers, uniformly cross-bedded sands, intermixed flaser bedding and layers of rip-up clasts. 29 feet.

dark gray laminated clay which laterally on the east side of exposure grades into interbedded sands and clays, carbonaceous rich layers. 8 feet.

dark gray alternating sands and clays. 8 feet.

Correlation: Palynological studies indicated that the Magothy is Santonian in age. This suggests that the Coniacian is absent due to disconformity. This is confirmed in the subsurface on the absence of marine assemblages of Coniacian age.

9.5 Return to Ernston Rd. Continue north.

9.8 Pass under Garden State Parkway

10.4 Turn right on Route 9

13.4 Turn right on Cliffwood Avenue.

14.1 Cross R.R. tracks, Midland Glass Co. on left

14.5 Turn right on secondary road just past old church on left and just before Garden State Parkway (GSP) overpass

14.7 Turn left at beige-colored house

14.75 Park and walk across road to pit

STOP 3 Woodbury, Merchantville, and Magothy Formations. The Merchantville Formation represents the second major transgression in the Upper Cretaceous sequence of New Jersey. Subsequent transgressions and regressions of the Cretaceous appear to have fluctuated about the Merchantville strandline.

Woodbury Formation 5-10 feet
dark gray micaceous clayey silt

Merchantville Formation 12 feet
dark gray to greenish black, uniformly bedded sandy silt and clay to sandy clay. Glauconite, mica, and siderite are abundant throughout. Many molds of molluscs are present.

Magothy Formation 8 feet
dark gray alternating fine sand, silt, and silty clay. Rare *Ophiomorpha* burrows.

Correlation: Ammonite species (*Scaphites hippocrepis* and others) found in the Merchantville in outcrop date this formation as early Campanian (Taylor) in age. In the subsurface marine assemblages (planktonic foraminifera) of Santonian (Austin) to early Campanian age are present in the Merchantville thus demonstrating its partial equivalence with the Magothy.

14.75 Turn around and retrace route to Cliffwood Avenue

15.0 Turn right and cross over GSP

15.3 Turn left at traffic light onto Matawan Rd. Exxon station on far right corner

15.6 Turn right onto Ravine Drive

16.7 Pass Matawan Lake on the right

17.0 Matawan. Turn right onto Main St.

17.5 Turn left (South) onto Route 34.

19.4 Turn left off of highway and park by furniture store. Walk to excavations to the rear.

STOP 4 The base of the section is exposed in the lower excavation and the upper part is exposed in the higher excavation behind the gymnasium

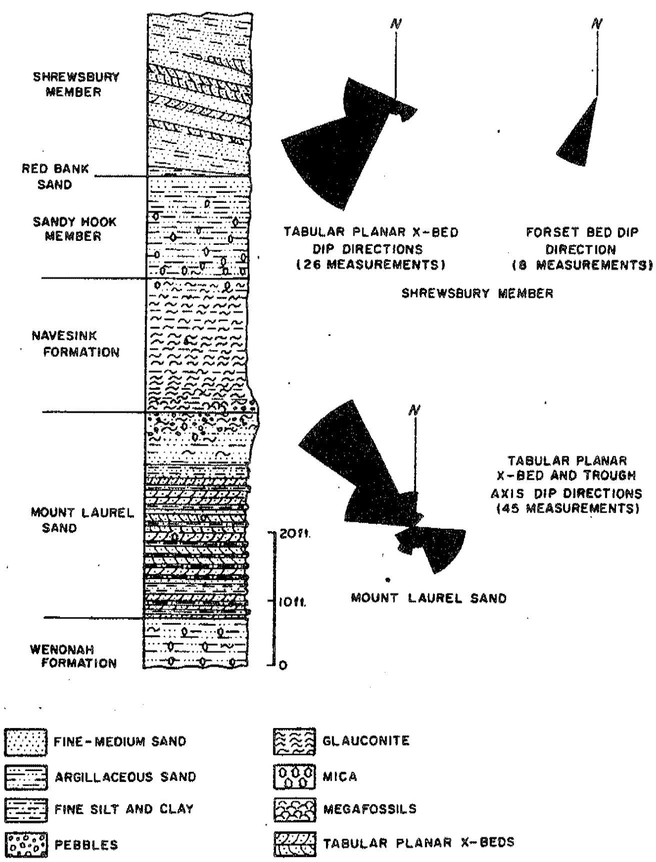

Fig. 7 Stratigraphic section for stops 4 and 5.

Wenonah Formation overlain by Mt. Laurel, Navesink, and Redbank formations. The sedimentary units at this stop and the next were deposited during a regressive-transgressive-regressive cycle. Bedding characteristics and trace fossil morphology position these units in a marine profile of the transgressive-regressive cycle. See fig. for a composite section.

Redbank Formation (Sandy Hook Member) 15 feet
dark gray, very micaceous, argillaceous, feldspathic, fine quartz sand with disrupted sandy laminae and occasional small-scale cross-laminae. Thick-bedded with mottled texture. Contains sand-filled burrow tubes and the trace fossil *Zoophycus*.

The above features suggest that the Sandy Hook was deposited in an inner shelf environment not far from the shoreface.

Navesink Formation 20 feet
dark gray clayey, silty, glauconite sand. Burrowed mottled. Contact with the over-lying Sandy Hook is gradational. The basal 2 feet of the Navesink contains abundant molds of megafossils and rounded pebbles. Megafossils include large bivalves, gastropods, and phragmacones of belemnites.

The Navesink represents the typical glauconitic shelf facies of the Cretaceous of New Jersey. Paleobathymetric indicators (various fossil groups and sediment characteristics) suggest deposition under mid-shelf conditions.

Mt. Laurel Formation 27-33 feet
Thin to medium bedded light gray to white fine to medium sand with thin chocolate brown silt and clay layers. The sand is well-sorted, angular, and slightly glauconitic with dark micaceous laminae. Tabular planar cross-bedding is common in the sand beds. The beds range in thickness from 2-3 inches at the base of the section to 4-6 inches at the top. Maximum thickness is 15 inches. Common broad shallow trough cross-bedding suggests shoreward migration of lunate megaripples. The paleocurrent direction is bimodal, being northwest and southeast. The predominate direction is to the northwest (onshore).

The upper 6 feet is bioturbated and consists of a poorly sorted clayey sand and containing rounded pebbles, abraded fossil molds, and glauconite. Glauconite infills burrows in the upper 3 feet.

Vertical cylindrical burrows of the trace fossil *Ophiomorpha* and cylindrical to rod-shaped burrows of the trace fossil *Asterosoma* are present in the lower 20 feet of the section. From about 15-20 feet above the base large robust vertical cylindrical and ellipsoidal horizontal burrows of *Ophiomorpha* predominate. *Thalassinoides* also occurs within this interval.

The sedimentary characterisitics and the trace fossil associations indicate that the lower 10 feet of the Mt. Laurel Sand was deposited in a transitional zone from offshore (innermost shelf) to shoreface (just below the surf zone). The interval from 10-20 feet above the base represents lower shoreface deposition. The uppermost 6 feet of the Mt. Laurel may be a lag deposit related to deposition of the overlying transgressive Navesink.

Wenonah Formation 8 feet
gray clayey, slightly glauconitic, micaceous, fine quartz sand. Burrowed mottled with indistinguishable bedding. Occasional large clay-filled subvertical burrows *(Asterosoma)* and *Zoophycus*

The Wenonah represents an inner shelf facies related to a minor regression prior to the Navesink transgression.

19.4 Proceed South on Route 34

19.7 Turn left off highway and park by Ern Construction Co. Walk to excavations to the rear.

STOP 5 The basal part of the section is exposed behind the Ern Construction Co. and the upper part is exposed above and just beyond in a long excavation.

Redbank Formation (Sandy Hook and Shrewsbury Members). Continuation of the section from Stop 4. It represents regression shoaling after the Navesink transgression.

Redbank Formation (Shrewsbury Member) 25+ feet
Light gray to white, micaceous, feldspathic, mostly well-sorted fine to medium quartz sand. The lower 10 feet is slightly silty. Occasional thin clay horizons define inclined bedding which represents forset beds of a prograding sand body. Planar cross-stratification occurs within the forset beds. Both dip south-westward.

The trace fossil assemblage includes vertical cylindrical and horizontal ellipsoidal *Ophiomorpha*, rod-shaped *Asterosoma*, and *Chondrites*.

Redbank Formation (Sandy Hook Member) 15 feet
Dark gray, very micaceous, argillaceous, feldspathic, fine quartz sand. Mottled texture with sand-filled burrow tubes and the trace fossil *Zoophycus*. The large light-dark mottled shapes are caused by weathering related permeability

19.7 Continue South on Route 34

22.5 Turn left at traffic light (Pleasant Valley Inn on near right corner) onto Route 520 towards Holmdel (520 is W. Main St.)

23.7 Turn left on Middletown Rd. Village School-Holmdel will be visible on the left

24.8 Bear left. Stay on Middletown Rd.

25.9 Traffic light. Continue across intersection

26.5 Cross over Garden State Parkway

26.8 Turn right onto Monmouth Co. Route 12 (Dwight Rd.)

28.5 Turn left onto Middletown-Lincroft Rd. Thompson School on left

28.9 Turn right into parking lot just beyond small bridge. Poricy Park fossil beds area. Walk along path to stream bank.

STOP 6 Navesink Formation overlain by Redbank Formation (Sandy Hook Member). In contrast to the Navesink at Stop 4, at this locality the formation is richly fossiliferous with skeletal material.

Redbank Formation (Sandy Hook Member) 25 feet
Dark gray, micaceous, feldspathic, fine to medium quartz sand. Glauconitic in the basal part which contains microfossils and small megafossils.

Navesink Formation 15 feet
Greenish-black, clayey glauconite sand. Several shell layers are present. The oysters *Exogyra, Pycnodonte,* and *Ostrea;* the brachiopod *Choristothyris;* and the belemnite *Belemnitella* are well-preserved and common. Molds of various molluscs are common and an extensive well-preserved epibiont bryozoan fauna is present. Microfossils include foraminifera, ostracodes, coccoliths, and dinoflagellates.

28.9 Turn around and retrace route. Stay on Middletown-Lincroft Rd.

30.0 Pass under GSP

31.9 Traffic light at major intersection. Continue straight across on Swimming River Rd.

32.8 Swimming River Dam on the right

33.1 Cross over R.R. tracks

33.8 Junction. Continue straight ahead on Route 537

34.2 Tinton Falls. Turn left and immediately park by restaurant. Walk behind restaurant.

Optional Stop

Type locality of the Tinton Formation, the only indurated unit within the Upper Cretaceous section. The formation is very limited in its geographic extent, disappearing within a short distance along strike to the southwest and in a downdip direction.

Tinton formation 22 feet
Brownish green, argillaceous, quartz and glauconite sandstone interbedded with layers and lenses of gray claystone. Molds of megafossils of gastropods and pelecypods are common. Rare specimens of the ammonite *Sphenodiscus* occur. A well-developed dinoflagellate flora is also present.

The Tinton probably represents an inner shelf facies related to the Redbank regressive facies. It is latest Maestrichtian in age.

34.2 Return to Route 537. Turn left and South

34.7 Turn right onto Wayside Rd.

37.1 Turn right onto Route 547 (Shafto Rd.)

41.6 Junction of N.J. Route 33 and Route 547

45.3 Farmingdale. Turn left on Routes 547 and 524

47.2 Turn right onto Squankum-Yellowbrook Rd.

48.5 Stop by dirt road on left. Walk along road to riverbank on the right

STOP 7 Manasquan and Shark River Formations overlain by Piney Point (?) and Kirkwood Formations. A major disconformity is present here wherein the middle and upper Eocene and the lower Oligocene is missing. More of the Eocene and the Oligocene is encountered in the subsurface, however. Marine deposition that began in the late Cretaceous continued in the early Tertiary. It ended during late Eocene time with a large scale regression. The overlying transgressive Piney Point was deposited under inner shelf conditions on an eroded Eocene surface. The basal Kirkwood is probably a shoreward facies of the Piney Point.

Kirkwood Formation 6-7 feet
Chocolate brown clay 5-6 feet

Piney Point Formation ?
Brown, medium to coarse quartz sand 1 foot

Shark River Formation (Squankum Member) 6 feet
Cream to gray brown, argillaceous, glauconite sand. Upper 1-3 feet indurated. Numerous molds of Molluscan megafossils, plus sharks teeth.

Return: Retrace route to Farmingdale. Turn left onto 524. Take 524 to Route 9, then to Route 18, and Route 18 to turnpike.

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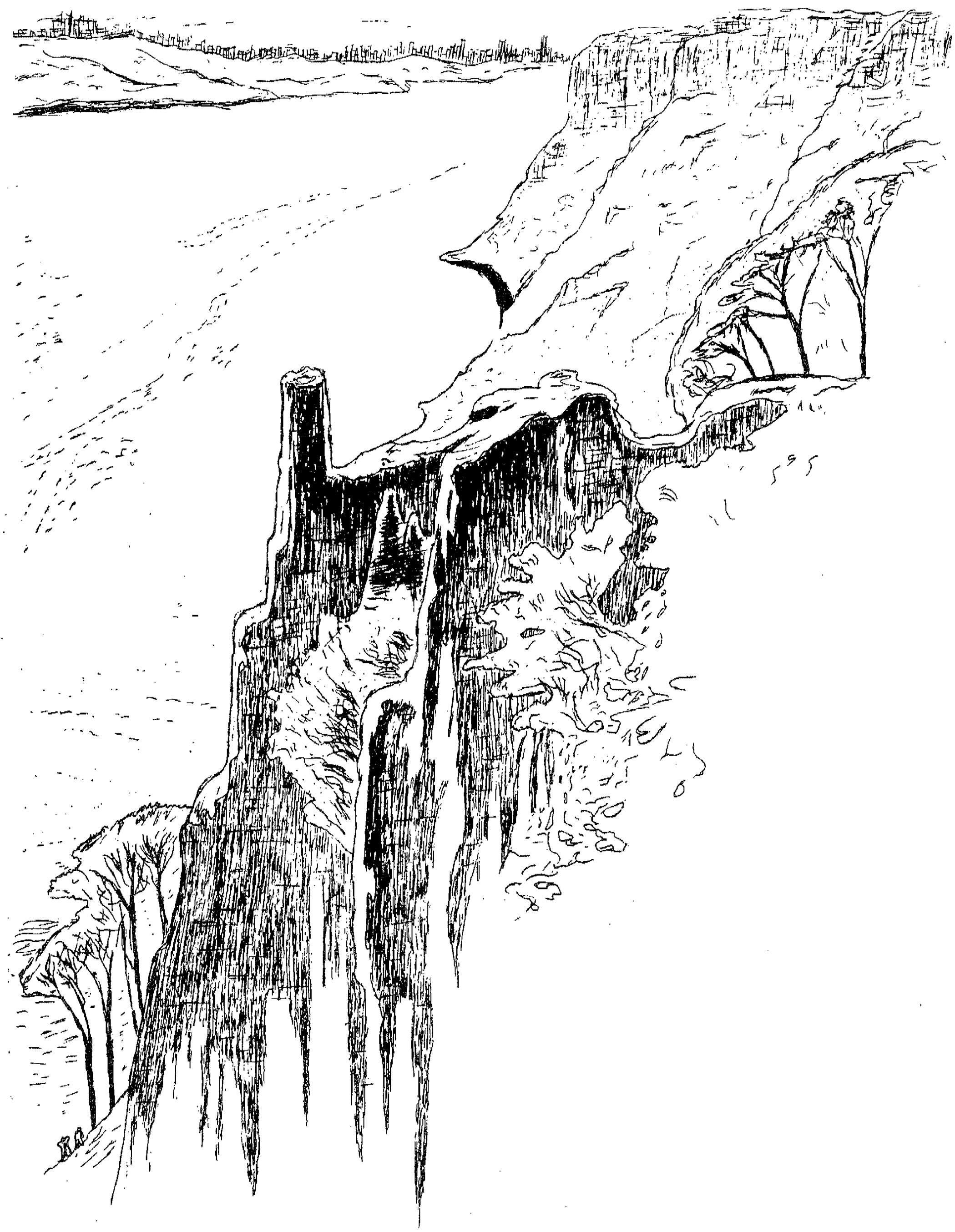

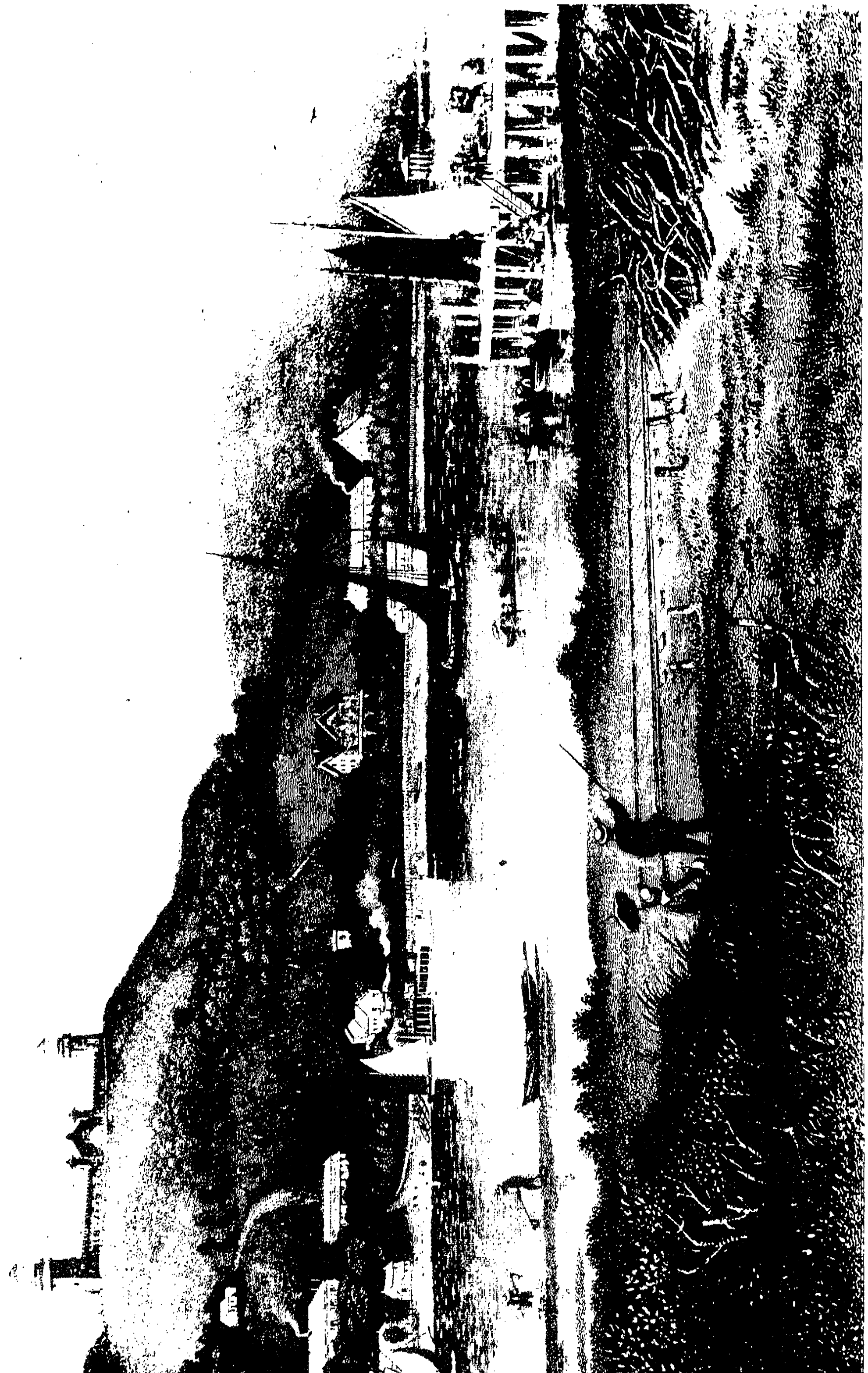

THE HIGHLANDS OF THE NEVERSINK
by W. Wellstood
From *Picturesque America*, Vol I, 1872.

COASTAL DYNAMICS AND ENVIRONMENTS ON SANDY HOOK, NEW JERSEY

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INTRODUCTION

Sandy Hook is a complex and compound recurved barrier spit located at the northern end of the ocean shoreline of New Jersey (Figure 1). The spit is formed from the northerly transport of beach material derived from the erosion of beaches extending approximately 40 kilometers to the south. The shoreline of Sandy Hook consists of several distinct segments with different rates and forms of development. The spit system may be conveniently broken down for analysis into a set of subsystems, each with differing shoreline orientations to the approach of ocean swell and each experiencing different equilibrium conditions. These subsystems, or beach segments are identified on Figure 1 as numbers 1 through 7. Certain beach subsystems may be further divided into subunits, identified by lower case letters on Figure 1. Each of these experiences slightly different shoreline development. These smaller subunits are strongly affected by man-made beach protection structures. The effect of these structures in producing longshore movement of sediment through the spit system is considerable, as revealed in the conspicuous erosion downdrift of the beach protection structures in Segments 1 and 5.

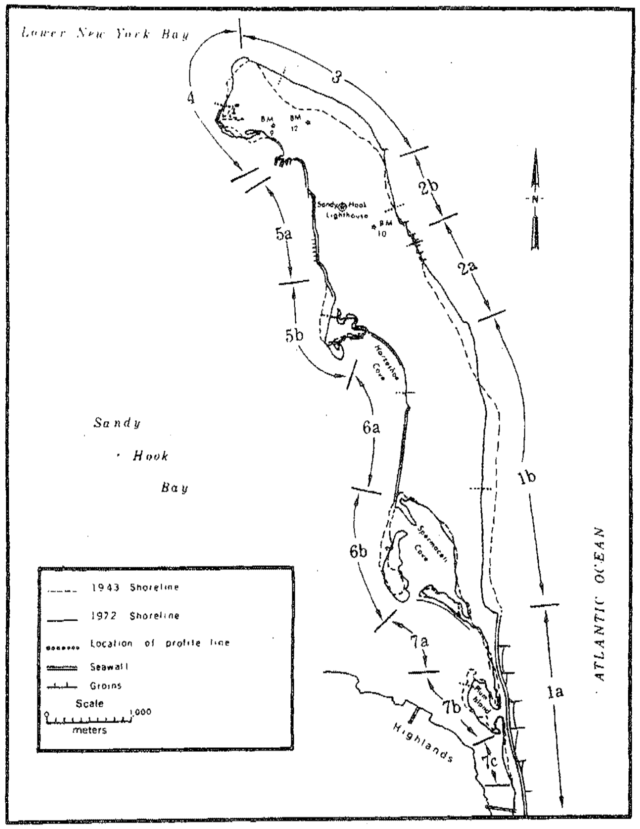

Fig. 1 Shoreline Change at Sandy Hook, 1943-1972.

The majority of high energy deep water waves approach the region from the east-northeast and east (Saville, 1954). However, wave refraction on the inshore portion of the continental shelf causes the shallow water waves to approach from the east-southeast (Fairchild, 1966). This region is also subject to the effects of mid-latitude and tropical cyclones, as well as to ocean swell generated by winds far out in the Atlantic Ocean. On the bayside of the spit, the limiting variables of wind speed, duration, and fetch distance favor wave generation from the northwest. Evidence of the importance of these northwest winds is seen in the orientation of bayside beaches perpendicular to this compass direction and also in micro-spit development to the south of these beaches.

Tides at Sandy Hook are semi-diurnal with a 1.4 meter mean range and a 1.7 meter spring range. However, during passage of a storm, strong easterly and northerly winds will pile water against the shore and raise water levels considerably whereas westerly and southerly winds will lower water levels. Foreshore sediments on oceanside and bayside beaches are composed of well sorted sands in the medium size range. The sands consist primarily of quartz particles with less than 5% by weight of potash and sodium-lime feldspars, and less than 1% by weight of heavy minerals concentrated in the size range of fine sand (McMaster, 1954).

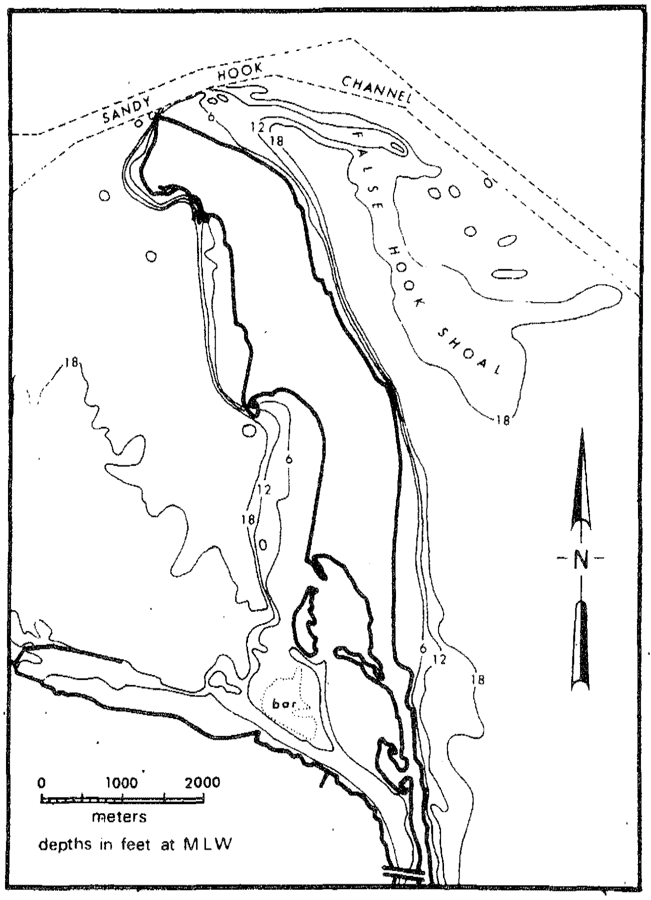

Fig. 2 Hydrography at Sandy Hook.

Figure 2 identifies the hydrographic features which influence the transport of sediment through the system. The Sandy Hook navigation channel at the distal terminus of the spit is the access route to Raritan Bay and Arthur Kill. It is used by large sea-going vessels and is maintained at a depth of about 10 meters. Periodic dredging of this channel precludes further northward growth of the spit. Channel maintenance, therefore, has a direct influence on the development of Segments 3 and 4. The sediments dredged from the channel are predominately sand and may be used as beach fill.

The spit platform, delineated by the 6-foot, 12-foot, and 18-foot contours, is the subaqueous extension of the headland beach upon which the spit ridge (beach and dune system) has formed. The platform extends out a considerable distance on the bayside and has a filtering effect on the higher bayside waves during low tide. This condition is most pronounced when strong northwest winds occur. These winds generate high energy waves and blow water out of the bay. During such periods, spilling waves may occur across the width of the shelf and a considerable amount of material may be moved alongshore within this broad surf zone. However, the presence of deep coves downdrift of Segments 4 and 5 prevents significant transfers of sediment between segments by this mechanism. False Hook Shoal appears to be the seaward extension of the spit platform formed by ebb tidal currents passing the distal portion of the spit. This shoal affects wave refraction and thus controls shoreline orientation and beach development on Segments 2 and 3.

Table 1 reveals the magnitude of beach processes within each of the subsystems. Table 2 identifies the amount of shoreline change which occurred within each segment from 1943 to 1972. The two tables reveal that bayside beaches are retrograding at surprisingly high rates. This is due to a reduction in the quantity of sediment being passed to downdrift segments, and to higher wave steepnesses.

The differences in response to changing wave processes on oceanside and bayside beaches at Sandy Hook have been discussed in detail in Nordstrom (1975). It was concluded that bayside beaches (Segments 4 through 7) appeared to be more in equilibrium with storm conditions than oceanside beaches (Segments 1 through 3). Lower bayside wave energies occurring between storms have little effect on profile development, and foreshore slopes inherited from previous storms undergo minor change. There is little or no deposition between storms. The rate of return is too low to provide adequate protection against dune erosion during the next storm, and dune and foreshore erosion will continue. On the oceanside, in contrast, long, high energy, constructive waves occurring between storms rapidly restore the sediment. These deposits provide a buffer zone to protect the beach and dune against the direct attack of storm waves. The net displacement of the shoreline, therefore, is reduced because of the beach recovery between storm periods.

Table 2: Change in the location of the Sandy Hook shoreline, by segment, from 1943 to 1972. The values were determined from Figure 1 and represent the change, in meters, along representative lines running perpendicular to the 1973 shoreline.

Shoreline Change 1943 - 1972

Site	Along line of maximum change	Average for entire segment	Average for segment per year
1a	*+90 meters*	*+50 meters*	*+1.7 meters*
1b	*−190*	*−153*	*−5.3*
2a	*+150*	*+142*	*+4.9*
2b	*+60*	*+31*	*+1.1*
3	*+460*	*+325*	*+11.2*
4	*−90*	*−20*	*−0.7*
5a	*+40*	*+40*	*+1.4*
5b	*−120*	*−95*	*−3.2*
6a	*0*	*0*	*0*
6b	*−170*	*−104*	*−3.6*
7a	*+25*	*+9*	*+0.3*
7b	*−85*	*−69*	*−2.4*
7c	*+100*	*+43*	*+1.5*

Sandy Hook As A System

The net sediment migration along Sandy Hook spit is from south to north on the oceanside and from north to south on the bayside. This implies that the movement of sediment from Segment 1 to Segment 7 may be treated as one continuous system with unidirectional flows of energy and matter. Shoreline development within any of the subsystems will then be dependent upon perturbations in the energy-matter relationships in all updrift segments as well as changes in the direct application of energy to the individual subsystem. Perturbations in the system may be man-induced such as the construction or removal of groins and seawalls, dune destruction, or beach fill operations. Natural perturbations, usually associated with storm events, may also occur.

Oceanside beach segments are highly dependent on activity in the updrift segments and yet exhibit distinct differences in form because of variations in wave energy and sediment supply. The ocean beach system is characterized by alternating natural and controlled beaches, and by discrete segmental orientations that differ from the equilibrium logarithmic spiral form. [For a discussion of planimetric curvature as a definition of the state of adjustment of the spit form, see Yasso (1964a, pp. 66-68)]. As such, the distinct character of the segments defines complex subsystems within an open ocean system extending around the distal recurve from Segment 1 through Segment 4.

Although the application of an open system model appears suitable for the study of the oceanside segments, it may be argued that the bayside behaves more as a series of closed systems where deep coves and extensive seawalls prevent the transfer of sediment into, or out of, some of the subsystems. This is particularly true of Segment 5. The use of an open system model for the entire spit is not incompatible with bayside beach development, however, since inevitably, such barriers to longshore sediment movement will be bypassed. However, because this paper is intended to establish a model which can be used to solve short-term beach protection problems, Segment 5 will be considered a closed system.

The broad shallow spit platform which extends from Segment 6 to Segment 7 may allow transfers of sediment and this may be considered a separate open system. At present, however, little is known of sediment transfers within this complex region, and this definition is quite tenuous.

Therefore, Sandy Hook spit may be separated conveniently into several units. The highly interrelated ocean beach segments can be considered as an open system. Because of the lack of sediment exchange between the bayside segments, Segments 5, 6, and 7 can be viewed as closed systems.

Marine Biota

In addition to providing intertidal and shallow subtidal essentially sandy substrate, Sandy Hook separates two distinct, albeit transitional into each other, bodies of water: the open water on the east side lying on the continental shelf; and the partly enclosed waters of Sandy Hook Bay on the west side.

These bodies of water differ environmentally. Perhaps the most immediately obvious factors bearing on the environment are the waves generated over the ocean and continental shelf that affect most strongly the east side of Sandy Hook, the partial enclosure and generally shallower bathymetry of Sandy Hook Bay, and the influx of fresh water, and silt and other terrigenous matter into Sandy Hook Bay from the Navesink and Shrewsbury Rivers. These factors can be expected to result in a greater degree of mixing and turbulence of the open water on the east side of the hook resulting in smaller ranges of water temperature and salinity, and in the maintenance in suspension of cells and particulate organic matter. In contrast, the waters of Sandy Hook Bay, particularly at the Shrewsbury Inlet, are subject to dilution by fresh water and the entry of silt and other terrigenous matter which is responsible for the development of tidal mud-flats locally on the south eastern shore of Sandy Hook.

These expectations appear to be confirmed by data interpreted by Powers and Backus (1951) who show annual surface temperature ranges of 44 to 75 °F off Horseshoe Cove; 45 to 71 °F off the northern tip of Sandy Hook; and 46 to 68 °F off the southeastern shore of Sandy Hook. Furthermore, Stockton and Backus (1951) show annual surface salinity ranges of 24 to 27 ‰ off Horseshoe Cove; 25 to 27 ‰ off the northern tip of Sandy Hook; and 27 to 30 ‰ off the southeastern shore of Sandy Hook. Temperature and salinity data for Sandy Hook Bay taken by Ayers (1951) in December 1948 and by Ichiye (1965) in August 1963 are consistent with the interpretations of Powers and Backus (1951).

These, and other environmental differences result in and are reflected by the geographic distribution of the marine biota. For the purposes of the present trip, the shells and fragments of benthic organisms washed into the intertidal zone provide a relatively accurate and conveniently studied sample of such organisms in the vicinity.

SEGMENT DESCRIPTIONS

East Shore Biota

The intertidal and shallow subtidal substrate on the east side of Sandy Hook is overwhelmingly sandy with a minute, but important, aggregate area of hard substrate provided by the artificial rock groins built to control the erosion of sand.

Owing to its unstable nature, the sandy substrate of the intertidal zone carries a sparse biota principally of anthropods (May, 1980): *Ovalipes ocellatus* (lady crab) and *Hippa talpoida* (sand bug) at its lowers limit, and various amphipods. More or less complete and fragmentary shells washed up on the beach are indicative of shallow subtidal benthic species. In point of numbers, these are dominated by *Spisula solidissima* (Atlantic Surf Clam), infaunal in sand at shallow depths from the strand line to 30 meters. Less abundant, but still common, is *Mytilus edulis* (Common Blue or Edible Mussel), a byssate epifaunal bivalve that is capable of establishing itself on stable bottoms. In addition, there are small numbers of *Aequipecten irradians* (Atlantic Bay Scallop), *Crassostrea virginica* (Eastern Oyster), *Crepidula fornicata* (Common Atlantic Slipper Shell), *Anomia simplex* (Atlantic Jingle), *Anadora transversa* (Transverse Ark), *Lunatia heros* (Common Northern Moon Snail), *Bittium?* sp., *Cancer irroratus* (Rock Crab) and *Limulus polyphemus* (Horseshoe Crab).

The localized hard substrate, represented by artificial rock groins, shows vertical zonation: a barnacle zone overlying and merging into a blue-mussel zone.

SEGMENT 1

This portion of Sandy Hook, aligned on a north-south axis, is made up by two distinct subsystems. The southern subunit, 1a comprises the groin field and seawall protected section. North of this, Segment 1b is a natural unprotected beach whose orientation to storm and swell waves is the same as Segment 1a but the location is offset to the west. The artificially stablized shore extends south to Long Branch and thus Segment 1a represents an armored barrier spit beach system. Segment 1b can be viewed as being representative of the equilibrium state of the total Segment in the absence of beach protection structures.

Segment 1 is the portion of the spit most exposed to hydrodynamic processes because of the minimal refraction of dominant waves from the eastern quadrant. Energy inputs to this subsystem are therefore higher than to the other subsystems (see Table 1 for wave statistics). Sediment transfers within this high energy subsystem are not correspondingly high because of sediment entrapment in the groin field within Segment 1a. This deficit of particulate matter results in removal of stored sediment from Segment 1b during storms when the energy to sediment disequilibrium exists. Beach profile development in response to erosional and depositonal waves is along classic lines and the beach in Segment 1b demonstrates the cyclic form of development noted by Hayes and Boothroyd (1969) on high-energy East Coast beaches (Nordstrom, 1975). Analysis of the sweep zone profiles presented in Figure 3 reveals the beach to be a narrow equilibrium beach with the profile responding to changes in wave energy by sediment migration between the upper limit of swash and the surf zone, with the beach pivoting about an intertidal fulcrum.

The cumulative effect of beach processes is the extension of Segment 1b into Segement 2a by both beach and longshore bar drifting processes. In the absence of beach protection structures, high wave and current energies transport a considerable volume of sand

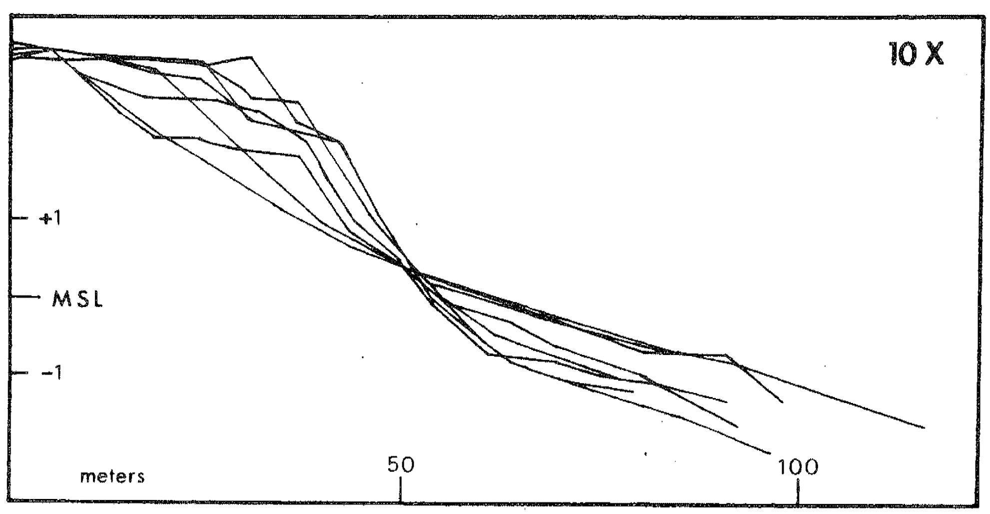

Fig. 3 Sweep Zone Profiles, Segment 1b.

alongshore, resulting in conspicuous Segment growth. It is thought that the segmental extension primarily occurs during storm periods when the disequilibirum exists between the alongshore sediment budget and wave energy input. This, in turn, suggests a pulsating sand conveyor system along the oceanside beaches that might be profitably studied through the application of the kinematic wave theory suggested by Leopold, Wolman, and Miller (1964, pp. 212-214).

In the kinematic wave context, the transport rate is minimized when the linear concentration approaches zero. [Linear concentration at any place is measured by the quantity of sediments per unit of distance alongshore]. This occurs in low energy states when few particles are in motion. The transportation rate is also minimized when linear concentrations are large and sediment concentrations are very dense. This occurs during high energy states when, because of high frictional energy losses, little energy is available for sediment transportation. This condition occurs during the storm stage following the peak erosion of the beach. As storm energy decreases, sedimentation will occur. The location of the disposition will be downdrift of the source area because of sediment movement during the build up of energy prior to maximum concentration. Following sedimentation, the linear concentration is reduced to a point where the transportation rate again is maximized. The kinematic wave theory thus suggests that longshore transport is higher prior to, and just after, the maximum concentration of suspended sediment occurs. This pulsational sediment transport model is much different than the common model of the "conveyor belt" that transports an increasing quantity of sediment with increasing storm intensity and deposits the material when the storm dies out.

The general model of storm-caused sediment pulses can be applied to the segmental extensions along the ocean beaches as the matter linkage between the various subsystems. Allowances must be made, however, for decreasing energy states and man-controlled fluctuations in the alongshore sediment budget and the types of processes that are operative when applying the model to any specific segmental growth. The model also defines the dynamic interfaces across which the subsystems are linked and, thereby, the downdrift limits of each segment.

SEGMENT 2

The orientation and lower energy equilibrium state of Segment 2 has been shown by wave refraction and simulation studies of Sandy Hook (Allen, 1972 and 1973b) to result from the location and north-westerly alignment of False Hook Shoal (Figure 2). This middle shoreline segment is made up of two distinct subsystems. Subsystem 2a consists of a high, steep beach that is planar in form and profile. The beach is sheltered from the major disruptive effects of storms by the longshore bar representing the extension of Segment 1b.

Segment 2a has been studied in some detail by Strahler (1964) and Nordstrom (1975), who noted that the offshore bar favors an equilibrium shoreline configuration. Due to the sheltering effect of the offshore bar, beach erosion does not always occur with the passage of small storms. When erosion does occur on Segment 2a it is not always accompanied by conspicuous change in foreshore slope as it is on Segment 1. Usually there is considerably less slope variability here than is experienced on Segment 1. The cumulative effect is the deposition of beach material derived from Segment 1b with little change in beach slope and shoreline orientation. The progradation of the foreshore, then, is both parallel and planar.

Segment 2a and Segment 2b are separated by a groin field at the north end of Segment 2a. The groin field prevents beach drift of sand through this portion of the system because the downdrift groins are not quite full. The offshore bar continuation from Segment 1b along Segment 2a terminated at this groin field and therefore does not favor a stable shoreline. The higher wave energies and decreased inputs of sediment to the foreshore result in a readjustment of the equilibrium state of the shoreline from the stable linear form characterizing Segment 2a to the retograding log-spiral shoreline configuration suggested by Yasso (1964b) for headland-bay beaches. A longshore bar, representing the offshore extension of beach Segment 2a, has recently extended across the reentrant created at Segment 2b. This bar creates a situation similar to that at Segment 2a, and beach response at Site 2b is similar to Site 2a. The beach has a steep slope with parallel and planar shape dynamics, retreating because of the decreased alongshore sediment supply showing the necessity of the system to maintain itself by drawing on sediment storage within the system. The removal of sand from storage at Segment 2b thus represents the most important source of sediment input into Segment 3.

SEGMENT 3

The northwest extension of Segment 2b has been the most conspicuous change along Sandy Hook in recent years. Figure 4 reveals a growth of about 360,000 square meters from October, 1969 to September, 1973. In October, 1969 a single micro-spit form is shown arcing from the segmental break. By May, 1970 this had attached onto the shoreline but was breached by lagoon tidal-head energies. Creation of a second spit, curving from the fulcrum of the primary spit is also shown, along with some lagoon infilling from high tide

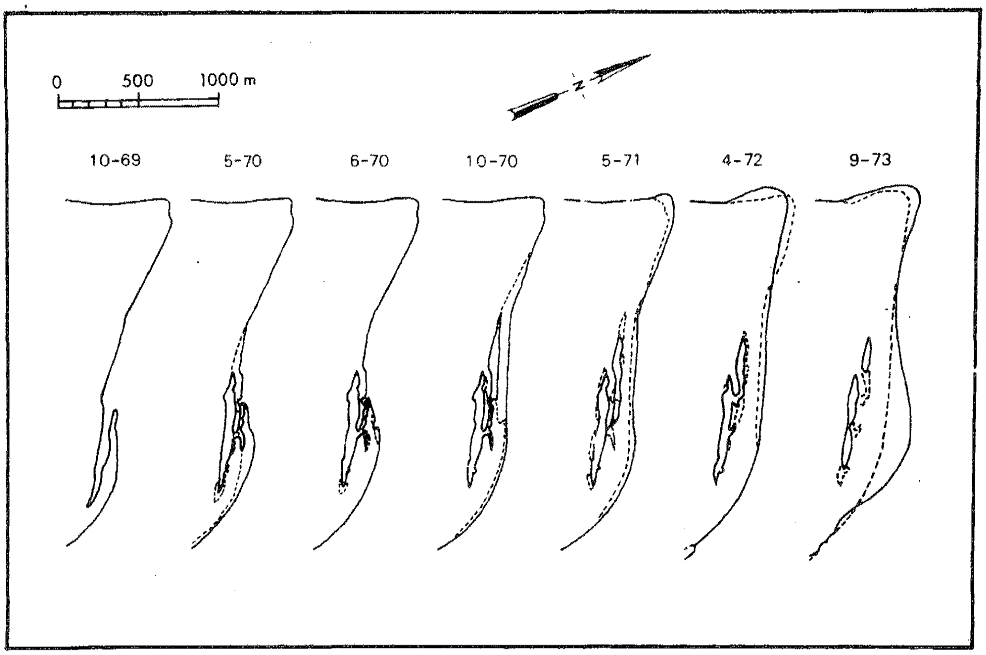

Fig. 4 Accretionary Extention in Segment 3, 1969-73.
The dashed line represents the beach outline in the previous temporal unit.

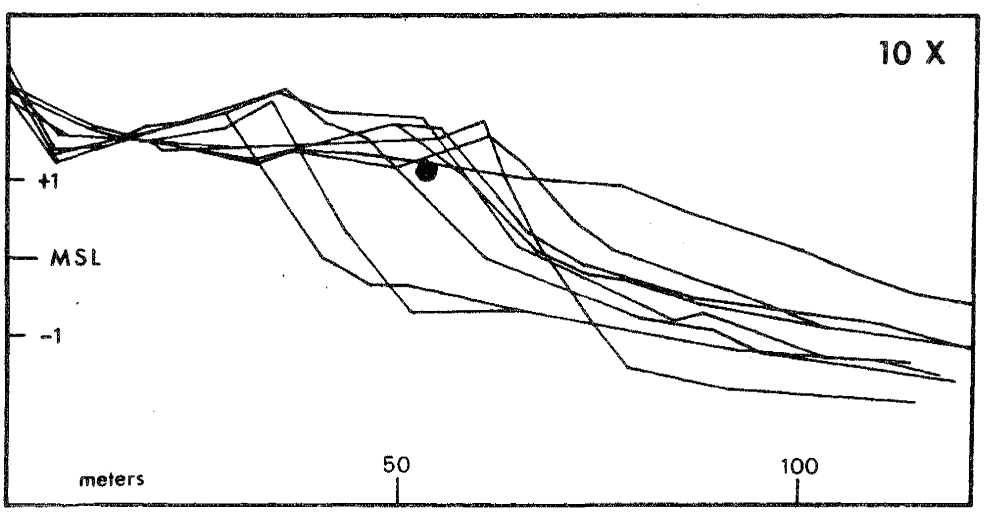

Fig. 5 Sweep Zone Profiles, Segment 3.

washover. One month later (June, 1970) the size of the second spit had attached its downdrift terminus to the beach of Segment 3. During the 1970-71 winter, the complex lagoon was separated into two parts with connecting flow occurring only at high tide. This was accompanied by further accretion around the distal point of the Hook. The April, 1972 shoreline shows continued lagoonal readjustment from overwash and internal circulation, a general oceanside straightening (with alternate erosion and deposition), and continued growth of the distal lobate beach. Another wedge of sediment, representing a future extension of Segment 2b, also appears to be entering the system. The September, 1973 shoreline shows even further lagoonal infilling and distal accretion. The wedge of sediment from Segment 2b has been greatly enlarged and has resulted in considerable progradation at the arc.

The complex form of the segmental extension is favored by the sharp break in shoreline orientation. Allen (1973a) showed this extreme recurve angle to be a function of extreme wave refraction caused by very shallow water and the orientation of the north end of False Hook Shoal. Field work conducted at this site in the summer of 1970 to determine rates and mechanisms of formation suggested that the primary method was beach drifting. The extreme break in orientation appears to diffuse the longshore component causing general nearshore sedimentation which, in turn, results in spit platform construction. The beach itself shows accretion by swash bar processes and subsequent extension of the spit to close the tidal inlet. Afterwards, the profile development displays continued accretion with little change in foreshore slope (Figure 5). The prograding equilibrium is favored by the low wave energies that, in turn, are constrained by feedback caused by growth of the spit platform. The wide, shallow platform decreases the available ocean swell energy that can be applied to the foreshore. Reversing shallow water currents generated by waves and ebb and flood tides also enhance the depositional trend. The general accretion has resulted in the straightening of the shoreline and the promotion of sediment transport through beach drifitng in Segment 3. In this sense, the rate of progradation is lessening with the new shoreline shape, and sediment input for lateral segmental growth along the shoreline axis is increased.

The extension of Segment 3 is complicated because of its location at the distal portion of the spit. Not only does it thus represent a partial sediment sink but energy inputs are correspondingly complex. Steep, storm-generated bayside waves may represent higher energy spectra than the filtered ocean swell. NOAA tidal charts reveal high velocity tidal races. All of these in combination appear to modify the segmental extension to a lobate shoal form at the end of this spit recurve. General shoreline advancement appears to result, as in the extension from 2b to 3, predominately from beach drifting. Spit platform progradation and filling of the Sandy Hook Channel appears to result from nearshore sedimentation from longshore currents. The redistribution of nearshore deposits prevents this area from being termed a true sediment sink in that tidal currents move the outputs of Segment 3 towards False Hook Shoal. This shoal increases the feedback control by filtering ocean swell energy through bottom friction losses and wave refraction. Furthermore, there is evidence that the oceanside system effectively bifurcates at the distal portion of the spit into beach drifting outputs towards Segment 4 and longshore component outputs to the spit platform and eventually towards False Hook Shoal.

The recent extension of Segment 3 is largely associated with recent erosion along Segment 2b (this erosion is not revealed in Table 1 or Figure 1) and, less so, with the erosion at Segment 1b. In future dredging operations in Sandy Hook Channel, much of the dredged spoil may be pumped back to Segments 1 and 2. The implementation of this sediment recycling operation would result in the establishment of a closed exchange of sediment in the ocean beach system.

SEGMENT 4

Despite having the highest bayside wave energies and high wave steepness (Table 1), Segment 4 experienced very little erosion over the period from 1943 to 1972 (Figure 1). This is due to the inputs of sediment from Segment 3 offsetting some of the loss through bayside processes. The profiles indicate that erosion and deposition occur with little change in foreshore slope, particularly on the lower part of the foreshore. This zone is protected by the shallow spit platform that causes the larger storm waves to break about 150 meters offshore. Considerable quantities of sediment may be moved on the spit platforms during these periods when the surf zone is exceptionally wide. With return to non-storm conditions, the surf zone is limited to a narrow band on the foreshore by low wave heights and the steep foreshore slope.

The cumulative effect of beach processes at this location has been the straightening of the shoreline and an increase in the area of the spit platform. The material deposited represents the residual foreshore, dune, and ocean drift sediments. The deep cove, Coast Guard dock complex, and seawall in the northern portion of Segment 5 impede longshore transport out of Segment 4. This segment therefore represents the terminus of the ocean-wave dominated transport system.

WEST SHORE BIOTA

As on the east side, the substrate is predominantly sandy with artificial hard substrate represented by local seawall, wood pilings, and rocks. In addition, there are mud and silt flats on the east side of Spermacetti Cove and the east of Plum Island.

The sandy substrate in the intertidal zone between Sandy Hook lighthouse and Horseshoe Cove carries a sparse biota principally of arthropods: *Ovalipes ocellatus* and *Cancer irroratus*. Shells and fragments, representative of the shallow intertidal benthos, are dominated in point of numbers by *Mya arenaria* (soft shelled clam) with somewhat smaller numbers of *Mytilus edulis* and *Mercenaria mercenaria* (Northern Quahog or Hardshelled clam). In addition, there are *Modiolus demissus* (Atlantic Ribbed mussel), *Crepidula* sp., and *Limulus polyphemus*. There is a peat bed exposed on this beach at low tide.

The sandy beach located south of Spermacetti Cove and extending to Plum Island shows a greater area of silty and muddy sand deposition as well as silt and mudflats bound by smooth cord-grass, salt meadow grass, and marsh spike grass. *Modiolus demissus* occurs in the plant-bound silt. The most abundant shells and shell fragments on the beach are *Mya arenaria* with lesser numbers of *Modiolus demissus* and *Mercenaria mercenaria*, and rare examples of *Aequipecten irradians* and *Ensis directus* (Atlantic Jacknife clam). *Littorina* sp. grazes on algae in shallow pools left on mud substrate at low tide. The polychaete *Glycera dibranchiata* (Bloodworm) occurs as an infaunal element in the organic-rich sediment. *Limulus polyphemus* and rare individuals of *Cancer irroratus* can also be seen in the intertidal zone. There are poorly developed encrustations of barnacles on some of the few wood pilings and artificially placed rocks.

The western shore of Plum Island has a sand and pebbly sand beach; a peat bed, exposed at low tide, ranges up to 18 ins. in thickness. The dominant molluscan species represented by shells and fragments on the beach is *Mya arenaria* with lesser numbers of *Mercenaria mercenaria* and *Crassostrea virginica. Aequipecten irradians* and *Modiolus demissus* are rare. A sponge (*Chalinopsilla* sp.) is represented by rare detached fragments. *Limulus polyphemus* is common in the vicinity of the Shrewsbury Inlet: many individuals bear barnacles and *Crepidula.*

SEGMENT 5

Segment 5a is protected by a long seawall and there has been no change at this location. At Segment 5b, however, the rate of shoreline retreat is about 3.2 meters per year which is the highest of the bayside beach segments. The erosional imbalance results from seawall construction and is somewhat analogous to that occurring within Segments 1 and 2. Very little beach material passes the seawall to replace that lost in longshore transport and the beach experiences a negative sediment budget. The sediments derived from the eroding shoreline at Segment 5b are forming the prominent spit at the south end of the Segment. [This spit has been described in considerable detail in Antonini (1962), Wright (1962), and Yasso (1964)]. Considering the sharp break in orientation at the tip of this spit and the depth of water in Horseshoe Cove, it is unlikely that, much sediment is moved from Segment 5 to Segment 6.

Wave heights on Segment 5b are lower than at Segment 4 (Table 1) and tidal currents are not very well developed on the broad spit platform. The beach accordingly experiences little change as shown in the plotted profiles (Figure 6).

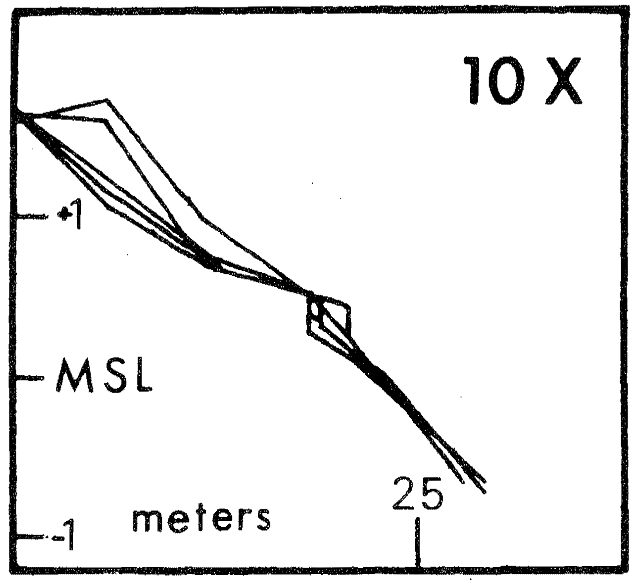

Fig. 6 Sweep Zone Profiles, Segment 5b.

SEGMENT 6

Segment 6 consists of two segments with dissimilar equilibrium conditions as a result of seawall construction. Segment 6a experiences minimal shoreline alteration - largely due to seawall protection and low wave energies (Table 1). Beach profile development is also minimized through low wave energies and a sheltered position relative to tidal currents. The profiles show considerably less change than that which occurs on the unprotected portions of Segment 4 and 5 which experience considerably higher wave energies.

Segment 6b has been subjected to extreme shape disruption recently where the bayside spit has been breached (Figure 1). This probably occurred under extreme storm conditions, which, in this case, may be considered cataclysmic. The return to equilibrium conditions is incomplete, pointing out the inability of low energy-low sediment mobility systems to readjust to prior conditions following extreme (low recurrence interval) events. This demonstrates the fragility of the limited oscillatory equilibrium levels of bayside beaches.

There is some accretion at the breach. This appears to represent storm overwash deposition and subsequent tidal modification with a small contribution from beach drifting. The slight southward extension, however, can be explained by normal wave processes - the shallow inlet would allow for the longshore transport of shelf sediments to the southern terminus of the island.

SEGMENT 7

The shoreline from Segment 6b to 7c represents the interaction of complex tidal and wave processes. Segment 7a and 7c have experienced less change than 7b (Plum Island). This is due to their sheltered position with respect to waves and tidal currents. Plum Island, however, is more exposed to bay waves and, more importantly, to high tidal current velocities. The latter probably account for the rather high rate of shoreline retreat in this segment compared to the unprotected portions of Segment 6 despite the higher average wave heights on that segment (Table 1). These tidal currents have been observed on the foreshore at 0.28 meters per second during periods when wave action was negligible.

The beach at Plum Island changes very little in form despite retrogradation. Beach development is, in that sense, similar to Site 5. The cumulative result is shoreline retrogradation with much of the sediment being lost to the spit platform or to spits which have formed to the north and south ends of Plum Island. Spit formation on the north end of the island attests to the importance of ebb tidal currents as mechanisms of sediment transport. The south spit has been shown to be affected by wave and flood tide deposition (Lipman, 1969). Internal tidal current gyres also appear to be the mechanism for accretion within Segments 7a and 7c.

BEACH MANAGEMENT PROBLEMS

The value of the application of systems theory in this study of the linkages of Sandy Hook is that information is provided on the sensitivity of the several parts of the spit system. The foundation is laid for an evaluation of many alterations of the spit system proposed for development of the spit into a Federal recreation area.

These include:

1. removal or relocation of groins and seawalls;
2. beach fill;
3. dredging of False Hook Shoal;
4. dredging of Sandy Hook Channel;
5. location and character of access roads and park structures.

REMOVAL OR RELOCATION OF GROINS AND SEAWALLS

The removal of groins and seawalls from selected locations along the spit would initiate a return of predisturbance shoreline geometry. The removal of the groins in Segment 1a would probably result in a rapid loss of sediment from storage, placing great stress on the seawall. The system will tend toward establishment of a locational equilibrium in line with Segment 1b. The enhancement of alongshore drifting, however, will add to inputs of sediment to Segment 1b and thus buffer Segment 1b from erosion. The inputs from Segment 1a will negate the need for retrieval from storage of sediment at Segment 1b and increase the connectivity between these subsystems. The effects of removal of groins from Segment 2 would be similar to those at Segment 1 with Segment 2b benefitting from increased sediment inputs. Losses from Segment 2a would not be as critical as at Segment 1a however, since the beach would still be protected by the longshore bar discussed earlier. Further, sediment storage is considerably greater here than on Segment 1 which lacks the broad high backshore and prominent dune line.

Some beach protection structures may be necessary for portions of the bayside shoreline where erosion is critical. Each extension of the seawall will lead to a reduction of the erosional zone, but will also reduce the exchange of sediments from one unprotected beach to another. Rock (rip-rap) and other static forms should be viewed as viable alternatives here for protection of buildings and roads. However, the attendant personal safety and aesthetic problems associated with these static forms would limit land use options.

BEACH FILL

Proposals for beach fill in Segments 1a and 1b exist. The result would be that added sediment inputs to Segment 1a will fill the groins (increasing the seawall protection) and enhance beach drifting. Offshore losses, while unknown, might be considerable. Beach fill at Segment 1b, on the other hand, would displace the equilibrium shoreline seaward. Beach fill in Segment 2b would help restore the shoreline of the whole second segment to its pre-disturbance geometry. Beach fill operations at this location were conducted in two phases during 1975 and 1976. This involved deposition of 270,000 cubic meters of sand dredged from the Sandy Hook Navigation Channel. The operations resulted in stabilization of the shoreline. Similarly, a short-term beach fill project was conducted in 1977 at Segment 1b to deter a serious erosion problem. The project included excavating and trucking approximately 153,000 cubic meters of sediment from Segment 2b. The project was successful in protecting the access road throughout the winter. A large-scale beach fill operation involving 1.5 million cubic meters of sand is presently being considered for this segment.

In most cases, bayside retreat does not presently offer a threat to buildings and roads nor does it result in a reduction of bathing space since bayside beaches are, as yet, undeveloped. In some cases (as in Segment 5b where the main road is being undermined), beach protection measures are required, and beach fill offers an alternative. The dominance of erosional conditions on the bayside sites and discontinuity of the closed systems suggest that much of the beach fill would be lost under winter (storm) conditions and not naturally replaced. Sand fill is thus viewed as inefficient.

Beach fill materials may be derived from the navigation channel during maintenance dredging operations or may be derived from any reasonable offshore borrow area. If the dredging operation in the borrow area is carefully controlled, desired changes in the offshore contours may be simultaneously effected. This will introduce changes in wave refraction patterns and thus affect the distribution of wave energy along the coast.

DREDGING OF FALSE HOOK SHOAL

The dredging of False Hook Shoal is attractive in that material which would otherwise be permanently lost to the system could be recycled updrift or passed on to the bayside beaches as beach fill. However, the presence of this shoal is highly associated with the present upper spit shoreline dynamics. Loss of the energy filter would lead to higher energy inputs to System 3 effecting less distal growth. This would appear to reduce sediment transport into the ship channel but with uncertain shoreline displacements. Dredging the northern portion of False Hook Shoal would also theoretically result in a displacement of the distal recurve to the west, thus lessening the problem of channel filling. [The displacement of the offshore tidal shoal of a spit towards the proximal portion of the spit has been simulated by computer by King and McCullagh (1972) and Allen (1973b) who point out that the major effect is a tendency for the distal portion of the spit to recurve more sharply bayward.]

LOCATION AND CHARACTER OF ACCESS ROADS AND PARK STRUCTURES

As an alternative to permanent coastal facilities which must be protected by standard beach protection measures, limited or temporary facilities (e.g., graded roads rather than black top, removable bath houses) may be constructed which may be dismantled and reused or "written-off". Care should be taken that such structures, when eventually reached following long term erosion, do not form obstacles to sediment transport along the foreshore and introduce undesired perturbations in the natural system.

SUMMARY AND CONCLUSIONS

The spit system is seen to be the result of complex energy (wave and current) and matter (sediment) flows within, and between, several very distinct beach segments. Each of the segments is characterized by different equilibrium conditions resulting from its orientation to ocean swell, winds, and tidal currents. Some of the subsystems, such as Segments 5a and 6a are protected by seawalls and undergo no change. In others, such as 5b and 7b, storage of matter is being rapidly reduced without replenishment. The latter condition shows a tendency toward destruction of system identity, and such segments are considered closed systems. Still other systems, such as 2a and 3 are open systems and there is a continued rapid influx and outflow of energy and matter. Examination of the rate and form of the extension of Segment 2b into Segment 3 indicates that this influx and outflow may be periodic rather than continuous and that accretion and erosion between adjacent segments are highly related, as expected of open systems.

Once the mechanisms for transport and the quantities of sediment moved are known, recommendations can be made for recycling sediment in the open system of the ocean beaches and for sediment augmentation in the bayside closed systems. Given a calibrated model, it should be possible to predict the effects of different energy levels and different sediment inputs and thus more completely anticipate the future development of the Sandy Hook spit.

ROAD LOG

Mileage	Description
0.00	Entrance gate to Sandy Hook Unit of Gateway National Recreation Area. Proceed straight (north) on Hartshorne Dr. Segment 1a. Seawall to the right (east) was constructed at the turn of the century and fronts the narrowest portion of the spit.
1.15	Enter parking lot on right (east) and walk out to seawall. Segment 1a. This represents the northern terminus of a seawall and groin field that extends 8.5 miles (14 km) southward. Beaches in this segment are either non-existent or very narrow. High wave energy, a low littoral drift rate, and excessive downdrift erosion combine to produce a negative sediment budget.
1.20	Turn right (north) at parking lot exit and continue along Hartshorne Dr.
1.40	Segment 1b. At this point the road parallels the most critical zone of erosion on Sandy Hook. The beach here is narrow and forms a log-spiral in plan. Recent beach nourishment and sand bag dike operations have been employed as shore protection measures. Note the absence of dunes and the presence of overwash deposits on left (west) side of the road.
1.75	Segment 1b. Site of bath house destroyed by storm activity in February, 1978. Parking lot forms on extensive impervious surface which facilitates backbarrier flooding.
1.90	Turn right (east) into National Park Service Visitors Center parking lot and walk out to beach. Segment 1b. Regressive log-spiral shoreline of Segment 1b and offset terminus of seawall in Segment 1a are evident in a southward view. This Segment experiences cyclic beach response and very high erosion rates (Table 2). Ocean swell and wave-induced currents are dominant processes. Sands on the oceanside are well-sorted and medium size. Beach cusps are a frequent occurrence. The site of a second bath house lies 100 yards (30 m) to the north.
2.05	Return to Hartshorne Dr. and proceed north (right).
2.35	Continue through main gatehouse.

2.75 Bear right (east) on gravel road to South Fishing Beach. Segment 2a. This Segment primarily responds to waves and wave-driven currents. and experiences relatively high storm and swell energies. Backshore features a natural dune belt. Beach is wider than that found in Segment 1.

3.50 Return to Hartshorne Dr. Turn right and continue north.

4.30 Bear right (east) on paved road (Atlantic Dr.)

4.50 Continue left (north) along Atlantic Dr.

5.20 Enter gravel parking lot on right (east) at Battery Gunnison and walk to beach. Segment 2b. The nearshore in this Segment is characterized by a longshore bar which shelters the beach under high wave conditions. Cyclic beach response is solely associated with major storms. Ocean waves and wave-driven currents are dominant processes. The entire Segment is backed by a natural dune system. The beach north of the timber groin is used as a beach fill borrow area for nourishment of Segment 1b.

5.30 Exit parking lot and turn right. At intersection turn right (north) on Atlantic Dr. Lighthouse to the left (west) marked the terminus of the spit in the 18th century.

5.75 Turn right (east) on gravel road to North Fishing Beach parking lot and walk to beach. Segment 3. This beach is sheltered by longshore bars and False Hook Shoal. Net deposition occurs in this Segment which is effected by the complex interaction of waves (ocean and bay) and currents (tidal and wave-induced). The shoreline in this Segment is not straight but displays a concave seaward geometry as one walks northward. The tip of the spit exhibits the highest dunes and an ebb shoal which forms False Hook Shoal. Spit growth occurs to the northwest but is limited by annual dredging of Sandy Hook Ship Channel.

5.90 Return to Atlantic Dr. and turn right (north).

5.95 Bear left (west) and proceed straight to bayside.

6.20 Continue through intersection and turn left (south) on Hartshorne Dr.

6.40 At this point a seawall fronting large houses (Officer's Row) is visible. Segment 5a. Tidal currents and bayside waves are important processes. Bayside Segments possess shore protection structures and deep coves which inhibit sediment transfers to adjacent Segments. The highest bayside waves are experienced here and Segment 4 to the north. Segment 4 lies under jurisdiction of the U.S. Coast Guard and is a restricted area.

6.90 Bear right (south) at intersection.

7.10 This is the terminus of the seawall in Segment 5. The formation of a log-spiral beach is occurring immediately to the south of the seawall. This Segment is undergoing the greatest amount of erosion due to locally generated swell and storm waves. A peat bed is exposed on the low tide foreshore and a transgressive sequence is forming over the salt marsh deposit. Sediment eroded from this beach is important to development of a spit farther south.

7.60 The aforementioned accreting spit can be seen to the right (west) across Horseshoe Cove. Segment 6a. Wave activity and tidal currents are less important here than other bayside sites. The beach is extremely thin and erosion is threatening the road adjacent to the seawall.

8.40 Limited access parking area. Segments 6a and 6b. This Segment experiences net erosion. Sediments are continuously eroded from behind the timber bulkhead and a deep cove updrift limits input of sediment. The southern extent of this Segment exhibits a small flood tidal delta formed in a breach at Spermacetti Cove. Sediments in this Segment are primarily coarse sands and lag gravels.

9.40 Return to Hartshorne Dr. and turn right (south).

11.60 Segment 7. This permits a view of Plum Island and the Shrewsbury River. As would be expected, the lowest wave energies are encountered here. Plum Island is undergoing erosion with accretion occurring at both ends. Such accretion favors formation of a salt marsh habitat. Coarse sands and lag gravels are present. Much of the sediment composing this island is fill, including the land that connects it to Sandy Hook.

End of trip.

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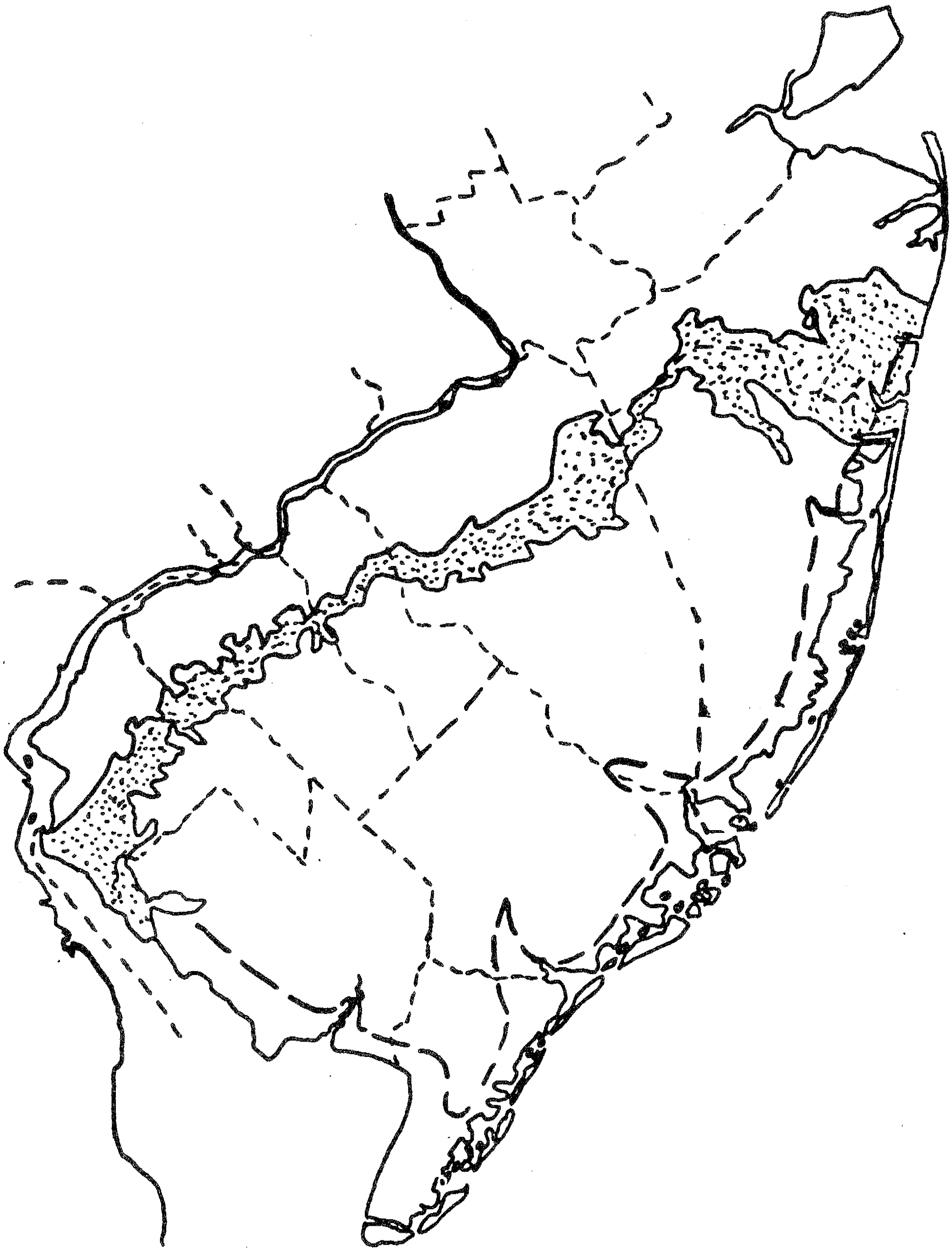


Fig. 1. The Cohansey sand outcrop. The Cohansey sand overlies the Kirkwood Formation which outcrops west and north of it (shaded area) and underlies the thick Quaternary deposits which are to the south and east, delineated here by the heavy dashed line. (from the Pinelands Commission, draft Comprehensive Management Plan, June, 1980, Fig. 2.2).

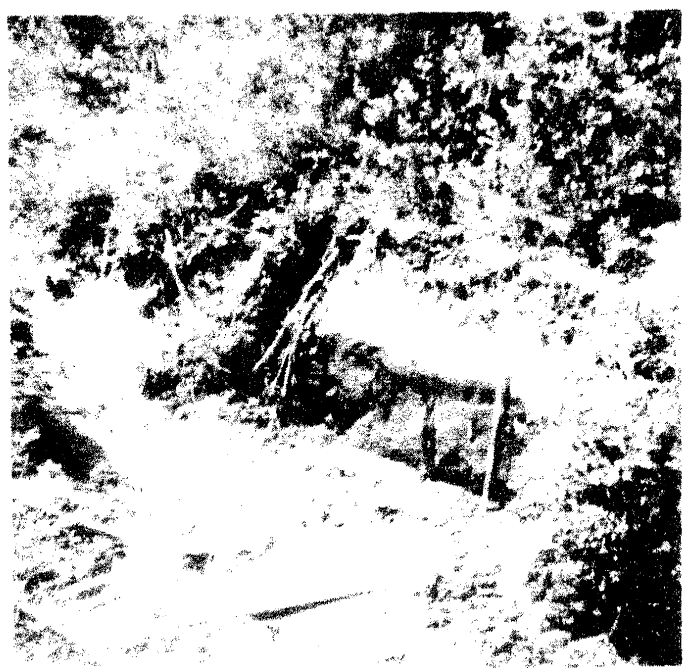
York and on Long Island (Whittaker 1979) may suggest that this type of vegetation was at one time more extensive than it is now. It persists where local conditions such as low nutrients, dryness, or frequent fires prevent the surrounding vegetation from becoming established. However, the extensiveness of this type of vegetation in the New Jersey Pine Barrens has allowed the fuller expression of the entire combination of ecosystems, including lowlands and a large number of animal species which do not survive in the smaller areas.

The vegetation in the New Jersey Pine Barrens today reflects not only topography and geology but also human history. Whether fire, a very common occurrence in this area, was a major force before the advent of man in the region is unknown. The dryness of the uplands and the inflammability of the trees might allow a lightning-set fire to burn, but lightning-set fires are rare in this part of North America, since most thunderstorms are accompanied by heavy rain (Schroeder and Buck 1970). Indians used fire and at least inadvertantly must have set some fires. The major influence of fire has been felt since European colonization. There is evidence that fires were set on purpose in the 18th and 19th centuries, for example to create pasturage. (Wacker 1975, pp.115-116). The advent of the steam locomotive in the mid-19th century added another major source of fires. More than one third of the fires in this area in 1902-1904 were caused by sparks from locomotives. Many of the others were caused by fires being used to clear brush. None was attributed to lightning (Meier, 1903, 1904, 1905). As fire control became more effective in the 20th century the size of fires and the area burned decreased, to a relatively constant amount by about 1940 (Forman and Boerner 1980).

In addition to fire, these forests have been subjected to heavy cutting for charcoal and timber and clearing for agriculture. Cedar trees have been harvested from swamps and bogs, and bogs have been flooded for cranberry production; many of these have since been deserted and reverted to wooded swamps. The landscape is thus a complex pattern of varied human disturbance superimposed on a natural landscape in which minor topographic variations are associated with major vegetational variation (Forman 1979). Although the ancient age of the landscape with its low topography and rare flooding creates a fairly stable geological system, with little downward erosion of streambeds, the human and climatic factors have produced a highly disturbed vegetational pattern. This field trip visits sites demonstrating both the stability of the geologic landscape, and a specific result of this stability in the formation of bog iron ore (Fig. 3), and the variability and instability of the local vegetational patterns.

Fig. 2. Soil profiles of New Jersey Pine Barrens podzols.

a. A podzol developed on a well-drained site.



b. A podzol developed in the presence of a high, seasonally-fluctuating water table.

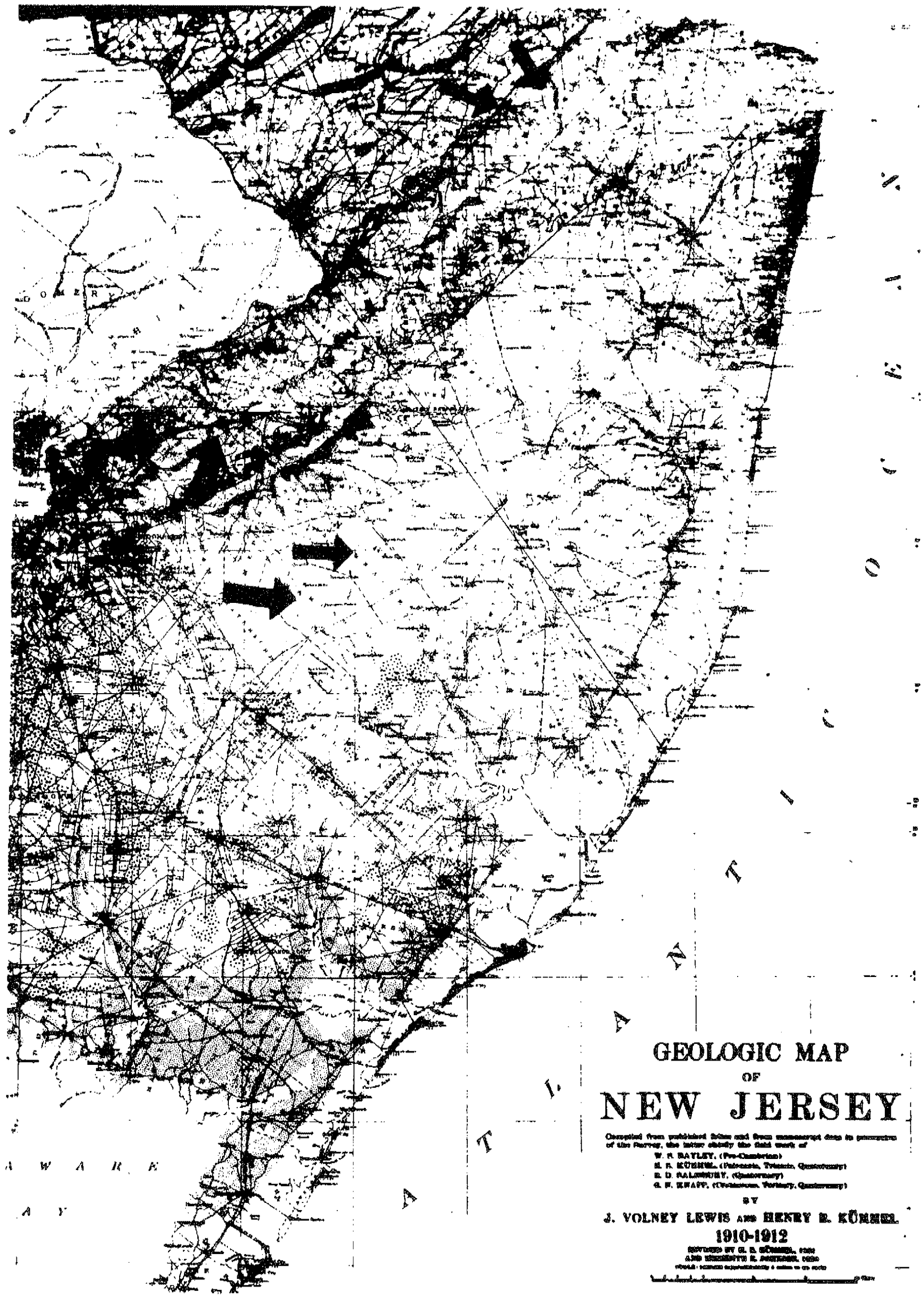


Fig. 3. Geologic Map of New Jersey.
Arrows indicate areas of bog iron ore.

BOG IRON FORMATION

Topography

The Coastal Plain of New Jersey is a raised plain whose parent materials have been laid down and reworked by numerous marine transgressions and regressions; stream and aeolian agencies have also reworked these materials. Examination of U.S. Geological Survey 7.5 minute topographic quadrangle maps indicates that the Coastal Plain may be divided into two topographic categories on the basis of stream downcutting: where streams have made significant down-cutting in the plain and where they have made little or no mapable down-cutting. Interestingly enough, the latter category exclusively contains the bog iron mining iron centers of the past (Krug, 1980). Here topographic relief is usually slight and river flow sluggish, e.g. surface gradients of 3 to 10 feet per mile are typical of the Wharton Tract (Rhodehamel, 1973) and the Mullica and Great Egg Harbor Rivers drop 5 feet in 16 and 23 miles, respectively (Crerar, *et al,* 1979).

Impedance of drainage and concomitant formation of fluviatile and related base-level swamps are the result of such slight topographic relief. The numerous streams and small rivers of these areas commonly develop slight (several feet high), semi-continuous levees and relatively broad, sandy alluvial plains, generally better drained and higher riverside and lower and swampy away from the stream.

Topography and the acidic, quartzose, sandy parent materials have promoted the formation of podzol soils as the predominant soil type of the bog iron area (Tedrow, 1962, 1979) while sandy, extremely acidic (pH 3.6-4.4), alluvial soils commonly occupy the flood plains. The sandy alluvial soils are described as having their water tables controlled by the streams and in places "cemented iron is in forms ranging from small spherical concretions to 6-inch layers of ironstone" (Soil Survey, Burlington County, New Jersey, 1971).

Iron sandstones form in, and were mined from, the low discontinuous levees and similar low (2½ to 5 feet of relief above low stream flow level) flat lands abutting the stream (Figure 4, 5a, b, c, and d). Groundwaters of these landscape features are recharged during droughty periods by the streams that they embank and not from adjacent lands from which they are hydrologically isolated or remote. Iron deposits do not form in, or were mined from, any of the other landscape features associated with the streams or groundwater podzols.

Bog iron does not form in appropriate landscape features where the surface waters are not the brown, tea-colored waters typical of the Pine Barrens. Therefore, the formation of the pedogenic bog iron is related to both topography and surface water quality (Krug, 1980).

GENESIS: A GEOCHEMICAL SOIL CATENA

Strakhov (1966) related the formation of lake ores (which are sesquioxide deposits formed in open waters) and surface water quality to the podzolization process. "Rust waters" (waters rich in iron flocs), from which lake ores form, are the result of an intermediate stage of the podzolization process. Brown waters, from which lake ores can not form, are the result of the end product of this pedogenic process, the mature podzol soil (Figure 2a, b).

Podzols form on acidic, quartzose, generally very permeable parent materials in temperate climates. What is particularly critical for podzol development is the formation of non-flocculated humic acids that are free to percolate through the soil enabling them to react with and transport cations through the soil profile. The presence of even moderate amounts of basic materials, especially containing iron, creates a flocculated humus and hinders podzol formation (Duchaufour and Souchier, 1978).

Organic acids in podzols complex strongly with Fe^{3+} and Al^{3+}, and relatively weakly with Fe^{2+} and other common cations. Iron is bound as cationic ferric hydroxide.

This organometal becomes immobilized in the presence of reactive sesquioxides. Thereby, iron is mobilized by these organic acids in the leached, iron-poor, upper horizon and immobilized in the underlying, sesquioxide-richer horizon (Schnitzer and Skinner,

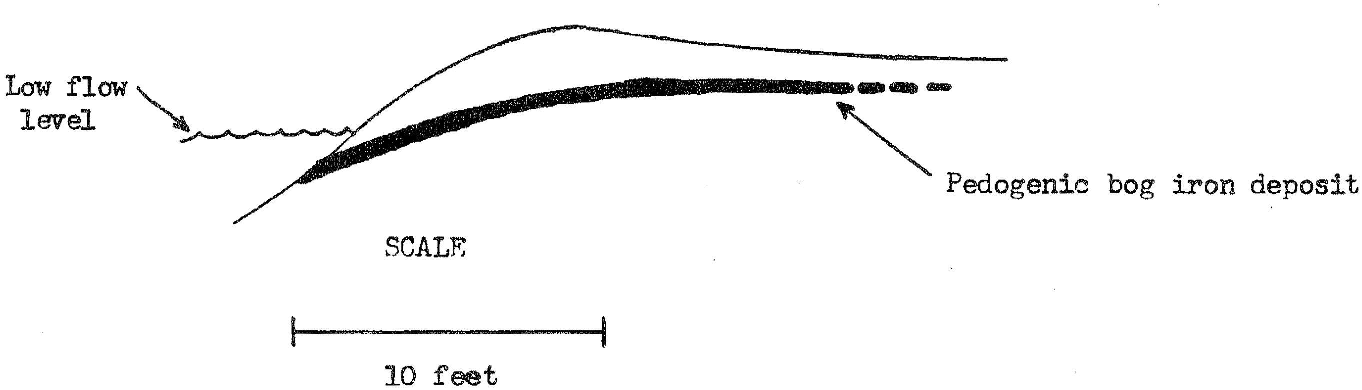


Fig.4. Idealized crossectional profile of pedogenic bog iron ore.

Fig.5. A pictoral essay on the relationship between bog iron formation and topography.
A unique bog iron deposit located at Rancocas State Park, stop no. 3 of the field trip. Tidal fluctuation of this freshwater river enables viewing of the bog iron deposit at low tide. It is seen that the higher the landscape feature, the lesser the influence of river water on groundwater, and the lesser the magnitude of the bog iron phenomenon.

1963a, b; and Schnitzer, 1969). Mössbauer spectroscopic studies have recently shown that ferric iron exists in combination with, and is preferrentially bound to, humic acids even in strictly anaerobic conditions (pure N_2 atmosphere) down to pHs even more acidic than is experienced in podzol soils (Goodman and Cheshire, 1978).

Reactive sesquioxide surfaces saturated with organoiron are probably regenerated, and more sesquioxides made, by soil microbial metabolizing of the organic fraction of organometals that leave metal oxides as wastes (Krug, 1980). Indeed, *Pedomicrobium sp.*, which is ubiquitous in podzol soils, will not grow even on simple organoiron substrates like iron ammonium citrate and other simple media proposed for iron bacteria cultural determination; they are known only to grow on iron humates, with some species known to specialize on manganese humates (Aristovskaya and Zavarzin, 1971). Therefore it is unlikely that these organisms are not metabolizing such substrates in podzol soils.

Much of the organoiron not immobilized in the soil profile is carried in solution and eventually emerges to form the brown waters that are characteristic of podzol watersheds. The coloring agent of these waters is ferric organoiron colloids, 0.1 to 0.2 microns in diameter (Moore and Maynard, 1929; Shapiro, 1957, 1966, and 1969; and Coonley, *et al,* 1971). Soil and limnological studies suggest that organoiron complexes peptize through cationic ferric hydroxide bridging of carboxy groups, the process beginning in the lower podzol soil profile (Shapiro, 1966; and Dawson, *et al,* 1978).

Surface waters pulled, by evaporation and transpiration, during droughty periods into select landscape features result in the concentration of organoiron colloids and the formation of pedogenic "bog iron ore". Organoiron immobilization and iron concentration is by the same mechanism that is in operation in podzol soils.

Laboratory examination of in situ pedogenic bog iron shows that hydrous organic matter is the cementing agent of the stone and that the iron oxides are porous and very friable being a poor cementing material (Figure 6, 7a, b, and 8). Organoiron colloids become immobilized and create a cementing plasma across the smaller void spaces. The large void spaces fill up with the iron oxide residue, if given enough time because these iron oxides are porous thus permitting solution movement which enables continuing supply and metabolism of organoiron (Krug, 1980).

CONCLUSIONS

Iron mobilized from podzol soils of the Pine Barrens enters surface waters as ferrihumates. The resulting organoiron colloids from these surface waters are concentrated in select landscape features to form bog iron ore creating a geochemical soil catenary sequence.

The formation of bog iron ores have been, and are, largely explained as being controlled by Eh/pH parameters: iron is solubilized from underlying ferruginous strata or non-apparent iron mineral-bearing materials, transported in reduced form in groundwaters and becomes oxidized and precipitated as these solutions approach oxidizing surfaces; oxidation may be aided by iron-oxidizing bacteria. Nevertheless, this generally-accepted hypothesis of bog iron formation does not explain the inability of it to form in areas of such emerging groundwaters, why it forms where it does and why it takes on the form that it has.

Bog iron researchers have been faced with special problems besides today's lack of economic interest in bog iron deposits. One problem is the unlikely fact that iron mobilization requires such iron-poor parent materials. This is probably what had led many investigators to hypothesize obscure, or somewhat removed, sources of iron rather than the white sands covering the watershed, from which iron has, and is, being removed. Another is that, until recently, the only accepted chemical models for iron movement were various Eh/pH models, even for organically-complexed iron.

Furthermore, the bog iron literature is extremely confused. For example, generation times estimated for lake ores, as little as 20 years, have been given as those of bog iron ores, including the bog ores of New Jersey. However, none of the examined mined sites (140 to 200 years ago) in the Pine Barrens give any indication of renewal. A similar observation as to lack of regeneration of bog iron has been made by Crerar, *et al,* (1979).

Additional research suggests that the development of podzol soils from the parent materials of the Coastal Plain first resulted in the formation of lake ores during an intermediate soil development stage, as described for the lake ores of Fennoscandia and the Soviet Union by Strakhov (1966). The development of pedogenic bog iron came with the predominance of mature podzol soils in Pine Barrens watersheds. Apparently both lake ores, probably buried fossil lake ores, and pedogenic bog iron ores were mined in the Pine Barrens (Krug, 1980).

Fig.6. A photomicrograph of a flat, polished pedogenic bog iron surface (secondary electron).

Fig.7a. A slightly higher magnification photomicrograph of the same surface viewed in Figure 6 after one week of vacuum desiccation (secondary electron). Hydrous organic matter plasma cement shrivels up under vacuum desiccation. Large iron oxide-rich plasma body at lower edge of picture has not lost volume.

Fig.7b. Photomicrograph of large iron oxide-rich plasma body/dehydrated organic matter/quartz sand grain interfaces (secondary electron).
Higher magnification view of the large iron oxide-rich plasma body viewed in Figure 7a. Quartz grains occupy upper right and lower central, dehydrated organic matter central and lower right, and the iron oxide-rich plasma occupies the central and upper left portions of the photomicrograph.

Fig.8. Iron elemental map of a flat, polished pedogenic bog iron surface (secondary electron).
Central white mass is a large iron oxide plasma body. White lines at edges of view are iron oxide coatings of quartz sand grains. Electron microprobe analysis shows these iron oxide coatings and plasma body to be almost pure iron oxide. Sand sized, ferruginous, lower left particle is ilmenite, $FeTiO_3$.

ROAD LOG

Mileage

0.0 Start at Rutgers University, Newark Campus. Enter New Jersey Turnpike at Interchange 14.

24.0 Exit New Jersey Turnpike at exit 9, East Brunswick. At the toll booths bear right to take Rt. 18 west towards New Brunswick.

24.6 Rt. 18 goes over Westons Mill Pond and curves left passing over Rt. 1. Keep right on Rt. 18 overpass of Rt. 1 to take Rt. 1 south exit.

26.4 Proceed south on Rt. 1, make right onto jughandle about 0.1 mi. after going under the second overpass. Bear left on jughandle to cross Rt. 1 to Rt. 130.

31.4 After going south on Rt. 130 for a little over 4 mi. a pond and a motel are seen on the left. Ahead is farmland on both sides of the highway. Past the farmland is woods on both sides of the highway. When you get to the woods travel slowly on the shoulder of the highway. Stop when you find the stream that goes under the highway.

STOP 1. PEDOGENIC BOG IRON FORMATIONS OF PIGEON SWAMP, SOUTH BRUNSWICK.

Unmined bog iron site that shows the relationships of podzol soils, surface water quality, and pedogenic bog iron formation . This is posted private land. Viewing of bog iron is best achieved by walking in the stream itself. The south bank of the stream is disturbed by dredgings (parts of this stream were straightened) and by bedding of long-abandoned dirt roads.

54.4 From Stop #1 continue down Rt. 130 south to the intersection of Rt. 206.

66.4 Take Rt. 206 south to Vincentown Diner and make a right. Sign says "To 38".

68.7 Continue down highway to first fork in the road; the main highway bears left, you go right.

68.9 Shortly you come to a stop sign. A school is on your right. Make a right turn at this stop sign and proceed down Pine Street.

69.5 After going over railroad tracks look to take last right before going over a small river, North Branch Rancocas Creek. Make this right and you are now in Iron Works Park, Mount Holly.

69.7 Drive towards the green foot bridge going over the river. Stop vehicle in parking space available nearest the bridge. On the other side of the bridge are the two large trees growing over the remains of an iron ore dump.

STOP 2 BOG IRON DUMP, MOUNT HOLLY.

The remnants of an iron ore dump still exist under two large trees growing at the edge of the North Branch Rancocas Creek, Iron Works Park, Mount Holly. Both lake and bog ores are in these piles. The ores were presumably used by the Mount Holly Iron Works which was destroyed in 1778 by the British Army and never rebuilt.

70.6 Leave Iron Works Park, making a left onto Pine Street and proceed to the traffic light at the Rt. 38 intersection. Make a right onto Rt. 38.

72.7 Proceed west to the traffic light at Hainesport-Lumberton Road. Make a right onto Hainesport-Lumberton Road. If this turn is missed you will pass over the Southeast Branch Rancocas Creek in 0.1 mi.

73.0 Follow this road to the first stop sign. Make a left here onto Rt. 537 (Marne Highway).

73.1 Make the first right onto Rancocas Avenue.

73.8 Proceed down this road to the entrance of Rancocas State Park. This park is open to 8pm in the summer and 5pm for the rest of the year. Check sign for open hours. Continue straight.

74.3 View swamp on left at the first fork in the road. Swamp water is not brown nor is it rust stained in the summer. Soils of the area are not the bleached white sands characteristic of podzols.

74.4 Take right fork in the road. Road forks again almost immediately, bear left and stay on "main" dirt road. Park in clearing by the river. Walk left along beach at low tide to view iron formation and its relation to topography. At its maximum extent, ironstone goes 80 feet inland. Iron formation continues to the right of the clearing under rubble and shoring. The tides here are about 3 hours ahead of those of Sandy Hook.

STOP 3 WATER QUALITY, SOILS, AND TOPOGRAPHIC RELATIONSHIPS TO PEDOGENIC BOG IRON FORMATION OF RANCOCAS STATE PARK, HAINESPORT.

Soils are extremely acidic, pH approximately 4, but are not podzols, the vegetation is typical of that of the Pine Barrens. Water draining this land is clear, not organic stained or rusty, not participating in significant iron cycling. At low tide the relationship of pedogenic bog iron formation to topography is easily observable. River water is the source of iron, the brown river waters coming from the upstream podzols. Shallow groundwaters of the Pine Barrens (podzol zone) are also brown (and ferruginous). Therefore this site is unique in that pedogenic bog iron is visible on the surface because of tides and formed in an area where there is little doubt that the local groundwaters can not supply iron for deposition. This iron deposit is unusual in that ocherous earth forms both above and below the ironstone layer whereas it usually only forms below. This sandwiching effect is probably due to the tidal variation.

78.0 Return to Rt. 38 and turn left (east). After passing Mt. Holly in a couple of miles the route number will change to Rt. 530.

STOP 4

81.5 In the middle of the field on the south side of the road is a typical pingo, a common local land feature. Similar structures with raised edges are formed in areas of permanently frozen soils in the Arctic, by a complex process of thawing, erosion and deposition (Tedrow, 1969). The permanently wet center here prevents cultivation and is thus seen by the brush growing there. Pingos appear to have attracted Indians and frequently have artifacts on their raised edges. They may also account for the existence of small bogs where the ground water table is well below the surface, since they are usually underlain by clay lenses.

82.0 Cross Rt. 206.

84.5 Traffic light. Go straight. You are now on Rt. 644

90.5 Traffic circle. Take Rt. 72 east. Lebanon State Forest with typical Pine Barrens upland forests is on the left, interrupted in places by streams.

94.0 Right on Rt. 563 towards Chatsworth.

98.5 Village of Chatsworth, locally known as the "capitol of the Pine Barrens."

109.5 Note large cranberry bogs along the way. These are located where the water table is at the surface and are periodically flooded to protect the plants from frost in the spring and to assist in the harvest in the fall, when the berries are knocked off the vines and floated off. Bear left on Rt. 579.

STOP 5

111.0 Harrisville Pond. This is the site of an old iron works. Evidence for mining of bog iron ore can be seen along the river. Much of the lowland forest here is pitch pine, with a canopy of almost pure pine. The understory is dense and includes many shrubs of the heath family (Ericaceae), for example sheep laurel (*Kalmia angustifolia*) and blueberry (*Vaccinium* spp.). These lowland areas occur often along streams with low levees, the same conditions conducive to the formation of bog iron ore.

The Oswego River here has a drainage area of 64 mi² and discharge of 18.7 in/yr (Pinelands Commission, Draft Comprehensive Management Plan, June, 1980).

Just up on the left is an exposed soil profile and upland forest. The canopy here is mainly pitch pine (*Pinus rigida*) but also includes the typical blackjack oak (*Quercus marilandica*). Tall shrubs are mainly scrub oak (*Q. ilicifolia*); other prominent shrubs are black huckleberry (*Gaylussacia baccata*) and lowbush blueberry (*Vaccinium vacillans*). The litter is thin and scattered where there have been frequent fires. Sandiness and leaching show in the podzol. Without fire the upper humic horizon would be deeper. Below this is the bleached zone. A zone of accumulation of the leached iron and humic compounds may form below this, just above the parent material or Cohansey sand. In places this yellow sand is brought to the surface and deposited on the white sand by ants.

Turn around and return to Rt. 563. Turn right.

112.5 Turn right toward Oswego Lake.

116.0 **STOP 6** Oswego Lake (Penn State Forest).

There are two types of swamps in this vicinity, hardwood and cedar. Note the pointed tops of the cedar trees (*Chamaecyparis thyoides*) compared with the flat tops of the pines. The short gradation between these two indicates the small changes in elevation associated with the change from upland to lowland vegetation. The understory here includes highbush blueberry (*Vaccinium corymbosum*) and swamp azalea (*Rhododendron viscosum*). In openings the sphagnum moss mat also includes the tiny plants of cranberry (*Vaccinium macrocarpon*). Both of these species of *Vaccinium* are grown here commercially.

In places in the cedar swamp, red maple (*Acer rubrum*) and black gum (*Nyssa sylvatica*) form an understory which may eventually replace the cedars. Such an area of hardwood swamp can be seen shortly downstream from Oswego Lake. The red maple and black gum are here accompanied by sweet bay (*Magnolia virginiana*). Continue on past the lake.

125.0 Turn left on Rt. 72. At the Burlington and Ocean County line there is a pull over on the right shortly after you get on Rt. 72.

STOP 7 Pine Plains

These dwarf forests are the most distinctive feature of the Pine Barrens. There are no other such forests approaching the areal extent of these elsewhere in the world. Stunted, many-trunked blackjack oak and pitch pine dominate the low canopy. Broom crowberry (*Corema conradii*), a species which reaches its southern geographical limit in the Pine Barrens, is found here. It is a species which probably migrated south along the exposed coastal area during the Pleistocene and has since been isolated from northern populations by the rise in sea level. Note also that the soil here is coarser than in the other upland site, a characteristic of the Pine Plains which may increase dryness and thus fire frequency.

Turn around and go east on Rt. 72.

133.0 Garden State Parkway. Go north.

STOP 8

141.0 Oyster Creek rest area.

Oyster Creek with 7.43 mi^2 of drainage area has a flow of 51.4 in/yr. Compare this with the values for Oswego River. This difference is caused by interbasin transfer of ground water. Much of the water that falls in the Oswego River watershed soaks quickly down into the aquifer below the bed of the river and flows past it, to come to the surface eventually in such streams as Oyster Creek.

205.0 New Jersey Turnpike. North to Newark.

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NOONDAY HACKENSACK MEADOWS
by Mrs. M. Nimmo Moran
American Etchings, Part XVIII, 1881

LATE WISCONSIN-HOLOCENE HISTORY OF THE LOWER HUDSON REGION: NEW EVIDENCE FROM THE HACKENSACK AND HUDSON RIVER VALLEYS

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INTRODUCTION

The study area (Fig. 1) is the central and upper Hackensack River valley of northeastern New Jersey and adjacent New York State with reconaissance study of the surrounding area in Bergen County, N.J. and Rockland County, N.Y. In the text, town names will be in New Jersey unless indicated otherwise. Geologically, the area is the northern portion of the Trias-Jurassic Newark basin where a gently dipping (14°W) homoclinal sequence of Brunswick Formation red sandstones and shales form the deeply scarred bedrock surface. The Palisade Sill and basalt lava flows of the Watchungs, interbedded with the Newark series sediments, form prominent topographic ridges in the region. The western slope of the Palisade Sill, whose well-studied eastern escarpment forms the Hudson Palisades, is at the eastern margin of the Hackensack Valley. Resistant sandstones of the Newark group form the ridges and cliffs along its western border as well as the divide between it and the parallel drainage system of the Saddle River. The Ramapo fault system slices northeast at the northern terminus of the basin separating it from the rugged Precambrian crystalline mass of the Ramapo Mountain portion of the Appalachian chain. The Hudson River and glaciation have carved an impressive gorge through the Hudson Highlands. The Ramapo River lies in a similar but less spectacular gorge ten miles to the west at Suffern, N.Y. Continental glaciations overdeepened both gorges before overwhelming the Ramapos to push south to their maxima. The deep preglacial Hackensack Valley has been partially overdeepened by glacial ice, then mostly filled by proglacial lake sediments (Lovegreen, 1974). The present terrain is gently rolling, with drumlinoidal hills generally aligned north to south paralleling the strike of the bedrock. Essentially glaciation has subdued the preexisting topography, even occasionally reversing it.

Previous work: At the turn of the century Salisbury, et al. (1902) reported the glacial geology in the New Jersey portion of the study area. Geomorphic forms were described with great detail and accuracy with lesser emphasis on stratigraphy. There is a notable lack of description to distinguish between the two tills and their associated outwashes. The latter is not a reflection on their abilities but rather on the "state of the art" circa 1900. Reeds (1926, 1927) studied and counted the 2,550 glacial Lake Hackensack varves at Little Ferry. Heusser (1963) examined the recent vegetational history of the tidal marsh at Secaucus from about 2,000 YBP (radiocarbon years before present). Lovegreen (1974) compiled a mass of subsurface data indicating that prior to glaciation, the Hudson River, after passing through the Highlands Gap in the Ramapo Mountains, had flowed westward through the Sparkill Gap in the Palisades. Then turning south it excavated channels in the Newark series shales approximating the present course of the Hackensack River to the ocean.

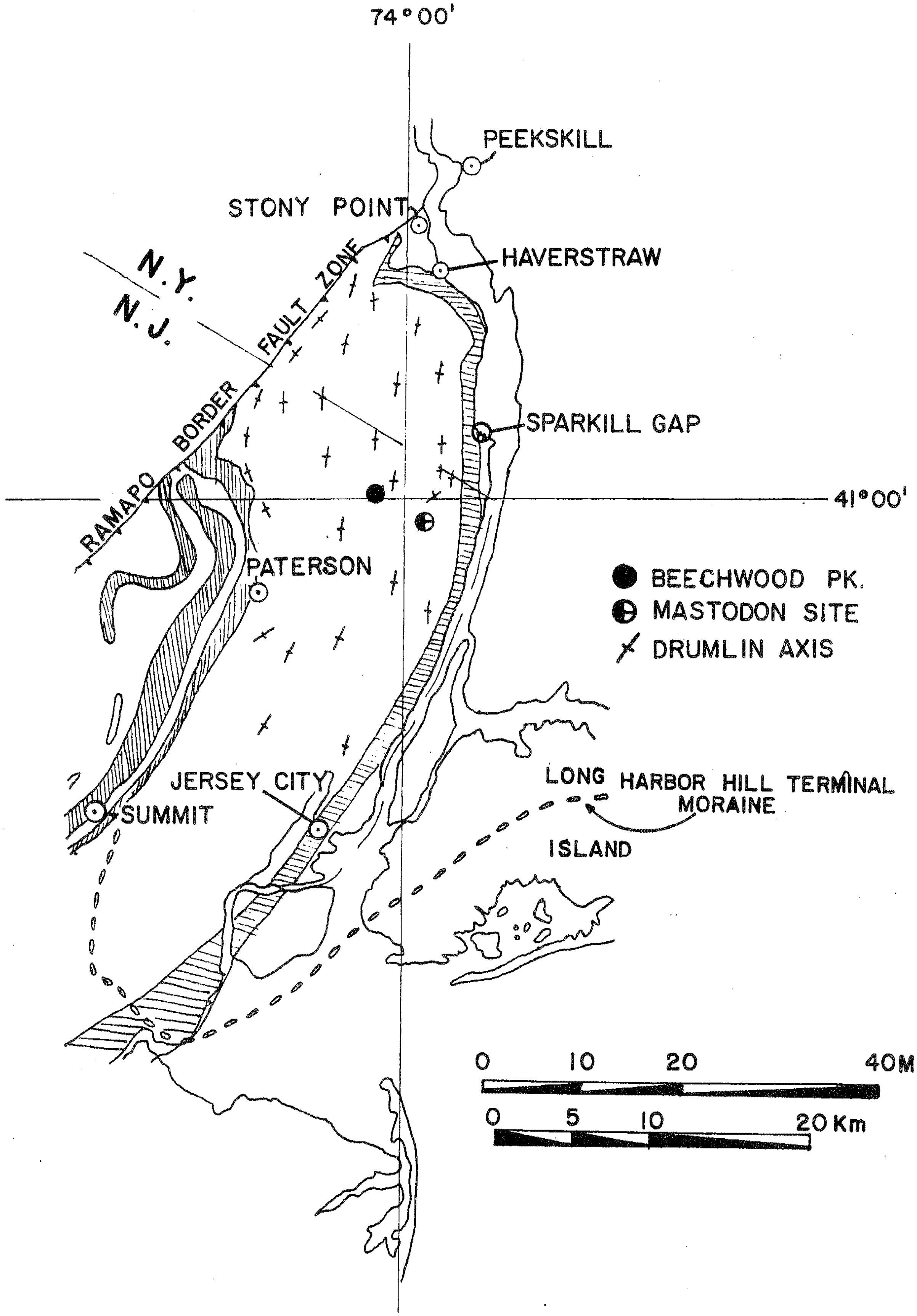

Fig. 1. Study area and adjacent region
Key: Watchung lava flows are lined vertically while the Palisade Sill is lined horizontally.

Glacial geology of the Hackensack Valley: The present study.

Within the study area, there is no surficial evidence of any glaciation earlier than late Wisconsin age. However, evidence of two earlier glaciations is present from the subsurface. Brown drift is known from deep borings along the New York State Thruway near Mt. Ivy, New York. In River Edge, excavation of red till revealed deeply weathered rock fragments whereas the red till examined in Norwood and elsewhere contained much more durable "fresh" clasts. This appears to agree with the till and drift sequence found on Staten Island by Sanders and Rampino (1978). These tills (the brown till and the "rotten clast" red till) are probably of early Wisconsin age or older.

The late Wisconsinian (Woodfordian) glacial maximum of the Hudson Valley ice lobe overrode the earlier drifts and built the Harbor Hill moraine across western Long Island, Staten Island, New York and at Perth Amboy, New Jersey across to Summit (Fig. 1) sometime after 22,800 B.P. (Sirkin & Stuckenrath, 1975). The thin Roslyn till overlies the Harbor Hill Moraine in western L.I. This undated till marks the most recent readvance to the terminal position by the Hudson lobe of the Woodfordian ice sheet (Connally & Sirkin, 1973).

Proglacial lakes Hudson, Flushing and Hackensack, conterminous (Reeds, 1926) and dammed on the south by the Woodfordian terminal moraine, expanded as the ice beat an oscillating retreat northward. Lake Passaic, which formed between the First Watchung Ridge and the Ramapo Mountains to the west, lay at a higher elevation and is presumed to have been essentially coeval with the other three.

The preceeding is relatively well known and has been presumed to have been the entire late-glacial history. It was thought to have been followed only by draining of the lakes and the stream flow that presumably deposited a three to six meter thick sheet of sand across the lake bed. Both events were believed to have been the result of postglacial differential isostatic rebound.

The present study indicates the occurence of a post-Lake Hackensack glacial readvance into the lower Hudson River Valley region following a significant interstade, and provides details of the post-glacial events. The supporting evidence includes stratigraphic, sedimentologic, geomorphic, seismic and palynologic data as well as a series of supporting C-14 dates.

SPARKILL GAP: SEISMIC STUDY

Sparkill (Spar Kill) Gap has been most important to the late and postglacial history of the Hackensack River. It breaches the otherwise continuous wall of the Palisades that extends from Jersey City, New Jersey to Haverstraw, New York. Because of the northward glacially induced isostatic crustal tilt, it served as the drainage for the Hackensack River on several occasions. For this reason, this detailed study of the Gap is presented.

Seismic Studies - Sparkill Gap

Sparkill Gap is underlain by the Triassic Palisades Formation (Perlmutter, 1959). These sandstones and shales are cut by several northeast-southwest trending normal faults (Thompson, 1959). Sparkill Gap is on the north end of a +180 ft. to +200 ft. A.S.L. (above sea level) terrace that was eroded by the southwest-flowing, preglacial Hudson River (Fig. 2a, and Woodworth, 1905, Johnson, 1931). The preglacial Hudson was consequent on a graben that broke the crest line of the Palisades ridge (Thompson, 1959). The Tappan and Sparkill Moraines lie west of the Gap; these moraines were deposited by ice lying in the valley between Orangeburg and Mt. Nebo (Fig 2a, and Woodsworth, 1905). Stratified drift (outwash) lies between the two moraines (Woodworth, 1905).

The Gap is filled by over 60 ft. (18.3 m) of glacial drift, based on test borings and water wells (Perlmutter, 1959). These wells, with supplemental test borings, unpublished USGS water well data, and NYSGS seismic refraction data, has been used to generate Figs. 2b and 2c.

Geophysics: Seismic refraction was used to provide additional data points in the Sparkill Gap area. Seismic profiles were run along rights-of-way and in town parks. Each of the profiles was reversed, and was 170 to 250 ft. (52 to 76 m) long; the length depended on the distance available between power lines, road intersections, and fences. "Shot points" were 10 feet (3 m) apart in the first 60 ft. (18.3 m) of each profile, and were 20 feet (6.1 m) apart for the rest. The "shot points" were impacts of a 16 lb sledge hammer on a 1 ft.^{2} (.4 m^2) steel plate. The signal was recorded on a Huntec FS-3 single-channel seismograph. The resulting time-distance graph was interpreted using both the critical distance and time-intercept methods (Mooney, 1973, Zohdy and others, 1974).

Two areas were studied - The northernmost area was at the mouth of the Sparkill (seismic profile 73-13, Fig. 2c), and the southernmost was just southwest of U.S. Rt. 9W crossing of the Sparkill (profiles 73-10, -11, -12, Fig. 2c). Each seismic profile generally had three seismic layers (Fig.2c). The uppermost, or low-velocity layer

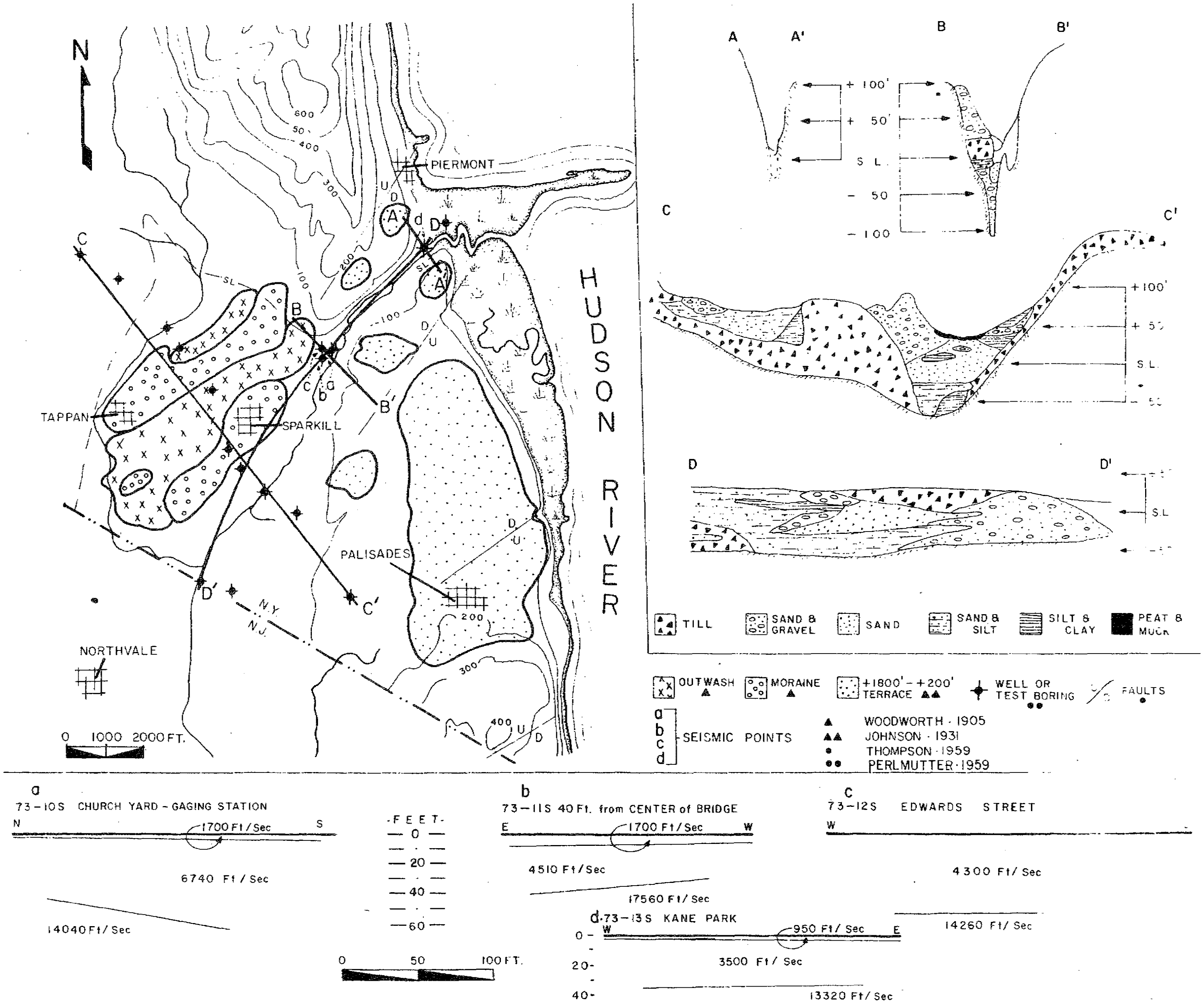

Fig. 2. a. Detailed map of Sparkill Gap and vicinity: contoursdrawn on bedrock surface.
b. Geologic cross-sections
c. Seismic profiles.

had seismic velocities of 950 ft./sec. to 1700 ft./sec. (290 m/sec. to 520 m/sec.) and was 0.9 to 6.9 ft. (0.27 to 2.1 m) thick. Test borings in the vicinity of the seismic profiles contained dry fill or silty sand in this depth range. Seismic layer # 2 had velocities from 3500 ft./sec. to 6740 ft./sec. (1070 m/sec. to 2050 m/sec.), and was 24 to 58 ft. (7.3 to 17.7 m) thick. Test borings indicate that this material is bouldery stratified drift (cross sections C-C', D-D', Fig. 2b). The bottom-most layer had seismic velocities from 13320 ft./sec. to 17560 ft./sec. (4060 m/sec. to 5350 m/sec.) and was bedrock, based on nearby wells.

Glacial Geology and Bedrock Topography (Fig. 2)

Sparkill Gap is a hanging valley, with a rock sill at an elevation of -25 ft. at Sparkill's confluence with the Hudson, the valley's gradient is down towards the southwest . A narrow V-shaped gorge is incised into a -25 ft. bedrock terrace (cross sections A-A', B-B', C-C'), the -25 ft. terrace widens towards the southwest. The floor of the inner gorge is at an elevation of -25 ft. at the mouth of the Sparkill, and deeper than -110 ft. at the US 9W crossing of the Sparkill (cross sections A-A', B-B', C-C').

The gorge is filled with a sequence of southwest-fining stratified drift (cross section D-D'). Till underlies the Sparkill and Tappan Moraines (cross section C-C'), and overlies part of the southwest-fining outwash sequence near Sparkill Village (cross sections B-B', D-D'). The high-velocity floodplain deposits fill the mouth of Sparkill Gap (cross sections A-A', D-D', seismic profile 73-13).

Interpretation:

The bedrock gradients suggest persistent southwestward drainage. The broad, − 180 to − 200 ft. terrace has been modified by proglacial drainage, but eroded by either preglacial or interglacial southwestward drainage, flowing into the Hackensack Valley from the Hudson Valley, over the col formed by the graben between Mt. Nebo and Alpine. The V-shaped gorge underlying Sparkill Gap is a fault that forms the north edge of the graben, the south edge is probably a fault in the Palisades area, based on the re-entrance of the + 150 ft. contour just south of Palisades. This terrace might have been formed during an interglacial period, particularly if the Hudson was dammed by a moraine south of Palisades. The Sparkill gorge was eroded along the northern fault by proglacial meltwater, its V-shape suggests that the erosion might have taken place during the late Wisconsinan. The divide or base level at -25 ft. in the mouth of the gorge controlled northward, reversed-drainage during the Woodfordian.

Distribution of the drifts:

Two surficial drifts exist within the study area, a red till and a yellow-brown till each with distinctive outwash and loess. Found throughout the central and lower Hackensack River region is a red (10 R 5/4) compact sandy to clayey stoney till. In Norwood, this till was found to be overlapped by the red varves of glacial Lake Hackensack and so correlates the lake with red till. The red color is so distinctive as to be easily identified in kames constructed of coarse outwash material. In the sandy and more distal portions of the stratified drift deposits, the red color is not nearly as prominent and it becomes more light brown in appearance. Its derived loess is red.

Yellow-brown (10 YR5/4 wet & 10YR7/4 dry), generally sandy, round cobble till covers the surface northward from a line extending across the Newark basin in New Jersey (Fig. 1) from Norwood (south of Piermont, New York) through Old Tappan, Hillsdale and Ridgewood to Oakland. This till is from 0.3 m to 2.6 m thick near its southern margin and is at least as much as 13 m thick in Montvale near the New York State line. The line of demarcation is not sharp and is more properly described as a zone several kilometers wide. Boring records indicate the red till and red varves lie beneath yellow-brown till in much of northeastern New Jersey and adjacent Rockland County, New York. However, outcrops demonstrating this relationship are rare. Salisbury (1902) also reports this relationship in the study area as well as to the west in the northern Passaic drainage basin. Averill has traced this yellow-brown drift through the Suffern-Haverstraw, New York axis and into the Highlands portion of the Hudson and Ramapo valleys.

The two tills show many of the same relationships and general characteristics of the upper and lower tills in New England (J. Hartshorn, 1976, pers. comm.) and present the same sort of "two till" dilemma (i.e., 1. two tills representing two glaciations; 2. two tills representing one glaciation [lodgement till overlain by ablation till]; or 3. two tills representing reorganization of ice flow direction of a single glaciation.) In the writer's (Averill) opinion, the two tills in the Hackensack valley represent two late Wisconsin stades separated by a significant interstade.

Stratigraphy

Recent excavation of a shallow northern segment of the Oradell Reservoir in Norwood has proven to be critical in determining the late- and post-glacial history of this region. The stratigraphy of the reservoir was visible in different parts of a 1.5 square kilometer area over a three year span. The entire section was never visible in

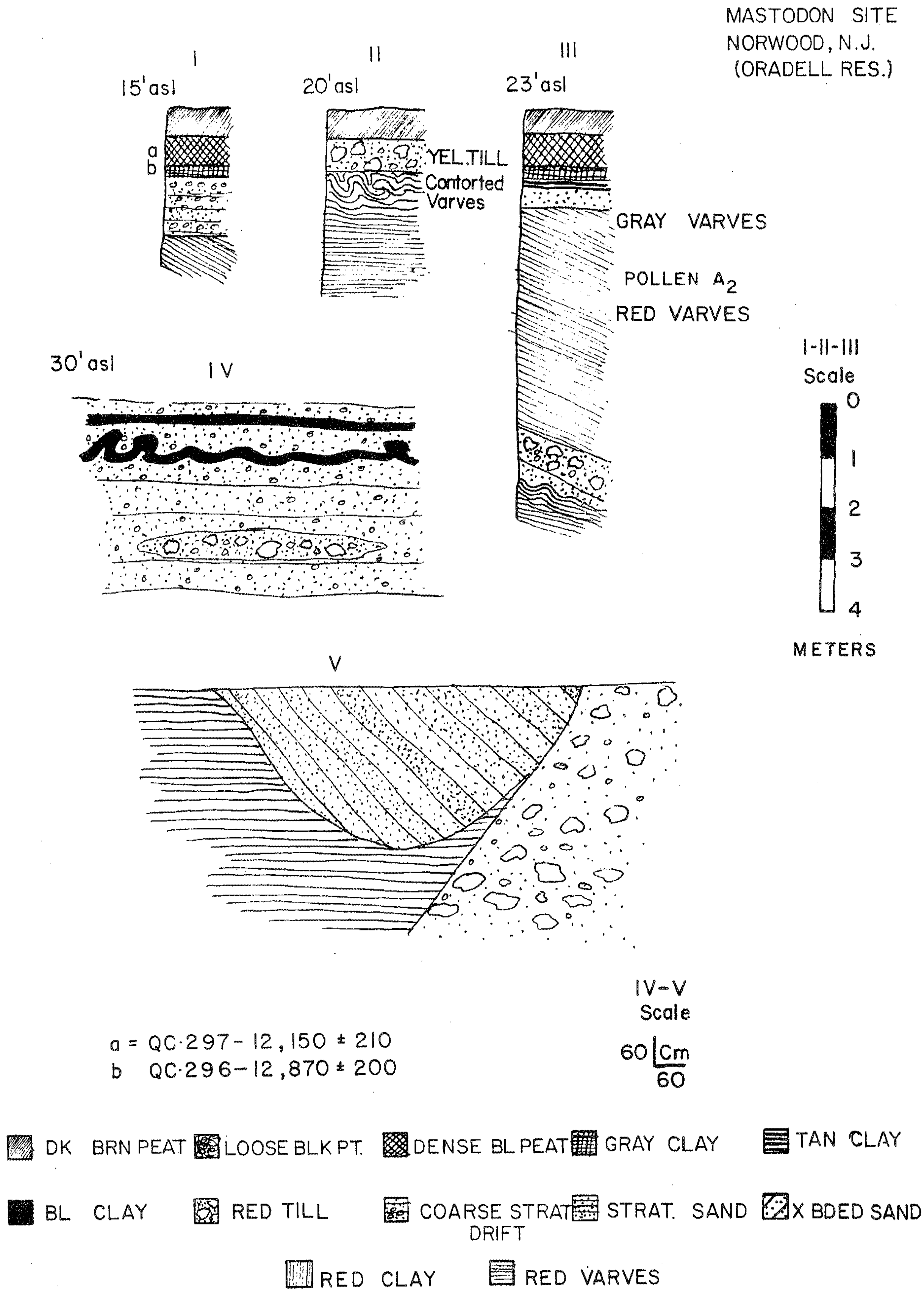

Fig. 3. Mastodon Site, Norwood, N.J. (Northern-most section Oradell Reservoir) Stratigraphic sections I-V

Fig. 4. Interstadial stream channel cut into red varves and red till. Channel is lined with red clay and filled with cross-bedded outwash sand. Location is 0.5 Km south of Mastodon Site, Norwood, N.J. (See Fig. 3V)

Fig. 5. Periglacial involutions
Black clay layer in outwash sand. Lower sand is fluvial outwash. Clay layer deposited in proglacial Lake Sparkill. Upper sand finer with small scale crossbedding deposited in the same lake prior to unblocking and drainage through Sparkill Gap. Location is 200 m east of fig. 4. (See Fig. 3IV; note large slab or red till enclosed in lower outwash.)

a single outcrop but sufficient outcrops were available to construct an accurate composite. It is as follows (Fig. 3): Red till overlain by a thick sequence of extremely compact red varves interrupted near the top of the sequence by 1.5 m layer of sand; 3 m of identical compact red varves continue the red varve sequence (most varves were about .5 cm thick). Red till, 1 m thick, overlies distorted varves and red sandy outwash in one exposure. Comformably overlying the red varves is 1.7 m of gray varves. Each gray varve is about .4 cm thick. Stream channels, one over 14 m deep, with a strike of N.40-60°E. are cut into the varves and/or red till (Fig. 4). The channels, where visible in cross-section, are lined on the bottom, or partially filled, with red clay. Sand, much of it coarse and exhibiting large scale cross-bedding, fills the channels and overlies the entire reservoir as well as the surrounding area. The overlying upper sand layers are interbedded with several organic black clay layers each about 8-10 cm thick. The lower of these is involuted (Fig. 5). Reeds (1926) reports virtually identical sand with clay layer stratigraphy over eroded inclined varves in Little Ferry. The uppermost sand (stratigraphically) at the Norwood portion of the Dwarskill valley floor is about 3 m lower in elevation than the black clay layers and exhibits reverse graded-bedding. It is a coarse sand grading upwards into coarse gravel with embedded cobbles and boulders (Fig. 6). One gigantic boulder, about 3 m in diameter and composed of very coarse Palisade diabase, has a lag concentrate of 30 to 40 cm boulders on its northeastern side. The boulder group tapered to a point toward the northeast (Fig. 6). Ten to fifteen cm of tan lacustrine clay overlies the coarse gravel and surrounds the embedded boulders. Gray clay succeeds this and rapidly grades into black organic rich clay 20 to 40 cm thick and then into .7 to 1.3 m of dense black peat. The bones of a mastodon, known as the Dwarskill mastodon, were found buried in the black organic clay (Fig. 7). Dark brown, "fluffy when dry", peat (about .5m) unconformably overlies the black peat (Fig. 4).

A single outcrop at the northernmost part of the reservoir reveals a different and highly significant part of the story. Stratigraphy from borings indicates a red till beneath 1.8 m of red varves. Excavation shows red varves overlain by about 20 cm of fine sand and succeeded by about 50 cm of yellow-brown sandy till containing many gneiss and quartzite cobbles and one slab of red sandstone. That it is till and not outwash is indicated by the clay-filled interstices. The fine red sand and upper 10 cm of varves are severely deformed as shown in the photographs (Figs. 8 & 9; also Fig. 3-II). Folds are overturned to the SSW parallel to the stream valley and opposite to the direction of the Sparkill Gap at Sparkill, N.Y. Black peat, about 40 cm thick and with many visible Spartina stems and roots, overlies the till. This thin till is found across the northern segment of the reservoir and the nearby Norwood kame grouping constructed of tightly packed red cobble outwash.

Beechwood Park in Hillsdale is about 9 km to the southeast, just north of the yellow-brown till margin. The park includes a kettle, situated in a sandy outwash head kame, immediately behind a head-of-outwash near the Hillsdale-Westwood border. Its stratigraphy is known only from numerous boreholes (Fig. 10). Drill-

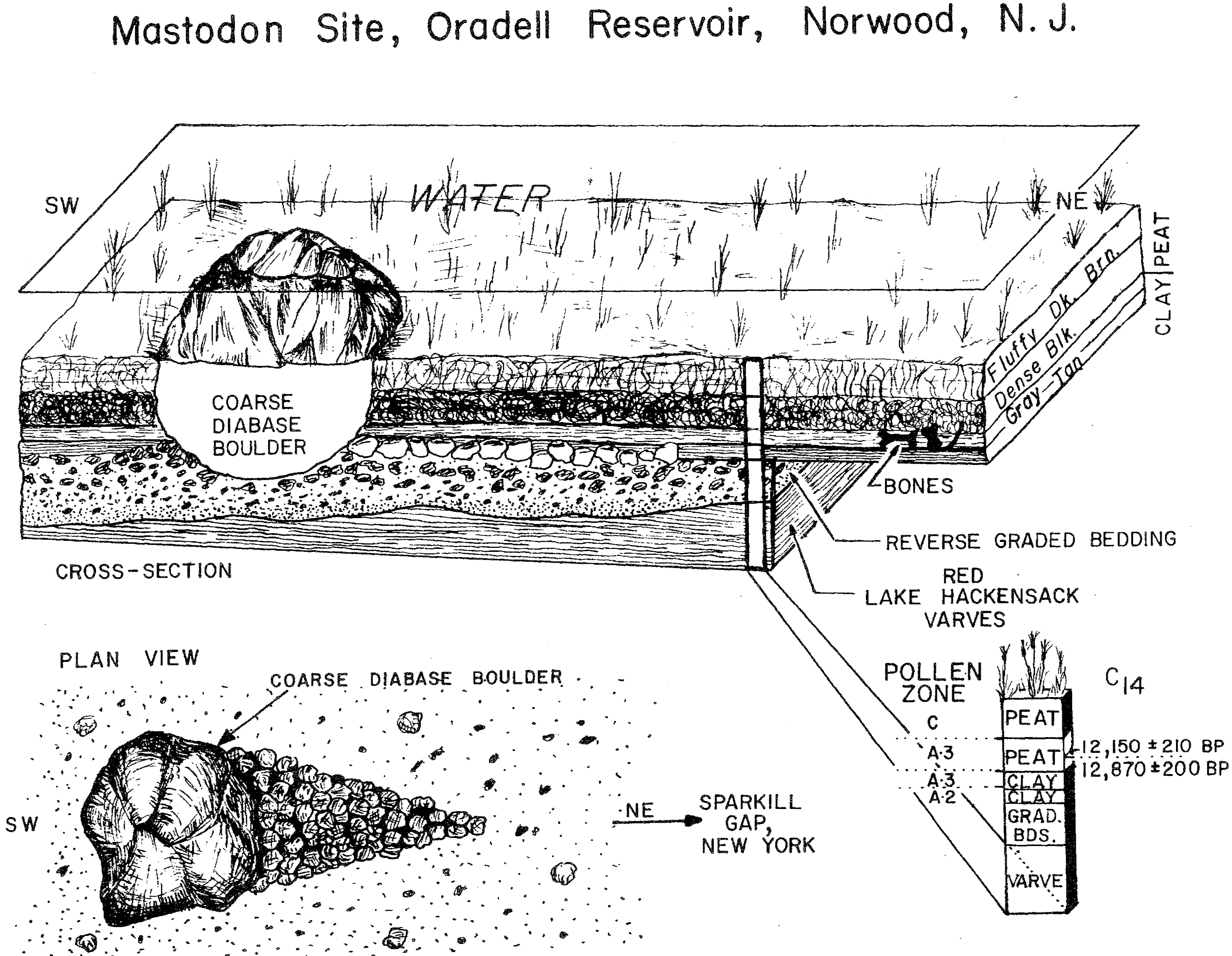

Fig. 6. Mastodon Site Reconstruction, Oradell Reservoir, Norwood, N.J.

The block diagram shows the area prior to excavation. The plan view shows the 3 m boulder after the peat and clay had been removed.

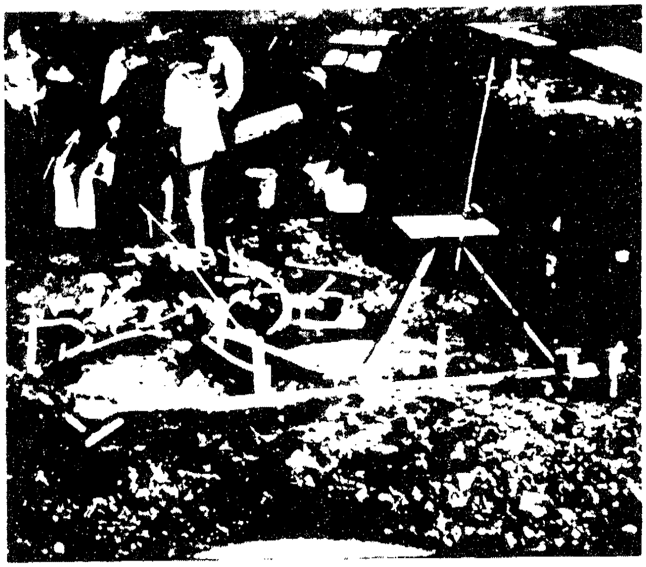

Fig. 7. Mastodon Site Excavation, Norwood, N.J.
Bones in pit, depth of pit 1.3 m. Reverse graded-bedded gravel in foreground; tan clay covers bottom of pit, bones (some already removed) had been encased in gray to black clay that graded up into the peat that formed the walls of the pit (See fig. 6)

Fig. 8. Yellow-Brown Tappan till over distorted Lake Hackensack varves.
Folds are overturned to the SSW (left). The Tappan till is above the black MnO2 line and the point of the trowel. Black recent peat at top contains roots of Spartina growing at the surface. Location is 50 m north of Mastodon Site

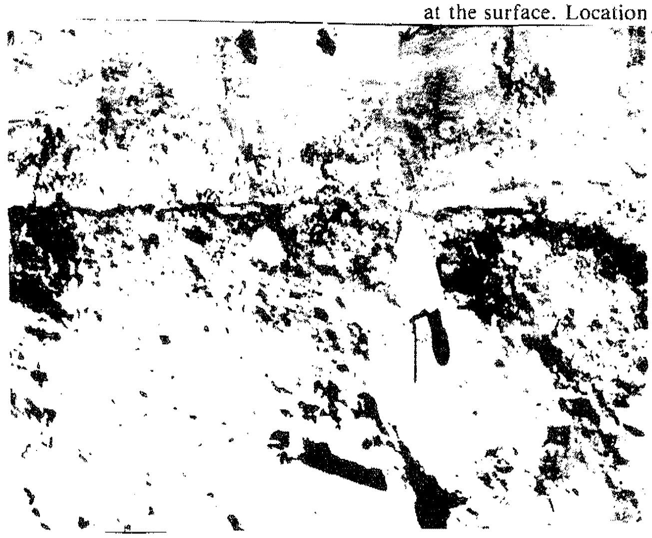

Fig. 9. Distorted red varves and fine red sand overlain by Tappan till. Close-up of Fig. 8. Note MnO2 stain at base of till. Trowel point at base of till.

ing shows that from the surface downward there is up to 3.75 m of peat and just over 2 m of lacustrine gray grading to tan clay in the kettle bog. It is underlain by at least 1.3 m of coarse clean sand of the outwash sheet. Beneath that is 1.9 m of massive lacustrine gray clay and gray clayey silt with two thin layers of peat. Beneath that lies more than 5 m of red Lake Hackensack varves which become progressively coarser with depth until they can only be described as sand and gravel rythmites. Triassic-Jurassic red shale is penetrated at a depth of 16.9 m.

The southern and central Hackensack River Valley, south of Emerson, is known as the "Meadowlands" and has been a tidal marsh for at least the past 2,000 radiocarbon years (Heusser, 1963). The marsh is underlain by a sheet of sand over the generally flat surface of the eroded and carbonate leached varves of glacial Lake Hackensack. The varves are inclined south with a slope of .426 m/Km (2.25 ft./mile) (Reeds, 1933). South of Rutherford the varves are dessicated up to a depth of 17 m (Lovegreen, 1974). Reeds (1927) and Salisbury (1902) report peat up to .7 m thick between the varves or red till and the overlying sand in River Edge, and on both sides of the valley at Carlstadt. The "sand sheet" is variously glacio-fluvial valley train, loess and fluvially reworked stratified drift. At Little Ferry the "sand sheet" is interrupted by a thin black clay layer (Reeds, 1926).

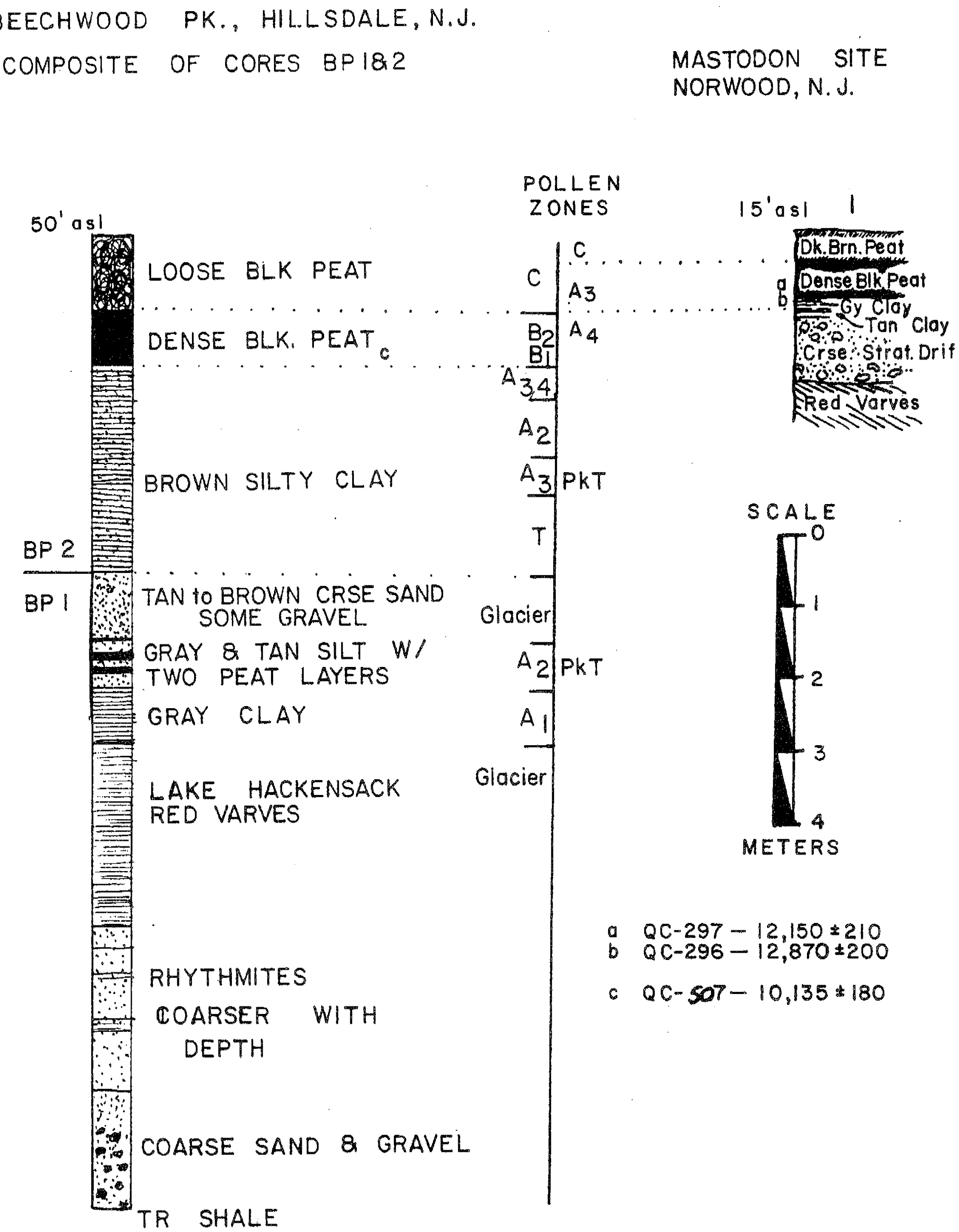

Fig. 10. Stratigraphy of Beechwood Park and the Mastodon Site compared. A summary of pollen zonation and C-14 dates are shown.

Geomorphology

North of Oradell the broad monotonously flat meadowlands give way to an irregular but gently rolling terrain which becomes much higher and hillier to the north. The western margin of the Hackensack Valley is flanked by steep hills and cliffs of Triassic sandstone. Eastern margins of the valley and its tributaries usually exhibit more gentle slopes.

More than 100 drumlins are to be found in this northern segment of the Newark basin (Fig. 2). With some significant exceptions, their long axes strike approximately north-south. In most of the region the drumlin axes are parallel to the regional strike of the bedrock and in the area south of the recurved arm of the Palisades (Hi-Tor) at Haverstraw many are rock-cored. North of Hi-Tor, the bedrock strike is significantly different (N50°E) and drumlin orientation shows no particular relationship to bedrock structure and is not believed to be bedrock-cored.

All the red till drumlins studied in Oradell, Rutherford and Paramus are rock-cored. They indicate southerly ice flow in the Hackensack Valley. Yellow-brown till drumlins are found north of the yellow-brown till border into the Hudson Highlands. These indicate ice flow from the Hudson River valley into the Haverstraw lowland and south into New Jersey as well as down the Hudson axis. In the Oakland and Franklin Lakes areas adjacent to the ridge of the First Watchung Mt. lava flow, drumlin orientation (NW-SE) and the Oakland moraine indicate topographic control of ice flow near the thinner terminal margin of the yellow-brown till ice. Yellow-brown till and stratified drift deposits indicate ice also entered the Newark basin through the Sparkill Gap, penetrating as far south as the Norwood kame grouping and the Dwarskill valley mastodon site (Fig. 1).

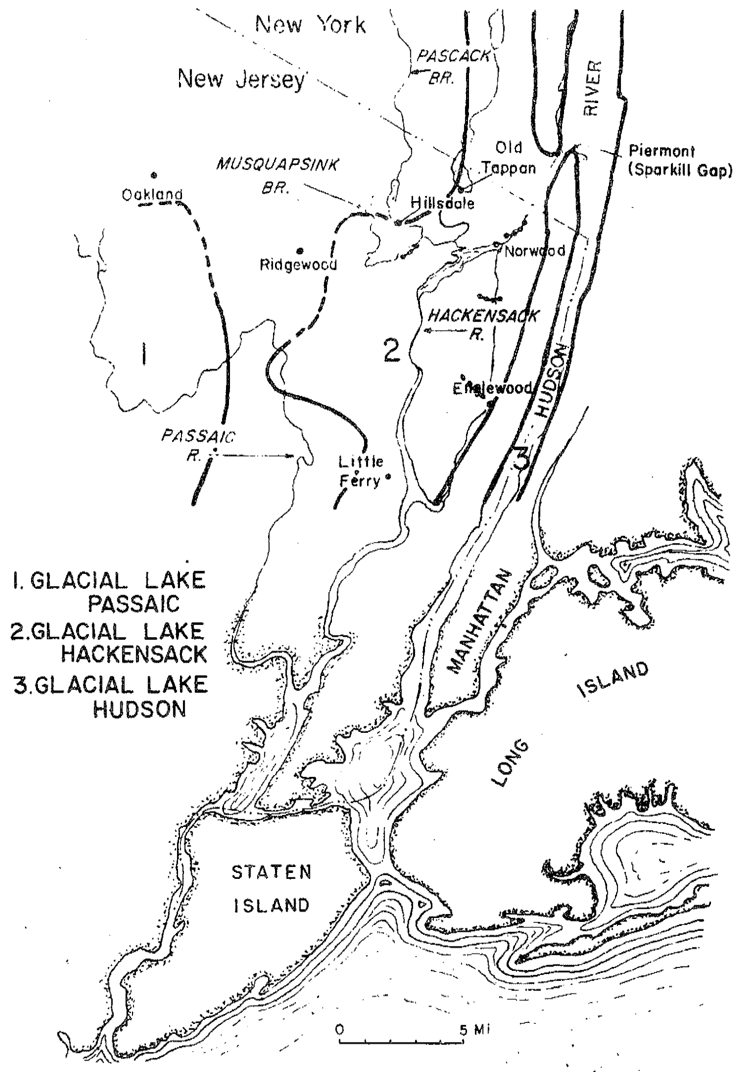

Fig. 11. Location Map of Proglacial Lakes Hackensack, Hudson and Passaic
Shorelines are approximate-lakes not shown to full extent. Dotted lines in Lake Hackensack are kame groups built into the lake.

Red drift ice-contact deposits, essentially kame deltas,were built into Lake Hackensack at numerous localities (Salisbury, 1902). Major deposits relevant to this study are shown on Fig. 11. The kame grouping at Englewood has produced the divide between Tenakill and Overpeck Creeks. The kames and outwash at Westwood were formed across the location of the present southernmost east flowing segment of the Musquapsink Brook (Fig. 11). The kame grouping at Norwood was built out into Lake Hackensack. Its sediments overspread the red varves eastward to the Palisade ridge and to the south. Associated red till and outwash in the subsurface indicate the arcuate kame grouping was built after the ice had readvanced into the lake. Use of Koteff's (1974) ice-contact sequence, slope projections and grain size analysis indicates that the outwash banked on the eastern side of the broad valley against the western slope of the Palisades is the distal portion of the east-spreading outwash fan. Varve deposition continued after the retreat of the ice front from the kame group. The southwest-northeast Dwarskill valley across this outwash fan was apparently initially cut many years later when the lake drained, at least in part, through Sparkill Gorge. At present the valley is occupied by two underfit streams which head near the New York State line where a low sandy divide separates their drainages. The Dwarskill is tributary to the Hackensack River drainage while Sparkill Creek flows northeast through the gap of its name to join the Hudson at the Piermont salt marsh.

Along the southern margin of the yellow-brown till is a series of ice-contact deposits (Fig. 12). They are chiefly kame groups as found in River Vale, Ridgewood and Old Tappan, a crevasse filling tributary to a massive

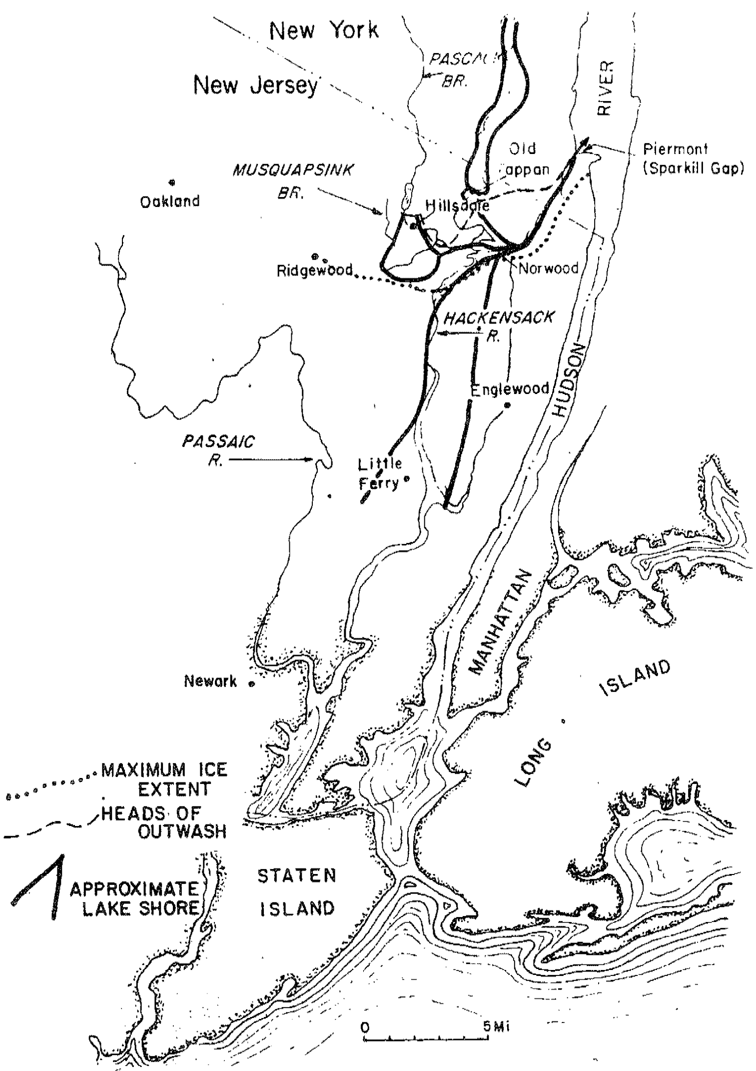

Fig. 12. Maximum extent of Tappan (yellow-brown till) glaciation and the line of Heads-of-outwash across the Hackensack Valley.

Arrow shows early post-glacial Hackensack River drainage through the Sparkill Gap. Proglacial Lake Sparkill is the largest. Pro- and post-glacial Lake Musquapsink is the smallest. Pro- and post-glacial Lake Tappan, twice the length shown extending to the northernmost end of the Hackensack Valley, was three times deeper than the other two.

outwash plain in Hillsdale, a collapsed moraine in River Vale and end moraines in Old Tappan and Franklin Lakes-Oakland. Outwash fans and valley trains extend south from these deposits for as much as 16 kilometers. These deposits are dissected by the present Hackensack River and its tributaries. Many kettles and kettle lakes dot the outwash deposits. Eskers, with a north-south alignment, are found in the Ramsey area as well as a single esker in Hillsdale (Salisbury, 1902).

This complex series of ice-contact deposits forms an undulating line just north of the approximate maximum penetration by the latest ice advance in the Hackensack Valley and is perpendicular to the general drumlin trend (Fig 12). They extend from Sparkill Gap to Woodcliff Lake, N.J., a distance of some 12 kilometers. Their nature and distribution indicate deposition as the result of ice-stagnation zone retreat (Koteff, 1974). Base level control for all but one of the deposits seems to have been the elevation of the then still isostatically higher land to the south of the ice sheet. Variations in slope are determined by the local elevation of each deposit and the local relief to the south.

From east to west these deposits are: the Sparkill moraine immediately north of the town of Sparkill, New York, the Old Tappan moraine and associated River Vale kames, the River Vale collapsed moraine and outwash, the Hillsdale-Westwood outwash plain with crevasse feeder and the Woodcliff Lake kame delta. All of these lie in the Hackensack River drainage basin (Fig. 12). The ice is believed to have penetrated several kilometers farther south in all the major valleys. Evidence is from the presence of scattered patches of thin yellow-brown till or from disrupted or missing older Lake Hackensack varves and ice-shove deformation in stratified drift.

Sparkill Moraine, Sparkill, New York:

Ice entered the Hackensack Valley in this region from two directions, from the north via the Haverstraw lowland and through Sparkill Gap (Fig. 12). Yellow-brown till and deformed varves are found as far south as the mastodon site (Norwood portion of the Oradell reservoir). At the Gap is an east-west morainic ridge across part of the valley immediately north of Sparkill Creek. Outwash was spread down the valley as a valley train at least as far south as Little Ferry. A proglacial lake, formed in front of the Sparkill ice tongue, and existed until the ice in the Hudson valley retreated north of the Sparkill Gap opening it to post-glacial Hackensack River drainage into the Hudson River. This early drainage and subsequent post-glacial events have altered the surface of this outwash plain (Fig. 13b).

Old Tappan Moraine, Old Tappan, New Jersey:

This east-west ridge, 2.3 km in length, lies across the path of the Hackensack River and stands some ten or more meters higher than the extensive and thick outwash plain to the south (Fig. 13c). The moraine consists of intercalated yellow-brown till and outwash indicating the presence of active ice. However, along its lateral margins, especially the western side, and in back of the moraine are found large kames and outwash deposits partially burying the moraine and indicating transition to a stagnant ice regime (Koteff, 1974). This is the only evidence of other than ice-stagnation zone retreat in the Hackensack drainage basin, probably because it is the major north-south valley in which ice flow was most ac-

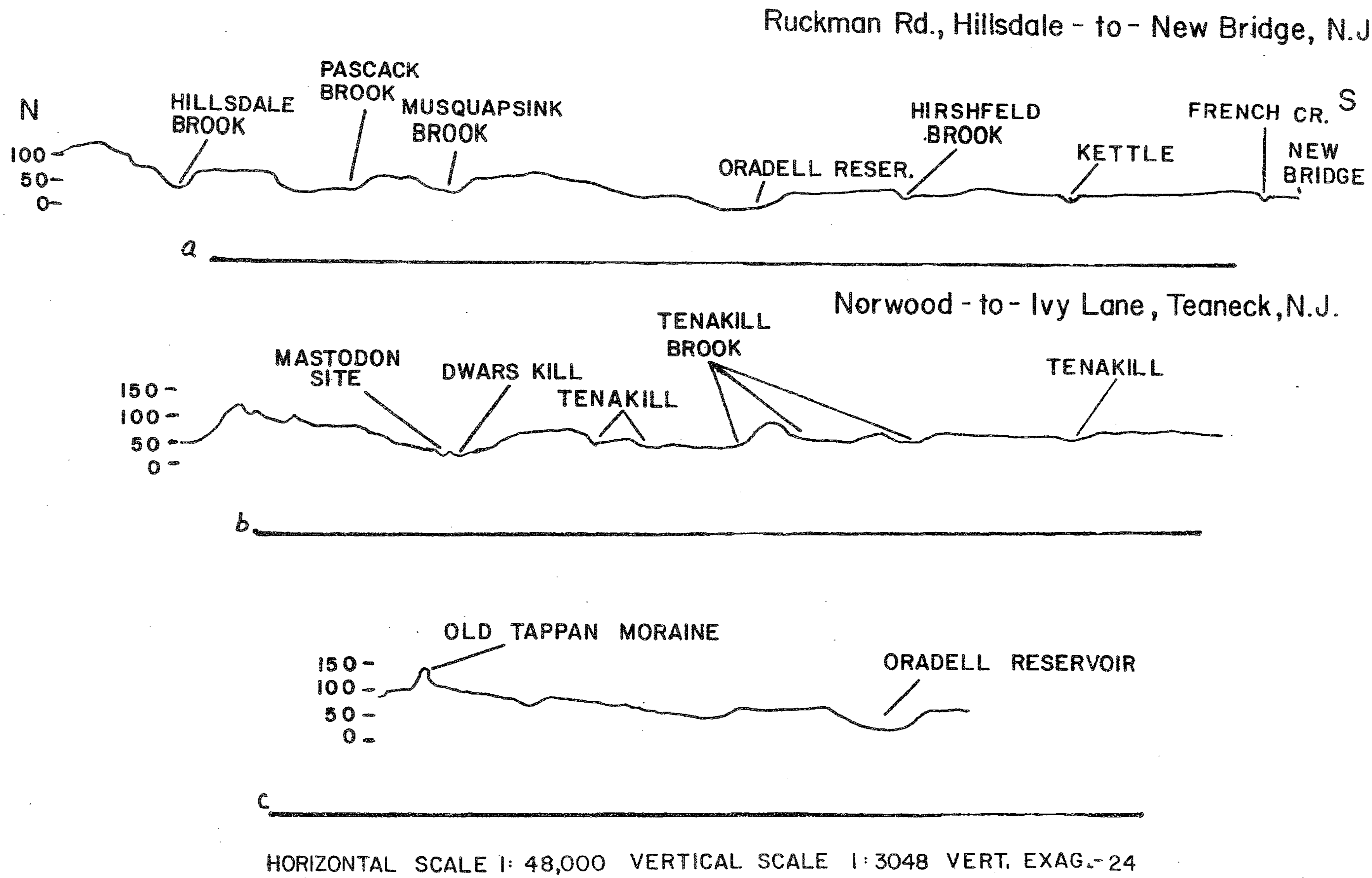

Fig. 13. Topographic Profiles from Heads-of-outwash

a. Hillsdale-Westwood Outwash Plain from Ruckman Rd. crevasse feeder at the north

b. Norwood Kame Group with dissected outwash to the south. Dwarskill and mastodon site in early post-glacial Hackensack River valley.

c. Old Tappan moraine and outwash plain

tive. The surface between the Sparkill and Old Tappan moraines is of subdued morainic habit or covered by outwash and the ice front position is difficult to trace. A series of large kames, referred to as the River Vale kames, curve northward from the eastern end of the Old Tappan moraine.

River Vale collapsed moraine, River Vale, New Jersey:

This area, immediately east and a little south of the Old Tappan moraine and about 1 kilometer wide, is more complex. A stagnant ice mass head-of-outwash front formed parallel to Cleveland Avenue. The moraine and overwash collapsed when the stagnant ice melted. It formed the low hummocky terrain north of Cleveland Avenue to Piermont Avenue where it is overlapped by outwash from the River Vale kames that formed along the western margin of the main Hackensack valley ice lobe. South of the collapsed zone at Cleveland Avenue is found an outwash plain which has been dissected by Pascack Brook and which grades into a valley train in the Hackensack Valley near the Oradell reservoir.

Hillsdale-Westwood Outwash Plain, Hillsdale, New Jersey:

East of Cedar Lane, River Vale-Hillsdale, and fed near its eastern margin from a north-south crevasse about 1 kilometer in length (Ruckman Rd.-Everdell Ave. ridge) the ice constructed a massive ice-contact outwash plain. The sequence illustrated here is typical of Jahns' prototype and Koteff's fluvial ice-contact sequence (Koteff, 1974) with the ice channel filling, kames, outwash plains and a valley train (Fig. 13a). The margin of the ice stood along Washington Avenue, Hillsdale and farther west along the line just north of the present northwest-southeast course of Pascack Brook (Fig. 12). The head-of-outwash is not as well defined in parts of the western segment.

Kame delta, Woodcliff Lake, New Jersey:

This sequence is a lacustrine ice-contact sequence with the stand of ice at the present site of the Woodcliff Lake dam. Base level in this sequence was different from all others. It was the level of the proglacial lake which lay to the south in the valley of the present Musquapsink Brook (Fig. 12). The earlier deposited Lake Hackensack kame delta in Westwood (Fig. 11) formed a dam at about 70 feet above present sea level across its present drainage just west of Kinderkamack Rd. at Old Hook Rd. in Westwood. Forset beds are found at the dam site (Salisbury, 1902) and thin yellow-brown till overlies the stratified drift to the north on the islands of the reservoir.

This series of deposits ends at the steep east-facing sandstone ridge at the western side of the Hackensack River drainage basin. Yellow-brown till is found only as a thin veneer on top of the ridge this far south and no distinct marginal deposit was located. The yellow-brown till thickens rapidly northward along the ridge and completely blankets the red drift beneath.

North of the Border:

North of this drift border, as at Park Ridge in the Pascack Brook and in the Hackensack River valley at Nauraushaun, New York (both at Convent Avenue and 5th Avenue) are some of the larger outwash deposits found north of the glacial readvance limit. Most are of the fluvial ice-contact sequence type.

Till Fabric Analysis

In the Saddle River valley, immediately west of the Hackensack River divide, a large excavation into the side of a drumlin has exposed the yellow-brown till in north-south and east-west walls (Stop 8 Fig. 16). Gully erosion has removed the finer particles and allows easy measurement of elongate cobbles. As of late April 1980, excavation has revealed more of the same. More than fifty of these clasts were measured. The majority of clasts have a bimodal compass orientation of S.20°E and S. 20°-40°W. The majority have the westerly trend (S20°-40°W) and a few large cobbles are oriented almost east-west. One steep-faced exposure shows a strongly fissile fabric to the till matrix. This fissility, even more strongly developed, was also observed in Park Ridge in the excavation for the Howard Savings Bank on Kinderkamack Rd.

The large clast till fabric supports the flow direction as indicated by the drumlin axis alignment. However, the major purpose here is to demonstrate that this yellow-brown till is a lodgement till and not an ablation till as suggested by Salisbury (1902) and also demonstrate that this "two tills" problem is not one of ablation till over lodgement till. Such a strong large clast lineation in the till indicates strong directional motion not achieved in an ablation till. Furthermore, the fissility of the till indicates a lodgement type till as well (Muller, 1974).

Palynology

Samples for pollen analysis were taken and analyzed from two stratigraphic levels; interstadial and post-glacial (Fig. 10). Both levels were found at the two sampling sites. The mastodon site area, in the Norwood section of the Oradell reservoir, yielded interstadial pollen from gray Lake Hackensack varves as well as from a partial but very significant post-glacial section.

Beechwood Park in Hillsdale yielded pollen from a thin clayey peat layer in interstadial lacustrine gray clay. The clay was beneath the sand and gravel that was co-extensive with the adjacent kame. The large fairly shallow kettle bog, set in sandy outwash against kames constructed at the distal end of a very large yellow-brown till drumlin, has yielded an apparently continuous post-glacial vegetational record.

A series of C-14 dates was obtained from the two sites. Four of the dates are substantiated by stratigraphy and pollen data and are considered valid. They are used to reconstruct the late and post-glacial events in a partial absolute chronologic framework. The C-14 dates are discussed in the next section.

The pollen data is summarized in this paper because of its field trip orientation and space limitation. A forthcoming paper will present the data in some detail.

Interstadial pollen

Light gray Lake Hackensack varves, that conformably overlie virtually identical red varves (except for color), were sampled in Norwood. They yielded a small amount of pollen. Two slides were made and each contained about 75 grains, two-thirds of which was arboreal pollen (AP). Pine, birch, spruce and popular were the predominant species. Grasses, sedge, heath and compositae comprised the majority of the non-arboreal pollen (NAP) type. Some aquatic species were in the sample. Sufficient NAP was found to indicate local derivation and demonstrates that the vegetation grew in and around the lake.

The Beechwood Park, Hillsdale sample was removed by drilling with a large truck-mounted rig. Sixty-five grains were counted. the NAP and AP percentages were the same as in the varves and the vegetation was similar. Birch, pine and alder were the predominant species with small pollen forms of the birch and pine much more abundant. Spruce and alder are present at both localities but have reverse percentage values. Grass, aquatics, lilaceae and sedge are the most abundant NAP with some subordinate heath and Typha tetrads. They both indicate the presence of an open boreal forest and the associated subarctic climate.

Post-glacial pollen

The Beechwood Park stratigraphy is summarized in Fig. 10. It is notable for an unusually long tundra (T-zone) sequence. Following the "textbook" pattern, it begins with a low pollen sum that increases upward. As is the case with virtually all bogs in the area, the pollen sum increases dramatically in the Spruce-Pine (A-zone) portion of the section. The transition to cool climate mixed-forest types (B-zone) is indicated by the disappearance of spruce and small pollen pine with replacement by large pollen pine and a doubling of oak pollen sum. Later increases in oak are at the expense of the compositae (ragweed) and pine. Compositae grains and other NAP make up an unusually high proportion of the pollen sum in most of the section. This is probably due to the high permeability of the underlying medium to coarse sand which blankets the area and which apparently prevented establishment of a closed forest. It presumably delayed the establishment of the invading forest as well. The bog was virtually filled by the end of B pollen zone time, for only about one meter of peat belonging to the C-zone is present at the top of the sequence.

The mastodon site in Norwood has only a partial post-glacial record but it is this which permits us to decipher much of the post-glacial history of the Hackensack River (Fig. 10). The post-glacial pollen record here begins abruptly when fluvial sediments change to lake clays. A thin layer of tan clay at the base was barren of pollen except for one "ghost" of Picea (spruce). Gray clays above contain much pollen with 55% spruce in the next decimeter. There is a sudden drop in spruce and a concomitant increase in pine pollen at that level. It is clearly the A2-A3 pollen subzone boundary. The gray clay grades rapidly upward into dense black peat and yields A3 zone type pollen (pine, alder, poplar and subordinate spruce) to its top. The upper 10 cm were leached of clay and the pollen showed signs of oxidation. The overlying dark brown, "fluffy when dry", peat contained C zone pollen and clearly demonstrates the presence of an unconformity.

Radiocarbon Dates

A total of eight radiocarbon dates were obtained on various materials. Four of them, all obtained on large amounts of peat, are considered consistant with the other data and are themselves internally consistent. They are also in agreement with similar dated sequences in the surrounding region. An attempt was made to date the remains of the mastodon, heavily impregnated with shellac, but all three dates, two on bone and one on tusk dentine, yielded ages that were far too young. Further, there was a date spread of some 1,200 radiocarbon years between the bones and the dentine. The fourth rejected date is on a small sample from interstadial peat at the Beechwood Park site. This previously reported date of 9,125 ± 150 B.P. (I-6286) (Averill, 1975) has been rejected as too young as the result of the establishment of a complete post-glacial pollen sequence and the above mentioned acceptable C-14 dates.

All four acceptable dates are from post-glacial peat. Two dates were obtained on the black peat in the lacustrine sequence at Norwood in which lay the mastodon remains. The basal peat, some 10 cm higher than the A2-A3 pollen subzone boundary, dates at 12,870±200 B.P. (QC-296). A sample some 15 cm higher produced a date of 12,150±210 B.P. (QC-297). At Beechwood Park, Hillsdale, in borehold #2 (B.P.-2), a date on the lowest peat 2.0-2.1 meters deep, near the B1-A4 pollen boundary, was 10,135±180 B.P (QC-507). Subsequent investigation of the bog located the deepest portion of the bog about 30 meters east of the B.P.-2 site. The deepest peat of B.P.-3 was at 3.75 m, some 1.7 m deeper than B.P.-2. The kettle has a total depth of 6.95 m at the B.P.-3 site. The date on the lowest peat from 3.5 to 3.75 m is 10,575±250 (QC-700). As both dates are on the lowest peat encountered, it appears as if they date the transition from an ideally eutrophic lake to a strongly eutrophic condition with the onset of the formation of peat. The two dates closely mark the A-B pollen zone transition.

Bog-bottom Sedimentation

The C-14 dates obtained tell us glacial ice abandoned the area more than 12,870 YBP. The question is how much more? Sedimentation rates of 0.08 cm/yr (Davis, 1969), and 0.036 cm/yr (Davis and Deevey, 1964) have been used in an attempt to estimate the time of glacial recession. The sites here indicate that Davis' revised rate of 0.08 cm/yr is more accurate at the Hillsdale Beechwood Park kettle bog.

Site B.P.-2 is 5.9 meters deep. The lowest peat occurs at 2.1 m. The C-14 date at 2.0 to 2.1 m is 10,135±180 B.P. (QC-507). The age of the silty clay sediment beneath the peat is determined by the following arithmetic: 5.9 m - 2.1 m = 380 cm ÷ 0.08 cm/year = 4,750 years + 10,135 years = 14,885 B.P. for the time of the onset of bog sedimentation.

Site B.P.-3 is 6.95 meters deep. The lowest peat is at 3.75 m. The C-14 date at 3.5 to 3.75 m is 10,575±250 B.P. (QC-700) as the peat had begun to accumulate a little earlier in the deepest part of the lake. The age of the silty clay sediment beneath the peat is: 6.95 m — 3.75 m = 320 cm ÷ 0.08 cm/year = 4,000 years +10,575 years = 14,575 B.P. for the time of the onset of bog sedimentation.

As both bore sites are near the center of the bog, we have assumed sedimentation began at the same time and that the rate was the same at both sites. The difference between these two dates is only 310 years and is well within one standard deviation of the two C-14 dates (430 years). It indicates the probability that they date the same event. Use of the 0.036 cm/year sedimentation rate places the date range well outside of two standard deviations for the C-14 dates (860 years) making this sedimentation rate unrealistic. It also places final ice recession from the lower Hudson Valley at about 20,000 YBP which is much earlier than any present data indicates.

The low pollen sum in the lowest 1.5 meters of the Beechwood Park bog supports either very slow encroachment of vegetation following glaciation or a rapid sedimentation rate. As vegetation existed in the area prior to the readvance, it probably existed just to the south of the ice margin and so very slow encroachment by vegetation seems unlikely. The alternative must be a high rate of sedimentation. In fact, correlation of the A2-3 pollen subzone boundary and the date of 12,870 B.P. in Norwood with the same pollen level in the Hillsdale section infers a slightly more rapid rate of sedimentation than 0.08 cm/year, at least in the lower portion of the bog.

With this in mind, it is probably safe to say that glacial ice began its retreat from the Hillsdale head-of-outwash within a few centuries of 15,000 YBP.

THE PIERMONT TIDAL MARSH

The Piermont estuarine tidal marsh fringe abuts the Palisades ridge along the west shore of the Hudson Estuary between the Piermont Pier on the north and Sneden Landing on the south (Fig. 2a). The marsh exactly spans the 3 kilometer wide Sparkill Gap of Johnson (1931). The marsh is about 0.6 kilometers wide at its northern end and tapers to a feather edge at its southern terminus. Although examination of the Nyack 7½-minute Quadrangle Sheet suggests that the marsh developed as the delta of Sparkill Creek in the apex bounded by the Palisades Ridge on the west and the Piermont Pier on the north, our boring program within the marsh indicates that a portion of the marsh has been in existence for at least several thousand years. The Piermont Pier was built as the eastern terminus of the Erie Railroad in 1841. An 1882 map of the area, when compared with the most recent topographic map of the area, indicates that the marsh has gained about 25% in area during a 73 year interval.

According to Lehr (1967), the Piermont tidal marsh contains the most northerly concentration of true halophytes in the Hudson Estuary. Adjacent to the road at the base of the Palisades escarpment, the marsh is dominated by cattail *(Typha sp.)* while the marsh adjacent to the estuary is covered with *Spartina spp.* with minor amounts of other salt marsh halophytes. Leveling from a Palisades Interstate Park bench mark adjacent to the swimming pool complex indicates that most of the marsh surface is within 30 centimeters of Mean High Water. Therefore, the marsh surface appears essentially in equilibrium with contemporary sea level and forms a convenient reference datum.

We have sunk numerous bores through the marsh to refusal since 1966. Our initial boring instrument was the Davis (U.S.G.S.) Peat and Marl Sampler, later a one inch I.D. Davis-type sampler fabricated in the Queens College Machine Shop, and for the past two years, the "Dutch-type" Gouge Auger which secures a continuous sample up to six centimeters in diameter in one meter flights. Most of these samples were mixtures of estuarine organic silt and peat composed for the most part of phreatophytic culms and roots. With the exception of the two oldest samples, we did not encounter basal peat nor sedge peat at any point just above refusal. The two deepest and oldest samples are true basal peats. Refusal, encountered at increasing depths toward the east, appeared to be a stratum that included sand and gravel but could not otherwise be identified. All our basal samples contained specimens of either brackish water diatoms or the foraminifer *Trochammina cf. inflata* or both of these taxa.

We assume that the first peaty material to accumulate on the refusal substrate marks the level of the sea at that time. We further presume that the radiocarbon date obtained on these basal materials when plotted on a time-depth plot yields a reasonable plot of the late Holocene relative marine transgress at this locality. Indeed, the plot of our data (Fig. 14) yields a transgression rate of close to 2.0 meters over the past 7,000 millennia radiocarbon years which appreciably decelerates in the most recent millennia. Our plot also displays considerable noise. Some portion of this noise is undoubtedly due to operator and instrument errors of various kinds. In addition, neotectonics and sea level fluctuations may be a source of some of the variability. Finally, it may well be that some of our presumed basal peat is allochthonous and has moved to another level from its point of original accumulation.

Concluding this section, the sea level data obtained from the Piermont Marsh demonstrates that the Hudson Estuary has been in existence for at least 7,000 radiocarbon years and has witnessed a generally transgressive mode for much of this interval. Paradoxically, our micropaleontological data suggest that the estuary is perhaps less saline today than it was during mid-Holocene times. We believe that the valley has been shoaling more rapidly than the sea has been rising thus reducing the cross-sectional area of the estuary and attenuating the penetration of the salt-water wedge instrusion upstream.

Description of Woodfordian Deglacial Events

At a point in time, not yet determined precisely, the Hudson lobe of the Woodfordian ice sheet began its retreat from the Harbor Hill terminal moraine in western Long Island and Staten Island, New York and Perth Amboy, New Jersey. Our story begins with the formation of the large proglacial lakes (Hackensack, et al.) trapped between the Harbor Hill moraine dam at the south and the northward retreating ice front. We will not speculate here on the original flow direction of the late Woodfordian ice sheet and the source of the ice (Sanders, 1974; Sanders and Rampino, 1978; Salisbury, et al; 1902; Reeds, 1930, 1933; Gager, 1932) or the relationship of the lakes to the Harbor Hill and Roslyn tills (Connally and Sirkin, 1975).

The melting ice deposited a thick carpet of sediments over the irregular bottom of the expanding Lake Hackensack (Lovegreen, 1974). Pauses in the retreat of the ice are marked by kame deltas (Salisbury, 1902). After an unknown length of time, the ice front stood north of Little Ferry. Using modern retreatal rates for Alaskan glaciers, where the ice front terminates in water (Goldthwait, 1974) and extrapolating that rate to the late Woodfordian glacier in the Hackensack Valley, the retreating ice would have required about 500 years to reach the Little Ferry position. Reeds (1926) estimated the retreat rate at 100 feet/year, which would require some 1,200 years for the ice front to retreat to Little Ferry. Neither value allows any time necessary for possible minor readvances of the ice during this interval. At Little Ferry, Reeds (1926) counted 2,550 red varves and indicated that some of the upper varves had been removed by erosion. In Norwood, Averill (1980) found some 300 gray varves containing pollen. The use of the minimum figures indicates that glacial Lake Hackensack, from its small beginning to its maximum extent surrounded by a spruce-park forest, existed for over 3,350 calendar years.

Glacial ice was gone, temporarily, from the Lower Hudson. Lakes Hackensack, Flushing and Hudson remained as its legacy, the latter as Lake Hudson-Albany probably still growing larger somewhere up the Hudson Valley. The interstade was already some three centuries old.

The moraine dam was breached and the lakes drained, exposing the lake floors to erosion, carbonate leaching, dessication, invasion by vegetation and lacustrine deposition in isolated basins. One can only speculate as to the cause of the breach. However, it was almost certainly not due to isostatic rebound as is generally believed. As only about one-half of the differential rebound had occurred by about 13,000 Y.B.P., we suspect very little rebound had occurred by the time of drainage which was about 3,000 years earlier. Further, if the isostatic bulge concept of rebound is correct, then the southern end of the lake may have been close to its maximum differential elevation.

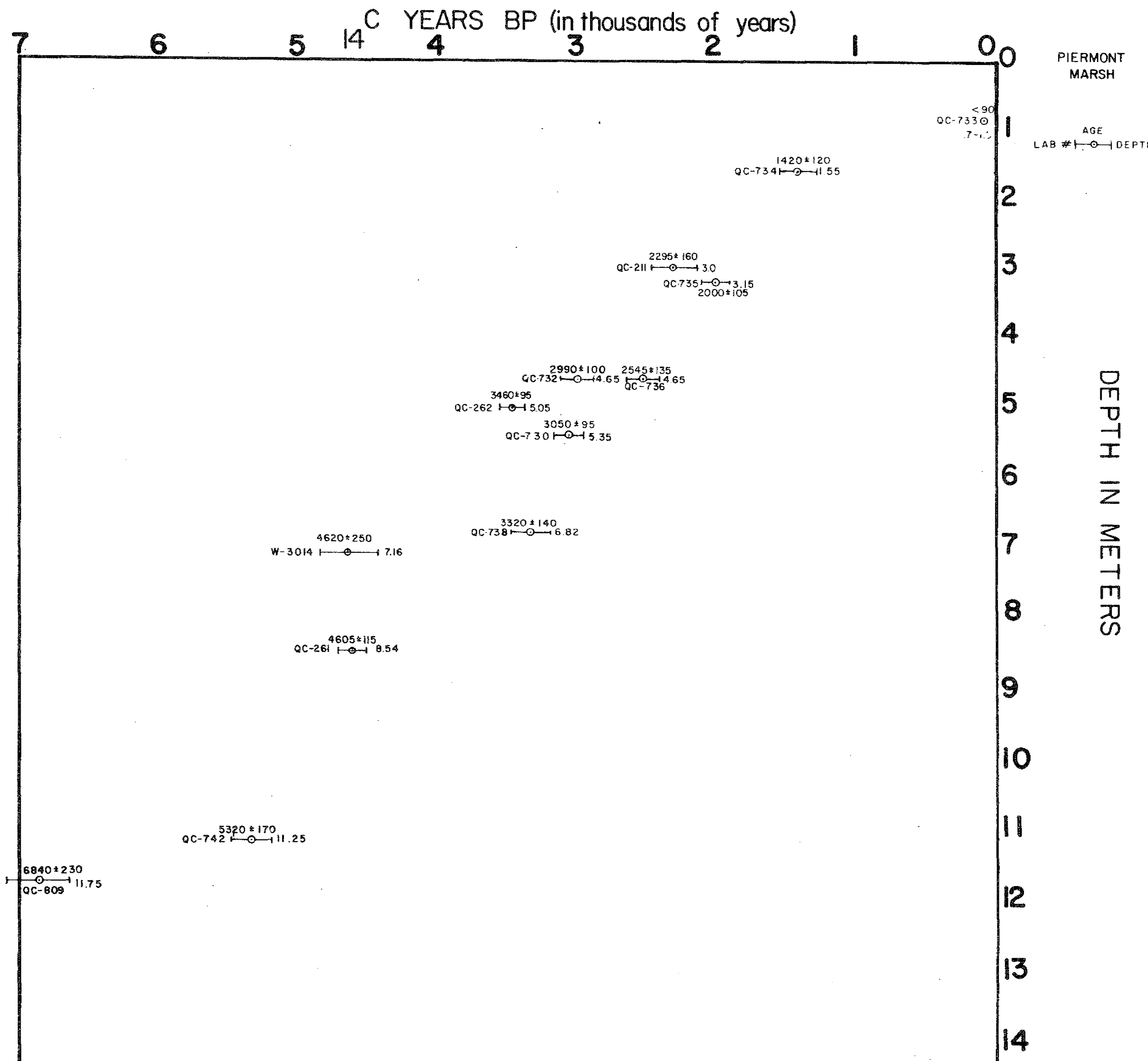

Fig. 14. Sea level curve - Piermont Marsh, Piermont, N.Y.

Thawing of the moraine dam, perhaps aided by melting of large buried ice blocks at the Narrows and Arthur Kill, supported by ground water sapping from the hydrostatic head of the lakes behind the dam are the more likely cause of the breach. A sudden increase of hydrostatic head might have been a precipitating factor. This could have been caused by the catastrophic drainage of Lake Passaic into Lake Hackensack, or readvance of glacial ice (a glacial surge?) down the Hudson Valley. Both would have raised the level of the lakes, either providing the extra pressure to break the dam or causing the water to overflow at a low point where recently melted ice blocks had lowered the crest of the ridge. Drainage of Lake Hackensack was through the lowlands near Jersey City and through the Sparkill Gap. Because of the northward isostatic tilt of the surface, most of the later lake drainage was through the Gap. The flow of water cut a broad valley across the outwash fan at the eastern margin of the Norwood kame group. The Dwarskill and Sparkill Creeks now lie in this valley. (Figs. 12, 13, 15).

Interstadial Hackensack River drainage was through the Sparkill Gap where it joined the Hudson River as a hanging falls. Streams flowed from the south and north through the Gap. It is likely that a large lake existed in the upper Hackensack Valley because of isostatic tilt.

The duration of the interstade is subject to conjecture. The meter of massive (unvarved) gray lacustrine clay and the 0.8 m of overlying silt and thin peat layers at the Beechwood Park site (Fig. 10) are interstadial and presumably deposited after Lake Hackensack drained. A conservative estimate of 700 years is proposed (Averill) for the time to deposit these sediments. Such an extended period of time is supported by the extensive erosion of the lake bed by interstadial streams. Further, the buried red glacial drift has been leached of carbonates to a depth of 30 cm. The 300 gray varves plus these estimated 700 years give an interstade of one millenia duration.

Readvance ice thrust down the Hudson Valley penetrating into the Hackensack Valley at Haverstraw, New York and at the Sparkill Gap. Just north of the line of maximum ice penetration, the glacier built a series of ice-contact deposits from Sparkill, New York across the Hackensack Valley to Woodcliff Lake, New Jersey. These deposits have been described earlier. Their outwash deposits have covered most of the till that would show the maximum spread of the ice. These ice-contact deposits indicate that the mode of deglaciation was ice-front stagnation zone retreat (Koteff, 1974).

The glacier apparently pushed farther south in the main Hudson Valley, as meltwater continued to pour through Sparkill Gap into the Hackensack Valley when the ice front was north of the Sparkill Moraine in the Hackensack Valley. The meltwater formed pro-glacial Lake Sparkill that headed at the Gap, covered the area of the present Oradell reservoir and apparently extended at least as far south as Little Ferry (Reeds, 1926) (Fig. 12). The baselevel dam was probably the still isostatically higher land to the south. For a time the flow of water into the lake must have been small because a black clay layer was deposited in the middle of the outwash and valley train sequence. Fine sand deposited over the clay tells us the ice began to melt more rapidly or had readvanced and penetrated through the Gap again to supply this upper sand. Certainly the periglacial involutions formed in the clay and sand tell us the ice was not far away. (Fig. 5)

After the ice began its retreat up the Hackensack River valley, sedimentation began in the kettle bog at Beechwood Park in Hillsdale. The extrapolated bog bottom date of 14,800 YBP discussed earlier in this paper is suggested also as the approximate time that the ice in the Hudson Valley retreated north of the Sparkill Gap. This allowed the proglacial lake to cascade into the Hudson from its hanging valley at Sparkill Gap.

Early post-glacial Hackensack River drainage was established through the Gap. A stream drained northward from the isostatically induced baselevel dam south of Little Ferry while another flowed southward from the proglacial lake impounded behind the Old Tappan moraine and the River Vale kames (Fig. 12). The course of the Pascack Brook was established just south of the line of the heads-of-outwash by meltwater after the construction of those great sheets of outwash. Note that the stream's angle of insertion into the Hackensack River is towards Sparkill Gap. The present valley of the Musquapsink Brook was dammed near its southern-most segment by outwash associated with the earlier glaciation. An interstadial lake presumably existed there and drained north and east into the Hackensack River. If the lake did not exist, there certainly was a proglacial Lake Musquapsink (Fig. 12) that occupied the shallow basin, for the Woodcliff Lake kame delta built into the lake. The lake drained northward into Pascack Brook in Hillsdale for some time until isostatic rebound raised its northern end slightly and the dam at the south was sluiced away.

The previously mentioned proglacial lake behind the Old Tappan moraine, herein called Lake Tappan, had remained as a post-glacial lake that extended well up the valley, probably to its northern-most limit at the recurved arm of the Palisades at Haverstraw. The isostatic rebound referred to earlier was tilting the land surface southward in the upper Hackensack Valley. Lake Tappan's dam was higher relative to its water surface and so it lasted for a longer time than Musquapsink Lake.

About 13,000 YBP the dam burst draining the lake catastrophically. The torrent of water poured through the Norwood portion of the Oradell Reservoir on its way to the Hudson through Sparkill Gap. This catastrophic outpouring could not be drained through the narrow rock-walled gorge quickly enough and it became choked with sediment. As a result, a sandy divide was constructed across the old drainage course at the New York-New Jersey border. The crest of the divide is presently 40 ft. ASL (above sea level).

The evidence for this story was found in the Norwood section of the Oradell reservoir where a reverse-graded coarse sand to boulder sequence lies directly beneath lacustrine clay (Fig. 6). The flow direction is clearly indicated by the boulders in the lee of the 3 meter diabase boulder (Fig. 6). The sandy divide dammed the drainage and formed a large lake, herein called Lake Norwood, that extended south along the river valley to River Edge and northward up the valley to the vicinity of West Nyack, New York. It included the area of the present Oradell Reservoir but was at least three times as large (Fig. 15).

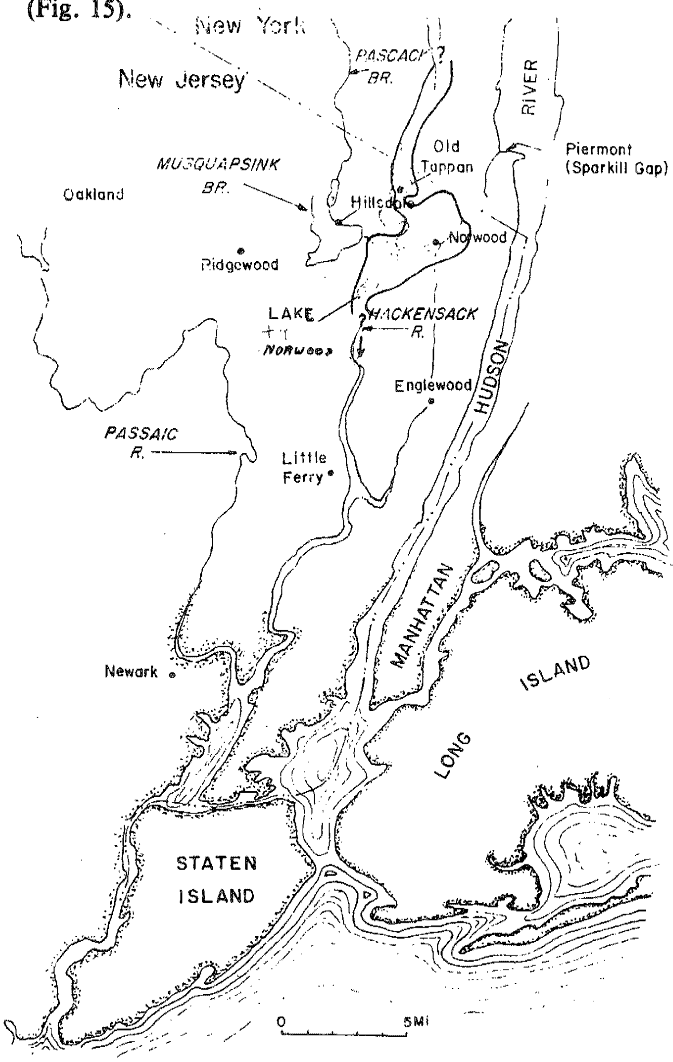

Fig. 15. Post-glacial Lake Norwood

The Lake Norwood sequence stratigraphy of coarse sand, tan clay, gray to black clay and black peat in Norwood (Fig. 6) is repeated at Fifth Avenue near Nauraushaun, New York at about 30 ft. ASL. The same stratigraphy repeats itself, but in an off-lapped sequence at 40 ft. ASL at Westwood Avenue in River Vale. As the dam top is at the same elevation it must mark the former shoreline. The elevation of the bottom of the lake sequence in Norwood is at about 5 ft. ASL. Therefore, the depth of the lake at Norwood, where the mastodon apparently fell through the ice and drowned, was about 10.7 m (35 ft.) deep (40 ft. ASL-5 ft. ASL). Assuming an original isostatic tilt of .426 m/Km (2.25 ft./mile) (Reeds, 1933), the 64 Km (40 miles) distance from the terminal moraine would place the Norwood area 27 meters (90 ft.) lower than today. This is in approximate agreement with the present elevation of the uppermost varves at opposite ends of the basin (Salisbury, 1902, Reeds, 1926). An interstadial stream channel is cut at least 9 m (30 ft.) into the varves below the bottom of the post-glacial lake at + 5 ft. ASL. This post-glacial lake was 10.7 m (35 ft.) deep at the same site so a rough estimate of somewhat more than one-half (perhaps two-thirds) of the rebound had occurred by the time of the catastrophic flood.

The basal peat in the lake sequence has been dated at 12,870 ± 200 B.P. (QC-297) and is the basis for establishing the 13,000 YBP date as the approximate time of the catastrophic flood and resulting lake.

Establishment of modern south-flowing through drainage occurred sometime after 11,000 YBP. The peat sequence deposited on the lake bottom was partially eroded after the lake drained and the modern Hackensack River began its history. The remaining peat is all of upper A pollen zone. Extrapolated peat sedimentation rates on the two C-14 dates at Norwood (Figs. 6 & 10), together with the pollen indicate the lake existed until at least 11,000 YBP.

The vegetation history of the area in post-glacial time is clearly shown at Norwood and the Beechwood Park kettle bog. Each of the pollen zones T, A, B, and C, C are clearly represented (Fig. 6). The T zone of tundra is unusually well represented. The A2-3 pollen subzone boundary is also very clearly marked and closely dated with C-14 at about 13,000 YBP. The two dates of 10,135 ± 180 B.P. and 10,575 ± 250 B.P. (QC-507 & 700) are close to the A-B pollen zone boundary, bracketing it. This is somewhat earlier than indicated by most other workers in the surrounding areas. Finally something that does not show on the pollen summation diagram is a *very* high birch pollen sum in A3 pollen subzone time. This last is a puzzlement and something to say on another day.

Summary of Late Woodfordian Hudson Ice Lobe Deglacial History.

All figures used here to calculate the dates of deglacial events are minimal figures. C-14 dates placing constraints upon these events are the Long Island date sequence of Sirkin and Struckenrath (1975) of 22,800 YBP for the emplacement of the Harbor Hill terminal moraine till and the oldest closely controlled postglacial date in the lower Hudson region of 12,870±200 B.P. (QC-297) (Averill, 1980)

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DATE	EVENTS
22,800 YBP	Emplacement of the Harbor Hill till (date approximate)
?YBP	Retreat with the formation of a proglacial lake and lake bottom sediments
?YBP	Readvance to western Long Island & emplacement of thin Roslyn till over lake sediments
19,250 YBP	Date of initial retreat of Lake Hackensack glacier from Roslyn till contact with Harbor Hill moraine.
19,250 to 18,750 YBP	Retreat with the formation of proglacial lakes Flushing, Hudson and Hackensack to the Little Ferry ice front position across the Hackensack Valley.
18,750 to 16,200 YBP	Deposition of red drift by Lake Hackensack glacier continues during retreat to the Highlands at the northern edge of the lower Hudson Region. During this time there was one known readvance of at least several kilometers. It is not calculated in the figures at the left.
16,200 to 15,900 YBP	Beginning of interstade: Lake Hudson-Albany expands with the retreating ice front. During this time some 300 gray varves were deposited in Lake Hackensack.
15,900 YBP	Catastrophic drainage of Lake Hackensack, et al, with the breaching of the terminal moraine at the Narrows and Arthur Kill.
15,900 to 15,200 YBP	Interstadial Hackensack River Valley drainage through Sparkill Gap. Erosion, dessication and reforestation of lake bed. Deposition of 1.8 meters of interstadial clay and silt lake deposits at Beechwood Park site.
15,200 to 15,000 YBP	Tappan (Yellow-Brown till glaciation) Readvance of the Hudson Valley ice lobe into the Hackensack Valley and lower Hudson Valley. Duration of active glacial ice in the Hackensack and lower Hudson Valleys is a rough approximation based on till and outwash thicknesses present in the Hackensack Valley by extrapolating modern sedimentation rates of temperate Alaskan coastal glaciers (Goldthwait, 1974). Figures are minimal values.
15,000 YBP	Retreat from the Sparkill-Old Tappan - Hillsdale-Woodcliff Lake heads-of-outwash. Formation of various temporary proglacial lakes (ie. Lake Musquapsink, Lake Tappan, Lake Sparkill).
14,800 YBP	Advent of sedimentation in Beechwood Park kettle bog. Return of vegetation. Stagnant ice mass remnant in Ramsey area. Drainage of Lake Sparkill.
13,000 YBP	Lake Tappan, behind the Old Tappan moraine, had

	remained as a long-lived post-glacial lake. Its dam burst and catastrophically flooded the drainage through Sparkill Gap. Formation of a new post-glacial lake in the mid-Hackensack Valley, referred to here as Lake Norwood.
12,870 YBP	Date on basal peat in Lake Norwood. Spruce to pine forest sudden change recorded in dark gray clay 10 cm below; and just 5 cm above the bottom of the lacustrine clay.
12,000 to 11,000 YBP?	Drowning of the mastodon.
11,000 YBP (maximum date, possibly several millenia later)	Final drainage of post-glacial Lake Norwood, largely the result of differential isostatic rebound and establishment of through-flowing southward Hackensack River drainage. Erosion predominates throughout the valley.
2000 YBP	Rise of sea level and advent of estuarine conditions in the Hackensack Valley penetrating north into River Vale. Tidal marsh sedimentation begins.
1915 A.D.	Construction of the Oradell Reservior dam.

MAPS Topographic maps of the study area are all U.S.G.S. 7½ minute quadrangles. The first five listed at the left cover the area of more detailed study. The latter five are the areas of reconnaissance examination. Those wishing to examine the area closely will find them invaluable.

Weehawken, NJ-NY	Haverstraw, NY
Hackensack, NJ	Thiells, NY
Park Ridge, NJ-NY	Central Park, NY -NJ
Nyack, NY-NJ	Jersey City, NJ-NY
Yonkers, NJ-NY	Brooklyn, NY

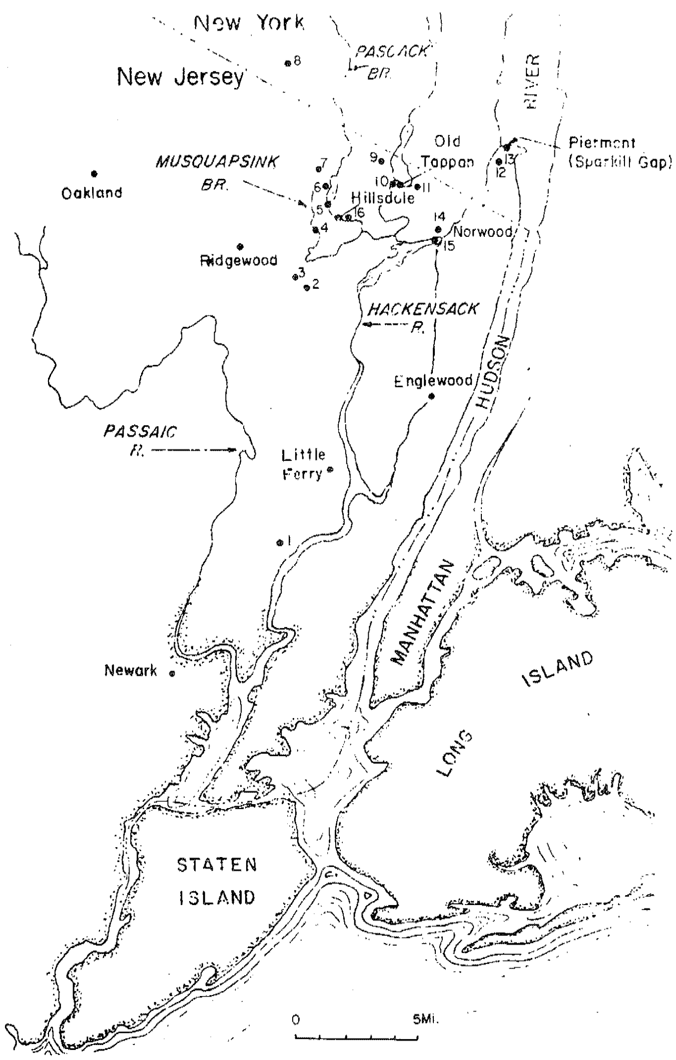

Fig. 16. Stop locations for field trip

FIELD TRIP ROAD LOG

MILEAGE

0.0	Rutgers-Newark parking lot; turn LEFT onto Warren St.
0.1	LEFT turn at 2nd traffic light onto Washington Ave.
0.5	Bear RIGHT onto Bridge St. (crossing Broad St.)
0.7	Take bridge over Passaic River. Continue STRAIGHT onto Harrison St. to the New Jersey Turnpike.
2.9	LEFT onto Turnpike Entrance. Proceed to Exit 16E and leave Turnpike. Mileage will restart at 0.0 at the toll plaza.
0.0	Toll Plaza: Exit 16E; Keep to left. Take Rt. 3, Secaucus; Proceed to light.
0.6	Turn LEFT. Proceed straight ahead. (at 0.8 mile, at County Rd., we may turn left if exposures are available). We are crossing the Secaucus drumlin. It is aligned with its long axis N-S. A relatively thin red till overlies this red and gray rock-cored drumlin. Contact metamorphism of the sandstone was observed throughout most of a very large excavation. The Palisade Sill cannot be far below.
1.1	At light bear RIGHT toward Rt. 3
1.4	Make RIGHT onto Rt. 3. We are crossing the old Lake Hackensack floor now covered by a 3 to 6 meter sheet of sand with the tidal marsh over the sand. The lake covered the "Meadowlands" as far as one can see. The ridges to the east and west formed the shores.
4.6	Turn onto Rt. 17 South (signs). Proceed to light (Polito Ave.). (at Holiday Inn)
5.5	Turn LEFT onto Polito Ave. Proceed to dead end road on right at 5.7 miles.
5.7	Turn in road (unnamed) and park.
5.8	**STOP 1** This is the Rutherford rock-cored drumlin. The Upper Triassic Brunswick formation sandstones and shales are exposed here at the side of the drumlin. Note the copper mineralization. Red drift, sometimes till, sometimes sand and gravel, blanket the drumlin. Some yellow "loam" may be exposed (if we're lucky). The "loam" here is about 15'

cm thick and is loess. This drumlin was at the western edge of Lk. Hackensack.
Leave Stop 1

5.9 Turn RIGHT onto Polito Rd. Proceed to Stop sign.

6.1 Turn RIGHT onto Valley Brook Rd. Proceed to light on Orient Way.

6.3 RIGHT turn on Orient Way. Proceed to traffic light.

6.9 RIGHT turn onto Rt. 17 North. We are leaving the drumlin and proceeding onto the old lake bed surface. As you drive north on Rt. 17, note what was the steep western shoreline of the lake. A deep preglacial valley exists under Rt. 17. The varves are by far the thickest here along the western side of the Hackensack Valley (Lovegreen, 1974).

8.5 At the center of the valley close to the Hackensack River are the former brick yard clay pits from which Reeds' extracted and counted 2550 varves. Mileage approx.

Intersection of I-80 and Rt. 17. We are now crossing one of the sandstone ridges that form the low divide between the Hackensack and Passaic valleys.

Intersection of Rts. 17 & 4, Paramus. We have just passed through the divide between the Hackensack and Saddle Rivers and are near the distal end of the outwash fan associated with the Ridgewood kame group. As we proceed north on Rt. 17, notice the slope of the outwash plain.

18.2 Turn RIGHT on Midland Ave. This is the northern-most known location of Lk. Hackensack red varves in the Saddle River valley. (G.S. Pkwy boring records.) Proceed on Midland to light.

19.0 Turn LEFT onto Farview. Proceed on Farview to fork.

19.6 Turn RIGHT onto Ridgewood Ave. Proceed .1 mile.

19.7 Turn LEFT into Parking Lot of Bergen Community Museum.

STOP 2 Mastodon display and rest stop.

19.9 RIGHT turn from parking lot onto Ridgewood Ave.

20.0 RIGHT turn at stop sign onto Farview Ave. Proceed to traffic light.

21.3 LEFT turn on Oradell Ave. (East Ridgewood Rd.) Proceed to Garden State Parkway Entrance.

21.5 RIGHT turn, NORTH on G.S. Pkwy. We are at the crest of the Ridgewood kame group. Travel almost to main G.S. Pkwy roadway. Do NOT enter.

21.9 **STOP 3** PARK ON MACADAM APRON ON FAR RIGHT.

Walk back to kame. South side of kame shows stratified drift. This used to be a gravel pit. We are told that much coarser gravel was removed from here than is presently exposed. Return to north side of kame. Clean off the face and note the vertical sand layers with minor asymmetrical folds. At the top of the exposure is a layer of fine to medium sand capped with yellow loess under the top soil and vegetation. Return to bus.

21.9 Enter G.S. Pkwy North; Toll Plaza at 22.8 miles. Proceed to Exit 168 on the right.

24.0 Bear RIGHT off the Parkway, Exit 168 to Stop sign.

24.1 RIGHT TURN onto Washington Ave. Proceed short distance to small bridge on Musquapsink Brook.

24.2 **STOP 4** Musquapsink Brook; exposure of red till in the banks to the south. Bedrock in stream to the north. Leave Stop 4.

24.2 Proceed along Washington Ave. (East) to light.

24.7 Turn LEFT onto Pascack Rd. (North) Proceed to Church Rd.

25.8 Turn RIGHT onto Church Rd. (Dam Rd.)

25.9 Park in church lot.

STOP 5 We will have to walk along the causeway. Please watch the traffic. This is the Woodcliff Lake kame delta that built into the proglacial lake in the Musquapsink Valley. Note the very sharp drop in elevation below the dam.

25.9 Return to Church Rd. and proceed to Stop sign.

26.0 Turn RIGHT onto Pascack Rd. and proceed to light. As we ride, note the till capping outwash on the island in the lake. It forms a small dark slightly overhanging layer at the top.

26.5 RIGHT turn onto Woodcliff Ave. Follow road to fork and bear LEFT (STRAIGHT) onto Mill Rd. Proceed on Mill Rd. to gate.

26.9 **STOP 6** Enter the Woodcliff Lake reservoir of the Hackensack Water Co. NO TRASH DROPS PLEASE. We will examine the wave-cut cliff exposure of yellow-brown till over readvance outwash. There is less than 1 meter of till here. One-tenth of a mile west, immediately west of Pascack Rd., the tightly packed red cobble till of the Lake Hackensack glaciation lies below the readvance outwash.

26.9 Proceed along Mill Rd. to Stop sign.

27.0 Turn RIGHT onto Pascack Rd. and proceed to Ridge Rd.

27.6 Turn LEFT onto Ridge Rd. Proceed to Wortendyke Rd.

27.9 Turn LEFT onto Wortendyke Rd. into Atkins Glen Park. At the "T" turn RIGHT into Park Ave.

STOP 7 This lovely glen is a preglacial valley (at least pre-Woodfordian) cut across the Brunswick fm. strata at right angles to the bedrock strike. This valley contains red till and near the top is overlain by the yellow-brown till. It is very close to the farthest north natural exposure of the red till. The valley was exhumed in post-glacial time when a large and deep lake left by the ice, in what is now the Bear Swamp section (Park Ridge 7½ minute Quadrangle), was drained by downcutting.

Leave Atkins Glen Park via Wortendyke Rd.

28.1 Turn LEFT and proceed on Ridge Rd.

28.6 Turn RIGHT onto Spring Valley Rd. Proceed to light.

29.6 Turn LEFT (West) onto Grand Ave. Proceed through light and down hill to 2nd light. We have crossed into the Saddle River basin.

32.0 Turn RIGHT (North) onto E. Saddle River Rd. Proceed into New York State. (@33.4 miles)

33.8 **STOP 8** Turn RIGHT into gravel surfaced area of pit. It is across the street from the *Cemetery of the Ascension.* The exposure is in the side of a drumlin. The yellow-brown till is well exposed here. A strong bimodal till fabric can be measured here and fissility of the till was noted in two steep-faced exposures.

33.8 Return south on E. Saddle River Dr. to light on Grand Ave.

35.7 Turn LEFT on Grand Ave. Proceed until road ends at a "T".

40.4 Turn RIGHT (South) on Middletown Rd. (River Vale Rd.) and proceed to Barr Ct.

41.1 Turn RIGHT up hill along Barr Ct.

STOP 9 The Yellow-Brown till is 2.7-4 meters thick here. Red till is below. This is the River Vale Rd. drumlin. View to the east (over golf course) is the line of River Vale kames that form a north-south ridge to the east of River Vale Rd. until they join the Old Tappan moraine at their southern end. The west slope of the Palisades is across the Hackensack Valley in the distance.

Return to River Vale Rd.

42.0 Turn RIGHT onto River Vale Rd. and proceed to Poplar Rd.

43.0 Turn LEFT onto Poplar Rd. We travel through some kettle bog areas before reaching the old (landscaped) kame crest line. The Old Tappan moraine is ahead of us (south). The present reservoir is the location of post-glacial Lake Tappan. Note the ice-pressed terrain on the back-side of the moraine dam. Many large kames were removed from here during construction of the reservoir. Ultimate drainage, resulting in that catastrophic flood, was through the present Hackensack River drainage exit at the dam.

As we drive up the back slope of the moraine ridge, we can see a steep-sided kettle to the left of the road and just north of the small cemetery. This road is now Washington Ave. North. Proceed to intersection, (Stop sign)

44.3 Turn RIGHT onto Old Tappan Rd. Proceed to Ledson Pkwy.

45.0 Turn RIGHT onto Ledson Parkway. Proceed to dead-end.

45.2 **STOP 10** Old Tappan Rd. and Ledson Parkway are on the sandy outwash plain. Erosion has cut a gully here and has revealed the yellow-brown till of the moraine at the base of the ravine.

Turn around and return to Old Tappan Rd.

45.3 Turn LEFT (east). Proceed to Bi-State Plaza shopping center. Park in the lot of the Plaza.

46.0 **STOP 11** Observe excavated end of moraine. It is mostly stratified drift here.

46.1 Leave lot. Turn LEFT onto Old Tappan Rd. Proceed into Tappan, New York. Go to light by the Town Green.

48.6 At light, proceed STRAIGHT through onto Washington St. (This town is where Major Andre, of Revolutionary War infamy, was imprisoned, tried, hanged and buried.) Proceed along Washington St. to the town of Sparkill.

51.7 Turn RIGHT (immediately before RR crossing) and park at entrance to sand pit.

STOP 12 This is a great sequence of outwash capped by a thin layer of yellow-brown Tappan till. The owner has suddenly died and at this writing we are not sure whether we will be able to enter legally. Return to Washington St.

51.75 Turn RIGHT, cross RR tracks and proceed to light in center of town.

52.2 At light, road becomes Main St. Proceed STRAIGHT on Main St. to next light.

52.4 Turn RIGHT toward 9W South.

52.5 Take LEFT fork onto 9W South. Proceed to Tallman State Pk.

52.9 Enter Tallman Mt. State Park.

Follow signs to picnic area for lunch. After lunch Dineen will discuss the geology of the adjacent Sparkill Gap. Averill will discuss the importance of the Gap to the Woodfordian history of the Hackensack Valley. Newman will discuss the origin of the Piermont salt marsh below and the rise of sea level. For the uninitiated, Dineen and Newman will demonstrate their seismic and coring procedures.

Leave Tallman State Park.

55.0 Because of the variable distances one may drive within the Park, I have arbitrarally set 55 miles as the exit mileage number. Proceed past brown toll house to fork.

55.02 Turn RIGHT, road will take us into the Sparkill Gap. Go to "T".

55.45 Turn LEFT on Ferdon Ave., Sparkill Creek will be on your right. Proceed straight across Rt. 340 at 56.0 miles. You are on William St. Proceed to fork.

56.15 Take LEFT fork. Proceed to Washington St.

56.25 Turn LEFT on Washington St. Proceed to Main St.

57.4 Turn LEFT on Main St. to fork. Take RIGHT fork at 57.45. The road enters New Jersey & becomes Tappan Rd. It begins to increase in elevation at the Norwood kame grouping and generally runs along the crest. Proceed to Broadway.

59.1 Turn RIGHT on Broadway, proceed to crest of rise (kame).

The Norwood kames were constructed into glacial Lk. Hackensack and were later buried by the readvance Tappan till glacier.

59.2 Park off side of road. **STOP 14** Enter new development on north side of road. Walk up hill to top.

Kame is constructed of red coarse cobble outwash and has patches of overlying yellow-brown till.

Return to Tappan Road.

59.4 Turn RIGHT on Tappan Rd. Proceed to Blanche Ave.

59.7 Turn LEFT on Blanche Ave. Proceed down hill to light.

The first slope is the outwash plain. There is then a break in the slope and the slope increases. This is the erosional slope first cut during the drainage of glacial Lk. Hackensack.

60.3 Light at Livingston Ave. Cross intersection and park in the open area on the right.

STOP 15 This is the Norwood portion of the Oradell Reservoir. This is where the mastodon remains were found. The large (3 meter) diabase boulder can be seen. Discussion....

Leave mastodon site and return up Blanche Ave. to Tappan Rd.

61.0 Turn LEFT on Tappan Rd. and proceed to "T" (Schralenburg Rd.).

61.7 Turn RIGHT, onto Schralenburg Rd. (NEXT TURN IS QUICK)

61.71 Turn LEFT onto Harriot Ave. Proceed on Harriot Ave. Follow road into River Vale where it becomes River Vale Rd. Proceed to light.

You are on the outwash plain of the Old Tappan moraine.

63.8 Turn LEFT on Westwood Ave. Proceed to Fondiller St.

To the immediate left is the 40 ft. ASL contour line and the shoreline of post-glacial Lake Norwood.

64.2 Turn RIGHT and proceed on Fondiller St. to end at "T". We have been ascending the River Vale collapsed moraine outwash plain.

64.6 Turn RIGHT onto Cedar Lane. Proceed north to Cleveland Ave.

Note the flood plain of Pascack Brook to the left (West). It cut deeply into the outwash plain south of the Hillsdale heads-of-outwash.

64.8 At YIELD sign, follow bend in Cedar Lane and proceed STRAIGHT ahead. Proceed to "T".

We have crossed Cleveland Ave. head-of-outwash and are going down hill into the area of collapsed moraine. At the end of Cedar Lane at the "T", is a new Condominium complex. These five story pre-cast concrete structures were built directly on glacial Lk. Hackensack red varves. No pre-construction preparation was necessary as they (the varves) were already in a preconsolidated state.

65.4 Turn LEFT onto Piermont Rd. (a right turn would take you to the Old Tappan moraine). Proceed west to Everdell Ave.

The 1st street on the right (Ruckman Ave.) is the crevasse channel outwash feeder. It can be seen on the left (south) across from Ruckman Ave. It is composed of medium clean sand with occasional large boulders. Piermont Rd. cuts through the crevasse filling in a small stream valley (more on that later).

66.3 Turn LEFT on Everdell Ave. along the crevasse filling. Proceed to East Liberty Ave.

66.5 Turn RIGHT (west) onto E. Liberty Ave. Proceed to Holdrum St.

We proceed down the hill to the flat valley floor. Ahead of us is the Kinderkamack Rd. drumlin, one of the largest in the area.

66.8 LEFT turn onto Holdrum St. Proceed almost to end of street and park in open area on the left.

66.9 **STOP 16** Beechwood Park, Hillsdale, N.J.

Walk into park. Note the kame on the west and the large kettle bog. The bog is also found south of Hillsdale Ave. beyond the confines of the Park. B.P.1 boring was made on the southeast side of the bog and penetrated to the bedrock floor of a deep valley 55 ft. down. Surface elevation of the bog is 50 ft. ASL. B.P.-2 was sited 10 m south of Hillsdale Ave. almost due south of B.P.-1. B.P.-3 was sited east of B.P.-2 just east of the sewer cut in the deepest part of the kettle.

Note the stratigraphy as shown in Fig. 10. Discussion.

The Hillsdale head-of-outwash is immediately south of us. A small, apparently very short-lived, proglacial lake formed behind the dam and between the drumlin on the west and the crevasse filling on the east. As the ice retreated, the eastern ridge was breached at Piermont Rd.

66.95 Turn RIGHT onto Hillsdale Ave. Proceed to Kinderkamack Rd. at first light.

67.0 Turn LEFT (south) onto Kinderkamack Rd. We will stay on this road until we reach Rt. 4.
Proceed south on the outwash plain of the Hillsdale heads-of-outwash. The 1st valley we cross is the Pascack Brook.

67.2 Farther south, after we pass through "5 Corners" in Westwood, we drop into a very large valley drained by the now tiny Musquapsink Brook. This is the valley cut by the draining of proglacial Lk. Musquapsink. The Woodcliff Lk. kame delta was constructed into this lake.
Proceeding south in Emerson we are still on the outwash plain. In Oradell, near the Xerox building, more of the same but on the west is the large Oradell drumlin; rock-cored and coated with red till. Lk. Hackensack red varves were encountered at the Xerox site under the outwash sand. Yellow "loam" loess as much as 30 cm thick overlies the area to the south. Man's activity has removed much of the loess.

END OF OFFICIAL TRIP.

Continue south of Kinderkamack Rd. At the southern end you will pass under the Rt. 4 overpass. Follow the sign to Rt. 4 East-New York. Turn RIGHT and proceed to Stop sign. Turn RIGHT onto entrance to Rt. 4 East. Proceed to Teaneck Rd. Turn RIGHT (south). Proceed to I-80, follow signs to I-80 East Local Lane. Proceed the short distance to the N.J. Turnpike South and proceed to Newark Exit. Reverse directions on page 1 of road log to campus.

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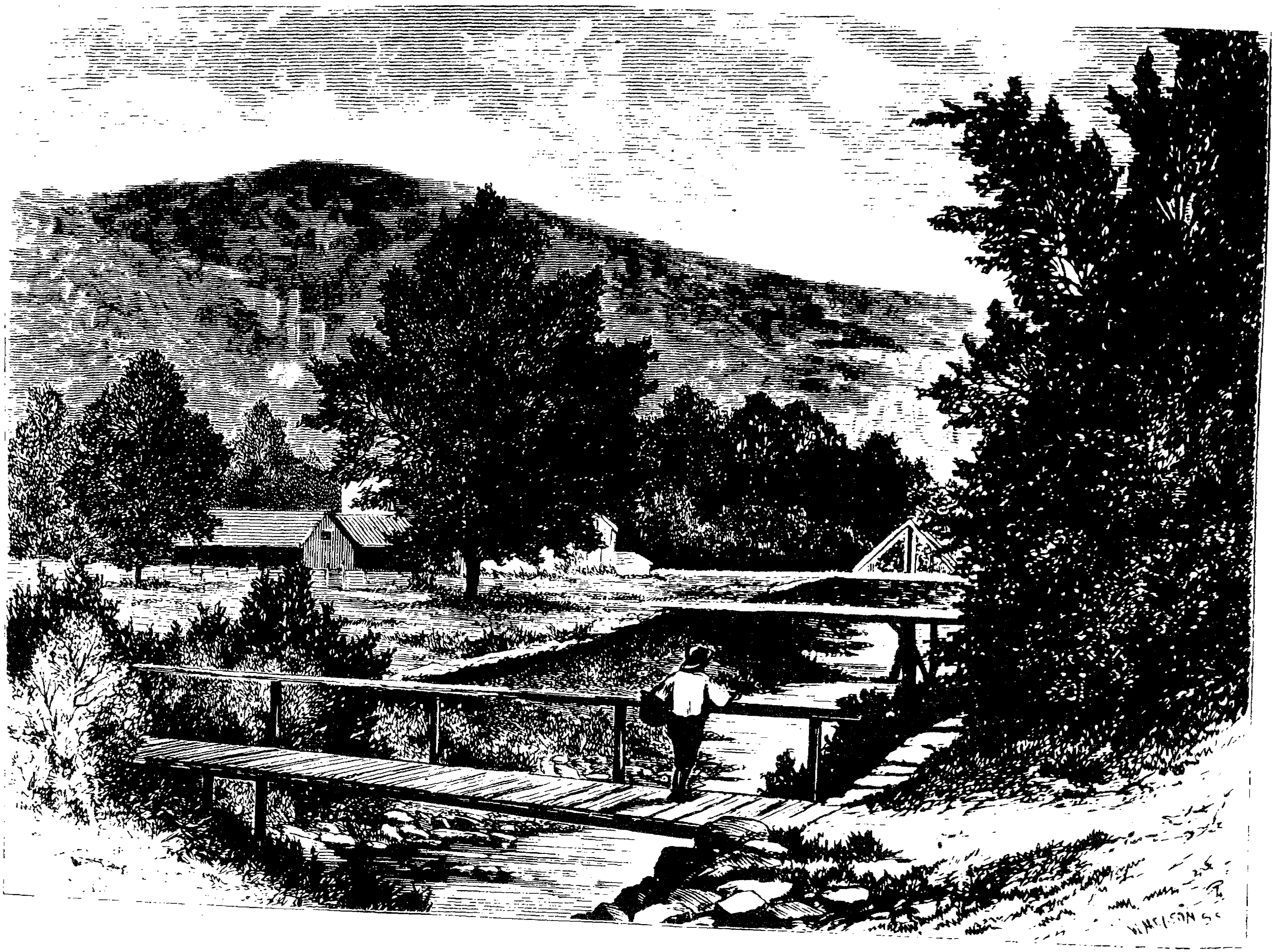

Near Greenwood Lake.

NEAR GREENWOOD LAKE by Jules Travernier

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ECONOMIC GEOLOGY: NEW JERSEY HIGHLANDS

General Introduction and Road Log

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The New Jersey Highlands province comprises the centermost portion of northern New Jersey, extending 96 Km northeasterly across the state and ranging in width from 16 to 40 Km. It is flanked on the northern side by the Valley and Ridge province and on the southern side by the Triassic Lowlands of the Piedmont province. The province, which is part of the Reading Prong of the New Jersey Highlands is essentially a belt of Precambrian crystalline rocks with certain narrow belts of folded and in-faulted Paleozoic sedimentary rocks. The three articles that follow this general introduction contain specific information on these rock types and their relationships.

The Precambrian rocks of the New Jersey Highlands have been hosts to several commercial mineral deposits. Historically, the magnetite iron ore deposits are of unique importance. These deposits have been mined since at least as early as 1710 (Buddington, 1957), perhaps the oldest iron mining in the United States. Geologic and other information concerning the major magnetite deposits of the Highlands was first outlined by Bayley (1910). For several years during the third quarter of the nineteenth century, New Jersey was the biggest producer of iron ore in the United States. Of the 136 mines active in 1880, none are operating today. However, some of the now abandoned mines are still accessible. During this field trip, John Puffer will lead us through two such mines: the Andover-Sulphur Hill Iron Mines (STOP 2) and the Edison Magnetite Deposits (STOP 3).

Interest in the mineralizatoin of the Franklin area has been worldwide and has continued, unabated, for more than a century. In certain rare cases, a significant accumulation of a wide variety of elements is possible in certain areas of the earth's crust, resulting in the formation of a large number of minerals, some of which are unique or exclusive to the area. Kostov (1968) lists only four such localities in the world, with the Franklin area being one of them. The Franklin deposits are enriched mainly in manganese, iron, and zinc, but the combination of the silicate-oxide ore minerals with numerous associated gangue minerals is unique and generally unknown elsewhere. Kushner (1970) compiled an abbreviated manual of Franklin minerals and listed about 200 species. Some of these minerals (e.g., franklinite, zincite, etc.) are either unique to Franklin or are rarely found elsewhere. Today, except for the mining operations at Sterling Hill and at the Farber White Limestone Quarry on Cork Hill Road, all of the mining activities at Franklin have ceased. Bob Metsger, who has been the chief geologist at the Sterling Hill Mine for several years, will lead us through the mine area and describe the occurrence and origin of this classic deposit (STOP 4). Mineral collecting will be available at the mine dump. However, those who are interested may also visit the Trotter and Buckwheat dumps for additional mineral collecting upon payment of a small fee.

The search for uranium in the 1950's is responsible for the greatest metal hunt in the history of the world. The New Jersey Highlands province was included in this hunt, and in 1955 a series of geiger counter hot spots were discovered along the perimeter of a large pegmatite near Cranberry Lake by Mr. Edward Koral and the New Jersey Geological Survey. In 1959 the Byram Exploration Minerals Company put down a vertical shaft on one of the hot spots and named the deposit the Bemco Mine. Throughout the summer of 1959 some uranium was recovered and shipped out (about 95 tons of ore), but the rare earth values of the ore were overlooked at the time. The Bemco Mine, also known as the Charlotte Mine, is located on land now designated as Green Acres and is, of course, inactive. The ore represents a highly unusual mineral assemblage of metamict minerals (e.g. fergusonite, uranothorite, zircon), and is of interest as a good example of hydrothermal mineralization relating to the intrusion of a pegmatite into the metamorphic host rocks. Diamond drill cores studied by Williams (1967) define the ore zone up to a depth of 30 meters. On STOP 1 of the trip, this writer will point out the relationships between the ore and the associated rock units and discuss the origin of the deposit.

As shown in Fig. 1 and in the Road Log that follows, the trip will consist of four main stops:

STOP 1: Bemco Mine, Cranberry Lake area, led by A. H. Vassiliou

STOP 2: Andover-Sulphur Hill Iron Mines, led by J.H. Puffer

STOP 3: Edison Magnetite Deposit, led by J.H. Puffer

STOP 4: The Sterling Hill Mine, Ogdensburg, led by R. Metsger.

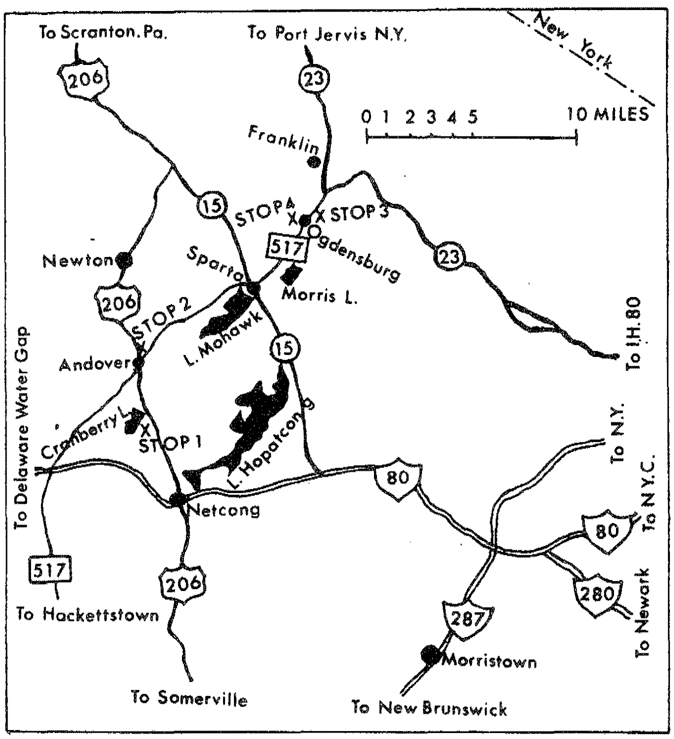

Fig. 1 Map showing location of field stops.

ROAD LOG

Mileage

0 Leave Rutgers-Newark, parking lot 500 next to Boyden Hall, turning right on Warren Street. Go for one block to traffic light.

0.1 Turn right on High Street. Go for about two blocks to first traffic light.

0.2 Turn left, but bearing to the right of the island, onto Sussex Street. Continue on Sussex which becomes Nesbitt Street after the first traffic light. Go to end of Nesbitt, about one block (T intersection).

0.8 Turn left to face traffic light and entrance to I 280 West. Stay on 280 West for about 15 miles. See Manspeizer (this field book) for description of columnar structures in basalt along I 280.

15.6 Exit for I 80 West. Stay on 80W for about 19 miles.

34.4 Exit for Rt. 206 North.

38.2 Left on South Shore Road, bearing left at intersection.

38.4 Left on to first dirt road. Continue on dirt road (old railroad line).

39.2 **STOP 1** (about one hour). At this point the dirt road has small parking area on the right whose path or trail (uphill) leads to the BEMCO MINE. Go 420 feet along the trail: "sulfide quarry" to the right, downhill. + 840 feet to "red flag" — turn right down the hill to lower trail (about 50 feet).
+350 feet, turn left for mine area.
+145 feet, to old shaft.

See attached article on the deposit by A.H. Vassiliou.

LEAVE FIRST STOP, go back to intersection with Rt. 206, continue on Rt. 206 North.

43.6 Right on Rt. 669 (Limecrest Road). Exxon at right corner.

44.5 **STOP 2** (about one hour). Park off road and follow path or trail (right side of road) to ANDOVER-SULPHUR HILL IRON MINES. See attached article by J.H. Puffer.

You will be asked to sign a waiver before entering the mine property, and are requested to wear a hard hat and safety glasses. Follow the path from the mine gate to an open clearing. The Andover Mine workings including adit portals and an open pit are found along a cliff located south of the central clearing. Highly altered diabase dikes are intruded along the cliff. The diabase is black to dark green, highly chloritized, fine grained rock that has been sheared and mylonitized. The magnetite ore is disseminated in a light gray Quartz-Oligoclase Gneiss. Dark green pyroxene-feldspar gneiss is exposed above the cliff east of the mine. The pyroxene-feldspar gneiss is green (highly epidotized) fine grained, migmatitic, locally calcareous rock. The pyroxene component is diopside. A light buff microcline granite gneiss is exposed along the road just west of the mine.

The Sulphur Hill open pit is located about 400 feet north of the central clearing. The pits are dangerous and are closed to visitors. Most of the rocks found in dumps at the north and eastern edges of the clearing are from the Sulphur Hill Mine. The rock is a magnetite and sulphide rich garnet skarn. Amphibolite is exposed south of the Sulphur Hill Mine. It is recognized by its black hornblende content, and is coarser grained than the pyroxene-feldspar gneiss.

LEAVE STOP 2, go back to intersection or Rt. 206 and turn left at intersection to get onto Rt. 206 South.

45.2 Left (at light) on 517 North. Stay on 517 for about 12 miles.

56.8 Right on road (no name shown) across from Danforth's Trailer and Vespa dealership (shortly after school on left).

59.3 **STOP 3** (about 30 minutes). Park off road (clear area on right). Climb up bank, cross fence, to the EDISON MINE magnetite deposit. See attached article by J.H. Puffer.

Buses will turn around. At the southern end of the open pit (The Old Ogden Mine) there are good exposures of a biotite, sillimanite and magnetite rich phase of a metasedimentary Quartz-Potassium Feldspar Gneiss. Sulfides including pyrite, chalcopyrite, and molybdenite are disseminated throughout the rock but are found concentrated near the south-east corner of the pit. Acid solutions leached through the sulfides have accelerated the alteration of the rock to a sericite rich saprolite. Please exercise extreme caution when approaching the open pit, and be on the alert for poison ivy.

LEAVE THIRD STOP, go back to Rt. 517, make a left at intersection on to 517 South.

59.4 Right on Passaic Ave. (just before school).

60.0 Left on Plant Street to the New Jersey Zinc Co. mine buildings.

STOP 4 — The Sterling Hill Mine (Ogdensburg). Here we shall have lunch, go on a mine tour, and then do some mineral collecting at the dump. See attached article on the deposit by R. Metsger.
Stop duration, two to three (or more?) hours.

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TROWBRIDGE MOUNTAIN AND WATNONG PLAINS, FROM SUGAR LOAF HILL, MORRIS CO.

TROW BRIDGE MOUNTAIN AND WATNONG PLAINS,
from Sugar Loaf Hill, Morris Co.
H. Carmiencke Del. 1856
From N.J.G.S. 2nd Annual 1856

URANIUM AND RARE EARTH MINERALIZATION AT THE BEMCO MINE NEAR CRANBERRY LAKE, NEW JERSEY

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INTRODUCTION

The Bemco Mine, also known as the Charlotte Mine, is in Sussex County, northwestern New Jersey, about fifteen miles southwest of Franklin (Fig. 1). The mine was created in the late fifties as a result of highly radioactive zones discovered along the perimeter of a Precambrian outcrop of granite pegmatite.

Exploratory mining in 1959, mainly in the form of open cuts, revealed a narrow ore band (average width about 30 cm) along the strike of the contact between the granite pegmatite and the surrounding wall rock, a pyroxenitic gneiss. Additional mining operations conducted in 1959 included a shaft and drift trending northwest along the strike of the pegmatite. The ore mined, a total of 95 tons, was sold for its uranium content, but its high rare-earth values were largely overlooked. The ore consisted of a friable matrix of magnetite (about 90%) and a suite of accessory ore minerals such as zircon, fergusonite and uranothorite which contained rare earths, thorium, uranium, and other associated elements.

Previous published reports on this occurence include Williams (1967) who briefly described the deposit as part of a Bureau of Mines reconnaissance report on rare-earth resources in northern New Jersey and two short reports by the writer and his associates (Haji-Vassiliou et al, 1974; Vassiliou, 1980). Diamond drill cores studied by Williams (1967) showed that the pegmatite as well as the ore zone narrow considerably with depth; however, the ore was shown to be quite rich in rare-earth oxides (up to 2.4 percent) and to contain 0.45 percent U_3O_8 and 0.24 percent ThO_2.

This report outlines the general geologic setting of the mine area and describes the mineral assemblage in the ore and in the associated rock units. In addition, a hypothesis on the origin of the ore is suggested on the basis of field as well as analytical data on the deposit.

GEOLOGIC SETTING

Regionally the Bemco mine is in the New Jersey Highlands Province which comprises the centermost portion of northern New Jersey. This province, which is part of the Reading Prong of the New England Highlands, is essentially a belt of Precambrian metamorphic rock 96 km long and ranging in width from 16 to 40 km. The trend of the major structure of the New Jersey Highlands is parallel to the general Appalachian Mountain system, trending N45°E (Sims and Leonard, 1952; Smith, 1969).

Spencer et al (1908) and Bayley et al (1914) mapped the New Jersey Highlands on the basis of four dominant rock units: The Pochuck, Byram, and Losee gneisses, and the Franklin marble. The Pochuck gneiss included all dark colored or black gneisses high in pyroxene, hornblende and biotite, and was considered an early dioritic or gabbroic differentiate. The Byram gneiss included brown and pinkish rocks high in potassic feldspars, and was thought to be indicative of a late stage potassium-rich granite. The Losee gneiss included all light colored or white rocks containing mainly oligoclase and quartz with minor diopside, hypersthene and biotite, and was considered indicative of a sodium-rich granite. The Franklin marble was considered metasedimentary in origin.

Later detailed mapping of smaller areas in the New Jersey Highlands province (Hotz, 1953; Hague et al, 1956; Sims, 1953, 1958; Smith and Baum, 1957; Buddington and Baker, 1961; Smith, 1969) led to the abandonment of Pochuck, Byram, and Losee as map units and the adaptation of mapping units based upon careful mineralogical subdivision of lithologies. The igneous origin for the gneisses was also abandoned in favor of a metasedimentary origin.

In the Bemco mine area, five major rock units (a granite pegmatite, a pink gneissic granite, a leuco-alaskite gneiss, a granite gneiss, and a pyroxenitic

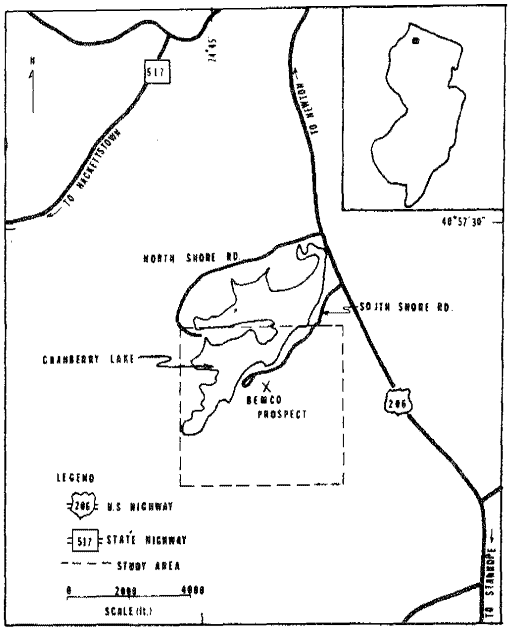

FIG. 1. Location map of the Bemco Mine.

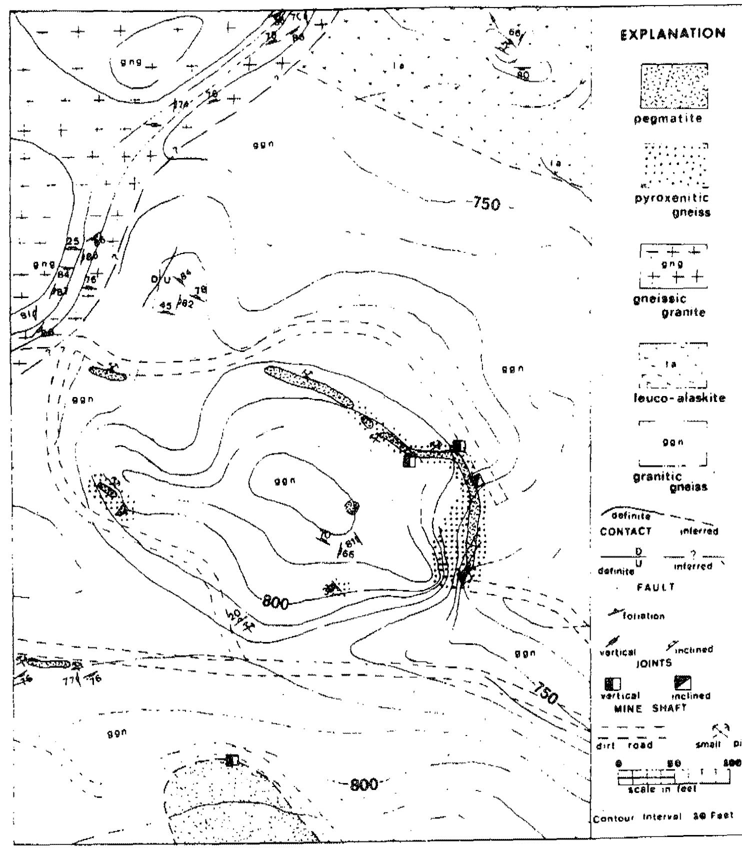

FIG. 2. Geologic map of the Bemco mine, Cranberry Lake, area. Field data provided by Donlon Hurtubise, Wayne C. Orlowski and David A. Fontaine.

gneiss) were differentiated according to their mineral assemblages and textures. The spatial relationships of these units are shown in a geologic map of the area (Fig. 2). A veneer of glacial drift overlies much of the area of Fig. 2. The metamorphic units are foliated and jointed. In general, the foliation strikes N45°W and dips 35°NE. Joint data plotted and analyzed by Fontaine (1976) show that jointing is less uniformly oriented and may be subdivided into two major and one secondary sets.

THE ASSOCIATED ROCK UNITS

Of the five major rock units in the area (Fig. 2), the granite pegmatite and the pyroxenitic gneiss are in direct contact with the ore zone. The mineralogy, texture and spatial relationships of these two units will be discussed in some detail, but a brief outline of the petrology of the other rock units not in contact with the ore follows.

Units Not In Contact With the Ore

Granite Gneiss. This rock was previously mapped as Pochuck gneiss (Bayley et al, 1914) and it is the most aerially extensive unit in the area. On the basis of mineral content and proportions, the rock may be subdivided into two varieties each characterized by the dominant minerals microperthite-quartz-plagioclase and containing either pyroxene-hornblende-magnetite or garnet magnetite. Smith (1969) and Young (1969) recognized the same basic granite gneiss varieties in the Cranberry Lake area.

Leuco-Alaskite Gneiss. This rock corresponds to two types of light-colored gneiss: the quartz-oligoclase gneiss or "leucogneiss" of Buddington and Baker (1961), previously referred to as Losee gneiss; and the sometimes pale pinkish and mainly homogeneous alaskite which is considered to be an igneous body syntectonically intruded into the leucogneiss (Young, 1969). The alaskite was originally mapped as Byram gneiss.

Pink Gneissic Granite. This rock rims the east shore of Cranberry Lake. The predominant minerals are quartz, microcline, microperthite and plagioclase, with minor hornblende and magnetite. Buddington (1957) discussed the origin of a compositionally similar granite associated with the Edison belt magnetite deposits.

Units in Contact with the Ore

The relationship between the narrow ore zone (or contact zone) and the adjacent rock units (the granite pegmatite and the pyroxenitic gneiss) is shown in Figure 3.

The Granite Pegmatite. This rock, which is easily recognized by its light color and coarse texture, is well exposed in the mine area, especially on the steep face

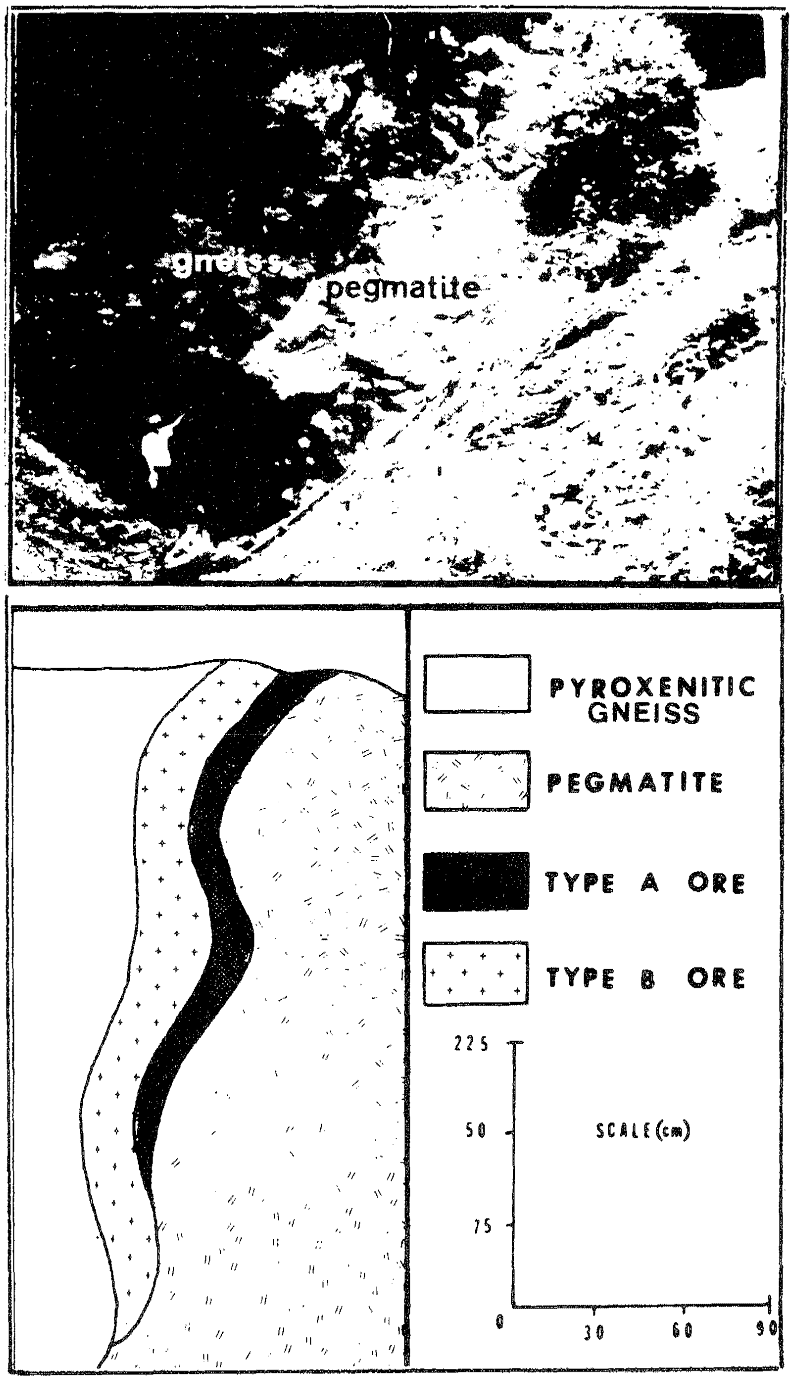

FIG. 3. The pegmatite--pyroxenitic gneiss contact at the Bemco Mine works. Light shaded rock (to the right of traced contact) is the pegmatite (photo). Schematic cross-section illustrating the spatial relationships between the associated rock units (gneiss and pegmatite) and the ore occurring at their contact (diagram).

above the lower mine portal (Fig. 3). Structural evidence indicates that the pegmatite was emplaced discordantly into the metamorphic host rock, the pyroxenitic gneiss, which it intrudes at a high angle to the foliation. The pegmatite strikes about N50°W and dips 60°SW on the average; it has an average thickness of about 2 meters and a length, along strike, of about 84 meters. Diamond cores show that the pegmatite narrows with depth; at a depth of about 30 meters the pegmatite narrows to about 1.3 metes (Williams, 1967).

The attitude of the pegmatite is nearly the same as the general attitude of one of the joint systems in the area (average, N47°W, dip 70°SW). On the basis of this and the absence of features such as wall-rock foliation deflections, drag folds, xenoliths, etc., the pegmatite may have been passively emplaced along a joint fracture possibly developed during regional deformation of the Precambrian gneiss (Fontaine, 1976).

The mineral composition of the pegmatite is shown in Table 1. Its core is essentially made up of K-feldspar (microcline micro-perthite) and quartz. The K-feldspar and quartz decrease and the magnetite increases as we approach the margin of the pegmatite towards the ore zone. Several accessory minerals, including a few grains of zircon and fergusonite, are associated with the major components. Both zircon and fergusonite are metamict and become important constituents of the ore at the contact of the pegmatite with the pyroxenitic gneiss.

Pegmatites are common in the Cranberry Lake area but they are much smaller than the Bemco pegmatite and they are not associated with uranium and rare-earth mineralization. Uranium and rare earth minerals are often found as accessory components in pegmatites (Heinrich, 1956, 1958, p. 189; Page, 1950).

The Pyroxenitic Gneiss. As noted above, in the Cranberry Lake area granite gneisses predominate and include massive, migmatic, and banded varieties. The gneisses in the immediate vicinity of the Bemco pegmatite have been banded with pyroxene (augite) and hornblende. These bands grade into amphibole-bearing pyroxenite lenses such as the pyroxenitic gneiss adjacent to the ore. The latter transition is illustrated by the modal composition of samples PG1 and PG2 in Table 1.

Sulfides are present in relatively high but variable quantities in the pyroxenite (Table 1). These sulfides include pyrite and pyrrhotite with traces of chalcopyrite, sphalerite and galena.

	P1	P2	P3	PG1	PG2	C1	C2	C3	C4
K-feldspar	56	40	10	43					
Plagioclase	11	24	28	18	tr				tr
Quartz	31	25	20	2					tr
Pyroxene (augite)	tr	4	6	30	75			2	1
Hornblende	tr	2	tr	2	20		43	1	1
Biotite		1	2	2	tr				
Magnetite	tr	2	32	2	tr	76	14	92	91
Ilmenite			tr		tr		tr		
Pyrite		tr	tr		2		tr	tr	tr
Pyrrhotite					2			tr	
Zircon		tr				14	19	1	4
Fergusonite		tr	tr			2	4	3	2
Uranothorite (huttonite)						1	9		
Allanite		tr					tr		tr
Apatite (francolite)		tr				7	8		tr
Fluorite		tr							tr

Note: P1-P3 pegmatite. P1: core of pegmatite; P2: intermediate between core and margin; P3: margin near ore contact.

PG1-PG2 pyroxenitic gneiss. PG1: near contact with ore zone; PG2: approximately one meter from ore contact.

C1-C4 ore samples. C1, C2: Type "A" ore (near pegmatite contact); C3, C4: Type "B" ore (near pyroxenitic gneiss contact).

Table 1. Modal composition of associated rock units and ore at the Bemco Mine.

THE MINERALOGY OF THE ORE ZONE

The ore minerals occur exclusively in narrow zones or bands along the hanging and footwall contacts between the pegmatite and the pyroxenitic gneiss. The zones average approximately 30 cm in width on both walls but there is considerable pinching and swelling and in some cases the zones are absent. Diamond drill cores show that the ore zone narrows considerably with depth; at a depth of about 30 meters the zone has a maximum width of about 2.5 cm (Williams, 1967).

Magascopically as well as optically the ore can be divided into two types. The spatial relationship between the two types is shown in Fig. 3. Type "A" ore represents a 7 cm thick zone, in contact with the pegmatite, that may be described as rusty or oxidized. It is composed of a fine-grained matrix of magnetite (up to 76%)that is rich in zircon in the form of euhedral crystals disseminated throughout the matrix (Fig. 4). It is also relatively rich in uranothorite (up to 9%) and fergusonite (up to 4%). Modal analysis of two samples (C1 and C2 in Table 1) shows that apatite (francolite) is a minor constituent of the ore and that hornblende may be a major constituent in certian sections of this ore zone.

Type "B" ore represents a 25 cm thick zone, in contact with the pyroxenitic gneiss, that is essentially a magnetite ore (up to 92% magnetite), but it also contains accessory fergusonite (up to 3%) and zircon (up to 4%). The complete model composition for this ore is in Table 1 (samples C3 and C4). Fergusonite and zircon are not readily recongized megascopically in this ore.

The occurrence of radioactive minerals in magnetite ore is not uncommon. Uranium minerals are associated with several magnetite deposits in the Eastern United States (Walthier, 1955), and rare-earths are associated with magnetite ore at the Scrub Oaks mine, Morris County, New Jersey (Williams, 1967).

With the exception of magnetite, the other ore minerals identified here (zircon, fergusonite, uranothorite) are metamict. A few black anhedral grains separated from the ore have been tentatively identified (through X-ray powder camera) as the yttrium silicate "rowlandite" by Fontaine (1976). The relatively rare metamict mineral "spencite" (calcium-yttrium silicate) has been reported as present in the ore by Williams (1967), but its presence has not been confirmed by the writer. A more detailed description of the ore minerals is as follows:

Magnetite

As much as 90% of the ore zone or contact zone is composed of coarse-grained magnetite. In addition, magnetite occurs in the form of veinlets (up to 16 cm in length) which cut through the pegmatite as well as the pyroxenitic gneiss host rock. It is also commonly disseminated in both the pegmatite and the pyroxenitic gneiss as well as in all the other rocks in the Cranberry Lake area.

The magnetite of the ore zone and the related veinlets is identical in chemical composition to the magnetite found in the pegmatite (with only 0.2% TiO_2 content). On the other hand, the magnetite found disseminated in the host rock (pyroxenitic gneiss) differs strongly from the latter (up to 3.5% TiO_2 content). This suggests a direct genetic link between the ore and the pegmatite.

Zircon

Euhedral crystals, mainly concentrated in the type "A" ore, (Fig. 4), average 4 mm in length, with some as long as 2 cm. These crystals are generally gray, strongly zoned, and some exhibit twinning. The zoning is visible in most crystals observed in thin section, with zircon forming the crystals walls (cyrtolite), and uranothorite and fergusonite occupying the core (malacon) of the crystals (Fig. 5).

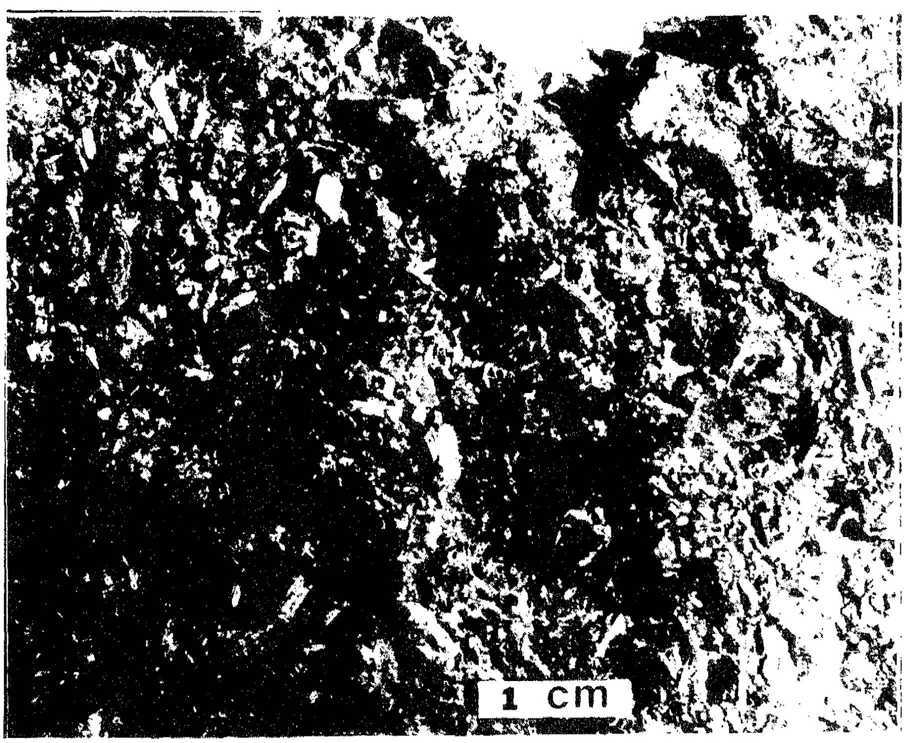

FIG. 4. Euhedral crystals of zircon (light-colored, prismatic) disseminated in fine-grained magnetite matrix of Type "A" ore.

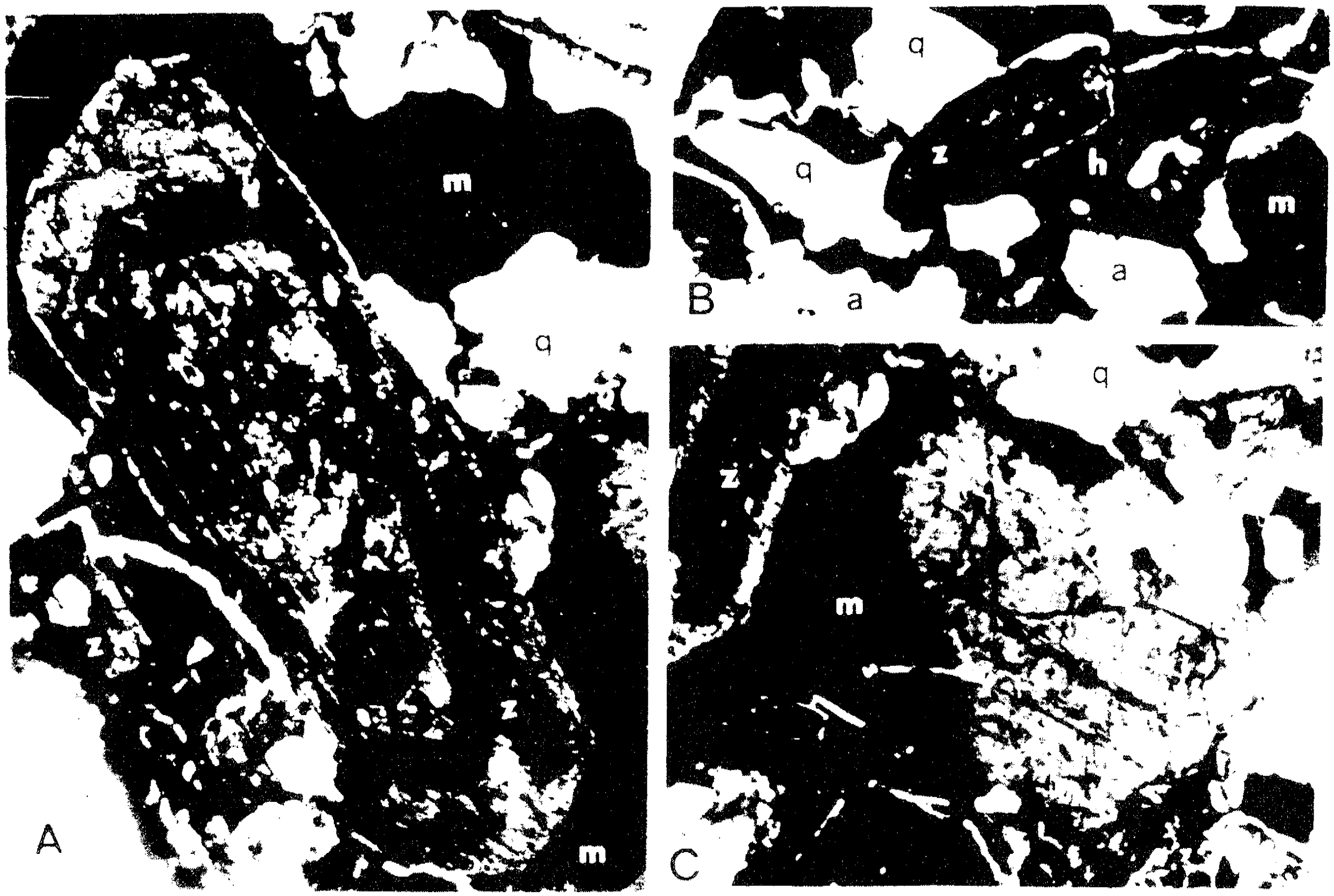

FIG. 5. A. Zoned euhedral zircon (z) with associated magnetite (m) and fergusonite (f) in type "A" ore adjacent to the pegmatite contact. Cyrtolite is represented by the outer zone of the crystal and malacon by the generally darker core which contains uranothorite and some fergusonite. Plane polarized light, 16X.

B. Zoned zircon crystal (z) associated with hornblende (h), apatite (a), magnetite (m) and quartz (q) in type "B" ore adjacent to the pyroxenitic gneiss contact. Plane polarized light, 40X.

C. Large fergusonite grain (f) in association with magnetite (m) and zircon (z) in type "A" ore. Plane polarized light, 16X.

Photomicrographs by L. M. Fukui and R. F. D'Andrea, Jr.

In Table 2 the zircons ($ZrSiO_4$) are shown to be rich in thorium and uranium. The most abundant rare earth present is ytterbium, with other associated elements being hafnium and yttrium.

The crystals are completely metamict. However, with heat treatment (1000 °C for one hour in a muffle furnace), the crystal structure of zircon could be ascertained through X-ray diffraction analysis.

Fergusonite

This mineral occurs mainly in the Type "B" ore, and occasionally in Type "A" ore, especially as part of the core in zoned zircons. Optically it appears as red-brown vitreous grains that often contain magnetite inclusions (Fig. 5).

Table 2 shows fergusonite, Y (Nb, Ta)O_4, to be rich in thorium, uranium, and several rare earths (ytterbium, erbium, gadolinium) in addition to elements listed in its chemical formula.

The mineral is metamict and, depending on heat treatment, it may exhibit one of several phases. Lima de Faria (1964, Table 18) lists four phases. In this study, the mineral was heated (in a muffle furnace) at 1000 °C for one hour, and its diffraction pattern correlated well with the monoclinic phase outlined by Lima de Faria (1964, Table 20).

Uranothorite

This mineral occurs mainly in the cores of zoned zircons and occasionally in the form of veinlets in the ore matrix. Optically it appears as black, isotropic

	Fergusonite	Uranothorite	Zircon
ThO_2	10.2	50.3	6.7
UO_3^*	4.3	26.2	2.8
ZrO_2	-	-	59.3
Nb_2O_3	36.4	-	-
Y_2O_3	27.9	0.7	0.3
$Fe_2O_3^*$	4.7	5.1	1.1
Yb_2O_3	1.7	-	2.2
Ta_2O_5	2.9	-	-
Er_2O_3	2.1	-	-
Gd_2O_3	1.1	-	-
HfO_2	-	-	0.8
CeO_2^*	-	2.1	-
As_2O_3	-	1.0	0.5
Total	91.3	85.4	73.7
100-Total	8.7	14.6	26.3

*Oxidation state unknown

Note: These quantitative estimations were obtained through X-ray fluorescence analysis. Selected peak intensities representing the elements in the oxides listed were compared to those present in artificially prepared standards. The standards were prepared by mixing various proportions of these oxides (weight percent) in a silica diluent.

Table 2. Composition of radioactive ore minerals at the Bemco Mine.

subhedral grains (medium- to coarse-grained), and its identification was confirmed by X-ray diffraction after heating at 1000°C for one hour.

Its X-ray diffraction pattern is very close to the monoclinic huttonite phase of thorite ($ThSiO_4$) as shown by Lima de Faria (1964, Table 1). However, the presence of large amounts of uranium (see Table 2) in its composition suggests uranothorite, (Th, U) SiO_4, as a more appropriate name.

ORIGIN OF THE ORE

The following is a summary of field and chemical analytical data which suggest that the ore was probably precipitated from hydrothermal solutions. These solutions were associated with the later stages of the istrusion of the pegmatite and were injected along the pegmatite-gneiss contact.

1. The pegmatite was emplaced discordantly into the metamorphic host rock, the pyroxenitic gneiss, which it intrudes at a high angle to the foliation. Permissive rather than forceful injection is suggested for the pegmatite mainly due to the absence of features that usually suggest forceful injection (i.e., drag folds, xenoliths, etc.) and the fact that the attitude of the pegmatite is practically the same as that of one of the joint systems in the area.

2. The ore zone occurs along the hanging wall and footwall contacts between the pegmatite and the pyroxenitic gneiss.

3. The contact appears sharp and discordant with magnetite ore veinlets cutting both the pegmatite and the pyroxenitic gneiss. Veinlets and pockets of sulfides (mainly pyrite, pyrrhotite and chalcopyrite) occur in the pyroxenitic gneiss, especially adjacent to the ore or contact zone.

4. The magnetite of the ore zone and the related veinlets is identical in chemical composition to the magnetite found in the pegmatite (ie., it contains 0.2% TiO_2). However, the magnetite in the host rock or pyroxenitic gneiss is different (i.e., it contains up to 3.5% TiO_2).

5. A series of samples of pyroxenitic gneiss taken at the contact zone and at intervals of 30, 60, and 90 cm away from the contact were analyzed for Fe_2O_3 content and total Fe content using X-ray fluorescence and atomic absorption. The results show that, in general, the iron content decreases away from the contact, thus suggesting that the ore is not the result of deuteric leaching from the pyroxenitic gneiss.

Acknowledgements

The author is indebted to David A. Fontaine, Donlon Hurtubise, Wayne C. Orlowski and Ralph D'Andrea Jr. for aiding in the analysis of samples and the preparation of the geologic map. My colleague, John H. Puffer, provided innumerable helpful comments and suggestions. Funds for the analysis were provided by the Research Council of Rutgers University.

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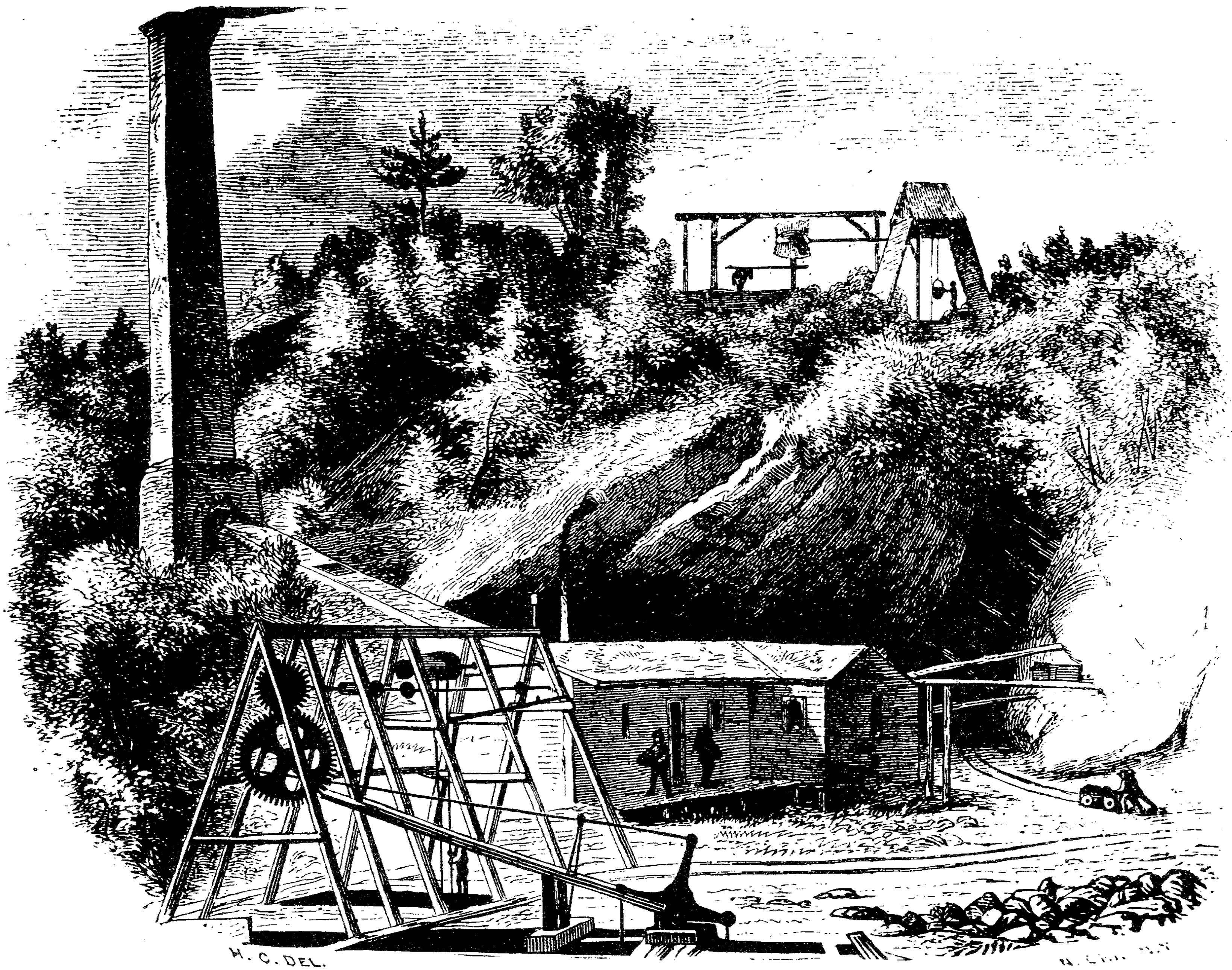

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IRON ORE DEPOSITS OF THE NEW JERSEY HIGHLANDS

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History

Iron mining activity in the New Jersey Highlands probably began about 1710 (Sims, 1958). Maximum production was attained in the early 1880's when New Jersey ranked second only to Michigan in iron ore production. For several years before and during 1880 New Jersey was the leading iron ore producing state.

Geologic Setting

The magnetite concentrations of the New Jersey Highlands are emplaced in a Precambrian complex of metamorphic and igneous rocks. The metamorphic rocks have reached the granulite facies (Turner and Verhoogen, 1960) and the igneous rocks (principally granites) were emplaced in a very deep-seated "catazonal" setting (Buddington, 1959). The Precambrian rock units include Granite, Quartz-Oligoclase Gneiss, Hypersthene-Quartz-Oligoclase Gneiss, Pyroxene Gneiss, Amphibolite, and Marble. A description of these rock units accompanies this guidebook (Puffer, this guidebook).

Characteristics of the Ore:

(1) The principal iron ore mineral throughout the New Jersey Highlands was magnetite, but a minor amount of hematite was also recovered. Both the magnetite and hematite typically contain exsolution lamellae of ilmenite and are described by Baker and Buddington (1970) as ilmeno-magnetite and ilmeno-hematite. These two ore minerals are commonly accompanied by minor to trace quantities of hemo-ilmenite (ilmenite containing exsolution lamellae of hematite) or titano-hematite (hematite containing titanium in solid-solution.)

(2) The chemical composition of the magnetite ore is quite variable. The TiO_2 content of magnetite concentrate from the Sulphur Hill deposit (a skarn) is 0.10 weight percent (Table 1) and is not accompained by any titanium oxide. Magnetite from the Edison deposit contains 0.70 weight percent TiO_2 and is associated with ilmeno-hematite, whereas magnetite from the Mount Pleasant deposit contains 1.30 weight percent TiO_2 and is accompanied by traces of hemo-ilmenite. There does not, however, appear to be any consistent structural or regional variation in the composition of the magntite. The composition of magnetite from the southern structural block of the Highlands is not consistently higher or lower than magnetite from the northern structural block.

(3) The occurrences of the magnetite ore range from a highly dispersed or disseminated mode to a highly concentrated vein mode. The largest magnetite concentrations occur as pod shaped lenses that grade into leaner material. The lenses are described as shoots while the low grade rock between them are called pinches.

(4) The magnetite concentrations are found emplaced in a variety of rock types. The most typical host rocks are Quartz-Oligoclase Gneiss, Amphibolite, Pyroxene Gneiss, Quartz-Potassium Feldspar Gneiss, and Marble Skarn. With few (if any) exceptions the host rocks are sedimentary units or interbedded volcanics that have been metamorphosed into granulite facies rock and then invaded by granites in a deep-seated "catazonal environment (Buddington, 1959).

(5) The magnetite concentrations are, without exception, emplaced concordant to the foliation of the metamorphic host rock.

(6) The magnetite concentrations are typically (probably without exception) veined with magnetite bearing pegmatites. The pegmatite veins are small, concordant, and comply with each of the characteristics of typical magnetite bearing pegmatites described by Puffer (1975).

(7) The magnetite concentrations are rarely found more than a few hundred meters away from a granite. The granite is most typically an alaskite but some deposits are located near Hornblende Granite and less commonly near Pyroxene Granite.

(8) Potassium feldspar, quartz, plagioclase, biotite, and hornblende are the principal gangue minerals associated with magnetite. Other silicates, oxides (principally hematite), sulfides (principally pyrite and / or pyrrhotite), and carbonates (principally calcite) are irregualrly distributed among the magnetite concentrations.

Source of Iron

There are at least three plausible sources for the iron that is found concentrated as magnetite deposits scattered throughout New Jersey Highlands: (1) Aqueous fluids released from magmas that formed the granites of the Highlands (particularly alaskite magmas), (2) The sedimentary sources of the metamorphic host-rocks that contain the magnetite concentrations, and (3) Aqueous fluids released from metasedimentary gneisses (particularly the Quartz-Oligoclase Gneiss) and Amphibolites.

Although each of these three sources and perhaps other sources may have contributed some iron, the relative importance of the various sources has been a controversial issue.

1. **The Alaskite Source:** It has been suggested by Buddington (1966), Baker and Buddington (1970), Smith (1933), Sims (1958) and others that hydro-thermal fluids emanating from granite magma carried iron into the meta-sedimentary country rocks intruded by the granite. According to Baker and Buddington (1970), the release of iron from the igneous magma transformed some of the granite into iron impoverished alaskite. This suggestion is supported by:

(a) The close spatial association of most of the magnetite concentrations with alaskite (see maps accompanying Baker and Buddington (1970), Hotz (1953), and Sims (1958).

(b) The barium enrichment of the feldspars associated with the magnetite ore; an enrichment that may have been induced through hydrothermal activity (Baker and Buddington, 1970). Uranium mineralization also accompanies some of the Highland magnetite deposits (Klemic and others, 1959) as well as minor sulfide mineralization.

(c) The occurrence of iron ore in a wide variety of rock types, each of which presumably had a different origin and a diferent capacity to concentrate ore through means other than hydrothermal activity.

On the other hand, each of these supporting statements are inconclusive. Detractors might argue that:

(a)The alaskite-iron ore association may be coincidental since the alaskite magma has intruded into positions close to a large percentage of the various Highlands rocks.

(b) Barium, uranium or other elements may also have been supplied by fluids released from the metasedimentary rocks or may have a syngenetic origin.

(c) Iron supplied by fluids released from the metasedimentary rocks may also have diffused into a variety of rock types before or during the emplacement of the granite magma.

TABLE 1

Principle Host Rock	Mine Name	TiO_2 Content
"Skarn" of Sims and Leonard (1952)	Rossville	0.27[1]
	Sulphur Hill	0.10[1]
"Oligoclase-Quartz-Biotite Gneiss" and "Albite-Oligoclase Granite Gneiss" of Sims (1958) and "Quartz Oligoclase Gneiss" of Baker and Buddington (1970)	Righter	1.58[1]
	Beach Glen	1.13[1]
	Lower Baker	1.10[1]
	Richard	0.30[2]
	Mount Pleasant	1.30[2]
	Scrub Oaks	0.49[2]
	Elizabeth	1.08[2] (average of 2 analyses)
	Hurd	0.93[2] (average of analyses)
	Hibernia	0.85[3] (average of analyses)
	Fairview	1.80[3]
Amphibolite	Dodge	3.01[1]
	Ford	2.43[1]
	Leonard	1.10[2] (average of 2 analyses)
	Scott	1.31[4] (average of analyses)
"Quartz-Potassium Feldspar Geniss" of Baker and Buddington (1970)	Edison	0.73[5] (average of analyses)
	Sherman-Bunker	1.01[5] (average of analyses)

1. X-Ray Fluorescence analyses - This Study
2. Sims (1958)
3. Collins (1969).
4. Hager and others (1963).
5. Baker and Buddington (1970).

It might also be argued that few typical hydrothermal mineral assemblages are found associated with the iron ore. But if the iron precipitated in a catazonal environment some of the most typical hydrothermal minerals, including several hydrous silicates, would be outside of their stability field. In addition, the foliated nature of the iron deposits suggests that the ore was emplaced before anatexis rather than as a late, perhaps deuteric, release of iron from a granite magma. But even if the iron was released as a late emanation from granite it may have been foliated by subsequent metamorphic events. The alaskite magma, therefore, remains neither proven or disproven as a source of iron ore.

2. **A Syngenetic Source:** Some of the metasedimentary rocks of the New Jersey Highlands may have always contained considerable iron ever since deposition as an iron rich sediment (Nason, 1922; Kastelic, 1980). Palmer (1970) also suggested a syngenetic origin for the iron ore of the Benson, New York deposit which has been described by Buddington (1966) as very similar to some of the Highlands deposits particularly the Edison deposit. Their suggestion is supported by:

(a) The strata bound nature of the ore and lack of any cross cutting structural relationship.

(b) The foliated nature of the ore which suggests that ore emplacement preceded metamorphism and subsequent igneous activity.

On the other hand, detractors might argue that:

(a) If iron was emplaced from fluids emanating from either granite magma or metamorphic rocks in a catazonal environment it is unlikely that cross cutting structures would be capable of penetrating down into catazonal depths. Catazonal environments are almost by definition devoid of cross cutting structures (Buddington, 1959).

(b) Both alternative origins allow for the possibility of a continuation of metamorphism following ore emplacement that could account for the foliated nature of the ore.

(c) If iron was originally precipitated as iron carbonate, as suggested by Kastelic, 1980 and Palmer, 1970 then why is so little iron carbonate found in the Franklin Marble? And why have the carbonates of the Franklin Marble survived the same metamorphic processes that allegedly destroyed the carbonate precursors of the iron ore at most Highlands locations?

(d) Since iron is found concentrated in several different rock types throughout the Highlands, a unique sedimentary environment capable of concentrating iron cannot, therefore, apply to each of these several rock types.

(e) A syngenetic origin is not easily applied to the thick almost pure magnetite vein mode of occurrence of some of the Highlands iron ore deposits (such as the Davenport Deposit).

(f) The very low Ti/Fe ratios found at most of the ore deposits rules out most common detrital sediments as the principal source of iron and the absence of significant jasper or its metamorphic equivalent rules out the kind of sediments associated with the syngenetic iron ores of the Lake Superior type.

3. **The Quartz-Oligoclase Gneiss as a Source:** A metamorphic diffusion mechanism such as that proposed by Hager and others (1963) and Collins (1969) may have mobilized considerable iron in the New Jersey Highlands. Recrystallization of an amphibolite into pegmatite, plus magnetite plus an iron depleted gneiss has been suggested by Hager and others (1963) as the origin of the Scott iron deposit. On a much larger scale, metamorphic processes may have also released iron from the widespread Quartz-Oligoclase Gneiss of the New Jersey Highlands (Puffer, this guidebook). If the Quartz-Oligoclase Gneiss is a metasedimentary rock as suggested by Sims (1958) Collins (1969) and Puffer, (this guidebook), it presumably underwent considerable prograde metamorphism to reach the granulite facies. Since water is generally released during each progressive stage of metamorphism a solvent for iron is generated that may be chemically equivalent to any hydrothermnal fluids released by the granitic magmas. Iron carried by aqueous fluids released by metamorphic processes may have diffused into any available sheer zone or low pressure zone. Precipitation of iron may have been forced by decreasing temperatures and pressures. This suggestion is supported by:

(a) The close spatial association of Quartz-Oligoclase Gneiss with most of the iron deposits of the New Jersey Highlands. (See maps accompanying Baker and Buddington (1970), Sims (1958) and Hotz (1953).

(b)The unusually low iron content of the Quartz-Oligoclase Gneiss. Regardless of whether the precursor of the Quartz-Oligoclase Gneiss was a graywacke (Puffer, this guidebook) or an igneous rock (presumably a tonalite, Baker and Buddington (1970), the iron content is low. About three percent iron oxide must be subtracted from a typical graywacke or tonalite to yield the average Quartz-Oligocalse Gneiss (Puffer, this guidebook).

(c) The way that the Fe/Mg ratio of ferromagnesian silicates decreases in response to increasing temperatures thus releasing iron given a fixed supply of magnesium. Biotite, for example, as it occurs in very high grade metamorphic environments will respond to this phenomena within temperature ranges approximating granulite facies conditions (Wones and Eugster, 1965). Iron rejected by such ferromagnesian silicates would be partitioned into any available aqueous phase rather than precipitate in place as an oxide. There is both empirical evidence (Mackin, 1968; Puffer and Peters, 1974) and experimental evidence (Martin and Piwinski, 1969) that iron is highly soluble in high temperature aqueous fluids generated by silicate systems. Water generated by the prograde metamorphic conversion of aqueous phases into anhydrous phases may have been the solvent that transported the iron.

(d) The common association of Highlands iron ore with magnetite bearing pegmatites. The same aqueous fluids may be responsible for the development of both the iron ore and the magnetite bearing pegmatites. Both the pegmatites and the iron ore were presumably deposited in the same low pressure zones.

(e) The association of iron ore with a potassium rich mineral assemblage. Both biotite and potassium feldspar are typically found as gangue minerals accompanying the magnetite. Both potassium and iron are depleted from the Quartz-Oligoclase Gneiss and probably were transported together in the same aqueous fluids. These fluids were probably mobilized when hydrous ferromagnesian silicates (particularly biotite) broke down in response to prograde metamorphism approaching the granulite facies.

The principal weakness with the Quartz-Oligoclase Gneiss source rock hypothesis is the lack of evidence pertaining to the pre-metamorphic iron content of the Quartz-Oligoclase Gneiss and the lack of evidence pertaining to the solubility of iron in any aqueous fluids released during metamorphism. These weaknesses, however, are shared by the granite magma source rock hypothesis. Fluids emanating from either source would actually have much in common.

Combined Sources

If aqueous fluids containing iron were driven out of the Quartz-Oligoclase Gneiss during prograde metamorphism approaching granulite facies conditions, these fluids would have been chemically similar to those driven out of any granite magma emplaced into the same "catazonal" environment. The solubility of iron in such fluids would presumably be controlled to a large degree by the same temperature and pressure considerations. Fluids simultaneously emerging from both sources may also have mixed with each other since there would have been a tendency for both fluids to migrate toward the same low pressure zones. The ultimate source of iron precipitated out of such a mixed fluid would be completely problematical. Still further mixing with at least some syngenetic iron would also be expected. It may, therefore, be impossible to ever sort out the exact contribution of iron from each source, unless, of course, this is accomplished during the anticipated lively discussion of the various possibilities that will hopefully take place among field trip participants.

The Edison Magnetite Deposits

The Edison Magnetite Deposits are located about three miles east of the town of Ogdensburg, New Jersey (Stop # 3). Iron was extracted from the Edison Deposits from 1772 to 1899 (Baker and Buddington, 1970). Most of the magnetite ore is disseminated within a biotite and sillimanite rich phase of a Quartz-Potassium Feldspar Gneiss. The Gneiss is locally a 1000 ft. wide N-E striking band of rock bounded on the southeast by Quartz-Microcline Gneiss and on the northwest by Syenite Gneiss (see map accompanying Baker and Buddington, 1970). The foliation of the Quartz-Potassium Feldspar Gneiss dips vertically or steeply to the southeast. It is a metasedimentary rock that is locally composed of variable amounts of potassium feldspar, quartz, sillimanite, and magnetite with accessory garnet, apatite, monazite, spinel, corundum, epidote, fluorite, zircon, ilmeno-hematite, pyrite, molybdenite, and chalcopyrite. The virtual absence of plagioclase feldspar from the host rock of the ore results in a very high K/Na ratio. The potassium feldspar of the ore contains over two percent barium (Baker and Buddington, 1970), and is non-perthitic. Alteration enhanced by acid solutions leached from the sulfides has deeply altered some of the rock, particularly were sulfides are concentrated. Some of the potassium feldspar has been deeply altered to sericite and some of the magnetite has been altered to martite.

Seams of magnetite and ilmeno-hematite bearing pegmatites are found throughout the Edison Deposits. The pegmatites were probably precipitated from aqueous fluids released from the metasedimentary host

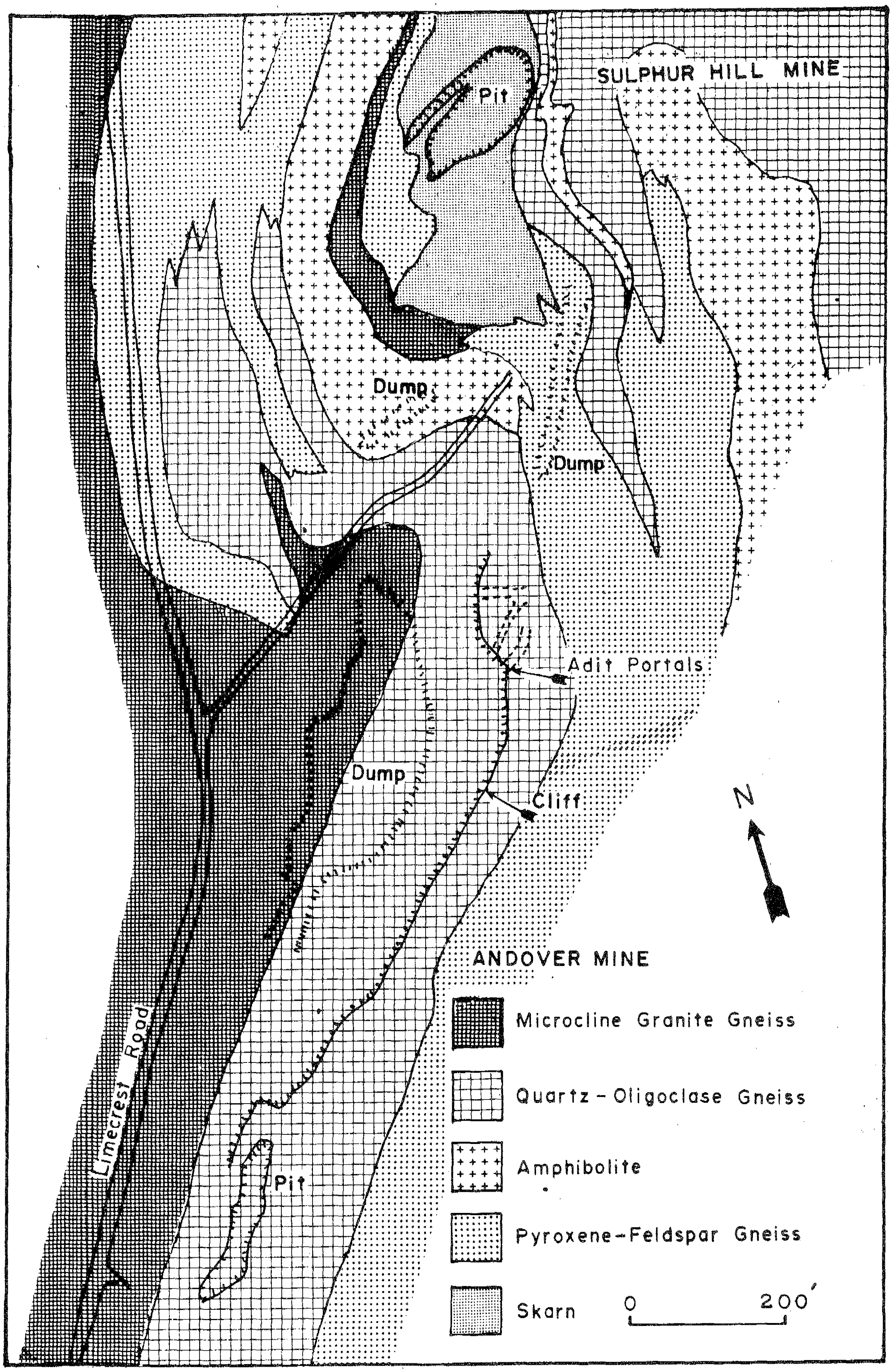

Fig. 1 Geologic map of Andover and Sulphur Hill mining district, New Jersey. This map is a slightly modified portion of a more detailed map by Sims and Leonard (1952). Some very highly altered rock described by Sims and Leonard (1952) as altered diabase is distributed throughout the mine area, particulary along the cliff (fault scarp?). Located near the Andover mine.

rock during prograde granulite facies metamorphism (Puffer, 1975). The concordant emplacement of the pegmatites, their small size, their lack of zoning or lithium, boron, or berrilium minerals and their catazonal metamorphic setting are characteristics that are typical of magnetite rich pegmaties found throughout the New Jersey Highlands and elsewhere (Puffer, 1975).

The Andover - Sulphur Hill Iron Deposits

The Andover iron ore deposit (Stop # 2) is located approximately two miles northeast of Andover, New Jersey. The Andover Mine was worked from some time before 1763 until 1863, whereas the adjacent Sulphur Hill mine was worked from 1855 until 1880 (Sims and Leonard, 1952).

The Andover Mine is cut into a 250 ft. wide band of N-E striking Quartz-Oligoclase Gneiss that is bounded on the northwest by microcline granite gneiss (containing accessory biotite and sillimanite) and on the southest by pyroxene-feldspar gneiss (Fig. 1). Both magnetite and hematite ore was extracted at the Andover Mine. An unaltered magnetite concentration is found at the northeast end of the Andover pit and is surrounded by a thick shell of "red ore" that is composed predominantly of hematite and silica. According to Sims and Leonard (1952) the hematite was formed by supergene alteration of hypogene magnetite.

Although the Sulphur Hill ore is rich in sulfides only minor traces of sulfides are found in the Andover ore. The Andover pit and underground workings are located along a cliff that Sims and Leonard (1952) describe as a fault scarp. They interpret the black, fine grained, highly chloritized rock exposed along the cliff as a diabase dike and suggest that it intruded during the Triassic Period.

The Sulphur Hill mine located about 500 ft. northeast of the Andover Mine is cut into a 200 ft. wide exposure of skarn (Fig. 1). The rock name skarn is used here in keeping with virtually all previous geologic references but no genetic implication is intended. Contact metamorphism may or may not have been responsible for the ore implacement. The skarn is in contact with amphibolite and pyroxene-feldspar gneiss on the northwest and with Quartz-Oligoclase Gneiss on the southeast. The skarn consists of calcite, garnet, magnetite, pyroxene, and pyrrhotite, with accessory sphalerite, galena, chalcopyrite, and molybdenite. The sphalerite is difficult to distinguish from the andradite garnet because of its dark brown color. Some of the magnetite has been altered to martite. The skarn is probably a very impure zone of Franklin Marble. Although similar iron oxide rich deposits occur in the Franklin Marble (such as the Furnace Magnetite Deposit near Franklin, New Jersey) the Sulphur Hill Deposit is not typical of New Jersey Highlands iron mines.

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Mine Hill, Franklin Furnace.

MINE HILL, FRANKLIN FURNACE
by H. Carmiencke
from N.J.G.S., 1856, 2nd Annual

THE GEOLOGIC SETTING OF THE STERLING HILL ZINC-IRON-MANGANESE DEPOSIT

BOB METSGER

The New Jersey Zinc Company
Sterling Mine, Ogdensburg, New Jersey

The Sterling Hill mine is located on the west side of the Wallkill River Valley in the Borough of Ogdensburg, Sussex County, New Jersey. Ogdensburg, about fifty miles from New York City, may be reached by taking County Rte. 517 either south from its intersection with N.J. Rte. 23 in Franklin or north from the town of Sparta, about four miles distant.

The Sterling Hill deposit together with its now depleted companion at Franklin, 2½ miles to the north, are a pair of silicate-oxide ore bodies that are unique in all the world. The combination of ore and gangue minerals that comprise them is unknown elsewhere. Indeed, the mineral franklinite is not known to have been found outside of these two places.

Both bodies of ore are enclosed within the Franklin marble which is one of two bands of Precambrian metalimestones which strike northeasterly near the western border of the Reading Prong. The two marble bands, indistinguishable from one another, are separated by roughly 300 meters of heterogeneously mixed gneisses which comprise a unit aptly designated the "Miscellaneous gneiss" by Buddington and Baker (1970) but which is more commonly called the Cork Hill gneiss. All three bands dip southeasterly about 55° in the vicinity of the ore bodies.

The regional structural pattern is interpreted by Hague et al (1956) and Buddington and Baker (1970) as a group of northeast trending overturned isoclinal folds. Generally the folds plunge from 10° - 30° NE. Normal faulting predominates in the area with the faults dipping from about 70° to vertical and striking parallel with the predominantly NE trend of the Precambrian rocks. The contacts between the gneisses and the metalimestones are straight-to-broadly warped and reveal none of the complex folding seen within the marbles themselves.

The metalimestone is a medium-to-coarsely crystalline calcite marble characterized by bands of disseminated silicates (tremolite, phlogopite, chondrodite, etc.), pyrite, and graphite. The latter is ubiquitous in the metalimestones except where they are associated with the ores at Franklin and Ogdensburg and in halos around certain pegmatitic bodies. Inhomogeneities in grain size appear to be, at least in part, a function of mineral banding. Calcite grain diameters range from less than a centimeter to as much as sixty centimeters. In general, the sparsely mineralized calcite has a coarser texture than that which is heavily mineralized. It might be said that the calcite grain size varies inversely with the concentration of other minerals contained within it. It also appears that the calcite grains are flattened in planes parallel with the mineral banding of the marble.

The contacts of the metalimestones with adjacent gneissic units are commonly characterizd by increasingly abundant coarse crystals of pyroxene, garnet, spinel, biotite, apatite and feldspar as the gneiss is approached. Grain diameters reach as much as 3-6 centimeters. Also common at the contacts are clots of white to pale yellow sphalerite. Dithizone analyses by the New Jersey Zinc Company of drill cores passing through marble into gneiss showed the presence of anomalously high traces of zinc at such contact.

A characteristic of the metalimestone belts is the presence within them of inclusions of "miscellaneous gneiss" which range from a few centimeters to many meters in diameter. They are not boudins but rather are fragments of gneiss which are far removed from the parent band. Were they isolated in an igneous rock rather than a marble they would be unquestionably called xenoliths.

Those xenolithoids which are composed of carbonate free amphilbolite, for example, typically have borders of randomly oriented 2.5-3 cm crystals of pyroxene, garnet, biotite and/or gahnite crystals. On the other hand, those fragments having some carbonate content generally have no obvious reaction rims.

Some xenolithoids are crossed by quartz filled fractures which terminate at the fragment boundaries. They clearly belong to the fragment and not to the enclosing marble.

The ore bodies at Franklin and Sterling Hill have afforded the best opportunities to study the metalimestone structure in some detail. The distinctive

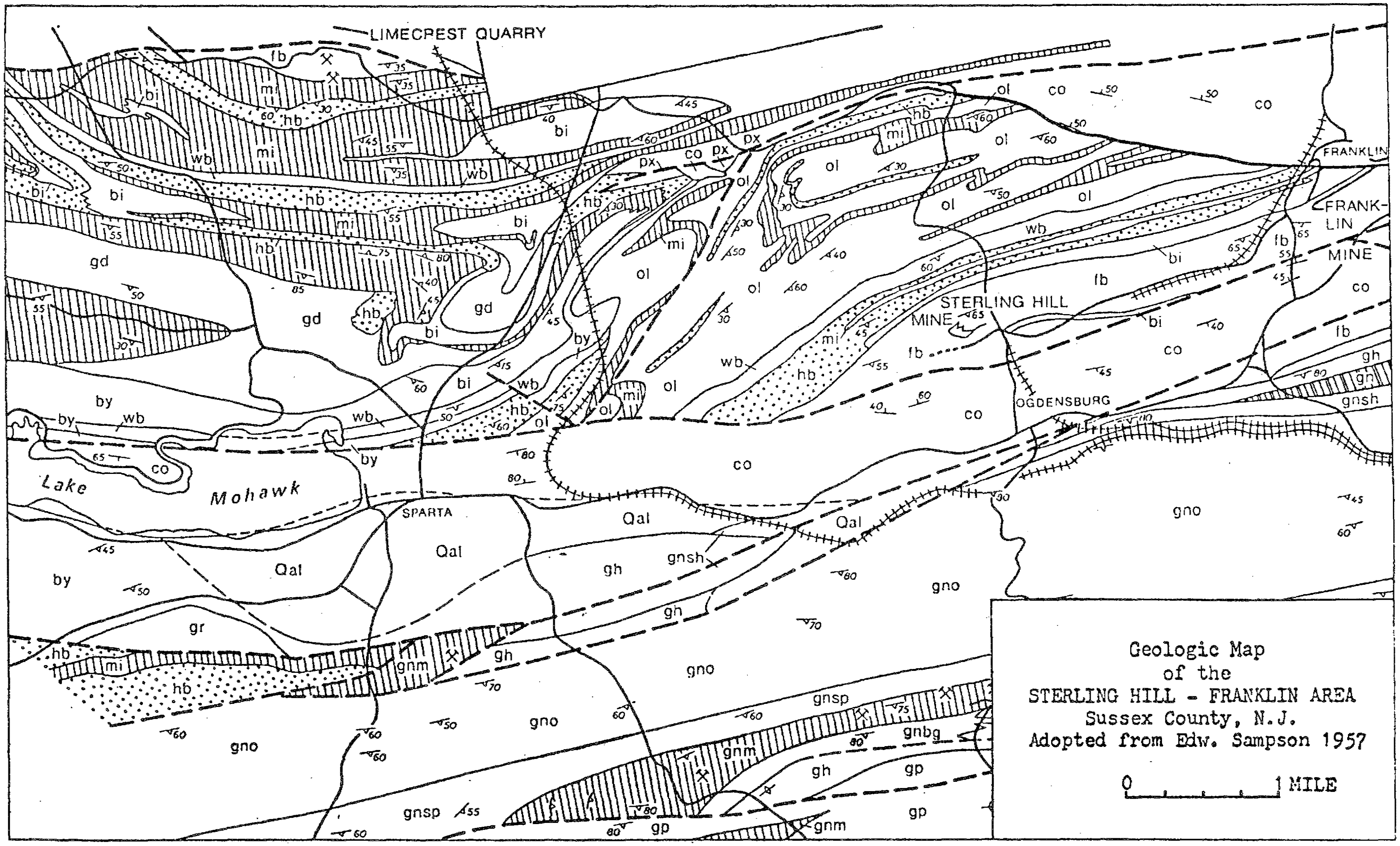
LIMECREST QUARRY
FRANKLIN
FRANKLIN MINE
STERLING HILL MINE
OGDENSBURG
SPARTA
Lake Mohawk
Geologic Map
of the
STERLING HILL - FRANKLIN AREA
Sussex County, N.J.
Adopted from Edw. Sampson 1957
0 1 MILE

FIGURE 1

EXPLANATION

QUATERNARY

Qal Alluvium and moraine

CAMBRIAN AND ORDOVICIAN

co Cambro-Ordovician sediments

PRECAMBRIAN

gr Granite

by Byram gneiss

gd Granodiorite gneiss

ol Oligoclase gneiss--possibly the same as

gh Hornblende granite with some alaskitic facies

gp Pyroxene granite with local pyroxene syenitic facies

ROCKS OF UNCERTAIN ORIGIN

gm Quartz-microcline granite-like gneiss

gno Losee gneiss of type locality. Quartz oligoclase gneiss.

ORTHOGNEISS

gnsh/gnsp

gnsh Hornblende syenite gneiss

gnsp Pyroxene syenite

METASEDIMENTARY AND METASOMATIC ROCKS

fb/wb Marble. Franklin band. Wildcat band.

gnh Hypersthene biotite quartz-oligoclase gneiss, in part with a very little accessory graphite

gnab Mixed gneisses: quartz-bearing hornblende and pyroxene-plagioclase gneiss, biotite mafic gneisses, local interbeds of sillimanitic or garnetiferous quartz-microcline gneiss

gnp Pyroxene quartz-plagioclase gneisses

gnbg Biotite quartz-plagioclase and other gneisses

gne Epidote-scapolite-quartz gneisses interlayered with pyroxenic and hornblendic quartz-microcline gneiss

mi Microcline gneiss

gnm Quartz-potash feldspar gneisses, in part seamed with pegmatite. Host to magnetite mineralization.

am Amphibolite

hb Hornblende gneiss, including calcareous facies

bi Biotite gneiss

px Pyroxene gneiss and related rocks, including calcareous facies

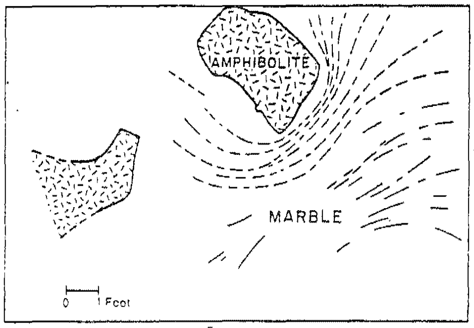

Figure 2

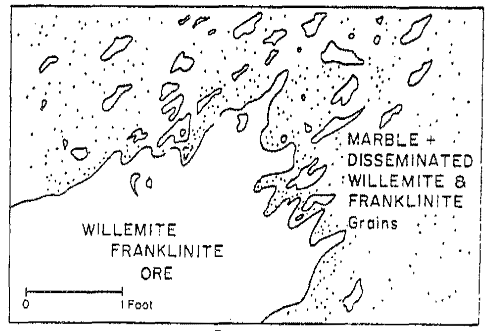

Figure 4

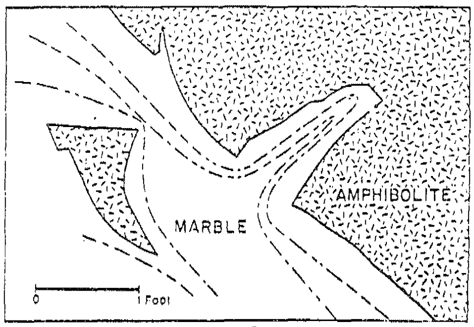

Figure 3

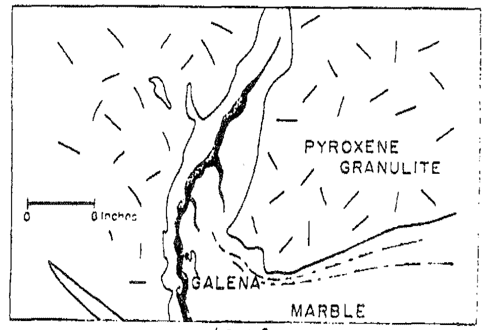

Figure 5

bands of willemite, franklinite, and zincite as well as those of more common calc-silicate minerals have made it possible to trace folding in the marble that would be otherwise obscure. A variety of textures, especially at Sterling Hill, reveal that ore and adjacent calc-silicates were originally carbonate free granulites. Certain distinctive graphite-phlogopite-chondrodite-pyrrhotite bands in the marble wall rock and a fluorite band at the contact between ore and marble as well as recognizable bands within the ore itself suggest that the ore was at one time stratiform.

Ore textures grade from massive granulose and gneissose to disseminated "pepper and salt". The appearance of the gradation suggests that the ore minerals as well as the adjacent calc-silicates were friable masses which became disaggregated within an extremely plastic or, in part, even fluid carbonate (fig. 4).

The shape of the ore body itself suggests a huge flow pattern influenced by a broken band of brittle gneiss fragments which it has engulfed. Where the sharply anglular gneiss blocks are near ore, the ore banding is bent around them. Where they are isolated in marble, the flow pattern is revealed by contorted silicate and graphite bands (fig. 2).

When the average density of the entire body (approximately 3.02) is considered together with the visual evidence for the plasticity of the enclosing marble (d = 2.75) it seems almost a certainty that the complex fold pattern of the ore body is due to its movement through the marble. The density contrast between ore and marble seems sufficient for gravity, in addition to tectonism, to have played an important part. It has therefore been proposed (Metsger, et al., 1967) that the ore body acquired its present shape as it sank through the limestone as an inverted diapir.

Marble "dikes" are common in the gneisses and granulites associated with the metalimestones. They were formed when the mobile carbonate flowed into fissures in the more brittle rocks (fig. 3). One such dike was observed in a pyroxene granulite fragment in the core of the Sterling ore body (fig. 5). The dike contained a vein of galena which occupied a fracture in the marble. The lead age of the galena, manifestly of more recent origin than the surrounding rock, was 1100×10^6 years.

From observations, chiefly in the Sterling Hill mine, it appears that the Precambrian history of the metalimestones and of the enclosed zinc, iron, magnanese ores was somewhat as follows.

1. Deposition of a series of limestones and siliceous sediments and volcanics beneath the sea. Within the carbonate horizon at least one metal rich bed was deposited.

2. The sedimentary series was folded and then—

3. forced to a depth where sillimanite grade metamorphic conditions prevailed. During this stage the granulites and gneisses were formed

from the siliceous and volcanic units. The metal rich horizon was metamorphosed to a granulose silicate and oxide band and the calcareous units to marble.

4. The region continued to subside until ambient conditions prevailed in which the gneisses and the ore were essentially unmodified while the marble became extremely plastic or, perhaps, fluid. During this period, currents in the viscous carbonates tore relatively thin bands of gneiss apart and produced complexly contorted folds in the less fragible ore and calc-silicate zones. Because of the low viscosity of the enclosing carbonate, the more friable bands of ore and calc-silicates disaggregated to produce the "pepper and salt" texture so common in certain parts of the marble units.

5. The subsidence was arrested and the region uplifted. As a result, uniquely metamorphosed ore deposits folded in complex flow patterns have been preserved which otherwise would have been destroyed by absorption into the mantle.

At the close of the Precambrian the metalimestones were exposed at the surface. Zones of rubble breccia have been observed, in the Sterling Hill ore body and in drill cores, which may be genetically related to the erosion surface that existed at that time. The brecciated zones cross-cut the ore structure and are comprised of rock and ore fragments, often mixed, in a matrix of the lithified insoluble residues from the marble and ore. Fragments range from a few centimeters to as much as a meter in diameter. The dimensions of the zones are measured in tens of hundreds of feet, with the principal dimensions vertical.

In general the marbles are quite pure calcite. Dolomitization has taken place principally along fractures and joints related to faulting of Paleozoic or more recent age. Such dolomitized marble is recognizable in quarry walls as a buff coloration against the pure white to gray color of calcitic rock.

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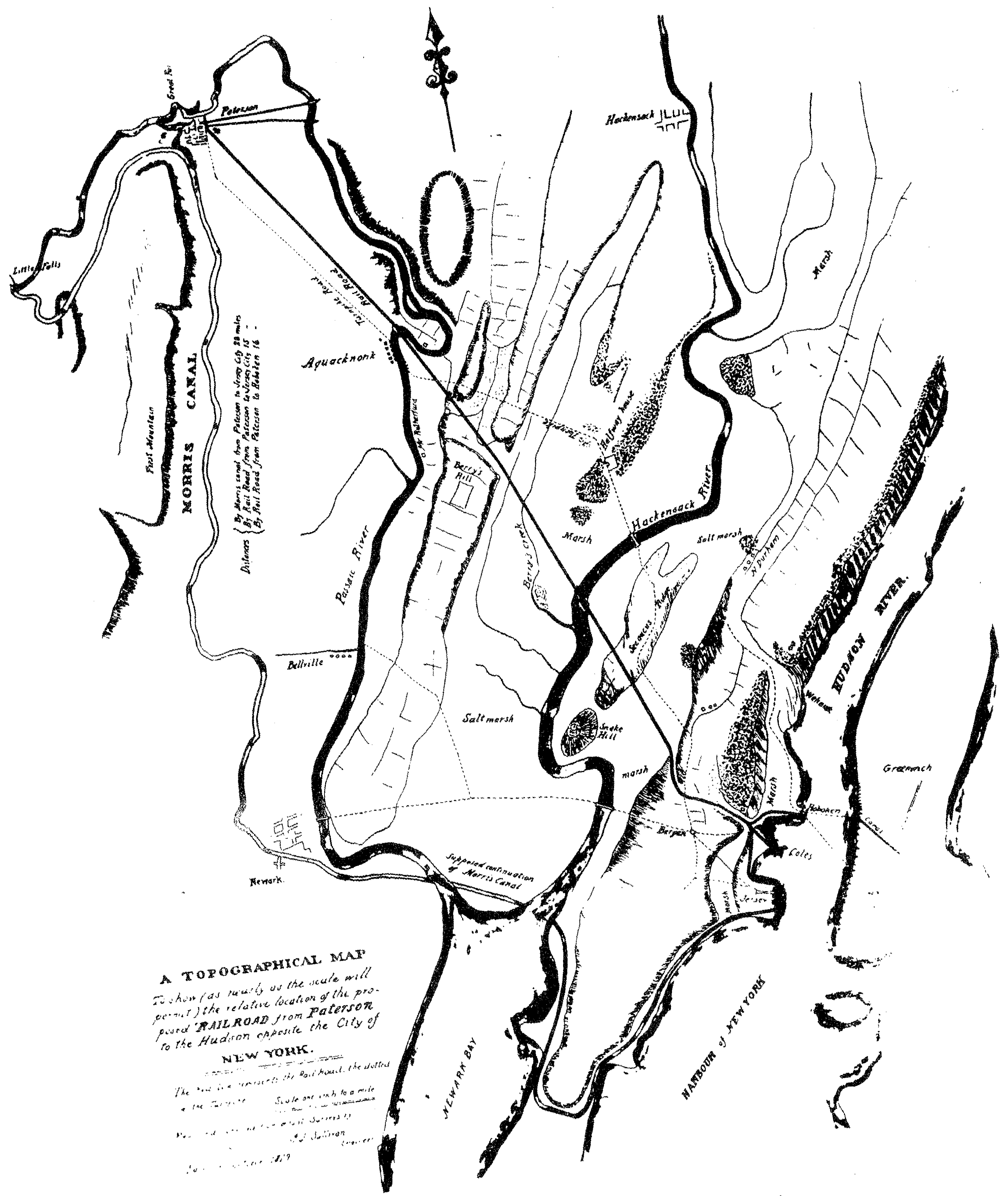

TOPOGRAPHICAL MAP, Hackensack Meadowlands Region
1829
by I.L. Sullivan

ENVIRONMENTAL GEOLOGY OF THE HACKENSACK MEADOWLANDS

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Introduction

This trip to the Hackensack Meadowlands District has several purposes:

1. To observe the natural environment of the Meadowlands, the problems and challenges it poses, and to gain some understanding of how the geologic history gave rise to that environment.

2. To see how numerous, complex, diverse, and seemingly incompatible land uses can be carried out harmoniously and profitably if a region's geology and ecology are adequately understood by planners; and if imaginative engineering, political and economic planning are applied.

3. To inspect several of the major projects that have been erected in the Meadowlands, consider their operational processes and how they impact on the environment and, above all, how geologic constraints were dealt with in designing foundations, etc.

The pioneering work done by the Hackensack Meadowlands Development Commission in planning and overseeing the harmonious growth of the District is unique in this country. A long-blighted area, where land was almost worthless some four decades ago, now contains some of the most valuable acreage in the country. What can be learned here may very well have application elsewhere.

Acknowledgement

I am grateful for the cooperation I have received from individuals and agencies in setting up this trip. Particularly helpful have been: Patricia Q. Sheehan, former Executive Director of the Hackensack Meadowlands Development Commission; Donald Smith, John Bolan, Vincent Nykiel and Louis J. Degange, all of the Commission staff; Michael Graime and Francis H. Werneke of the New Jersey Sports and Exposition Authority; Jerome F. Sheehan and Philip Bober of the Bergen County Utilities Commission; and Michael McNally of Hartz Mountain Industries, Inc. I also wish to thank Muriel Meddaugh, John Szalkowski and Phil Kortis of my own Department for their help.

Geology of the Meadowlands

The Hackensack River Valley, including the Meadowlands, lies in the Piedmont physiographic province of northeastern New Jersey. The bedrock is the Brunswick Formation of the Late Triassic Newark Group, 225 to 200 million years in age (Van Houten, 1970). The formation consists of fluviatile and lacustrine reddish-brown shales and some fine-grained sandstones. Associated basalts of the Newark Group include three younger lava flows forming the Watchung Mountains several miles west of the Meadowlands; the Palisades sill, in part a dike, bordering the Meadowlands on the east; and Laurel Hill (Snake Hill), a basalt plug adjacent to the New Jersey Turnpike in the southern part of the Hackensack Meadowlands.

The extrusive Watchung basalts and the intrusive Palisade diabase post-date the Brunswick beds in this area. They manifest volcanism accompanying the initial stages in the opening of the Atlantic basin (Manspeizer et al, 1978). Subsequent faulting has left the Newark Group with a dip of approximately 20 degrees to the northwest. Post-Newark erosion produced a very flat topography. Stream valleys such as the Hackensack were eroded in the weak shales, and NE-SW trending cuestas such as the Palisades and the Watchung Mountains formed on the resistant basaltic rocks.

The region was covered by at least three glacial advances in the Pleistocene. The last of these, the Wisconsin ice sheet, moved south across the area as far as Perth Amboy. Being over 1000 feet thick, it exerted a pressure of almost 400 pounds per square inch (JMA, 1978). A blanket of till was deposited as ground moraine over the Newark red beds. The till, consisting mostly of red and reddish-brown sandstone and shale fragments of the Newark Series, varies in thickness from 0 to at least 30 feet, as indicated by borings (JMA, 1974).

Glacial Lake Hackensack began to form about 15,000 years ago as a proglacial lake impounded behind the terminal moraine on the south. Its axis extended north along Arthur Kill, Newark Bay, the Hackensack River, and into New York State through West Nyack and eastward to Mount Ivy. Its greatest width, about 15 miles, was near the city of Hackensack (Schuberth, 1968). All of the Hackensack Meadowlands was submerged by Lake Hackensack, which was one of several adjacent proglacial lakes, separated by divides such as the First Watchung Mountain, the Palisades Cuesta, and Manhattan Island.

About 10,000 years ago the terminal moraine was breached and Lake Hackensack was drained into the Atlantic (Widmer, 1964). During the time the lake existed, varved clays, more than 200 feet thick in places, accumulated as seasonal deposits (Widmer 1963). There are at least 2,550 varves, each consisting of a lighter-colored silt (summer) layer and a darker-colored clay (winter) layer. The regularity of the varves was disrupted in places by local conditions. For example, coarser sediments washing down from the Secaucus Ridge masked the normal varve pattern on the adjacent lake bottom (JMA 1978). Even more striking is the unusual series of cores taken in the vicinity of Cromakill Creek, where varved segments of the cores were interrupted by coarse sand or other unvarved sediment, and where horizontal continuity of bedding was not very evident in the different test holes. This is attributed to the presence there of an unusually deep bedrock valley of the ancestral Hackensack River and of the nearby Bergen Ridge to the east. The ridge shed gravels, red sand and red silt into Lake Hackensack, producing a local sedimentary environment uniquely different from that prevailing generally in the lake (JMA, 1978).

Borings done for the U.S. Army Corps of Engineers (Fig. 1) show that the glacially scoured bedrock valley under the Hackensack Meadowlands is from one to two miles wide and lies buried under till and varved clay and silt, in places over 170 feet thick (U.S. Army Corps of Engineers, 1962). The valley of the present Hackensack River is incised in varved lake sediments to a maximum depth of about 35 feet and its width varies from several hundred feet to more than 1000 feet.

Following the breaching of the terminal moraine, some 10,000 years ago, and the draining of Lake Hackensack, the area was a level wetland for several millenia, with stands of lowland forest and grassy marshes. About 3,000 to 5,000 years ago, rising sea level accompanying the melting of the ice sheets, reached the elevation of the narrow outlets of the Hackensack River at Kill Van Kull and Arthur Kill, exposing the river to the tides. As sea level continued to rise, estuarine conditions extended northward into the Hackensack River Valley, producing the salt marsh environment that has existed into the present (Fig. 2).

A U.S. Geological Survey map of surficial deposits indicates Quaternary deposits (Qm) covering the area, and summaries the geologic, hydrologic and engineering conditions as follows:

> "Quaternary marshes, swamps, estuaries, and artificial fill...interbedded silt fine-grained sand, clay, and organic material in differing proportions...upper part dominantly organic..,soft noncompact, in part semifluid...commonly overlain by artificial fill...underlain by till...silt and clay...esturaries, salt marshes present below level of high tide...bearing capacity very poor. Compressibility high. Unstable, flows readily into underwater excavations. Very small water yields to wells. Has high porosity...low permeability." (U.S.G.S., 1967).

The Hackensack Meadowlands Development Commission

The Hackensack Meadowlands Development Commission, established by the New Jersey Legislature in 1968, was mandated to regulate land use in the Hackensack Meadowlands District, comprising 19,730 acres. This area is larger than Manhattan Island (32 square miles vs. 22-1/4 square miles). Despite its central location in the northern New Jersey - New York City metropolis (Fig. 3), the area was long avoided by developers because of the high costs and technical problems involved in building in an estuarine marsh with substrate of peat and clay. Consequently, it has been used largely as a waste—disposal site by the region's municipalities which grew up over the years on the surrounding higher elevations.

Development in the District had also been retarded because the land overlapped 14 municipal jurisdictions and because of complex riparian disputes. The Hackensack Meadowlands Development Commission's Master Plan (HMDC, 1972), while responding to mounting pressure to utilize this favorably situated real estate more intensively, also seeks to encourage balanced development between residential, commercial, industrial, and recreational uses. In addition to building and preserving parks, wetlands and wild life refuges, the Commission is concerned with sanitary landfills, transportation, liquid natural gas storage facilities, the Sports Complex and other uses of the land. The land use plan in force in the District (Fig. 4) regulates land use in 14 municipalities; nowhere else in the United States does a land use plan regulate more than one municipal jurisdiction. The Hackensack Meadowlands District, lying in the middle of the Northeast Corridor, is probably one of the most intensely used land areas in the world from the standpoint of the numbers of people criss-crossing it; the diverse industrial, commercial, residential, and recreational activities going on there; and the vigorous utilization of the wetlands by the wildlife.

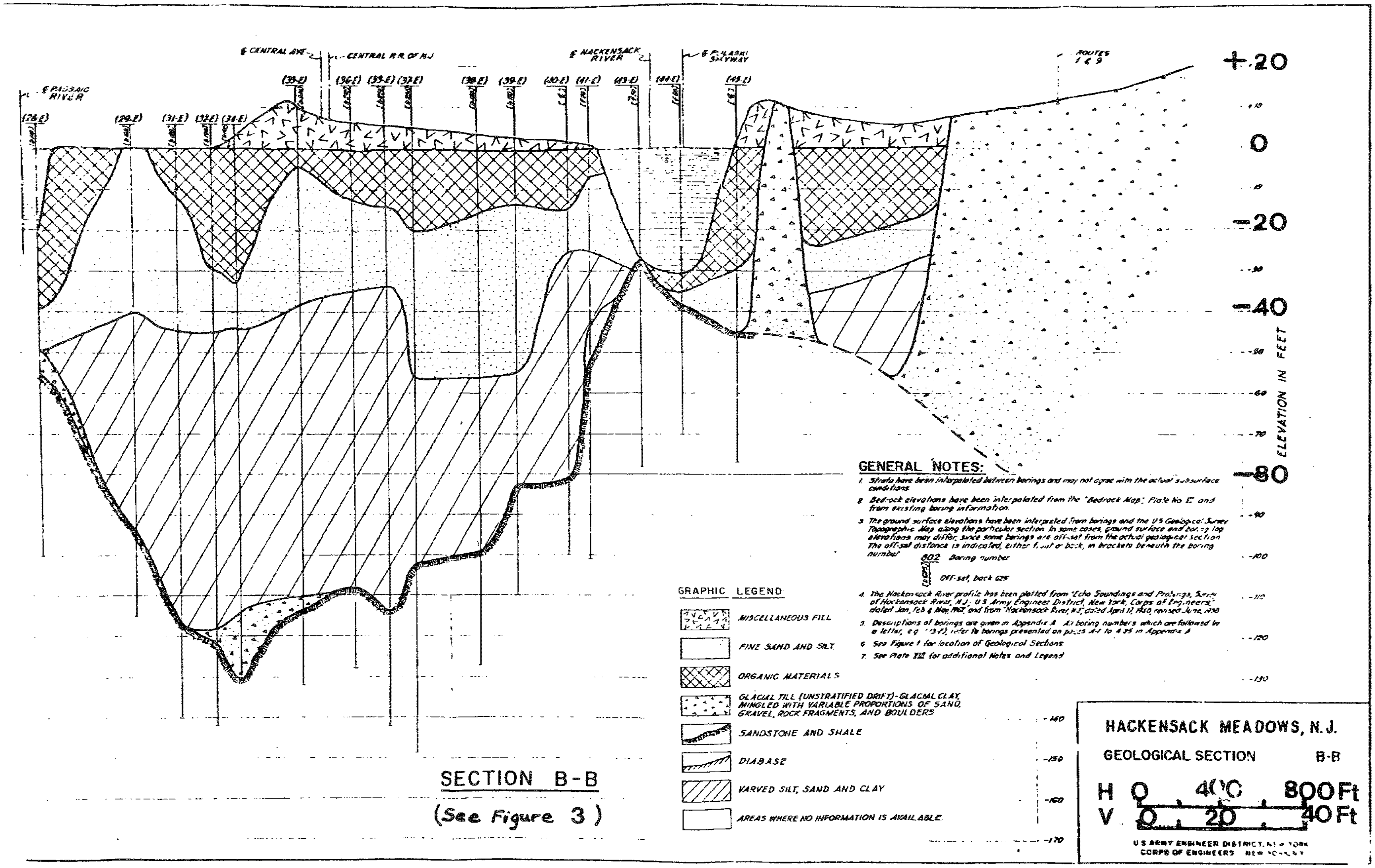

Fig. 1 Geologic section along Pulaski Skyway, south end of Hackensack Meadowlands (see Figure 3, B-B). Note the deep, glacially scoured bedrock floor of the ancestral Hackensack River. The present river bed is incised in lake sediments and organic deposits indicating Recent crustal rebound (U.S. Army Corps of Engineers, 1962).

Fig. 2 Tidal wetlands, Sawmill Creek Wildlife Management Area at high tide. Towers of railroad bridge across the Hackensack River can be seen in the distance, to right of center. Two LNG storage tanks are in extreme top right. View to north. (Courtesy, Chet Mattson, Hackensack Meadowlands Development Commission).

The region is expected to undergo intensive development during the next few years (JMA, 1974). By the year 2000, it is anticipated there will be 140,000 jobs, with annual wages of upwards of $1 billion in the Meadowlands (Hanley 1979c). The Commission projects that, upon full development, net tax revenues to each of the 14 municipalities, over the cost of delivering services to the District portion of the town, will average $2.9 million. In seven of the 14 towns this will pay for more than 85 percent of the total town budget (HMDC, 1979).

Transportation in the Meadowlands

The transportation problem in the Meadowlands is too costly for government alone to solve, without the private sector, according to the State Transportation Commissioner. He estimated it would cost more than $1 billion to build a highway system to serve a fully developed Meadowlands district (Roberson, 1980). Outside consultants had to be retained to evaluate the transportation impact of the 645 development applications that were pending before the Hackensack Meadowlands Development Commission at the beginning of 1980. By the year 2000, according to Senator Harrison A. Williams, Jr. of New Jersey, there will be an estimated 75,000 peak-hour trips to the Meadowlands, compared to the 30,000 peak-hour trips now (Roberson, 1980). The Meadowlands transportation master plan must envisage wider use of mass transit in the years ahead.

Currently, the transportation modes in the Meadowlands are highway, rail, pipeline, water, and air. The major highways are the east and west spurs of the New Jersey Turnpike, running north-south; Route 3, the major east-west highway, crosses the District near the midline; and the Belleville and Newark Turnpikes cross it in the south. Paterson Plank Road, Meadowlands Parkway, Washington Avenue, and Moonachie Avenue are also heavily trafficked arteries. Complex cloverleaf interchanges mark the intersections of some of the highways. Of the 19,730 acres in the Meadowlands, 2,100 are zoned for turnpike and limited access roads, and 430 for local roads. There are also 400 acres zoned for railroads, 670 for airport facilities, and 205 for transportation centers (bus and railroad stations). Thus, a total of 4,005 acres, about 20% of the total acreage, is zoned for transportation (HMDC, 1972).

Hackensack River Estuary and its Ecosystem

The Hackensack River flows in a glacially modified valley from Haverstraw, New York, south to Newark Bay, where it meets the Passaic River. In its lower 22 miles, the Hackensack is an estuarine, meandering, brackish stream flowing alternately south and north with the ebb and flood of the tides. Since 1922, when a dam was built by the Hackensack water company at New Milford to form the Oradell Reservoir, the impounded fresh water has been diverted to residential and industrial use leaving little fresh water to flow into the lower 22 miles of the river. Most of the freshwater that does enter arrives as run-off via storm drains and sewers, as industrial discharge, and as effluent from sewage treatment plants. The river's flow is now mostly tidal water, with a salinity range of 1 to 18 ppt from north to south. When the tidal water enters the Hackensack Estuary it has already acquired much fresh water from the larger Hudson and Raritan Rivers in New York Bay, and its salinity has been reduced from the 35 ppt in the ocean to the levels found in the river (Mattson and Vallario, 1976).

The Hackensack follows a meandering course for 13.6 miles approximately down the Middle of the Hackensack Meadowlands District, dividing it into an eastern part and a slightly larger western part (Fig. 3). The river's course covers some 1400 acres, and adjacent wetlands another 6,300 acres, both areas constituting about 39 percent of the total 19,730 acres in the District.

Five Wetland Bio-Zones are recognized in the District, based on salinity and vegetation (Mattson and Vallario, 1976):

Bio-Zone I -Shallow tidal bays, Mudflats (5-15 ppt salinity)
Bio-Zone II - Low salt marsh (5-15 ppt salinity)
Bio-Zone III - High salt marsh (5-15 ppt salinity)
Bio-Zone IV - Low salinity reed, cattail and cordgrass marsh (3-9 ppt salinity)
Bio-Zone V - Fresh water marsh (0-3 ppt salinity)
Their distribution is shown in Figure 5.

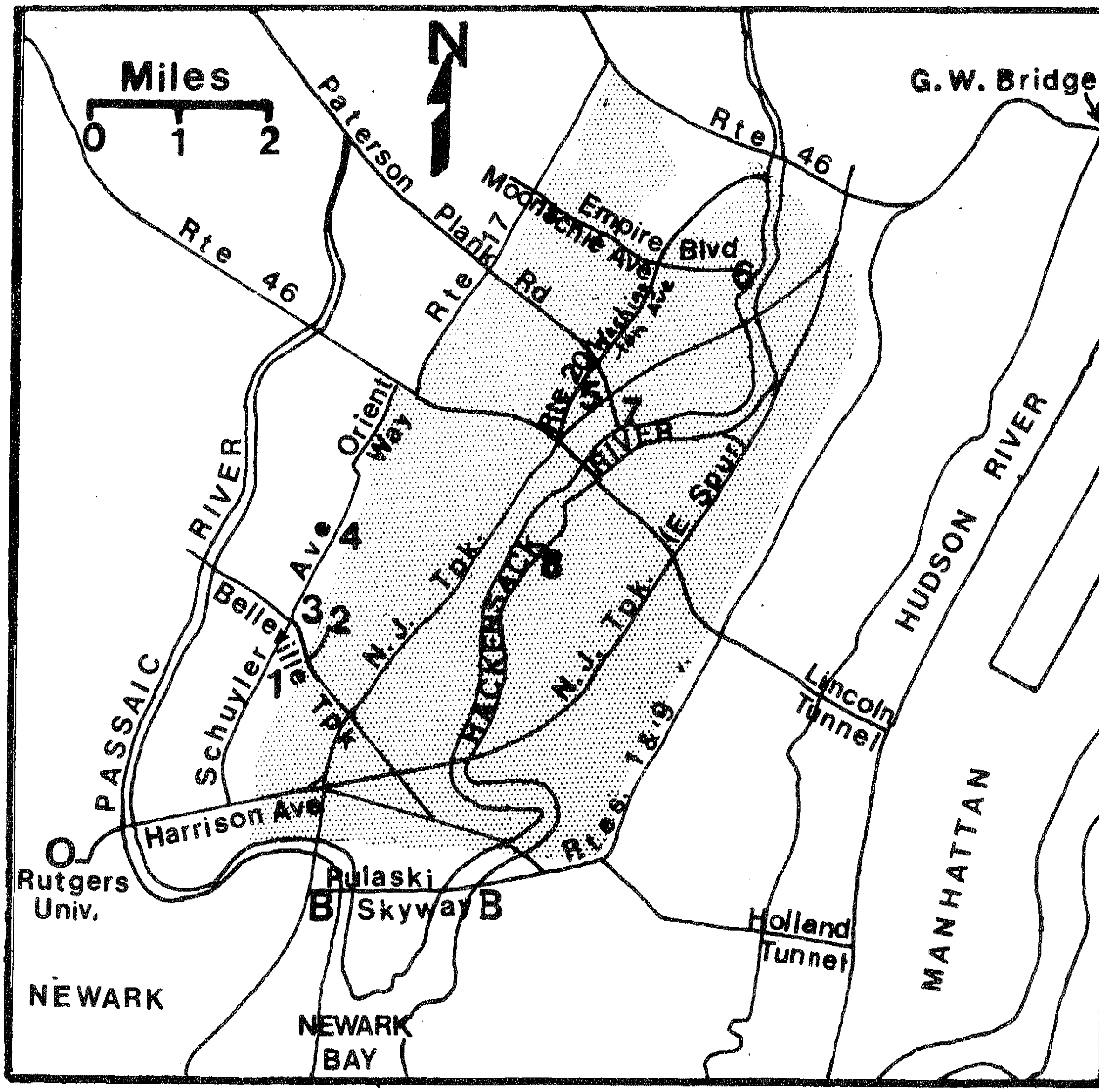

Fig. 3 Field trip stops (Nos. 1-8). Shaded area is Hackensack Meadowlands District. See Figure 1 for geologic section along B-B.

Early attempts to dike, drain, and tidegate the marshes for farming were not very successful because of muskrat damage. Dikes with sheet iron cores to thwart the muskrats were built in Kearny and North Arlington, but they failed when the sheet iron sank into the underlying peat (Kardas and Larrabee, 1976).

Railroad embankments built from 1830 to 1840 affected the movement of water and so did the construction of dikes, decades later, by the Mosquito Commissions in Bergen and Hudson Counties. In more recent years Route 3 and the east and west spurs of the New Jersey Turnpike were built on massive earth fills which have been very effective dikes offering security to fresh wetlands. Many dikes and tidal gates along the Hackensack River marshes were destroyed by a hurricane in 1950. As a result tidally responsive vegetation (*Spartina alterniflora, Spartina patens, Dichilis spicata, Typha latilfolia, Typha latifundia,* etc.) have replaced fields of *Phragmites communis* (Mattson and Vallario, 1976).

The Hackensack Meadowlands ecosystem is not a remote tropical rainforest, nor is it like Alaska or the Mississippi River delta, or almost any other ecosystem because it lies inside, at the very center of the nation's most dense megalopolis. Here has been sent the sewage from 52 New Jersey towns and the garbage from 144 towns. Interwoven with this stressed estuarine ecosystem are 8,000 acres of developed land, 41 percent of the total area of the Hackensack Meadowlands District (Mattson, 1978).

Wetland ecosystems are remarkably strong, simple, and contain a comparatively low variety of species. But the lines between the survival, transformation and destruction of these ecosystems are very fine, and our

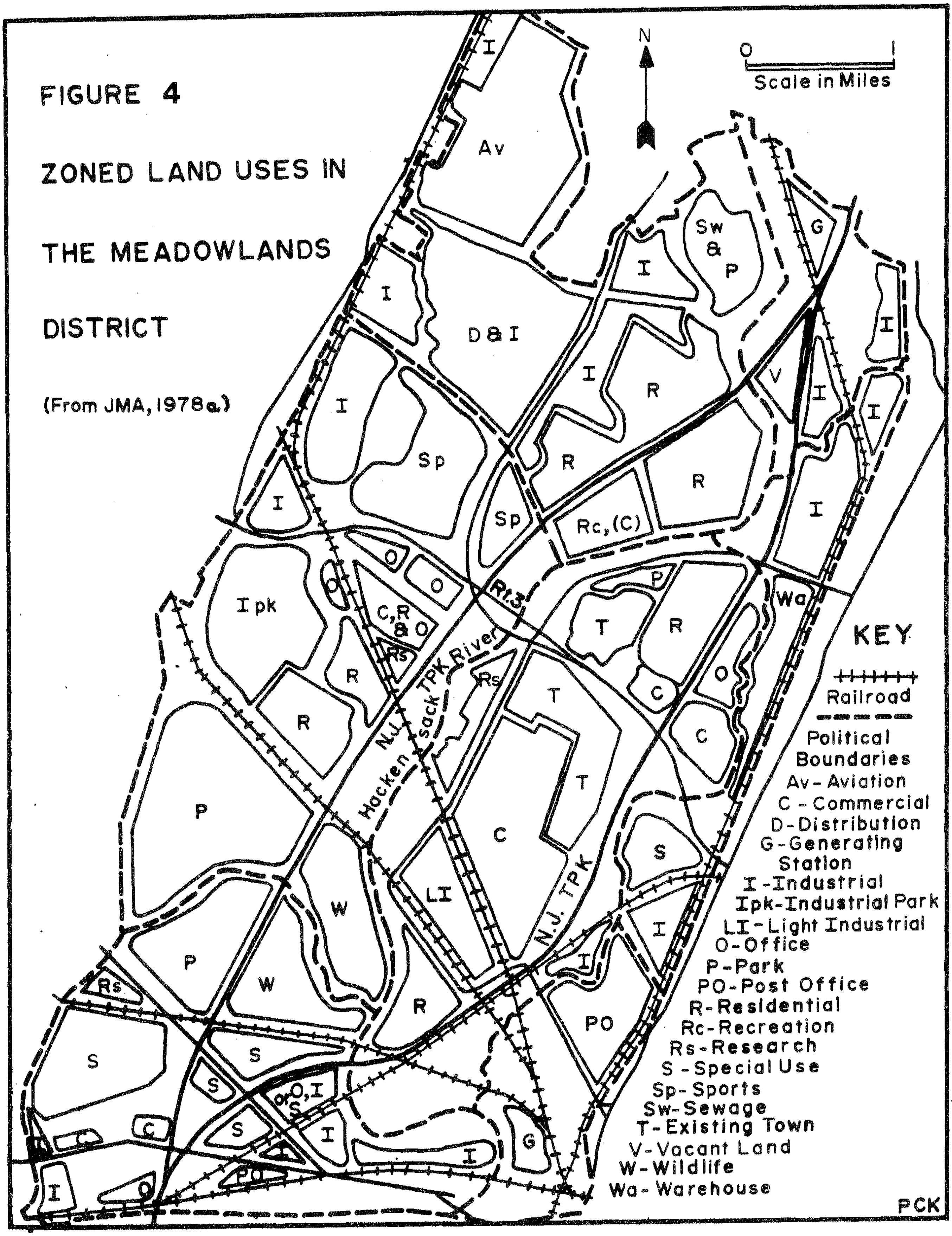

FIGURE 4

ZONED LAND USES IN THE MEADOWLANDS DISTRICT

(From JMA, 1978a)

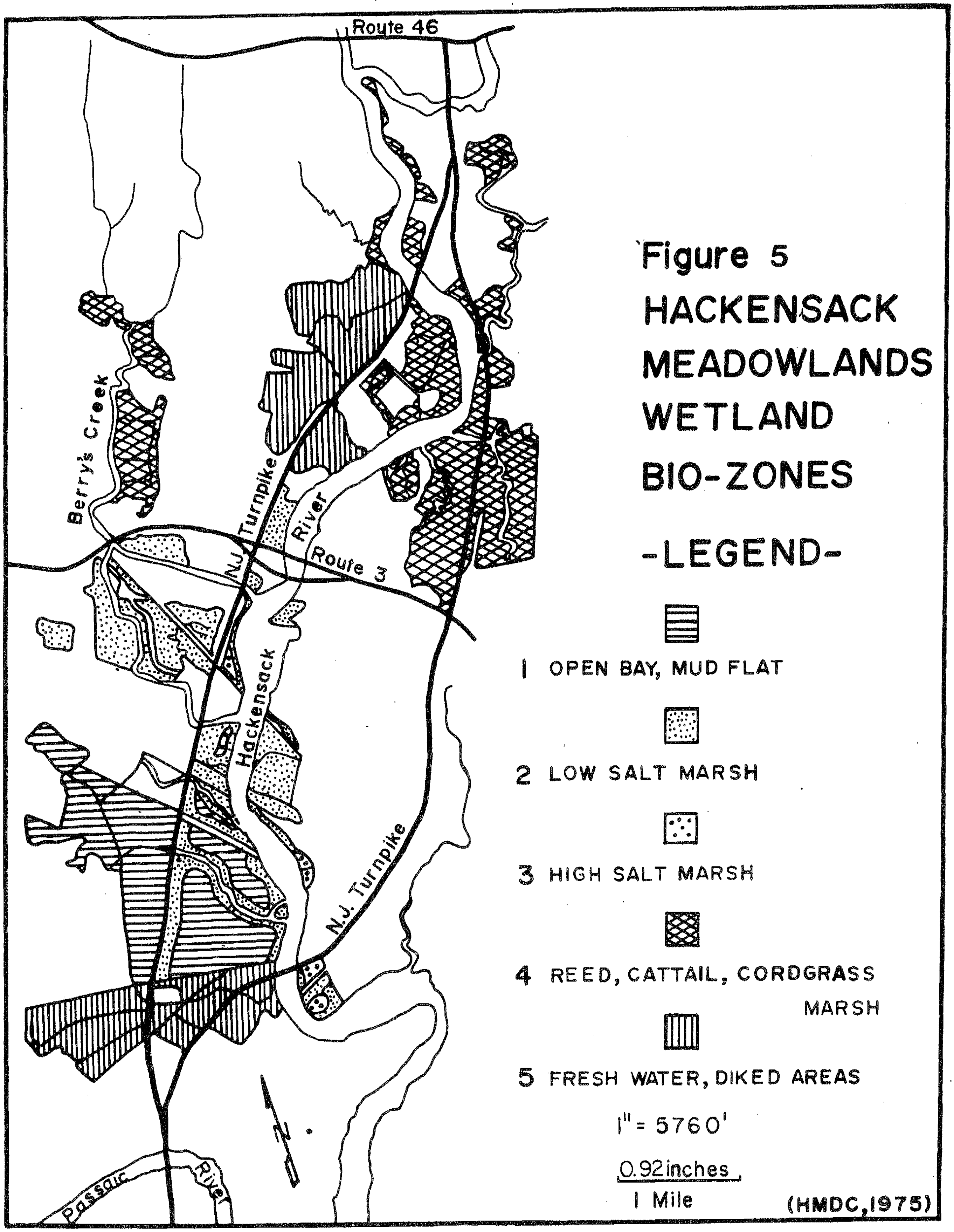

Figure 5
HACKENSACK MEADOWLANDS WETLAND BIO-ZONES

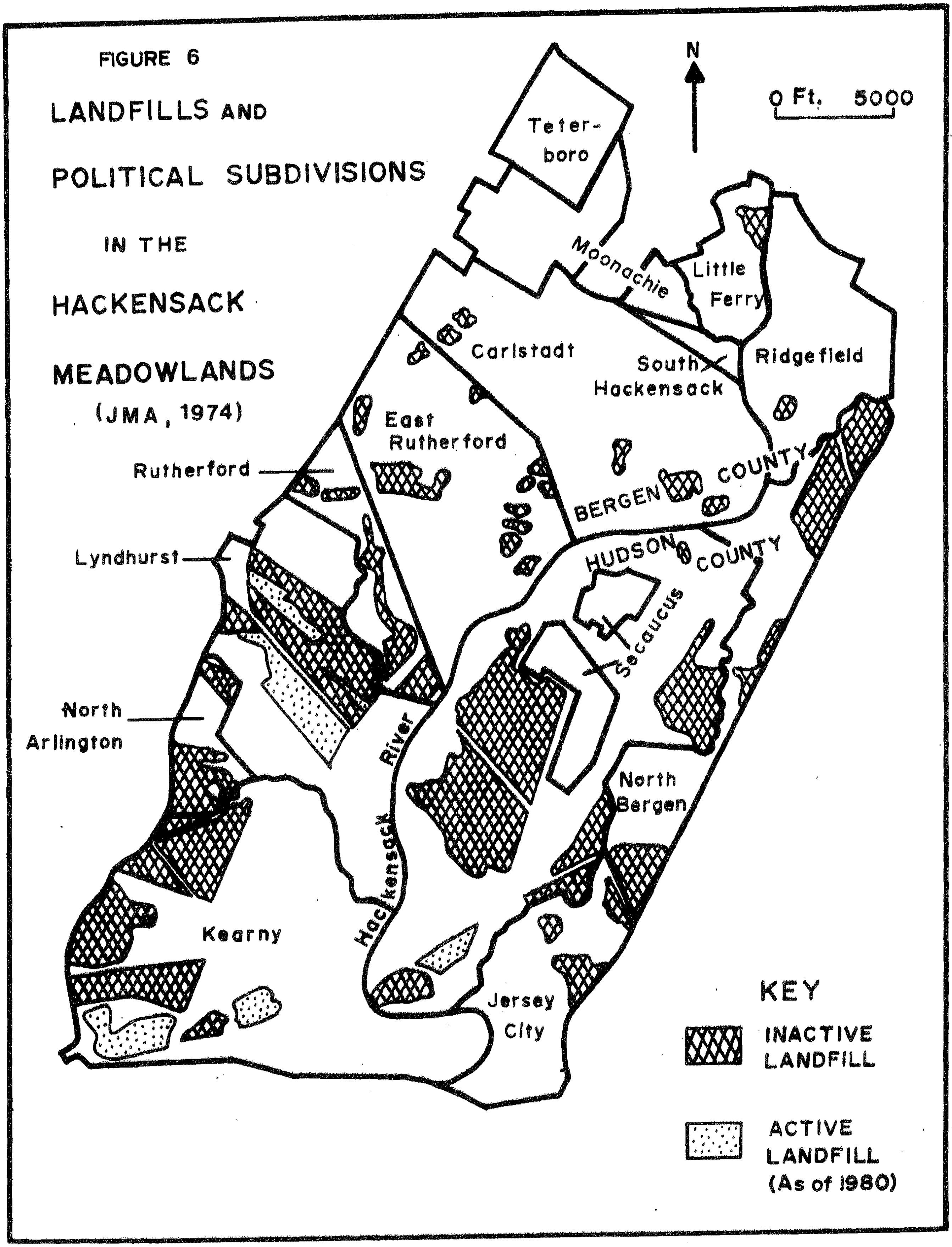

FIGURE 6

LANDFILLS AND POLITICAL SUBDIVISIONS IN THE HACKENSACK MEADOWLANDS (JMA, 1974) understanding of the combinations of complicated disrupting elements is inadequate (Mattson, 1978). It is, therefore, very gratifying to note the progress that has been made in the decade of the 1970's in stemming the deterioration of the Meadowlands ecosystem and in upgrading its quality.

An inventory of organisms in the several bio-zones of the District includes 19 varieties of wetland vegetation, 111 aquatic and wetland-associated birds, both breeding and migratory, 3 mammals (and 5 more around the edges of the marshland), 6 reptiles, 2 amphibians, 17 invertebrates, and 35 varieties of fish (HMDC, 1975).

Sanitary Landfill and Solid Waste Baler

According to the Solid Waste Administration Chief of the State Department of Environment Protection, 30,000 tons of waste are deposited each day (more than 10 million tons yearly) in the 300 solid-waste landfills of New Jersey. Slightly more than 20 percent comes from out of state: 1.7 million tons from Pennsylvania, 603,000 tons from New York, and 61,000 tons from Delaware (Friedman, 1980). Since these landfills will be filled to capacity by 1984, the state faces a formidable problem.

In the Hackensack Meadowlands in 1979, the active landfills were receiving 50,000 tons of solid waste weekly from 124 municipalities in six New Jersey counties (Fig. 6). The Hackensack Meadowlands Development Commission succeeded in reducing the 2,508 acres of garbage dumps and had sought to have all the landfills in its jurisdiction closed at the end of 1979. It has not been fully successful as the Legislature and the courts have granted brief extensions in some instances. Dumping of garbage from New York in the Meadowlands has been prohibited since 1973, but illegal dumping by private carters has taken place on a scale sufficiently large to disrupt the schedule for the gradual end to landfill dumping in Meadowlands (Boyd, 1980a). To complicate the matter further, the State Attorney General's office declared in June, 1980, that the Hackensack Meadowlands Development Commission cannot ban out-of state garbage from its landfills (Boyd, 1950b).

In order to block the migration of leachates into the water table, six-foot-high dikes have been built around the active land fills. At the DeKorte State Park site, excavations 15 to 20 feet deep were made through the peat, into the underlying clay. The excavations were back-filled with clay brought in from outside, except when it was locally available.

Solid Waste Baling Plant

The Baling plant was built by the Hackensack Meadowlands Development Commission at a cost of $6.9 million to dispose of garbage by compacting it into bales to be used as building blocks to contour the land for the Richard W. De Korte State Park. The 2,000-acre park will be built over dumps in the southwest part of the Meadowlands in the next decade or two.

The baler (Fig. 7) is on a 12.7 acre site about 0.4 miles north of Belleville Turnpike and 0.3 miles east of Schuyler Avenue, North Arlington, It is the largest garbage baling facility in the United States and has broken the world's record for compaction of garbage when it compacted 1,023 tons in 18-1/2 hours (Curico, 1980). It is a modular design; a second 1,000-ton per day unit will be installed at the plant by the end of 1981, at a cost of about $2 million. Twenty-eight private carting companies using the baler are charged $8.70 per ton for the waste processed there.

Baler Process:

Trucks enter into the warehouse and dump their garbage on the floor. Commercial trash is dumped on one side and residential garbage on the other. Front-end loaders move the trash and garbage onto a conveyor belt located at the bottom of a shallow trench in the middle of the floor, between the two types of garbage. Proportions of commercial and residential garbage are adjusted to maintain the desired density. The conveyor belt carries the trash and garbage up to a scale. When the pre-selected weight is reached, the conveyor belt automatically stops and the material drops into the compression chamber. It is compressed into a bale approximately 3 X 3 X 4 feet by three compression rams, delivering a final pressure of 2800 psi. The weight is kept constant, so that the size of the bale will vary with the type of garbage used. Straight cardboard or paper products produce a larger bale. The bales emerge from the compression chamber onto a loading platform and are automatically loaded onto a flat-bed trailer which hauls a load of 16 bales to the balefill site. There the bales are stacked to required elevations. They are stacked three bales high and covered with one foot of soil, giving a lift of 10 feet. There will be seven such 10-foot lifts, one above the other. The top will be covered with five feet of fill and topsoil, and will be landscaped to form a park. The first phase, about 10 percent of the park, at the south end of the landfill, should be completed by 1981. A total of 210,080 bales will be placed in the first bale-fill area. The end product of this operation is the State park which the bales will make possible. The average weight of a 3 X 3 X 4-foot bale, having a volume of 1 1/3 cu. yds. is 1.5 tons, (= .042 tons/cu. ft.). Five cu. yds. of residential garbage weighs about 1

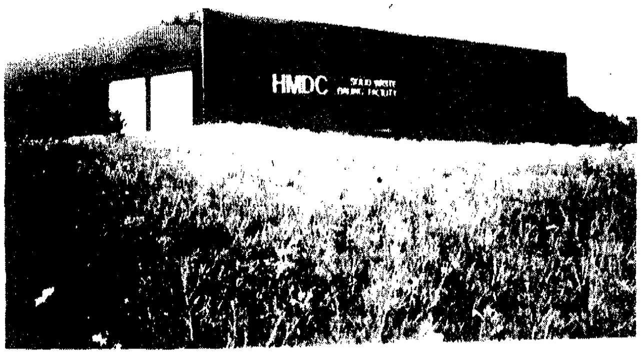

Fig. 7 Solid Waste Baler Facility in North Arlington, operated by the Hackensack Meadowlands Development Commission. A second baler unit will be installed in the two bays on the left. (Courtesy HMDC).

ton (= .0056 tons/cu. ft.). The bales are about seven times as dense as domestic garbage. They are so dense and coherent that a 50-ton truck can safely be driven over them, and sea gulls cannot penetrate them to get at the garbage.

Resource Recovery

The baler, which reduces the pressing need for new landfill sites, is an interim solution to the waste disposal problem in the Meadowlands. It will operate for 10 years and will be replaced by resource recovery plants to be built within the decade by counties now dumping solid waste in the Meadowlands. Bergen County's plant will be built in Ridgefield, next to Public Service Electric and Gas, to whom it will sell fuel recovered from garbage (Boyd, 1980 d). Ultimately, the solution would be total recycling of solid waste to yield fuel and resources recovery.

The New Jersey Department of Environmental Protection has proposed a bond issue to provide $50 million for planning, design, and construction of resource recovery facilities (Friedman, 1980). Senator Bill Bradley (N.J.) is planning to sponsor Federal legislation to authorize $196 million in loans over the next three years for facilities to convert waste into energy, from the nation's current level of 2 million tons a year to 18 million tons a year by 1990 (Gettlin, 1980). The Hackensack Meadowland Commission's chief engineer estimates that the legislation would provide up to $28 million in federal loans locally for a project to convert 3,000 tons of urban waste daily into fuel, having an equivalence of 1.2 million barrels of oil per year (Gettlin, 1980). However, an estimated $100 million would be needed to construct the two huge garbage recycling plants needed to handle the 50,000 tons of waste that the 120 or so New Jersey towns now dump in the Meadowlands (Hanley, 1979).

Methane Gas

Recovery of methane gas from the Meadowlands dumps has been considered by Public Service Electric and Gas. One engineer's conservative estimate in 1979 was that the dumps could yield 100 billion B.T.U.'s per year, with a then sales value of $200,000. The quantity of methane available, however, may possibly be 10 to 20 times the estimate (Hanley, 1979).

It obviously makes sense to make of garbage a valuable resource rather than a burdensome, land-consuming problem. This approach must be implemented quickly, before we run out of landfill space.

De Korte State Park

The Richard W. De Korte State Park will be created over garbage landfill in the southwest part of the Meadowlands (Fig. 8) and will extend from Kearny through North Arlington into Lyndhurst. The park will cover 2,000 acres, 814 of which are landfill where, over a period of 40 years, mounds of garbage have grown to heights of over 100 feet. Altogether, some 16 million cubic yards of garbage dumped in landfills or baled will be transformed into landscaped hills between 120 and 140 feet high in the finished park. The park will also include the 405-acre Kearny fresh-water marsh, the best such wildlife wetland in New Jersey (Kane, 1978).

Within 10 miles of the park live more than 11 million people. The park will be two-and-one-half times larger than New York's Central Park. Its master plan calls for walkways, hiking and horse trails, wildlife observation areas, boating, fishing, ballfields, campsites, tennis, swimming, and skiing "facilities" (Fig. 8).

According to the Chief environmental officer of the Hackensack Meadowlands Development Commission, the park could be fully developed in from 10 to 20 years, at a cost of between $50 and $85 million (Grant, 1980).

This was one of three state urban parks given priority in the Green Acres bond issue referendum, successfully passed in 1979, which permitted the first phase of construction to get underway. Public demand and the availability of funding will determine how soon the park can be completed.

Real estate values are expected to appreciate markedly along the western border of the park. The development of a 25-story condominium complex overlooking the park and Meadowlands has already been proposed for North Arlington. This could mean millions of

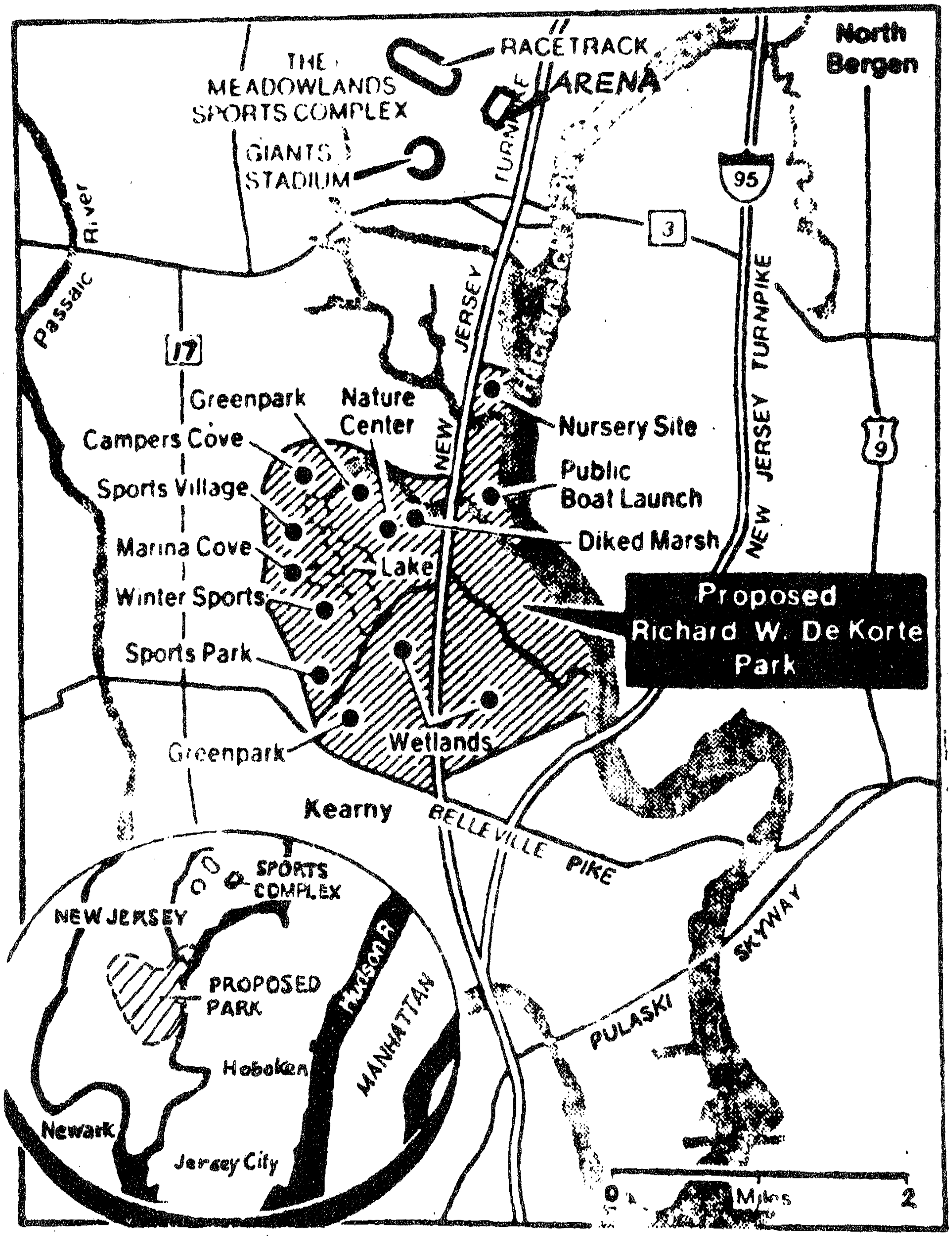

Fig. 8 The proposed Richard W. DeKorte State Park, extending over 2,000 acres, will afford a variety of recreational activities for urban dwellers, as well as wetlands for wildlife (after Hanley, 1979a).

dollars in new tax revenues for North Arlington (Fritzky, 1980).

Mercury Contamination (Berry's Creek)

The west boundary of the Meadowlands Sports Complex is Berry's Creek, which meanders southeastward before joining the Hackensack River at a point opposite the south end of the Harmon Cove development. Mercury contamination of the Berry's Creek tidal marsh was discovered in 1972, in an environmental impact study made prior to the construction of the Giants Stadium and the Meadowlands Racetrack.

Federal and New Jersey environmental and health authorities were already aware of the source of the contamination in 1969. That year they complained about mercury-laden waste water being discharged by a mercury processing plant located on a small upstream tributary of Berry's Creek, in the Borough of Wood-Ridge. The plant was shut down in 1973, but in the 36 year of its operation, an estimated 300 tons of mercury were discharged into drainage ditches and dumped onto the land. Levels of mercury exceeded the standard of 1 ppm in the marsh several miles downstream from the plant.

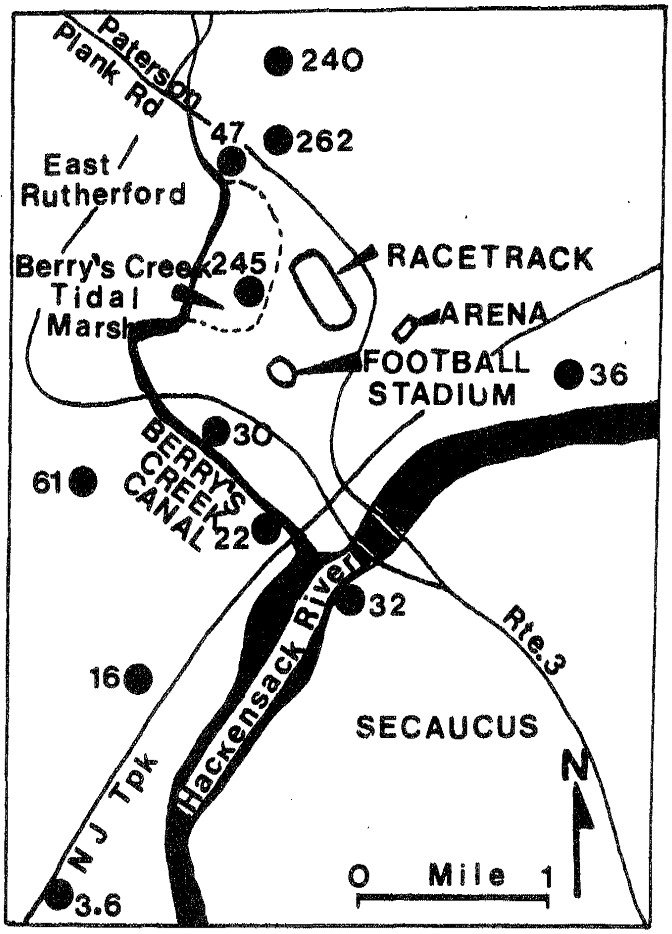

Fig. 9 Maximum mercury concentrations in parts per million at several soil sampling sites in the Hackensack Meadowlands. Mercury contamination begins at 1 ppm (After Hanley, 1978).

Jack McCormick and Associates of Berwyn, Pennsylvania, estimated that the soil in the 40-acre site once occupied by the plant still contained 286 tons of mercury (Hanley, 1978). This represents a mercury content 123,000 times higher than the normal concentration of mercury in soils and sediments, which is about 0.05 ppm (Klein, 1972). Soil samples in the Berry's Creek tidal marsh showed excessive levels of mercury to depths of over six feet. High mercury levels were detected to a distance of up to three miles south, and to lesser distances east and north of the marsh (Fig. 9).

Sediments near the plant contained up to 8,475 ppm of mercury, which is two-and-a-half times as high as any previously reported in the world. The water of Berry's creek, two-and-a-half miles south of the plant, averaged 9.9 ppm of mercury in 1974-1976 (Hanley, 1978).

An impermeable dike around Berry's Creek may be relied upon to keep the mercury from moving into the creek, until a better, more feasible way can be developed. Paving the marsh with asphalt and using it as a parking lot could also help contain the mercury.

Preliminary evidence from plant and animal tissue studies indicates that alarming amounts of mercury have not entered the food chain in the Hackensack Estuary. Monitoring may be necessary for decades before we will know the extent of the risk the mercury represents, if any, to people in the area. This, however, is not being done.

Meadowlands Sports Complex

The New Jersey Meadowlands Sports and Exposition Authority has constructed the Meadowlands Racetrack, Giants Stadium, and the Meadowlands Arena. This Sports Complex lies four miles west of the Lincoln Tunnel to Manhattan. It is bounded by Paterson Plank Road on the north, New Jersey Route 3 on the south, the New Jersey Turnpike on the east, and the estuarine Berry's Creek on the west (Fig. 10). The total area of the complex is 558 acres, of which 67 acres on the east side of Route 20 are devoted to the arena, which was constructed after the racetrack and stadium.

The racetrack has complete facilities for thoroughbred and harness racing. There is a one-mile convertible track constructed of compacted limestone for harness racing with an overlay of sandy loam for thoroughbred racing. Inside the one-mile track is a 7/8 mile turf track for the thoroughbred racing. There are a six-level heated and air-conditioned grandstand seating 9,300 spectators, and an out-door standee ramp for about 26,000 spectators.

The football stadium (Fig. 11) seats 76,500 spectators and has adjacent parking for 20,000 automobiles and 400 buses (N.J. Sports and Exposition Authority, 1975). The racetrack and stadium opened in 1976. The arena, to be completed in 1981, will seat 20,000 spectators for indoor sports such as basketball, hockey, ice-skating, as well as exhibitions. The trusses supporting the roof (Fig. 12) will span 428 feet, producing a column-free interior. There will be additional parking for 4,000 cars adjacent to the arena.

Extensive supporting facilities were constructed. For example, the racetrack has 12 barns to provide housing for a total of 1,320 horses, blacksmith shops, five dormitories providing facilities for 560 grooms, administration and cafeteria building, and storage facilities for feed, harness, and other equipment. The Pegasus Restaurant atop the track's grandstand can serve 2,250 patrons nightly. It employs over 300 people and occupies 100,000 square feet of floor space. Geologists may be particularly interested to know that 36,000

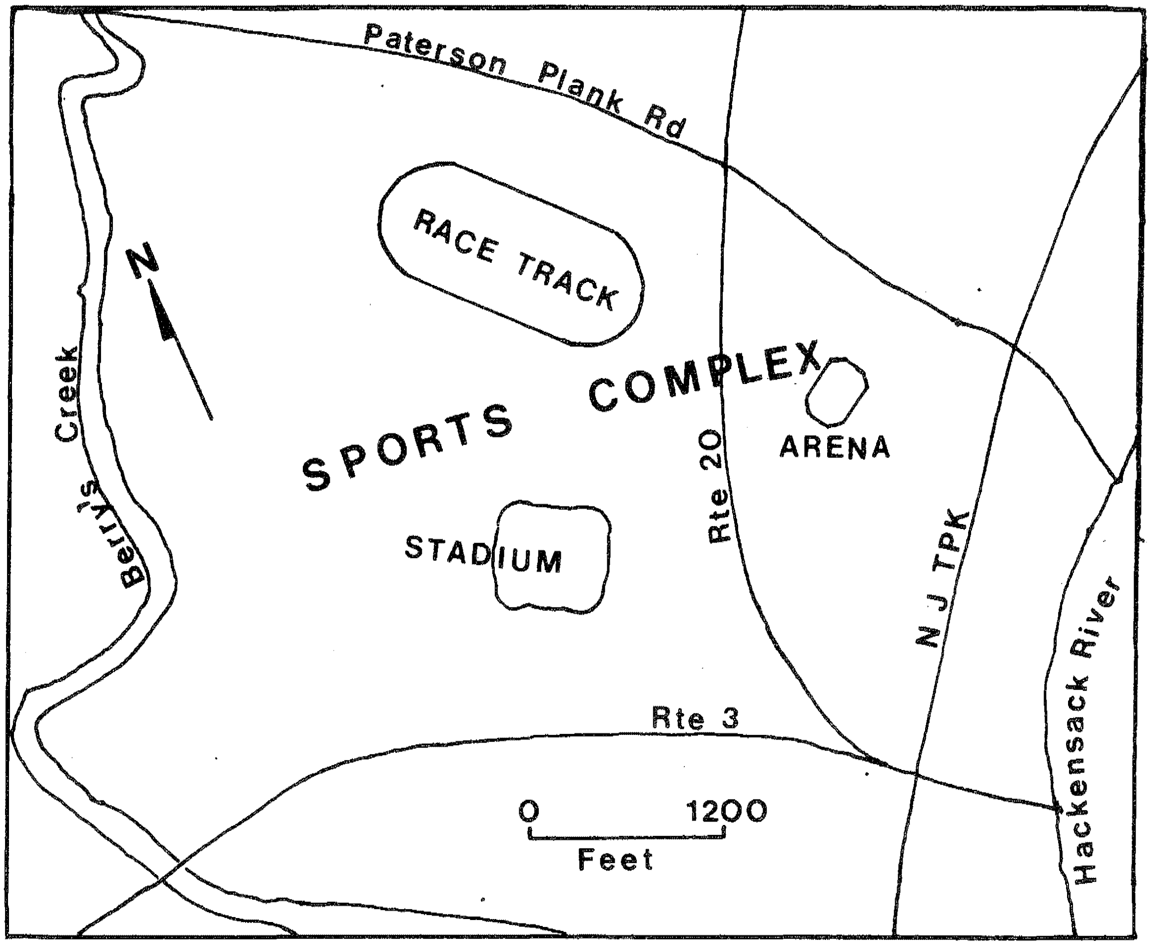

Fig. 10 New Jersey Sports Complex in the Meadowlands is bounded by Paterson Plank Road on the north, Rte 3 on the south, Berry's Creek on the West, and New Jersey Turnpike on the east.

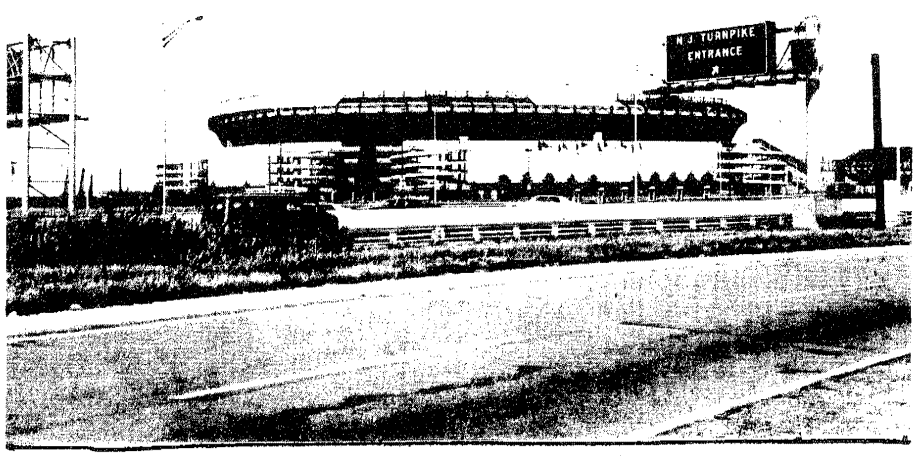

Fig. 11 Giants Football Stadium, Meadowlands Sports Complex, looking NE. The Racetrack is to the left and the Arena to the right.

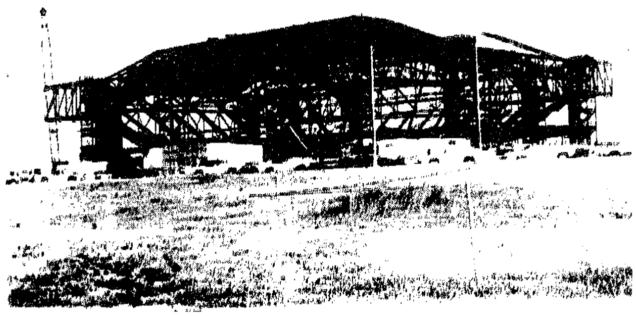

Fig. 12 Meadowlands Arena under construction.

square feet of marble, weighing 350,000 lbs. were used for the floors. Dolcetto, a beige-colored marble from Italy and Verde antique, a green-colored variety from Vermont, cover pedestrian walkways and heavily travelled areas such as dining rooms, bars, and mutuel windows. If the 11,516 pieces of marble used in Pegasus were held end-to-end, they would cross the Verrazano bridge between Brooklyn and Staten Island two and a half times (Anonymous, 1979).

In the Sports Complex area west of Route 20 (racetrack and stadium) about 3.2 million cubic yards of sand (15,000 cu. yds/day) were pumped in hydraulically via an 18-inch steel pipeline originating at the Hudson River. The sand was dredged from the New York Bight, barged up the Hudson River, mixed with river water, and pumped five miles to the site. It was spread in a layer two-to-eight feet thick over the miscellaneous fill. The Hudson River water, having a salinity of 15 ppt, drained from the discharged sand into the Hackensack River at a rate of 20 million gallons per day, changing the salinity gradient of the river that year (1974). Instead of a consistent salinity gradient for an estuary, the river showed higher salinities in its upper portions and lower, downstream, over the discharge period (HMDC, 1975). One thousand cu. yds. of sand fill were put under the racetrack to aid settlement. (Oral communication, F.H. Werneke, Director Engineering, N.J. Sports and Exposition Authority, May 19, 1980). At the arena site, within the area enclosed by the cofferdam, all the existing fill and the organic soil were removed down to the varved clays. Engineered fill was then deposited to achieve subgrade level for the concrete floor slabs. The varved clays below subgrade level at the arena site are 14 to 23 feet thick (CWDD, 1978). The parking lots are underlain by engineered fill placed over the meadow mat.

The major buildings are supported by steel H-piles or concrete-filled pipe piles driven to refusal in the glacial till or the bedrock.

In the construction of the west spur of the New Jersey Turnpike, incidently, the sand foundation was hydraulic fill dredged from Raritan Bay and barged up the Hackensack River to various points from where it was pumped to the turnpike.

Since colonial days significant development of the Meadowlands has been deterred because of tidal flooding and the presence of peat underlain by weak, varved clay deposited on the bottom of glacial Lake Hackensack. Since the Sports Complex site lies in the flood plains of the estuarine Hackensack River and Berry's Creek, it had to be protected from flooding with cofferdams and a system of dikes, reaching an elevation of 10.0 feet above mean sea level. The land elevation within the diked area was raised to an elevation of 6.0 feet (msl) by moving in fill. The maximum high-water elevation attained here was 8.4 feet in 1960 (N.J. Sports and Exposition Authority, 1975).

The dikes are 12 feet in vertical dimension. Their top is at an elevation of 10.0 feet; thus they extend down several feet into the underlying clay. Along the middle of the dikes is a two-foot-wide core of bentonite and sand emplaced as a slurry (oral communication, F.H. Werneke, May 19, 1980). The site is diked along Berry's Creek and along the roadbeds of the highways around the site's perimeter: Paterson Plank Road, Route 20, Route 3, and the New Jersey Turnpike (Figure 10). Where the roads are below 10.0 feet in elevation, the land is sloped up to that elevation away from the road.

Cofferdams of corrugated sheet-steel piling were constructed around the football stadium, race track grandstand, and arena to protect the building sites from flooding during the excavation and foundation work. The cofferdam piles, about 12 to 15 feet long, were driven down to refusal, the longer piles being nearer the river, as the valley floor slopes in that direction. The cofferdams were left in place to afford additional protection.

Using a calibrated computer model of the Hackensack Meadowlands channels and marshes, the maximum elevations of the Hackensack River were predicted for the Army Corps of Engineers, for 10 and 100-year intervals (TAMS, 1975). The model was modified to include anticipated development according to the Master Plan for the District (HMDC, 1971). The projections suggest that the maximum water elevation near the Sports Complex (probable recurrence interval of 100 years commonly used for design purposes) will be 6.4 feet (msl) by 1984, which is safely below the 10-foot elevation of the dikes. The projection for the highest level of flooding, however, is 10.7 feet (msl). It would occur in 1984 by the Standard Project Tide, whose return period is undetermined but in excess of 100 years (TAM, 1975). This could pose a problem in the near future.

Fig. 13 Sawmill Creek Wildlife Management area, Kearny, N.J. Cedar stumps, exposed at low tide, indicate the former presence of Cedar forests in the Meadowlands. This area will be part of the DeKorte State Park. View is to NW from Conrail tracks. (Courtesy J. Szalkowski).

The natural surface of the Meadowlands consists of a highly organic soil, either peat or meadow mat. If woody fragments are abundant, the organic deposit is called peat; if the material is mostly root stalks of the common root grass it is called meadow mat. Woody remains of the cedar forests that covered much of the meadowlands a couple of centuries ago are common in the peat (Fig. 13). In addition to the organic material, in various stages of decay, there is fine-grained admixed mineral matter that is carried into the estuary at high tides and settles in the quiet water among the marsh plants during slack water intervals. During dry periods in the summer months the meadow mat and peat may catch fire, often by spontaneous combustion, burning for days and constituting a serious pollution and safety hazard.

Two subsurface investigation programs were conducted before the racetrack and stadium were built. A preliminary program, included seven deep borings, 10 shallow borings, and 12 probes. The second program consisted of 118 borings, 306 auger holes, 250 probes, and 15 test pits (N.J. Sports and Exposition Authority, 1975). At the arena site there were, in addition, seven exploratory borings, two undisturbed sample borings and 11 test pits (CWDD, 1978).

The borings show (Figs.14 and 15) that man-made fill, four to sixteen feet in thickness, covered about helf the area of the site. The meadow mat (peat and organic silt) was about two-to-eight feet thick, but generally less than five and one-half feet. Elsewhere in the Meadowlands, it may reach 12 feet in thickness.

Under the meadow mat is a gray medium-to-fine sand between one-and-four feet thick. It overlies gray to red-brown varved clays and silts varying in thickness from near zero to about 110 feet. The varves are alternating one-eighth-inch layers of silt (summer deposition) and clay (winter deposition) in glacial Lake Hackensack.

Underlying the varved clay is glacial till, five-to-forty feet in thickness. It consists of red-brown coarse-to-fine sand, some clay and silt, and medium-to-fine gravel. Below the till is the red-brown shale of the Newark series, whose quality is extremely variable, from decomposed to sound (CWDD, 1978). The top of the bedrock varies in elevation from - 10 feet under Route 20, to -120 feet at the western corner of the site (N.J.S.E.A., 1975).

The meadow mat, a highly organic soil compresses in three stages when loaded. They are: initial compression, primary consolidation, and secondary settlement. The first two stages occur quickly, within a few weeks, but the last, secondary settlement stage takes place gradually, over a period of years.

Engineered and miscellaneous fill, that had been present in almost half the site, supported some pre-existing buildings and roads. Engineered fill, such as compact select sand, when placed on top of the varved clay proved a stable foundation for light buildings and roads. However, the miscellaneous fill, which includes concrete, bricks, steel, wood and other demolition materials, when dumped directly on the meadow mat, consolidated it unevenly and resulted in mud waves. Polito Road, in Lyndhurst, a heavily used truck route south of the intersection between Routes 3 and 21 has developed a washboard surface because of unequal settling. The road was built over the meadow mat without a proper sub-base.

Bergen County Sewage Disposal Plant

The Bergen County Sewage Disposal plant is operated by the Bergen County Utilities Authority. It is located on a 100-acre site at the foot of Mehrhof Road, on the west bank of the Hackensack River in Little Ferry. The eastern Bergen County area served by the plant includes 43 municipalities with an estimated population of 500,000. The area is about 90 percent sewered. The plant was originally built in 1950, with a capacity of 20 million gallons per day. In 1960 it was expanded to 50 mgd. In 1975, the first phase of a new expansion brought the capacity to 62.5 mgd. The current, second phase, costing $37 million will give the plant a capacity

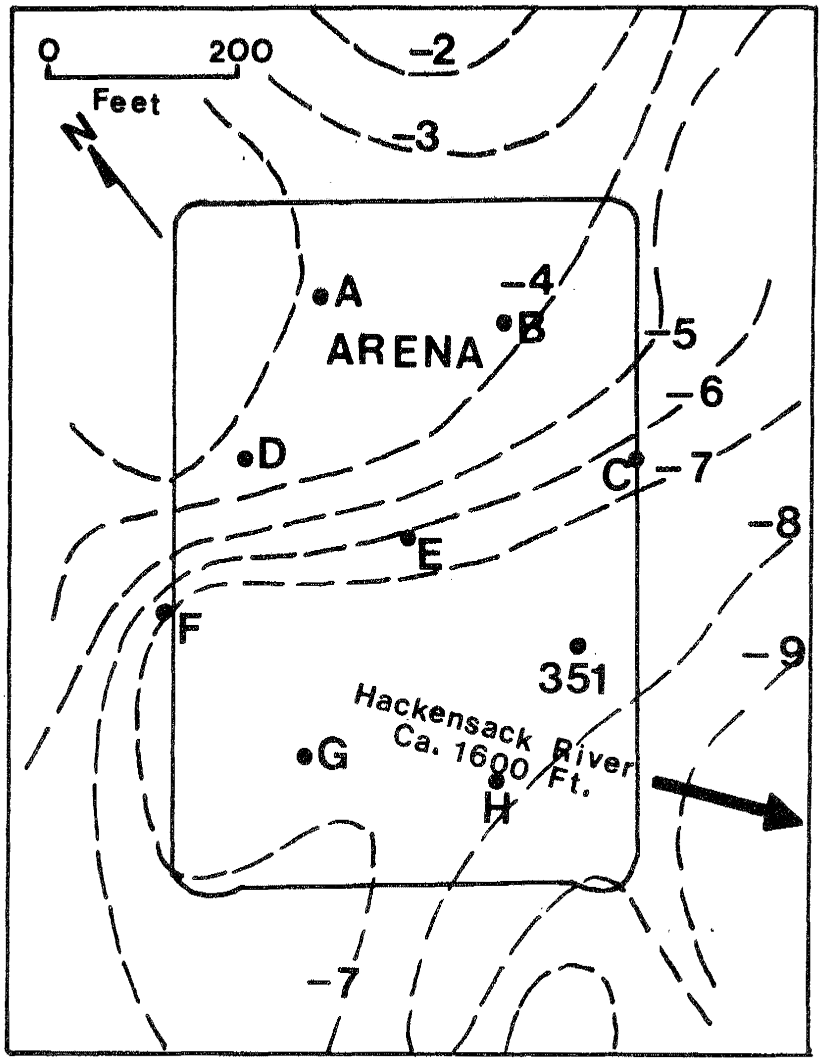

Fig. 14 Meadowlands Arena showing boring sites (black dots) and subsurface contours to top of firm material (top of sand stratum of top of varved clay). See Figure 15. (After CWDD, 1978).

of 75 mgd which, it is anticipated, will do until the year 2000. The plant currently gets an average flow of 65 - 70 mgd. During severe rainstorms, or prolonged periods of rain, when the inflow reaches 100 mgd, the excess is by-passed into the river.

The establishment of this plant permitted the continuing rapid expansion of the population of Bergen County in the years following World War II. Prior to the plant's completion, sewage treatment plants in several towns in eastern Bergen County were discharging inadequately treated effluent, polluting surface drainage. Some towns stopped issuing building permits because overflowing septic tanks were saturating the ground. The plant has caused a reversal of the pollution problem, an upgrading of the quality of ground and surface water in the area, and it has permitted the elimination of 130,000 septic tanks (Bergen County Sewer Authority, 1975). Borings for the new construction extend down to glacial sands at a depth of 70 feet. Overlying the sands are lake clays, organic clays, and silts. Timber piles are used for the structures (Fig. 16), except where hard clay must be penetrated by steel piles. The last two buildings are supported by steel sheeting which penetrates 10 feet of glacial material.

Treatment Process Description

Raw sewage enters the plant by gravity flow through 8-foot-diameter trunk sewer lines about 30 feet underground. The raw sewage, mostly water, contains less than one percent residential and industrial solids. After screening, blending, and removal of grit, the raw sewage is pumped into eight primary settling tanks (four more will be added), where it is retained for one hour

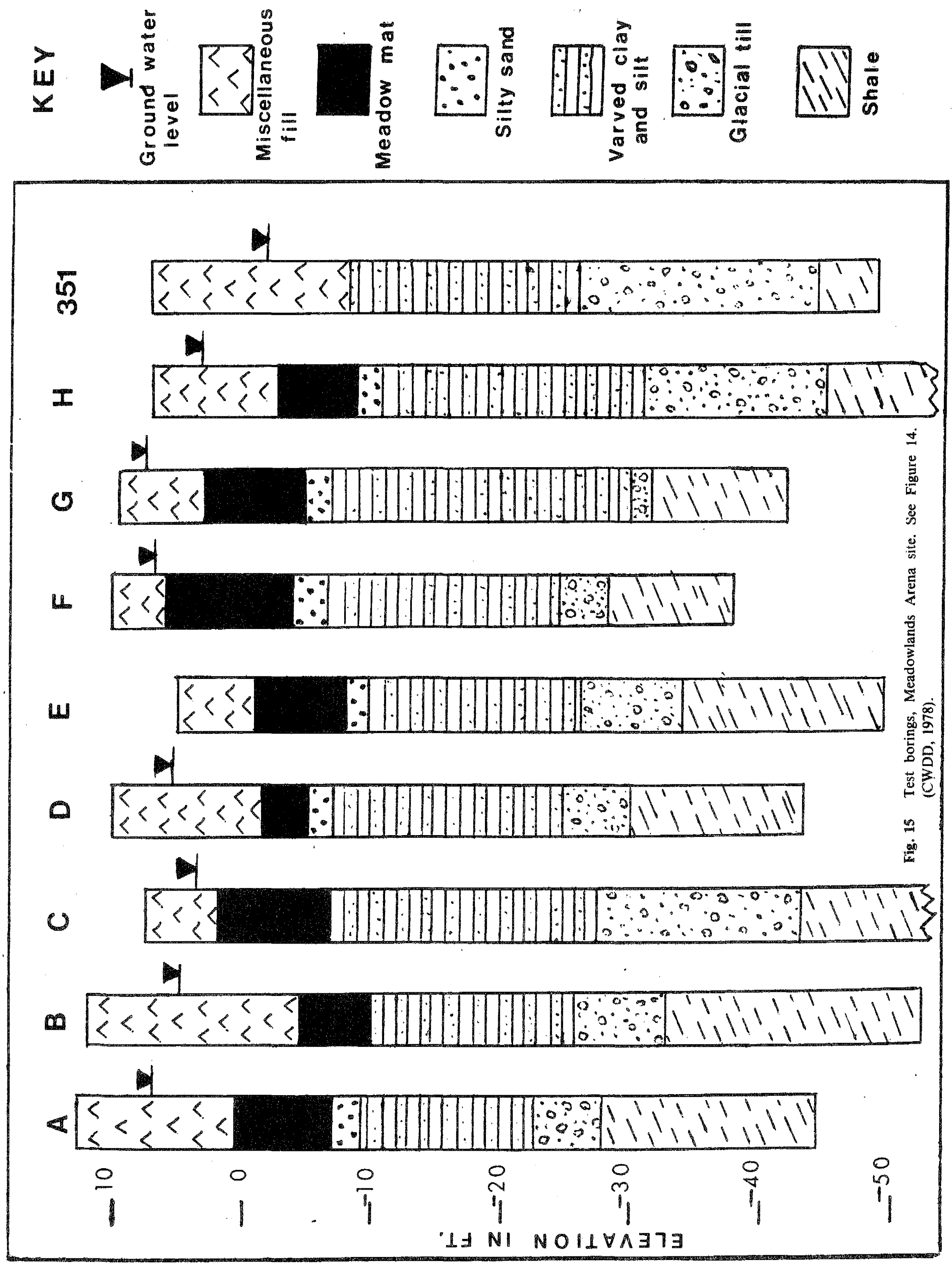

Fig. 15 Test borings, Meadowlands Arena site. See Figure 14. (CWDD, 1978).

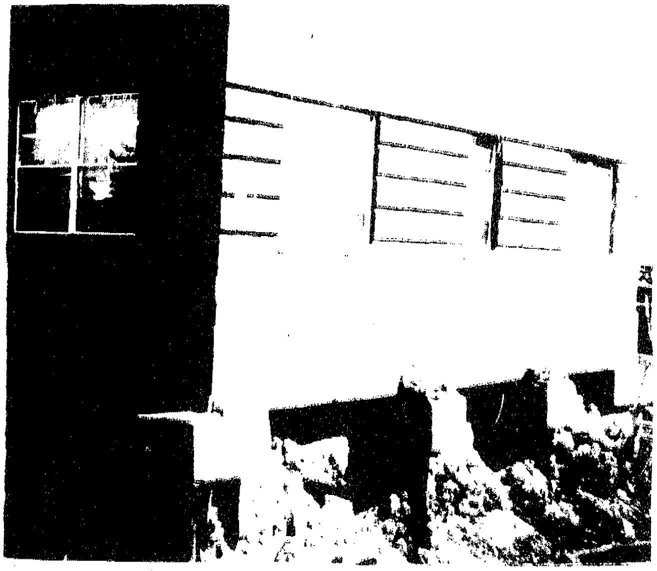

Fig. 16 Bergen County Utilities Authority, Sewage treatment plant office building, Little Ferry, N.J. Excavation has exposed concrete cap foundation over timber pilings.

while the sludge settles to the bottom. The sludge is then pumped to sludge thickening tanks. Grease and scum, skimmed from the top of the sewage waters in the primary settling tanks, is stored in scum tanks for use in the anaerobic digestion process. The effluent from the primary settling tanks flows by gravity to aeration tanks where activated sludge (micro-organisms) are mixed in. The micro-organisms are brought in from the settled matter in the final settling tanks. Air, bubbled through the mixture in the aeration tanks, furnishes oxygen for the micro-organisms which degrade the organic matter in the sewage in six hours. The aeration tanks effluent flows by gravity into the secondary settling tanks. There, the suspended material is removed, leaving a clarified effluent low in suspended solids and dissolved organic content. This effluent is disinfected by treatment with chlorine and discharged into the Hackensack River.

The secondary settling tank sludge is routed to the sludge thickening tanks for mixing with the primary sludge. The sludge mixture, containing 94 percent water, is pumped to the anaerobic digesters where it is retained for fifteen days, at a temperature of 95°F, for bacterial decomposition to gas containing approximately 65 percent methane and 35 percent carbon dioxide. About one million cubic feet of methane gas, with a heat content of 600 Btu per cubic foot, are produced daily. The gas fuels the three 900-H.P. and one 500-H.P. diesel engines that run the aerators in the aeration tanks. The digested sludge is pumped into holding tanks and then barged to a disposal site in the New York Bight.

About 237,000 lbs. of wet sludge are produced daily. Because of its heavy metal content (Table 1) and the great variability in composition from day to day, the sludge cannot be used in agriculture. The toxic substances dumped into the sewer system by industry make this sludge unusable, unlike the sludge from a residential community.

Liquid Natural Gas Storage Tanks and View of Hackensack River

Two large liquid natural gas storage tanks stand on a 44-acre marshland site on the west side of the Hackensack River, about 1,000 feet from the river and less than one mile from the Meadowlands arena (Fig. 17).

The first of the 135-foot high tanks was built for the Transcontinental Gas Pipeline Corporation (Transco) in 1970, and the second one shortly thereafter. Each tank can hold 290,000 barrels of L.N.G., equivalent to one billion feet of natural gas (Hanley, 1979). The gas arrives at the tanks via pipeline from the Gulf of Mexico fields and is liquified at minus 260 degrees Fahrenheit. During the heating season, from November to April, it is reheated to a gaseous state and is distributed by several utility companies for residential and industrial use.

At first the Hackensack Meadowlands Development Commission tried to stop the construction of the LNG tanks in the Federal courts, and went all the way to the U.S. Supreme Court, but lost. The Commission argued that the presence of the tanks would disrupt its zoning plans for housing developments around the site. Concern was expressed for the danger of huge combustible vapor clouds of LNG which might leak from the tanks. One industrial zoning and environmental expert declared he "wouldn't want to live within a mile of a tank site" (Hanley, 1979).

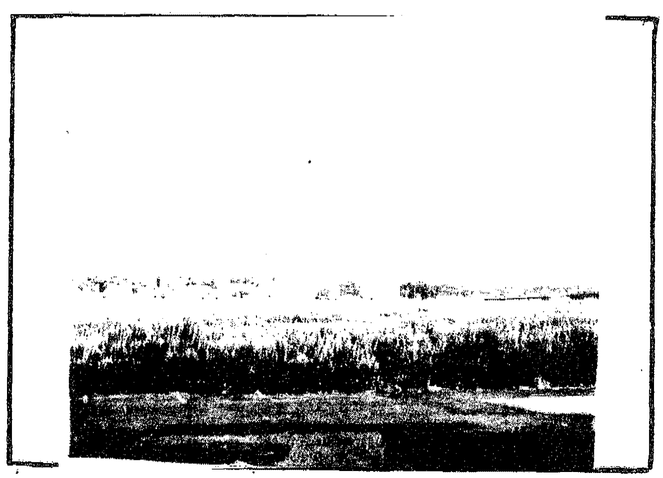

Fig. 17 Liquid Natural Gas storage tanks, Carlstadt N.J. looking E from Washington Ave., about one mile away. Behind the tanks is the back-slope of the Palisades ridge and, in the far distance, the New York Skyline.

TABLE 1

SLUDGE ANALYSIS

Bergen County Sewage Disposal Plant, Little Ferry, N.J. (CBA, 1978)

(All results as mg/l)

	Raw 12/1-2/77		Digested 12/1-2/77		Raw 12/7/77		Digested 12/7/77	
	Total Sludge	Sludge Filtrate	Total Sludge	Sludge Filtrate	Total Sludge	Sludge Filtrate	Total Sludge	Sludge Filtrate
Heavy Metals								
Mercury	.31	.008	.25	.005	.55	.005	.29	.006
Lead	25.3	< .10	23.6	< .10	29.2	< .10	24.2	< .10
Copper	48	.04	41	.06	61	.04	49	.06
Zinc	107	.03	83	.05	130	.04	84	.07
Tot. Chromium	40.4	< .05	31.4	< .04	44.5	< .05	34.0	< .06
Nickel	17.9	.68	13.8	.14	19.4	.76	14.5	.13
Cadmium	2.48	<0.01	2.38	< 0.01	4.10	< 0.01	2.76	<0.01
Selenium	< .02	< .004	< .02	< .004	.10	< .004	< .02	< .004
Vanadium	1.1	< .3	.6	< .3	.8	< .3	.8	< .3
Arsenic	.38	< .004	.40	< .004	.49	< .004	.42	< .004
Beryllium	.08	<0.02	0.04	< 0.02	0.06	< 0.02	0.04	<0.02

Now, ironically the Commission's master plan envisages a 781-acre development of mid-and high-rise apartment houses for 35,000 people to be located approximately within one mile of the tanks; and the Commission is fighting in the courts the opposition to its plan from a group of local mayors. The Commission argues that the Federal courts, in accepting the safety standards employed by Transco, has in effect discredited those who would question their safety. According to the Commission's chief environmental officer, "The courts held that the tanks were designed to be safe and we were told that our vapor-cloud argument was none of our business to make." (Hanley, 1979). The capacity of these L.N.G. tanks, incidentally, is about seven times larger than that of the two tanks that split apart in Cleveland in 1944, producing a fireball and explosion killing 130 people.

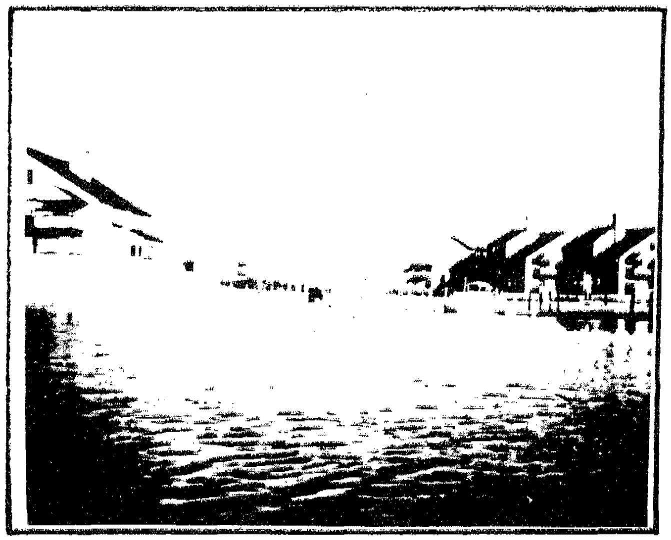

Fig. 18 Townhouse and Marina Harmon Cove Development of the Hartz Mountain Industries, Inc., Secaucus, N.J. (Courtesy HMDC).

Harmon Cove Development, Hartz Mountain Industries

Harmon Cove has been called "one of the most remarkable of all developments in the metropolitan area" (Oser, 1980). So far, Hartz Mountain Industries has invested some $300 million in this planned unit development in Secaucus. There is a housing component of 600 townhouses along the river (Fig.18), a 312-room Hilton hotel, racquet club, movie theatres, marina, 10-story office building, multi-deck parking garage, hospital, and an industrial park of some 80 structures. At the south end of the tract is the 25-story, high-rise condominium, Harmon Cove Towers, consisting of 1,480 apartments. An additional 1,215 units of mid-rise and low-rise buildings will be built by 1985 or 1987, depending on market conditions (Oser, 1980).

Hartz Mountain Industries purchased this 238-acre site in 1969. It extends along the east bank of the Hackensack River for about 1.7 miles and has a width of about 0.3 miles. Development of the site began almost immediately. The following engineering details were provided by Mr. Michael McNally, Vice President of Engineering and Planning, Hartz Mountain Industries (oral communication, June 3, 1980).

In 1970, two million cubic yards of natural fill was brought in at $1.63/yrd (in place). The fill came from a Federal dredging operation off Staten Island. It was carried by the dredge Hydromar to Jersey City. From there is was pumped via a two-mile, 18-inch diameter, steel pipeline which was strung to the site. The fill was deposited to a depth of five to six feet through 12-inch diameter distribution pipes.

Miscellaneous fill, as needed in construction, is trucked in currently from Manhattan and New Jersey. The fill consists of Manhattan schist from building-site excavations, bricks, stone, and debris from demolished buildings, and miscellaneous overburden.

Miscellaneous artificial fill and dredge spoil up to 10 feet thick were present in portions of the site prior to construction. The sub-fill stratigraphy is in general similar to that at the Sports Complex site (Fig. 15). Tidal marsh deposits 3 to 12 feet thick occurred at the surface, where fill had not been placed. The marsh deposits consist of peat and partially decomposed organic materials admixed with some fluviatile silts, clays, and fine sands (JMA, 1974).

The organic accumulations are considered to be highly compressible, to approximately 25 percent to 50 percent of their original thickness, over a period of a century (Woodward-Clyde and Associates, Inc., in JMA, 1978). The organic deposits are, therefore, commonly removed and replaced with relatively incompressible fill.

Beneath the meadow mat are varved silts and clays ranging in thickness from about one foot under Meadowlands Parkway to more than 50 feet near the Hackensack River (JMA, 1974). The varved clays have an upper, stiff zone that is incompressible, possibly because of past dessication. Here it is not more than 10 feet thick. The clays underneath are soft and highly compressible (JMA, 1974). Most of the compression would occur within 3 to 5 years after fill is placed over the clay, but some compression could be expected for many years. (JMA, 1978).

The till under the varved clays is the highest layer capable of supporting heavy foundation loads on pilings. It is very dense and consists of heterogeneous fragments of the Brunswick Formation ranging in size from clay to boulders. The till thickness is uneven, but may be 20 to 30 feet thick in some borings. The till surface slopes from an elevation of -10 feet (msl) beneath Meadowlands Parkway to more than -70 feet (msl) beneath the Hackensack River, towards the northwest (JMA, 1974).

The bedrock is the soft red shale of the Brunswick Formation of the Newark Series. It dips northwestward at between 15° and 20°. The bedrock surface is higher toward the east, where its elevation is approximately -40 (msl). In the southwest corner of the site its minimum elevation is about -100 (msl). About 500 feet east of the site, however, bedrock lies at about +1 foot (msl) (JMA, 1974).

All the initial buildings on the site (larger warehouse buildings) were built on 40-ton-capacity steel pilings, driven to depth of refusal, which is about two-to-five-feet penetration into the glacial till. Refusal is reached at a depth of 25 to 50 feet. The town houses were constructed next. They were built on 20-ton-capacity piles of timber and steel. This was an innovative piling system developed here. First, untreated timber piles of 40-to-60-feet in length are driven in their entirety below the ground water table, which stands uniformly at an elevation of 3 feet (msl). Only immediately adjacent to the Hackensack River does it fall to sea level. The water table shows no significant fluctuations with seasons or rainstorms. Since air is excluded below the water table, rotting of the wood doesn't take place and untreated wood pilings can be used at considerable savings, as compared to treated pilings ($0.45 per linear foot vs. $2.00 per linear foot). Steel pipe of eight-inch diameter and 12-foot length is driven several feet into the top of the wood piling, affording a tight seal. The pipe is filled with concrete and capped at the required height.

The 24-story high-rise structures are supported by 1/2 inch, steel-walled, 12-inch-diameter piles. The piles are 35 to 70 feet long, lengthening towards the river, and 80 feet long at the river's edge. They rest on 3/4 inch steel bearing-plate, within till overlying the bedrock. The pilings have a designed load of 100 tons and are tested to 200 tons. The pilings are filled with concrete. Corrosion of the steel in the upper few feet of the pilings is anticipated, where they pass through cinder surface-fill. To compensate for the corrosion, steel bars of equal surface area to the pipe are embedded in the concrete, near the top of the pilings.

Under warehouses, seven piles are used per 1,000 square feet of building. Stringer floor-supports bridge the pilings. Under certain warehouses, where organic material was thin (two to three feet thick), surcharges of sand were placed over the meadow mat for six months to compress the underlying organic material. The top of the surcharge is 15 to 18 feet in elevation. After the primary settlement was gotten out, all but about five to eight feet of sand was removed, leaving a finished floor elevation of 10 feet. The excess sand was trucked away for use elsewhere in the development. Additional minor settlement that may occur later does not affect the building, as it rests on pilings that extend down through the organic material and clay.

Where the organic material was thicker, it was mucked out and new fill put in its place. Muck-out can be a resource or an expense for the builder depending on the circumstances. It costs $1.50 per cubic yard to excavate and $1.50 per cubic yard to truck off the site. Compacted, new fill costs $5.00 per cubic yard, in place. If the muck-out can be sold for use nearby, as daily soil cover in a sanitary landfill, for example, then it can be a resource and a source of revenue.

Incidentally, borings and other soil investigations, foundation loads, footings, pilings, and similar matters must conform to the Master Plan - Building Code Foundations, developed by the Hackensack Meadowlands Development Commission (HMDC, 1969).

ROAD LOG

Mileage	Refer to map showing numbered stops (Fig. 3).
0.0	Parking lot S of Boyden Hall, Rutgers University, Newark. Go E, N, and E via Warren, Washington and Bridge Streets.
0.8	Cross Passaic River, E on Harrison Street.
1.8	N on Schuyler Avenue which follows bluff marking west margin of Hackensack Meadowlands.
3.2	Midland Ave. Turn right, park immediately. **STOP 1** (Kearny) Overlook, south end of the Hackensack Meadowlands. Panorama (left to right) shows sanitary landfills, more than 100 feet in elevation, over which the first section of the De Korte State Park will be erected; the New York City skyline including the World Trade Center towers (about 7 miles distant); Snake Hill; New Jersey Turnpike; Pulaski Skyway (Routes 1 and 9); and the Bayonne Bridge arch to Staten Island. The southern boundary of the Hackensack Meadowlands District, which is under the jurisdiction of the Hackensack Meadowlands Development Commission, lies about ½ mile north of the Pulaski Skyway. The meadowland environment continues south of the District boundary.
3.9	Turn right on Belleville Turnpike which descends into the Meadowlands.

4.4 Turn left immediately after passing under RR trestle. Take left fork. Follow Baler Blvd.

4.9 HMDC Solid Waste Baling Facility. Park adjacent to the large brown building (Fig. 7).
STOP 2. Tour of facility. See text above.

Return to Schuyler Ave.

3.9 N on Schuyler Ave., at Belleville Turnpike.

3.95 Right turn on Morton Place to dead-end (1 block). Follow dirt path at right corner of street partially down the bluff. Baler building and sanitary landfills to the east (Fig. 19).

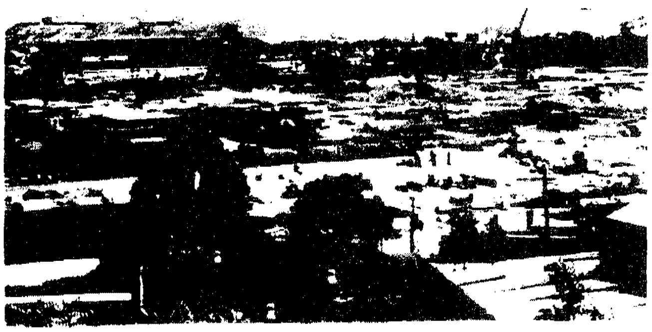

Fig. 19 Looking E across Meadowlands from vicinity of Schuyler Copper Mine, North Arlington, N.J. The Baler facility and landfill mounds are in middle distance; World Trade Center towers in the distance.

STOP 3 (North Arlington)

This is the approximate location of the Schuyler copper mine. The shaft was a couple of hundred feet to the NW. The mine was discovered about 1719 and was probably the first copper mine in the United States. It shipped 110 casks of ore from New York in 1721 (Lewis, 1907). Much detailed historical information can be found in Woodward (1944).

The mine was a source of considerable wealth before the Revolutionary War and continued to be worked intermittently until 1865. The primary ore mineral, chalcocite, occurs in unaltered gray arkosic sandstone overlain by red shale and intruded by small, irregular basalt dikes. The major secondary mineral is the bluish-green copper silicate chrysocolla which penetrates the rock along joints and bedding planes.

Return to Schuyler Ave.

3.95 N on Schuyler Ave.

4.7 Pull over to the right, onto a short "Y" driveway, just N of Carrie Rd.

STOP 4 (North Arlington)

Fig. 20 Looking E from Schuyler Ave. (near Carrie Rd.), North Arlington to wetlands in Lyndhurst, N.J. Kingsland Creek, in middle, flows towards the Hackensack River. To the right are landfills and the Sawmill Creek Wildlife Management area.

Overlook showing a panorama of the Meadowlands N of the one in Stop 1. Kingsland Creek, in the foreground (Fig. 20), lies towards the N end of the Sawmill Creek Wildlife Management Area (Fig. 13). The panorama from left to right shows the Meadowlands Racetrack, Giants Stadium, and the Arena; sanitary landfill; twin towers at S end of the Harmon Cove development; Empire State building and mid-town Manhattan skyline behind the Palisades ridge; sanitary landfill, World Trade Center towers are almost in line with Kingsland Creek. The W spur of the N.J. Turnpike is in the middle distance; the E spur passes behind Snake Hill, at the right. Note the wetland dikes.
Continue N. on Schuyler Ave.

7.9 Right on Orient Way (Route 11).

8.2 Right on Valley Brook Ave., descend to Meadowlands.

8.4 Left on Polito Ave.

8.65 Bricked-up entrance to copper mine exploration shafts in red beds behind Kuttner Prints plant on left. This is the Lyndhurst Office Industrial Park, one of 11 industrial parks in the Meadowlands. This park includes the Meadowlands Corporate Center and tenants such as Pugeot, Citroen, etc.

8.7 Polito Ave. has developed a "wash board" effect because the road was built directly on the meadow mat, which doesn't support the heavy truck traffic very well.

8.75 Follow signs to Route 3 East, around Holiday Inn.

10.00 Cross Berry's Creek. The very serious mercury pollution problem in Berry's Creek and its environs originated in an industrial plant about 3 miles upstream (see text above). The Creek forms the W boundary of the Meadowlands Sports Complex, whose three major structure loom large on the left.

10.4 Right to Rte. 20 N.

10.7 Passing under Route 3.

11.7 Stay left on Rte. 20 N.

(Note: Mileage and routing directions to parking site will be made available by the Sports Authority at time of the trip).

STOP 5. Meadowlands Sports Complex (East Rutherford). See text above.
Leave Sports Complex, Rte. 20 N to Washington Ave.

13.5 N on Washington Ave.

15.0 Right on Empire Blvd. (traffic light).

15.6 Turn ¼ left, follow Merhof Road towards two tall smoke stacks. Pass through gate at sign reading "Bergen County Utilities Authority."

16.2 Right at end of road.

16.3 Left into parking lot in front of office building, Bergen County Utilities Authority.

STOP 6. Sewage Treatment Plant (Little Ferry).

Fig. 21 Bergen Generating Station, Public Service Electric and Gas Co., Ridgefield Park, N.J. Looking NE across Hackensack River from Bergen County Sewage Disposal Plant in Little Ferry, about three-quarters of a mile distance. Conveyor belt ramps transport coal from storage pile into the plant.

Tour of the plant and new construction in progress. *See text* above. Opposite this stop, across the Hackensack River in Ridgefield Park, is the Bergen generating station of Public Service Electric and Gas Company (Fig. 21). This plant is in the extreme northeast corner of the Hackensack Meadowlands District. It is a conventional oil-burning power plant, but is also equipped to use coal and natural gas. In 1983 it will also burn garbage from the resource recovery plant to be constructed adjacent to it by Bergen County (Boyd, 1980d). Procedures are employed to minimize thermal pollution of the Hackensack River, to condense spent steam from the turbines for reuse in the boiler.

Several ponds to the northwest of the Sewage treatment plant were clay pits. Little Falls was once the center of a major brick-manufacturing industry.

Return to Washington Ave. (traffic light).

15.0 Left on Washington Avenue (Rte. 503). Look for sign "Paterson Plank Road East"

16.0 Two LNG storage tanks to the east (Fig. 17).

17.1 Turn left (U-turn).

17.7 Left to Paterson Plank Road East.

17.9 Right on Paterson Plank Road East.

18.4 Passing over N.J. Turnpike (W spur).

18.6 Dead End at Hackensack River.

STOP 7 - Stone pier S of Sky Harbor Marina (Carlstadt). Walk to end of pier for view of Hackensack River (Fig. 22). Sand and gravel storage facility can be seen on opposite (E) shore of the river, in Secaucus. Route 3 bridges cross the river to south. Behind bridge is the Harmon Cove development, our next stop.

Two LNG storage tanks can be seen about 0.7 mile to the NE very close to a superhighway (Fig. 23). Most of the area between here and the tanks has been rezoned for residential use. See text above.

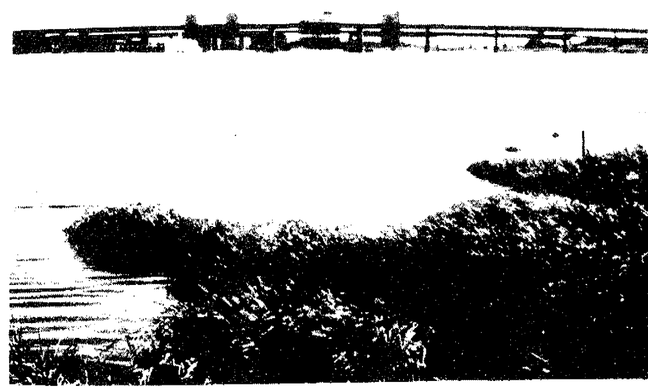

Fig. 22 Route 3 crossings of Hackensack River five-eighths of a mile distant, as seen from stone jetty at foot of Paterson Plank Road. Harmon Cove buildings are in the center distance. Looking S.

18.6 Proceed back to Rte. 20 S via Paterson Plank Road.

19.9 U-turn to Rtes. 3 and 20 S. Keep to right, Rte. 3E.

21.4 Bridge crossing Hackensack River. Harmon Cove development on the right.

21.7 Turn right for Meadowlands Parkway.

21.9 Left at light to Harmon Towers.

22.2 Turn right. Park alongside parking deck.

STOP 8 - Harmon Cove Development, Hartz Mountain Industries, Secaucus. See text above.

Fig. 23 LNG storage tanks about one-half mile E of N.J. Turnpike toll gate. View from Paterson Plank Rd. overpass, Carlstadt, N.J.

We will leave the bus here and board it at the Twin Towers high-rise condominium at the south end of the development. Start walking along the bicycle and jogging path that winds southward through the area of town houses that stand between Meadowlands Parkway and the Hackensack River (Fig. 24). The top of the 25-story Twin Towers affords a spectacular view of the entire Hackensack Meadowlands District lying on the floor of post-glacial Lake Hackensack. The Manhatan skyline looms impressively beyond the back slope of the Palisades, which marks the eastern border of the District. The Hackensack River can be seen as the central artery sustaining the watery ebb and flow of estuarine life in the wetland habitat. The network of highways includes the Pulaski Skyway, East and West Spurs of the New Jersey Turnpike, Rte. 3, and others. Five highway bridges and six railroad bridges cross the Hackensack River in the District. Landfills towards the SW mark the site of the De Korte State Park. To the north can be seen the Sports Complex, the LNG storage tanks and the PSE & G electric generating plant. Another power plant is at the far south end of the area. Several industrial parks are distributed throughout the District.

23.0 Board bus, go north on Meadowlands Parkway.

23.2 Right turn to Rte. 3 and N.J. Turnpike. Keep right for Turnpike South.

25.1 N.J. Turnpike toll gate.

26.1 Secaucus water tower on right. The town of Secaucus forms two "islands" inside the Hackensack Meadowlands District (Fig. 6). Its location was determined by the presence of bedrock at the surface, which posed none of the foundation problems found elsewhere in the Meadowlands.

26.6 Little Snake Hill on left.

27. Snake Hill (Big Laurel Hill) on right.

These are diabase plugs which may have served as vents or feeders for the Watchung lava flows. Snake Hill has been largely quarried out for trap rock crushed for use as road metal. It supplied crushed stone for Hartz Mountain Industries. Snake Hill is zoned for residential use (Fig. 4). Because the basalt provides an excellent foundation, housing can be built more cheaply here than at Harmon Cove or elsewhere in the District where costly pilings must be used. Low-cost housing has been suggested for the site because the cost per unit would be lower. The site's isolation, however, mitigates against this type of housing.

27.3 Sawmill Creek Wildlife Management Area to the right (Fig. 2). This will be part of the De Korte State Park.

28.7 Exit 15W - leave N.J. Turnpike.

29.7 E on Rte. 280 (Harrison Ave.) to Newark.

31.7 Cross Passaic River into Newark.

32.4 Arrive Rutgers University Campus, University Ave.

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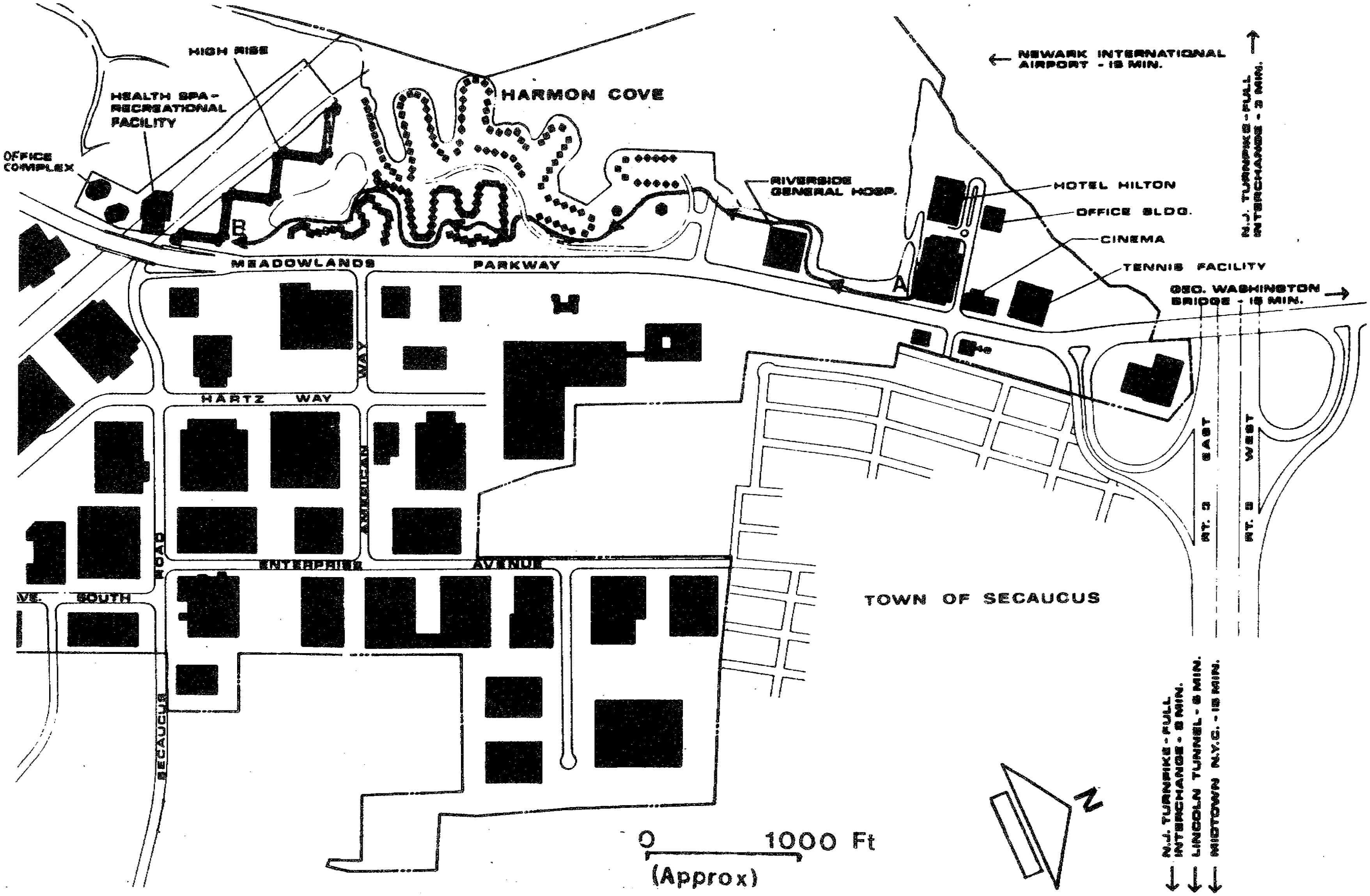

Fig. 24 Harmon Cove Development, Hartz Mountain Industries, Secaucus, N.J. The winding, solid line of arrows indicates route of walking tour through the townhouse complex (small dots), from the parking deck (A) to the zig-zag-shaped twin towers high-rise apartment complex (B). An industrial complex (partially shown) stands east of Meadowlands Parkway. (Courtesy Hartz Mountain Industries, Inc.)

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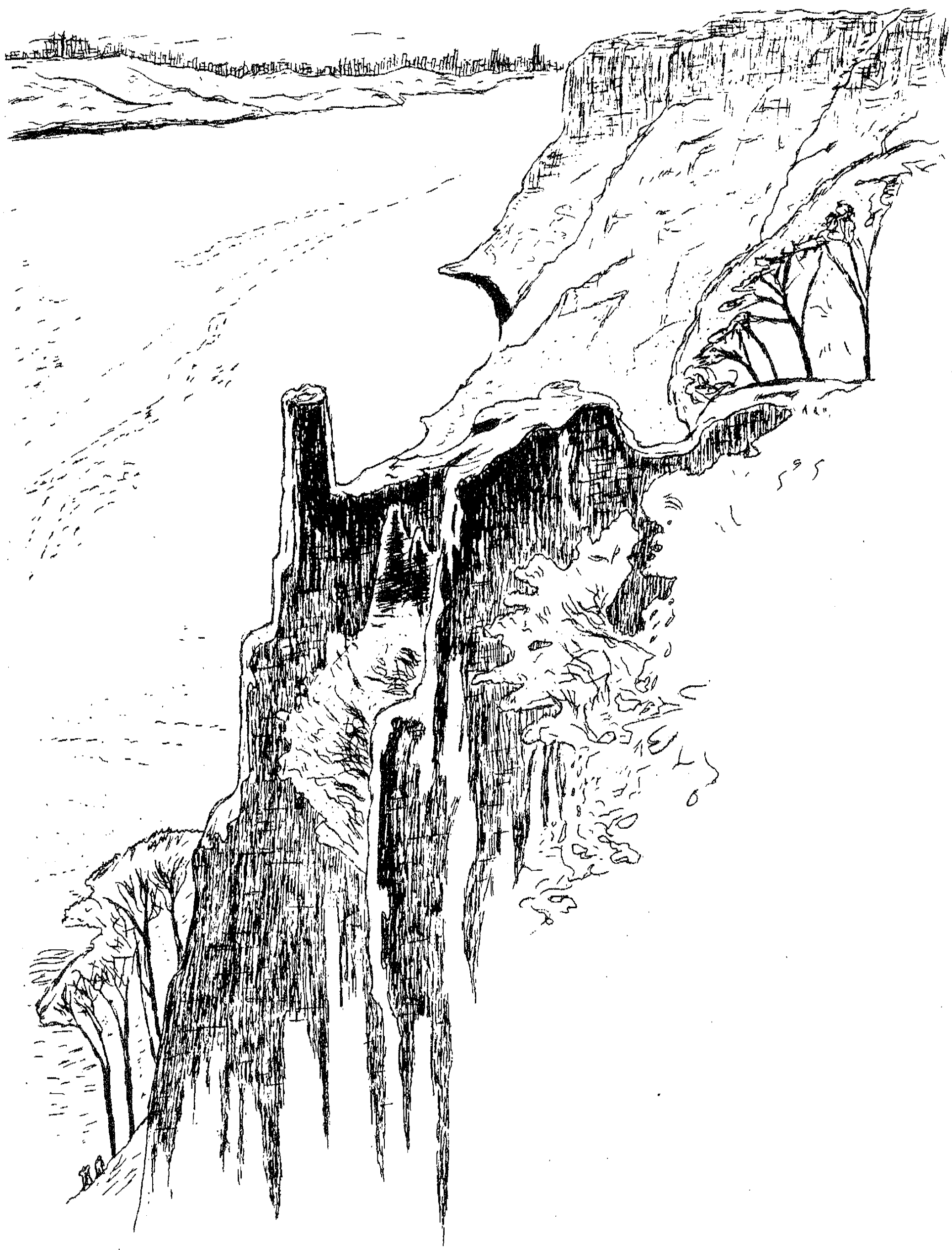

MINE HILL, FRANKLIN FURNACE
by H. Carmiencke
from Delaware
N.J.G.S., 1856, 2nd Annual

ENVIRONMENTAL GEOLOGIC TRAVERSE

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GENERAL CONCEPT

Initially, this trip was going to include a number of stops in the Appalachian Fold Belt, the Highlands, the Newark Basin, the Coastal Plain and right down to New Jersey's barrier beaches. As the detailed plans began to take form, there appeared to be no way to sample in one day, all the varieties of geology that New Jersey has to offer unless one did it from a speeding helicopter. Thus, the route shown on Figure 1 attempts to sample as many different geological environments and concurrent geologic problems as can be "shoved" into a single field trip.

A total of 10 stops are planned (as shown on Figure 1). These are:

1. Route 280 West Orange, road cuts in the First and Second Watchungs;
2. Ridgedale Avenue, Morristown, terminal moraine—semi-abandoned quarry;
3. Route 202 South of Morristown, Ramapo Fault, hospital across "active" fault;
4. Great Swamp, problems of managing 6,000 acres of wildlife preserve in a suburban environment and how the refuge affects its surroundings;
5. Millington Gorge—faulted (or erosional) cut through Second Watchung, flooding concerns;
6. Millington Quarry—blasting and transportation of trap rock in a middle class suburban environment;
7. Bridgewater Township—Route 78 road "cuts" in Second Watchung Mountain, compare with Stop 1;
8. Far Hills—Where does the Ramapo go?
9. Bernards Township/Bedminster, proposed 1,500 acre development, variable soil and rock, mostly impermeable soils, mostly shallow rock —how do you build a new "town"?;
10. Berkeley Heights—Whither goest Route 78?

GENERAL GEOLOGY

Introduction

The first portion of this trip crosses the same geologic conditions that are discussed in Trip No. A-1 and will not be repeated here (we will make one "stop" on Route 280 as subsequently discussed under Stop 1). We will leave the Trip A-1 route at the intersection of Routes 80 and 287 and head south along Route 287 into Morristown (Figure 1). At this point, we are just within the Newark Basin with the fault-bordered New Jersey Highlands to the west.

NEW JERSEY HIGHLANDS (READING PRONG)

The Highlands are a belt of primarily Precambrian rocks some 20 miles wide in this area. The Precambrian igneous and metamorphic rocks are generally in parallel northeast trending ridges. Paleozoic sediments occur in a number of the intermontane valleys. The principal Precambrian rocks are granite, gneiss and schist. Locally, there is significant variation in mineral composition (Smith, 1969). The principal Paleozoic rocks are quartzites, limestones, dolomites and shales.

The Highlands are variously interpreted to be part of a large nappe structure, with the Precambrian rocks lying atop Paleozoic formations or alternately deep rooted and true basement (Smith, 1969). It is generally accepted that the Highland Rocks in the northern part of the state (near the Hudson River) are true basement. Well to the South, the analogous Blue Ridge Mountains are allochthonous. Drake (1969) summarizes the information leading to an allochthonous conclusion for at least the Delaware River area and south, for the Highlands. Thus, there apparently is some possibility that both assumptions hold true in New Jersey.

The northeasterly-trending ridges and valleys are principally the result of folding along the ancient continental margin and stream erosion. Jointing is well developed, with northwest striking joints the most abundant, followed in number by N 45° E joints (paralleling the strike of the Highlands).

BORDER FAULT

A prominent border fault is found along the southeastern edge of the Highlands (Figure 1) in the

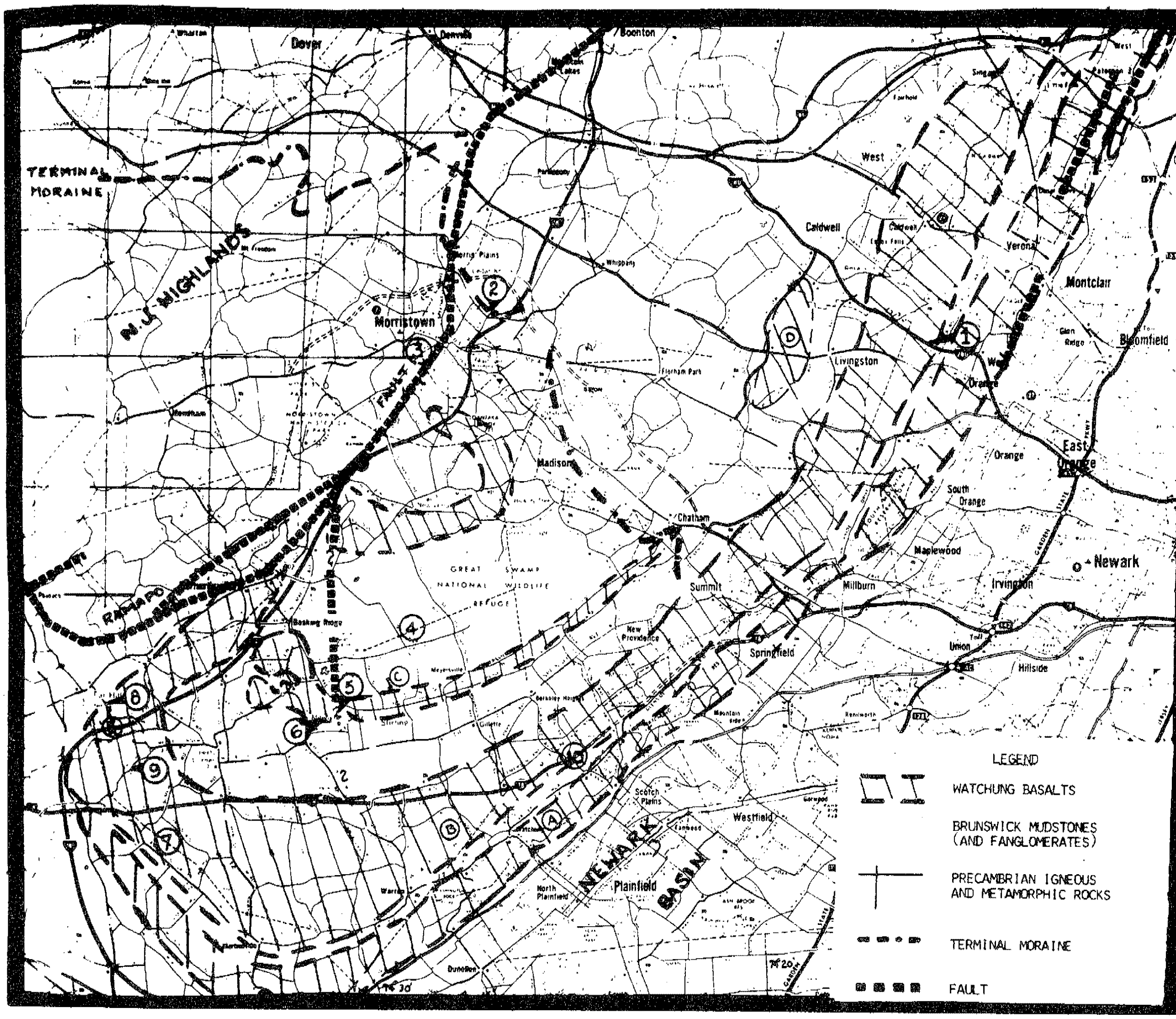

Fig. 1 Location map showing geology and field stops

field trip area. This fault system, the Ramapo, has been the subject of a great deal of recent controversy (also see Stop 2 discussion), concerning its relationship to current seismicity. What is generally accepted at present is the overall tectonic development of the fault system.

Two separate Precambrian episodes of faulting have been recognized. Initially, it is likely that ductile deformation was experienced during the Grenville Orogeny. Subsequently, Late Precambrian rifting along an ancient continental margin reutilized the older Grenvillian zone of weakness.

During Middle Ordovician, it is likely that block faulting, with attendant uplift resulted in further movements along the Ramapo System. The next recognizable phase of deformation, still in the Paleozoic, was characterized by a predominance of crustal shortening in the area and the suggestion of the Ramapo participation as a reverse fault. This phase of deformation is thought to have resulted in both syn- and post-regional metamorphism.

This reverse faulting was followed by regional right-lateral transcurrent faulting, at least along the northern portion of the Ramapo, and its northeasterly extension, the Canopus Fault System. The northeast trending systems, east of the Hudson River, were linked by several ENE-to-EW-trending fault zones to a second en-echelon system further to the east, the Croton Falls Fault System.

Transcurrent fault movements along these systems reutilized and in some instances, crosscut the earlier reverse faults.

During the Mesozoic, the major northeast trending zones (including the Croton Falls System) were reactivated with dip-slip and left-lateral movement. The sinistral episode of movement probably represents the response to ongoing rifting in the central portion of the Appalachian Orogeny.

The wrench faulting may have occurred during, and did occur after, the sedimentation and lithification of Newark Basin strata and the emplacement and cooling of Triassic-Jurassic basalt and diabase (the Watchung Mountains and the Palisades).

The Palisades and Watchung igneous events appear to have occurred in the transition from dip-slip to strike-slip faulting. The drastic decrease in the rate of sediment accumulation after the First Watchung flow may reflect the change from predominantly dip-slip to strike-slip motion along the Ramapo Fault. Both igneous activity and sedimentation in the Basin slowed and eventually stopped prior to the complete cessation of left-lateral movement on the Ramapo.

By Middle to Upper Cretaceous time, fault movements ceased. Thus, in summary, the tectonic function of the Ramapo System during late Triassic is interpreted to be primarily as a normal fault with an active role in the development and filling of the Newark Basin. From late Triassic to late Jurassic, the Ramapo and associated faults to the northeast were left-lateral strike-slip features. Thus, we would expect smaller faults which exist in the Basin would have experienced Mesozoic-aged movements related to left-lateral movement on the main fault system.

NEWARK BASIN

The Newark Basin in this general area developed and was deformed during the Mesozoic Era. The initial subsidence of the basin was syn-sedimentary although this early period of normal faulting was gradually replaced by a period of pervasive left-lateral faulting.

The rocks in the Newark Basin in the area of this field trip consist of the Brunswick Formation and the Watchung Basalt. The Brunswick is a relatively soft (compared with the Watchung Basalts and the Highland rocks) reddish-brown shale and sandstone, which generally (but not always) is rippable with conventional construction equipment. Close to the edge of the Highlands, beds of border conglomerate and pebble-bearing sandstone are reported (Lucey, 1972). These beds interfinger with the finer grained Brunswick.

Interlayered with the later Brunswick Formation sediments are three extrusive flows. These sheet basalts were more resistant to erosion than the overlying more recent sediments and presently occur in three main series of ridges known as the First Watchung Mountain (A-Figure 1), the Second Watchung Mountain (B-Figure 1) and the Long Hill (C-Figure 1), Riker Hill (D-Figure 1), Hook Mountain, Packanack Mountain alignment. Generally, at least two flows are observed in the First Watchung basalt. The lower is markedly jointed, the overlying one ropey and pillow lava (Van Houten, 1969). The Palisades, to the northeast of the field trip area, are of the same age as the Watchung extrusives but are generally considered to be an intrusive (diabase) although having a similar mineral composition.

Both the Watchung basalts and the Brunswick Formation are found in outcrop throughout this area of the Basin. From an environmental/engineering geologic standpoint, however, the relatively thin soil cover is also of importance.

UNCONSOLIDATED QUATERNARY DEPOSITS

The predominant soil covers in the area are:

1. Glacial drift;
2. Residual soils (both from the basalts and the sandstones/shales);
3. Glacio-lacustrine sediments;
4. Alluvial sediments.

The general location of the terminal moraine of the Wisconsin Glaciation traverses the area approximately as shown on Figure 1. Thus, any glacially derived materials south of the moraine should be Pre-Wisconsin.

The terminal moraine is breached at two locations, one just north of Morristown, and the other in Chatham Borough and Summit Township, along the Passaic. South of the Passaic, the moraine is irregularly noted from Baltusrol Country Club to south of Scotch Plains. North and east of the terminal moraine, the surface is covered by some 5 to 12 feet of ground moraine (Gill, 1965). The drift within and behind the terminal moraine is generally poorly sorted with low permeability.

To the south and west of the terminal moraine, the glacial deposits can be subdivided into three categories: (1) drift from earlier glaciations; (2) stratified Wisconsin glacio-fluvial deposits; and (3) glacio-lacustrine deposits.

The scattered deposits of earlier drift are reported to be generally thin, typically highly oxidized, deeply colored, stony materials (Gill, 1965). The glacio-fluvial outwash deposits generally have coarse-grained layers of sufficient size and permeability to be sources of ground water for domestic use. Thickness of outwash deposits of the order of 100 feet are reported along the Passaic River (Gill, 1965).

The glacio-lacustrine deposits generally consist of relatively impermeable silts and clays deposited in Lake Passaic. Glacial Lake Passaic first filled the natural basin south of the Wisconsin glacier terminal and southern boundary and the Highlands its northwestern border. An outlet through the southwestern corner of the Second Watchung Mountain, near Far Hills allowed drainage into a tributary of the Raritan and thence to the sea. The outlet elevation is about at 330 feet above sea level and is know as Moggy Hollow (E-Figure 1).

Thus, once the lake formed, its level rose to the lowest point at Moggy Hollow. With the northward retreat of the glacier, lake water followed the ice front to about Pompton Plains. At this time, Lake Passaic was about 30 miles long, eight to ten miles wide and had a maximum depth of about 240 feet (Schuberth, 1968).

As the ice retreated, an outlet was exposed first at Great Notch, (Figure 1) at elevation about 300 ft. and the overflow at Moggy Hollow stopped. When the ice freed an outlet at Little Falls, Paterson (just to the north of Great Notch) and the lake drained to the level of that outlet (today at 185 feet above sea level), Lake Passaic ceased to exist. However, today much of the area formerly covered by Glacial Lake Passaic is subject to flooding from the Passaic River (almost a regular occurrence). Great Piece Meadows, Hatfield Swamp, Troy Meadows, Black Meadows, Duck Swamp and Great Swamp (Stop 3) are all areas of regular and extensive flooding.

The lacustrine deposits of Lake Passaic vary in thickness over the field trip area but primarily have low to very low permeabilities. Overlying and/or cutting through portions of these lacustrine deposits are relatively minor deposits of alluvial soils along a number of the small streams presently feeding the Passaic River (see Figure 1). In most instances, the alluvial soils are relatively fine-grained as the source material are oft-time silts and clays. These alluvial soils in the area cannot be considered either a prime source of ground water supply or have high suitability for septic system use in home construction.

The residual soils vary in thickness as one would expect. The basalt cover is thin; 10-15 feet is considered quite deep. The exact extent of "weathering" over the Brunswick is generally difficult to define as the change from soil to firm rock is gradual and subject to interpretation. However, thicknesses of 10-20 feet is not unusual except in "baked" areas adjacent to the basalt flows. Permeability of the residual Brunswick soils is generally low while the residual basalts weather to anything from sands to clay and permeability is laterally variable.

ECONOMIC GEOLOGY

It may be somewhat surprising to many but the general area was once a principal source of New Jersey iron ore. Over 200 mines existed at one time in Morris County (Lucey, 1972). The ore body is magnetite, found in the gneisses of the Highlands. Copper was mined in the First Watchung in the mid- and late 1800's. Legend has it that the mines were originally opened during the revolution by George Washington's forces (Tobiassen, 1978).

The basalts of the Watchung and Long Hill flows are quarried in a number of locations in the field trip area (See Stop 5 discussion). The basalt is utilized as aggregate, road metal, roofing materials, railroad ballast and rip rap.

The clays derived from weathering of the Brunswick Formation have been used to make bricks and for impermeable liner construction in areas to the south of the field trip area. There is no economic use of the Brunswick Formation in any form in the field trip area to the author's knowledge.

Several sand and gravel pits of commercial size (Stop 2) have been worked in the area for a number of years (Kruckick, 1969). Despite the impetus of burgeoning population growth in recent years, the expansion of a sand and gravel industry does not seem to have occurred.

WATER RESOURCES

As previously indicated, flooding along the Passaic and a number of its tributaries in the valley between the Second Watchung Mountain and Long Hill is a relatively common occurrence. Surface water storage is presently inadequate, both as a means of reducing flood potential and as a source of water supply. Discussion and studies relating to flood control along the Passaic River, which wanders through the field trip area, have been underway for decades.

Existing surface water storage facilities are as follows:

1. Osborn Pond in Bernards Township;
2. Two offstream (Passaic River) impoundments at Canoe Brook north of Summit;
3. Clyde Potts Reservoir (upper reaches of the Whippany River);
4. Cedar Hill Reservoir (east of Florham Park);
5. Boonton Reservoir.

Good quality ground water is found primarily in two aquifers in the region: the stratified drift, and the Brunswick.

The glacio-fluvial deposits are significant water sources where their thickness exceeds 50 feet (and thus are not abundant). Yields of from 60 to 1200 gpm have been recorded (Gill, 1962) in wells into these deposits.

The other source is within joints and fractures of the Brunswick. Although the depth of significant fracturing is variable, highly fractured and saturated zones have been found to depths as great as 500 feet (Gill, 1965). Yields range from 4 to 650 gpm.

Low yielding aquifers also exist in the basalt and the Highlands gneisses and granites. Well yields range from less than 5 gpm to several hundred gpm (Gill, 1956).

ROAD LOG

Mileage	Route Description
	Route 280W from Newark (Newark Basin)
0	Route 280 and Garden State Parkway
3	**STOP 1A** Route 280W (First Watchung) — SEE STOP 1 discussion
5	**STOP 1B** Route 280W (Second Watchung) — note Riker Hill to the west as 280W descends to the area of Glacial Lake Passaic
11.5	Follow signs for Route 287 — Morristown/Boonton, will actually be in local lanes of Route 80W (Glacial Lake Passaic)
14	Exit onto Route 287 S/Morristown — (New Jersey Highlands to the west, traversing glacial deposits overlying Brunswick Formation)
20	Exit at Ridgedale Avenue, go to stop sign and turn north (right) on Ridgedale Avenue
20.5	North on Ridgedale Avenue to County Concrete Corp. Quarry (Terminal Moraine) **STOP 2** (see discussion) Abandoned Quarry South on Ridgedale Avenue (go through Morristown to Route 202 S) to Morris Avenue
21	Turn west (right) on Morris Avenue (Route 510) to Center of Morristown and Route 202 S signs
21.7	South on Route 202 (Mt. Kemble Avenue)
22.5	**STOP 3** Route 202 S, Morristown Memorial Hospital, Mt. Kemble Division, (on Ramapo Fault — Highlands immediately west of road) — SEE STOP 3 discussion
	Continue on Route 202S to North Maple Avenue. Notice new construction, homes, apartments, office buildings. Some are on septic systems; some are on Morristown sewage treatment plant system. Route 202 generally lies along Ramapo Fault
27.5	Turn southeast (left) on North Maple Avenue (traffic light) to Basking Ridge
28.5	Turn east (left) on Madisonville Road (blinker light) — descend to Glacial Lake Passaic terrain — outlier of Third Watchung basalt flow to the north and Long Hill (third flow) to south
29	Turn southeast (right) on Pleasant Plains Road (Glacial Lake Passaic)
31	**STOP 4** Great Swamp Refuge — SEE STOP 4 discussion Continue on Pleasant Plains Road
33.5	Turn south (left) on Lupine Way (second intersection of Pleasant Plains Road with Lupine Way) (rise from Glacial Lake to Long Hill basalts)
33.6	Turn west on Long Hill Road, through blinker light (bearing right) as Long Hill Road changes to Basking Ridge Road

35.2 Turn south (left) on Pond Hill Road (basalts)

35.5 **STOP 5** Millington Gorge at intersection with Erie Lackawanna (Conrail) (gorge in basalt) SEE STOP 5 discussion

35.5 **STOP 6** Millington Quarry (quarry in basalt) SEE STOP 6 discussion

Continue on Pond Hill Road to Haas Road

36 Turn west (right) on Haas Road to Stone House Road (shallow Brunswick)

36.8 Turn south (left) on Stone House Road to Valley Road (Route 510) (shallow Brunswick)

36.9 Turn west (right) on Valley Road to Martinsville Road (Route 525) (shallow Brunswick)

39.5 Turn south (left) on Martinsville Road to Route 78W (shallow Brunswick to basalts, Second Watchung)

42 Turn west (right) on Route 78 to Exit for Scenic View.

42.2 **STOP 7** Scenic View Parking Area on Second Watchung, can view road cut best from east end of Parking Area — SEE STOP 7 discussion — view to the west is across Newark Basin to New Jersey Highlands
Return to Route 78W and continue to Route 287N exit (Morristown) (descend from Second Watchung)

43.5 Turn north (right) on Route 287 to Route 202, 206N (first exit)

45 Turn on to Route 202N to Bedminster and Far Hills (probably Brunswick mudstone with perhaps some more conglomeratic facies toward Highlands to the west)

47.8 Turn south (right) on Far Hills Road (Route 512)

47.9 **STOP 8** Far Hills Road (N.J. Highlands to West, known Ramapo Fault bends to west) — SEE STOP 8 discussion

Continue on Far Hills Road to unnamed road with sign to Leonard J. Buck Gardens

48.7 Turn right to Buck Gardens — the proposed (Spring 1980) arboreteum is at Moggy Hollow

48.8 Return to Far Hills Road

49 Turn east (right) on Far Hills Road (becomes Liberty Corner Road) to Mt. Prospect Road

50.5 Turn south (right) on Mt. Prospect Road (Second Watchung basalts)

51.4 **STOP 9** Continue on Mt. Prospect Road to central portion of Johns Manville Properties site — SEE STOP 9 discussion

Return on Mt. Prospect Road to Liberty Corner Road

52.3 Turn east (right) on Liberty Corner Road (Route 512) to Valley Road (from basalt to Brunswick mudstone approximately where road crosses small stream)

53.8 Turn south on Valley Road (still Route 52 — continue to Martinsville Road (Route 525) where road bears right to Route 78

55 Turn east (left) on Route 78 and continue to temporary end at Berkeley Heights (Second Watchung basalt)

63 **STOP 10** SEE STOP 10 discussion.

Return to Newark

STOP #1
Rte 280 - West Orange

Rather than a stop, this will be a slow drive by (either by direction or limitations of the bus). As the elevation rises from the Northfield Road (State Route 508) intersection with Route 280, the first outcrops seen are of the Brunswick Formation (sandstones). Then Route 280 climbs into a major road cut within the Watchung basalts (First Watchung). The basalt cut is steep and the blocky, columnar structure of the lower basalt can be observed early. At higher elevations, the cut is in ropey and pillow lava. Along the cut in the Second Watchung, while it is still at a high angle, several failures can be observed along minor shear zones in columnar basalt. (see Manspeizer, and Olsen this fieldbook).

STOP 2
Ridgedale Avenue - Morristown

This is a semi-abandoned quarry. The main purpose is to observe the materials in the terminal moraine at this point. At this location, the embankment is primarily sand.

STOP 3
The Ramapo Fault, Morristown

Is it or isn't it an active fault? If it is active, how active?

Lamont-Doherty Geologic Observatory has indicated it is a capable* fault. The technical and judicial examiners on the recent (1977) Indian Point Nuclear Power Plant Appeal Board hearings declared it was not. The Nuclear Regulatory Commission and Consolidated Edison Co. consultants agree with the hearing board.

Controversy still rages with the planning of two water supply dams across the fault in southern Rockland County. Intervenor witnesses have quoted an April 1978 Science article (see References) concerning the Indian Point plants as their rationale for requesting a seismic factor even greater than that used in design of the nuclear plants across the Hudson River.

Yet here in New Jersey, there are hospitals and schools built across the fault in two towns we will pass through on this field trip — Morristown and Bernardsville. No controversy seems to exist in this area of the state concerning the activity of the Ramapo, despite experiencing a Mag. 3.1 earthquake in Bernardsville as recently as March 10, 1979.

At this stop we'll quickly look at the "fault" as it passes below a hospital. Is it disaster waiting to happen or is it a tempest-in-a-teapot? Look at the trace here in Morristown. The trip will pass over the Ramapo and related structures several times. The seismicity of the Ramapo will be discussed at Stop 4 (in greater comfort).

* 10CFR 100 Appendix A, Seismic and Geologic Siting Criteria for Nuclear Power Plants.

STOP 4
The Great Swamp (lunch)

The Great Swamp Refuge was established in 1960. It is only 26 miles west of New York City in the Boston-Washington metropolitan corridor. It is approximately 6,000 acres of swamp woodland, hardwood ridges, grass lands, old croplands, and water impoundments. As previously noted, it is within a portion of the area covered by ancient Lake Passaic.

Approximately two thirds of the refuge is designated as Wilderness Area and the remainder as Management Area. Man-made structures and motorized vehicles and equipment are prohibited by law from this area. In the Management Area, the habitat is controlled by cutting brush and timber, mowing, farming, planting shrubs, regulating water levels, and by providing nesting structures.

The problems of maintaining a wildlife refuge in an area where population and commerce are steadily growing will be discussed by members of the Refuge staff.

STOP 5
Millington Gorge, Millington

This steep-sided cut through Long Hill (the Third Watchung) is aligned with Osborne Pond in Basking Ridge and Mt. Kemble Lake in Harding Township as well as a valley through a ring of basalt in the New Vernon area. Is this an en-echelon fault of the main branch of the Ramapo or just differential erosion and coincidence?

Whatever the reason, during heavy storms the Gorge acts as a contraint to flow in the Passaic ponding water as far upstream as the Great Swamp and contributing to many flooded basements to the north (see Figure 1) along Black Brook and the Passaic River.

STOP 6
Millington Quarry, Millington

At the time of preparing this outline, it was not known whether we would be allowed within the Quarry or would have to walk from Millington Gorge to view the scope of the operation. The concern here is not the mere idea of quarrying the Watchung basalts, which are well exposed in the Gorge and many other locations for inspection, but in blasting rock and the resulting transportation in a middle-class, suburban environment. The quarry has continually been in litigation with the town because of the noise, dust and shaking caused by trucking and blasting operations.

Present New Jersey State law requires that a peak particle velocity of two inches per second should not be exceeded in critical areas away from any blasting. Whenever checked, the quarry has not exceeded these limits yet the complaints continue, not unexpected as the human body is an excellent vibration device. The present N.J. criteria were derived from work undertaken in the 1960's by the U.S. Bureau of Mines with subsequent confirmation (?) by others in Sweden, Canada and Great Britain. The presently proposed Bureau of Mines' criterion is a particle velocity of one inch per second. What will these criteria do to quarries like this and others in similar environment? The proposed criteria also establish air blast limitations.

We'll discuss all of the above.

STOP 7
Route 78 - Bridgewater Township

Two possibilities exist for the problems as encountered at this highway cut. One is that a fault zone cut through the basalt in this area; the other is that merely the broken columnar nature of the rock here made steep rock cuts impossible. The embankments at this location were cut originally at the same slopes as the remainder of the highway. Repairs kept the highway closed for over a year while the pavement was otherwise completed. After a long period of cogitation, the slopes were cut back to what you see at present. Rock falls were minimized and the ten miles of highway opened. The additional costs of time and excavating are not known but must have been considerable. Could a good site investigation have prevented this problem? — a discussion.

STOP 8
The Ramapo Fault - Far Hills

At Far Hills, we can compare the mapped location of the Ramapo (See Figure 1) with the local topography and discuss the effect of the fault upon local construction, both socially and from a general ground water viewpoint.

On the way to stop 9, we'll detour by Moggy Hollow. It will be at some future time, a Somerset County Arboreteum. A bit of New Jersey geologic history will be retained.

STOP 9
Development of New Town-Bernards Township/Bedminster

A new development comprised of housing and office buildings is planned for a 1,500 acre site. The site was in litigation for several years and the decisions in the two townships were totally different (and will be discussed). Some 400 acres (higher density — Bedminster) will be sewered while 1,100 acres (low density — Bernards Township) will be on individual or small combined septic systems.

The site has shallow basalts and shales, residual soils, lacustrine deposits, glacial till, high water table, protected streams, steep slopes and is adjacent to the Ramapo Fault. How do you develop this property (the largest single site planned for development in New Jersey)? We'll have a local geology map, test this pit data, percolation test data and some development concepts for discussion — a seminar.

STOP 10
Route 78 - Berkeley Heights

The highway has been completed to this location for some 5 to 10 years. The road *has* opened in 1978 from Millburn to Newark Airport (see Figure 1) but there has been extensive discussion concerning the most environmentally sound route (or non-route). We'll discuss it a little more, from primarily a geologic viewpoint.

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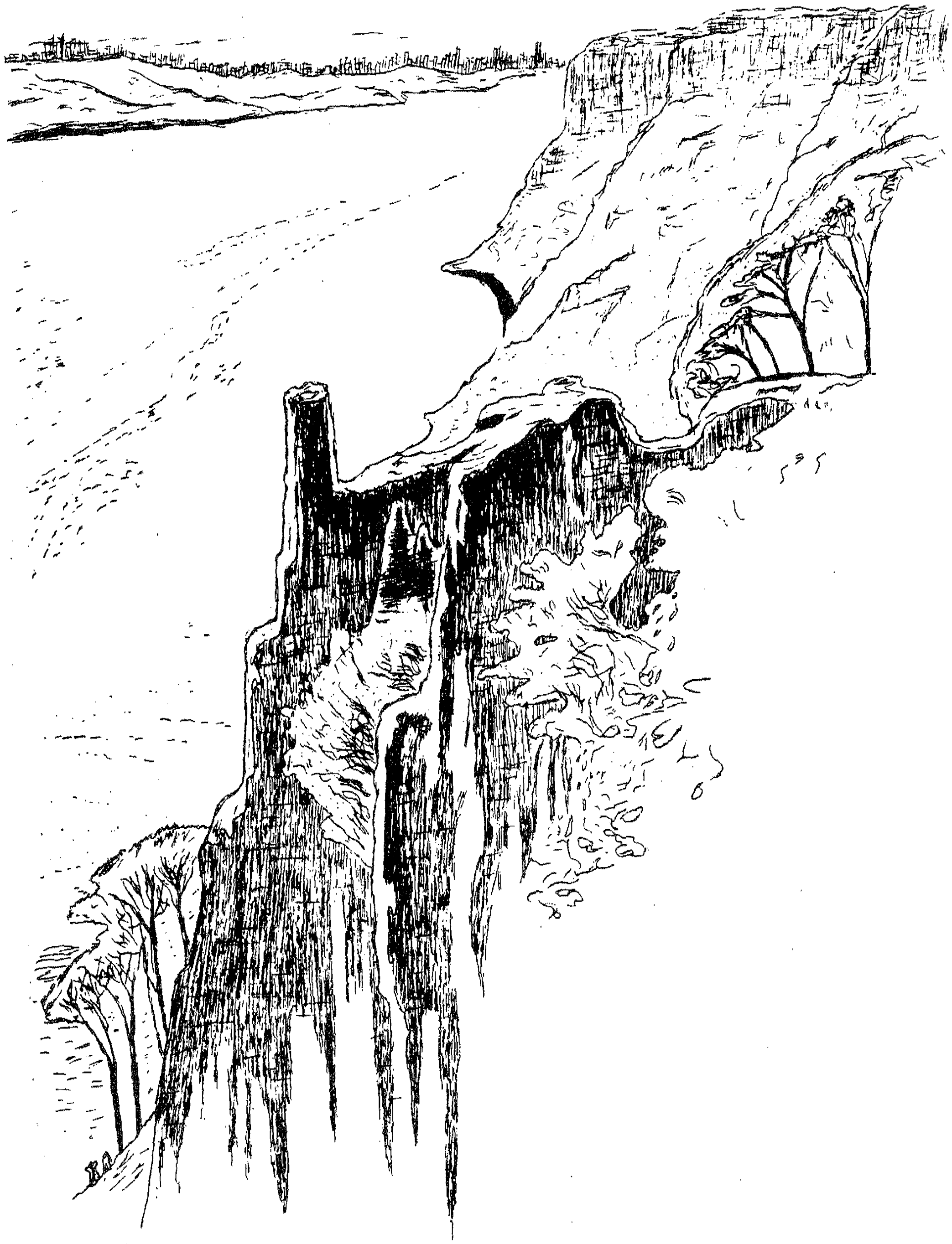

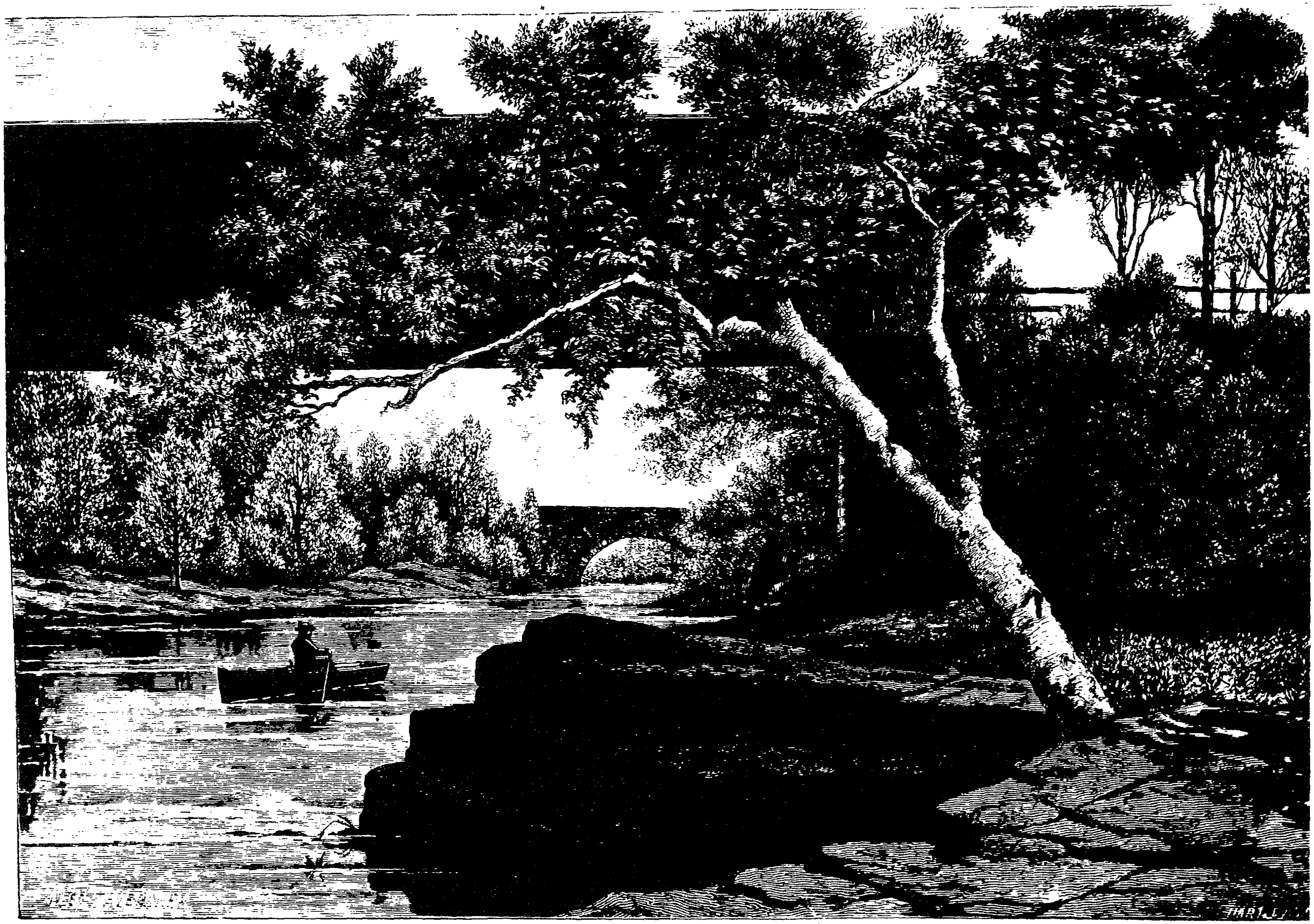

THE PASSAIC, BELOW LITTLE FALLS
by Jules Tavernier
from *Picturesque America,* Vol II, 1874

THE PASSAIC RIVER FLOOD PLAIN AND BASIN IN NEW JERSEY —

PROBLEMS OF ENCROACHMENT

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The field experience follows parts of the Passaic River and its tributaries beginning at the Newark Campus of Rutgers University. The trip parallels the course of the River. It then continues along U.S. Route 46 West to Wayne, Oakland, Lincoln Park and Fairfield in Passaic and Essex Counties near the confluence of the major tributaries; the Pequannock, Ramapo and Pompton Rivers and returns to Newark.

The Passaic River Basin

Created during the Wisconsin age, the present drainage basin of the Passaic River trends in a generally east-to-southeast direction in the Passaic-Essex County Region. The River, rising in Mendham Township, N.J. in Morris County, receives major tributaries as the Saddle River, Mahwah River, Third River, Rockaway River, Whippany River, Pequannock River, Pompton River, Ramapo River, and Wanaque River. All these tributaries drain a natural retention basin formed in the swamp made up of the Black Brook, Troy, Little Piece and Great Piece Meadows. These are part of the remnants of ancient Lake Passaic formed as an empoundment when the Wisconsin glacial advance closed a water gap at Short Hills and subsequently opened another in the Little Falls-Great Notch area.

Description of the Basin

The Passaic River Basin is a 56 mile long by 26 mile wide watershed with an area of 935 square miles; 84% (787 square miles) is located in Northeast New Jersey, the remaining 16% (148 square miles) is in southern New York State. The basin occupies three regions—the Highlands, the Central Basins, and the lower Valley. See figure 1.

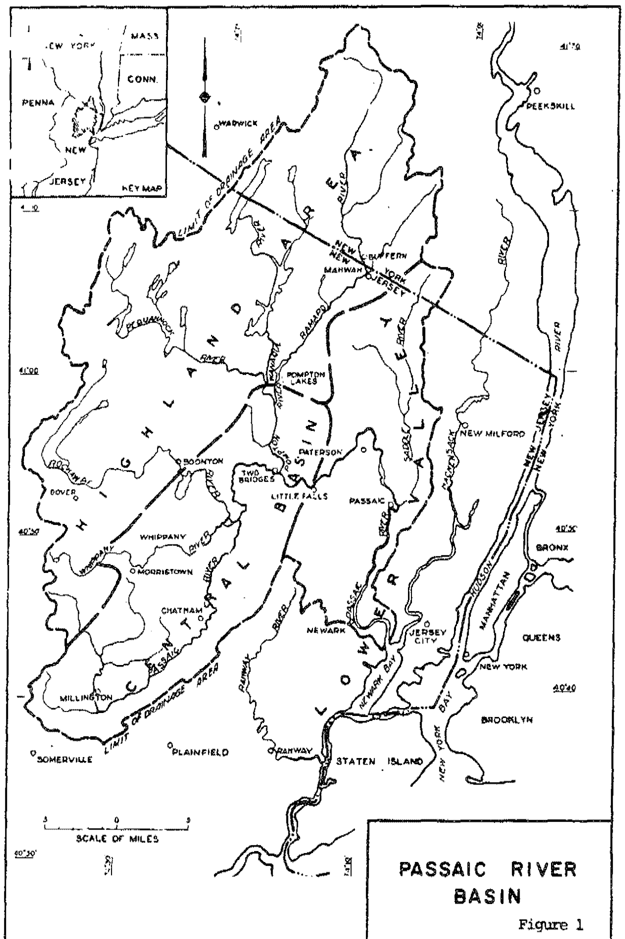
Two major physiographic provinces are part of the Passaic River Basin. The New Englands Uplands Province forms the Western Highlands. The Central Basins and Lower Valley are Triassic Lowlands in the Piedmont Province. See figure 2.

The "Jersey" Highlands extends from Pennsylvania's Reading Hills through New Jersey and beyond New York State. The Reading Prong, composed partially of the Highlands, is a series of crystalline gneiss ridges trending in a Northeast to Southwest direction. These crystalline ridges are nearly parallel throughout most of their length. In the upper western portion, sandstones and conglomerates are common with a veneer of glacial till dominant in the region. See figure 3 and table 1.

Predominantly, shales and sandstones underlie the Triassic lowlands. These units trend Northeast-Southwest along extrusions and exposed intrusives of basaltic origin. Both the sedimentary and igneous units of the Triassic Lowlands dip toward the Northwest at angles generally between 3-18 degrees. The Ramapo Fault designates the boundary between the Jersey Highlands and the Triassic Lowlands. The principal soil types of the central basin are glacially deposited silty clays and sands.

These combinations, along with rocky outcrops and thin soils results in poor drainage and impervious local regions. Steep terrain in most of the basin adds to the drainage problem leading to many large lakes and impoundments in the area. Man-made impervious surface and changes in topography and the retention basins formed naturally are compounding the problem in recent decades.

The Highlands. 489 square miles, the Highlands are in the northwest half of the watershed that is known as the Passaic River Basin.The major tributaries, the Mahwah, Wanaque, Ramapo, Pequannock, Pompton, Whippany, and Rockaway Rivers, originate in this region. In the Highlands, gradients are extremely high, 1:3 to 1:100 with stream flow reflecting bedrock trends. These are primarily characterized by ridges and narrow, steep valleys between the ridges. The stream flow is generally southwest in the north and northeast in the southern regions. The Highlands contain many lakes



PASSAIC RIVER BASIN

Figure 1

Source: U.S. Army Corps of Engineers

Generalized sketch map of Northern New Jersey showing the four physiographic provinces of the state.

and reservoirs in an area that ranges in elevation from 1200 to 1400 feet mean sea level in the west to 300 mean sea level in the east.

The Central Basin. Drainage in the 252 square mile central basin is controlled by the remains of the ancient glacial Lake Passaic bed. In this region, 43 square miles form swamp. The swamp is known as the Great Meadows and the Great Swamp. The Great Meadows is comprised of lowlands known locally by various names such as Troy Meadows, Black Brook Meadow, Great Piece Meadow and others. This oval shaped depression forming the central basin is elevated at 500 feet mean sea level in its southwestern borders to 160 feet mean sea level in the northwest.

Stream flow is controlled largely by the Watchung Mountains with gradients ranging from 1:10 to 1:2000.

The Lower Valley. The Lower Valley is a flattened region of about 190 square miles. The drainage pattern extends from the central valley to the lower valley through the water gap at Little Falls. It then continues to Newark Bay which receives the Passaic River flow. Elevation ranges from 500 feet mean sea level to sea level at the mouth in the bay.

The History of the Basin.

The Passaic River Basin is almost entirely the result of glacial erosion and depositon. Glacial Lake Passaic formed when the original water gap in the Second Watchungs was dammed by glacial debris. The original stream flow was diverted from this point of departure into the present system when a second outlet at Little Falls opened. This gap is at a higher elevation than the former gap and flow. Stream flow formerly South and East shifted in a Northern direction toward this second gap and then East to Newark Bay. The clay and silt deposited in the Central Basin are glacial in origin. Together with the thin soil and rocky surface, these soils are a major hindrance to drainage and modern sewerage disposal. Many swamps and meadows formed as the water reached the natural retention basin formed on the lake bed. The lakes and swamps today form a vast natural retention basin system comprising about 20.0 square miles in the region of the glacial lake bed. This occured as the original gap closed approximately 20,000 years B.P. and prior to the opening of the second gap.

Glacial Lake Passaic

New Jersey possesses a number of glacial lakes formed when streams were dammed by glacial ice. Glacial Lake Passaic occupied the region between the Highlands and the Second Watchung Mountains.

TABLE 1

SOIL ASSOCIATIONS IN THE PASSAIC RIVER BASIN

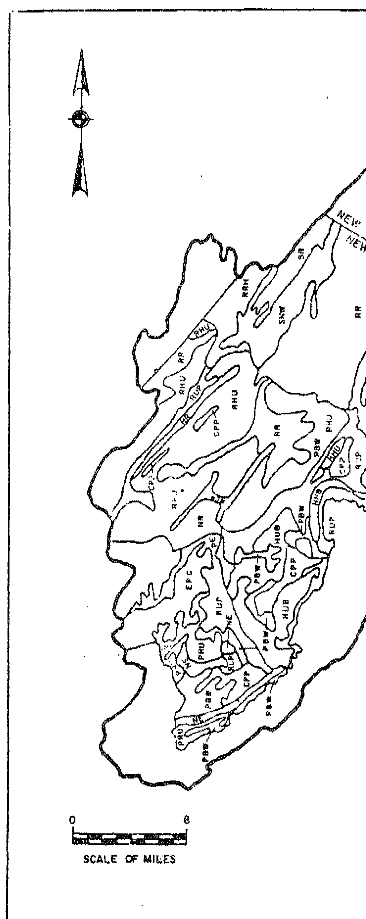
Map Symbol	Association Name	Drainage Description	Depth to Bedrock	Limitation for Development
RHU	Rockaway-Hibernia-Urban Land	Well to somewhat poorly	4-10	Steep slopes where present
RR	Rockaway-Rock Outcrop	Well to moderately well	0-10	Poorly suited due to rock outcrops
NR	Netcong-Rockaway	Well to moderately well	10+	Erosion control on steeper slopes
HHB	Holyoke-Haledon-Boonton	Well to somewhat poorly	0-10+	Rock outcrops and poor drainage-low density only
HUB	Haledon-Urban Land	Well to somewhat poorly	10+	Poor drainage-unsuited for on-site sewage disposal
CPP	Carlisle-Parsippany-Preakness	Poorly to very poorly	10+	Poor drainage-unsuited for development
PBW	Parsippany-Biddeford-Whippany	Somewhat poorly to very poorly	10+	Unsuited due to poor drainage & frequent flooding
NE	Neshaminy-Ellington	Well to somewhat poorly	0-10+	Poorly suited due to shallow bedrock & poor drainage
PRU	Penn-Peaville-Urban Land	Well to somewhat poorly	1-4	Steep slopes & depth to bedrock where present
EPC	Edneyville-Parker-Califon	Excessive to somewhat poorly	10	Suitable on gentle slopes
PE	Parker-Edneyville	Excessive to well	4-10	Steep slopes - unsuitable
RUP	Riverhead-Urban Land-Pompton	well to somewhat poorly	10+	Steep slopes & poor drainage where present.

Glacial Lake Passaic at its greatest extent, was 30 miles long by 10 miles wide and averaged about 200 feet deep. It has left a series of deltas in Morris County as well as outwash and ridges throughout the entire lower part of the county.

The water level in glacial Lake Passaic oscillated as the ice alternated in thickness. The final drainage however, was through the Little Falls gap replacing the gaps in the First and Second Watchungs at Short Hills. These were blocked by a moraine with the addition of ice damming. Some of the oscillation in water level may have been the result of other outlets which opened and closed throughout the glacial period.

The Passaic River

The Passaic River is 87 miles long. It rises in Mendham Township in Morris County. The stream flows South-to-East to the Great Swamp near Millington—a distance of about 11 miles. The stream then flows through trap rock ridges and is confined to intermontane valleys Northeast as a result of the Second Watchung Mountain. Below this region the stream flows for 40 miles northerly to Great Meadows in the Fairfield area (Essex County bordering Passaic and Morris Counties). After flowing through the ridges of the Second Watchung, stream flow is east-northeast through Little Falls and then to Newark Bay 25 miles to the Southeast.



PASSAIC RIVER BASIN N.J. & N.Y.

SOIL ASSOCIATIONS

Figure 3

Source: U.S. Army Corps of Engineers

The Passaic River varies from 165 feet to 800 feet in width and 8-45 feet in depth. Tributaries range from 80-510 feet in width to 7-24 feet in depth. The Passaic streambed ranges from 37.3 feet wide at the source to 7.9 miles wide at its mouth. Other tributaries range from 33.0-34.8 feet wide for the Ramapo River to 21-24.5 feet wide for the Pompton, through 33.0-34.6 feet wide for the Wanaque River, and 25.1-34.8 feet wide for the Ramapo River.

Located in a wet area for the United States, average precipitation is 47.3 inches per year. The rainfall throughout the Passaic River Basin is rather uniformly distributed. The Passaic River has a discharge capacity of 2900 cubic feet per second, the Pompton is 4,400 cubic feet per second, the Pequannock, Ramapo and Whippany Rivers are 600, 500 and 400 cubic feet per second, respectively.

The Problems of Flooding

The action that opened the second gap draining the Lake Passaic bed at Little Falls increased the drainage area for the Passaic River from 413 square miles to 762 square miles. This water, entering a constricted channel consisting largely of trap rock, leads to recurrent flooding with major and serious consequences. Among the sites of critical flood problems are the Lower Valley regions below Little Falls. The flood plain extends as much as 1000 feet beyond the river banks and the channel has insufficient capacity to retain large amounts of runoff, especially below the Great Falls in Paterson. In the Central Basin, over 5000 acres of flood prone land are present with about 1600 acres being swampland. The primary areas of drainage are along the Pompton River including much of the bottom land within the flood plain. The flood plain in the south central basin extends from one to four miles in width along the Rockaway River and the Whippany River. The flood plain narrows above the region of Two Bridges which is the confluence of the Passaic, Pompton and Pequannock Rivers. In the Highlands, the Ramapo River, Rockaway River, Mahwah River, and Whippany River are major flood producers with narrow flood plains of less than one mile. These upstream floods cause frequent flash flooding with serious erosional damage. Debris jams at a number of river crossings adding to the problem.

Major Floods

The record flood for most communities in the area is the flood of 1903. More recent floods serve as the flood of record for certain tributaries in the Passaic River Basin. Floods of major proportions have been experienced in 1917, 1936, 1938, 1945, 1951, 1955, 1960, 1968, 1971, 1972, 1973, 1975, 1977 and 1979. While precipitation rates vary, it appears that flood frequency increases as development continues to encroach the region.

In October of 1903, headwater runoff from the Ramapo River, Wanaque River and Pequannock River entered the confluence at Pompton. Regions of Wayne Township were flooded with 8-10 feet of water. In Paterson, 10 feet of water entered the lower city streets. In the meadows, all swamps and farms comprising 31,000 acres of land were inundated. Crops were destroyed along with the natural grasses and other flora in the region. The Ramapo River contributed the greatest amount of water. Along its length, nearly all dams, bridges, and many villages and industrial facilities were destroyed. In Paterson, the Passaic River discharged 33,700 cubic feet of water per second, in Clifton, the measured discharge was 35,800 feet of water per second while the Ramapo River discharged 15,800 cubic feet per second at Pompton Lakes. In Paterson the flood stage was 124.6 feet mean sea level and in Clifton it was 334 feet mean sea level.

In each successive flood, major damage was incurred by industrial plants facilities. Evacuations of hundreds of people were necessitated. Major disruptions to transportations were the result of flooding as numerous county, state and federal highways bisect the region. These are important truck routes for goods moving along the Eastern seabord. See figure 4.

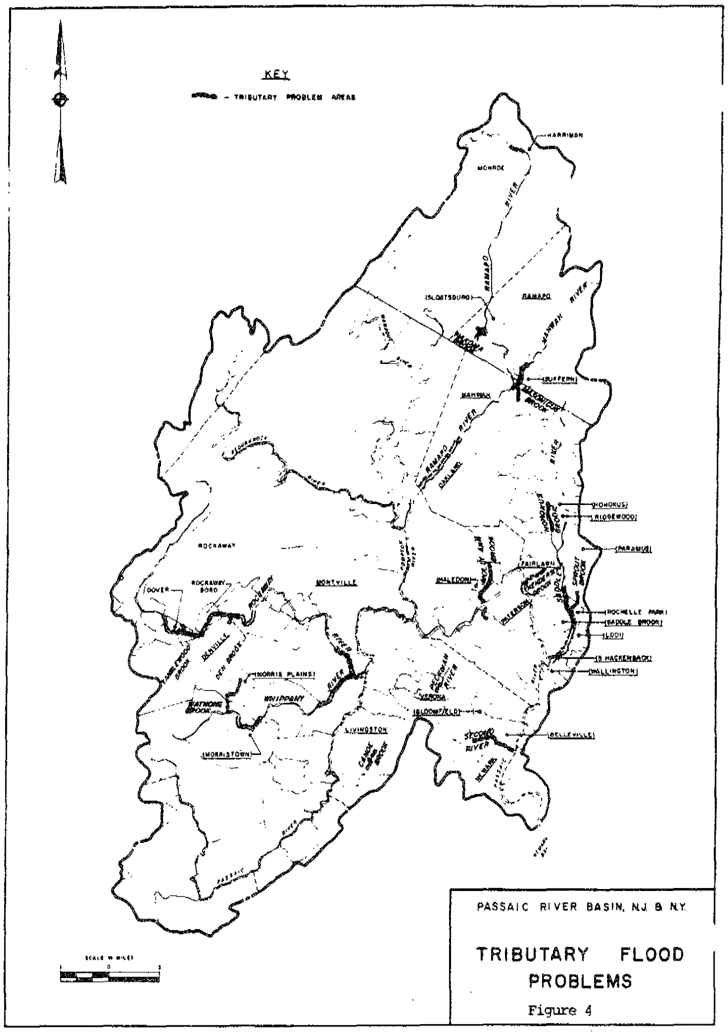
The Nature of the Basin

The population of the basin has shown a dramatic increase in the last few decades. Population has shifted from the urban centers of New York City and the surrounding industrial sites of the central and lower parts of the basin into residential areas in the upper portion of the Lower Valley and Central Basin. Almost all are zoned single family housing with supplemental industrial and commercial development.

The Lower Valley is the area with most urban centers and higher densities of dwelling units and population. Dwelling units per acre are 5 to 10 times denser than in the upper regions. Heavy industry dominates this part of the basin.

The Central Basin is the region in which most potentially developable land is located. The increasing development is placing pressure on the wetlands and meadows of the basin. In the Highlands, extremely low population densities are likely to remain as the topography does not readily lend itself to urbanization.

This part of the United States has been, for the most part, a high-income, relatively active economic region. Manufacturing and commercial enterprises are a major



TRIBUTARY FLOOD PROBLEMS
Figure 4

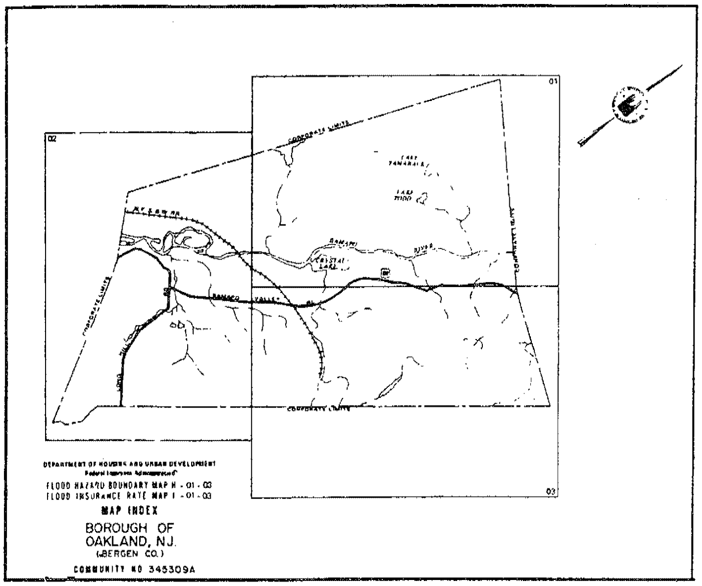
part of the region and population density remains high. While much land is being acquired for the preservation of habitations, unique geologic contribution (Dinosaur fossil sites are now parkland in Roseland), and recreational sites; it also represents a region that experiences severe droughts periodically; this is now viewed paradoxically, perhaps as an area important for water conservation and supply.

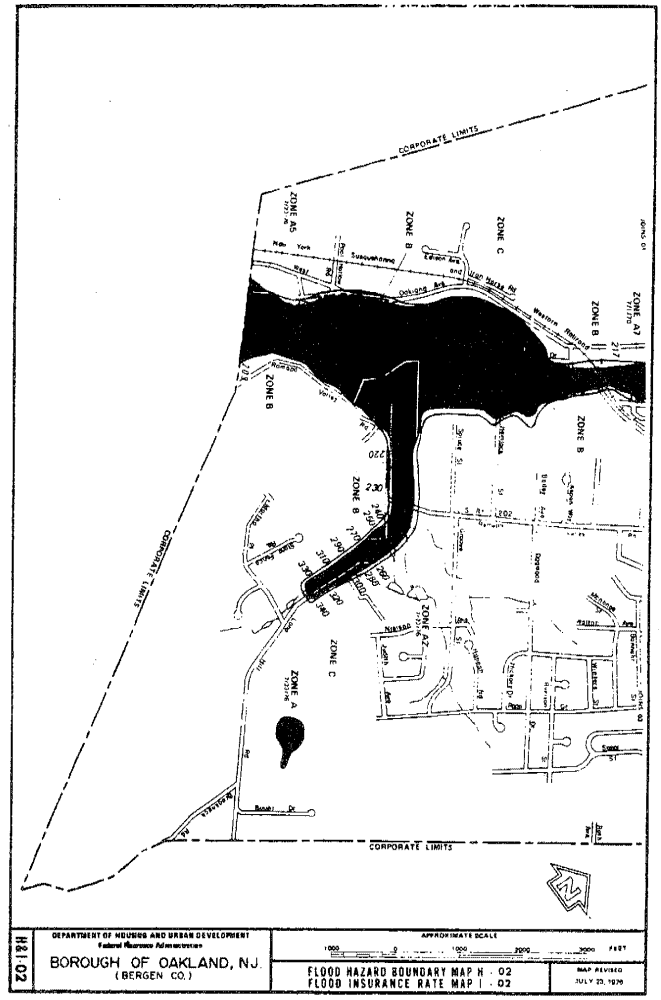
About 50 % of the precipitation runs off into streams or enters the ground water system. Much of the discharge is used for water supply and the flow rate is sensitive to this need and withdrawal of water. Water is also needed for the preservation of natural habitates to the south. A state Water Supply Master Plan is presently being developed for future water supplies in the region.

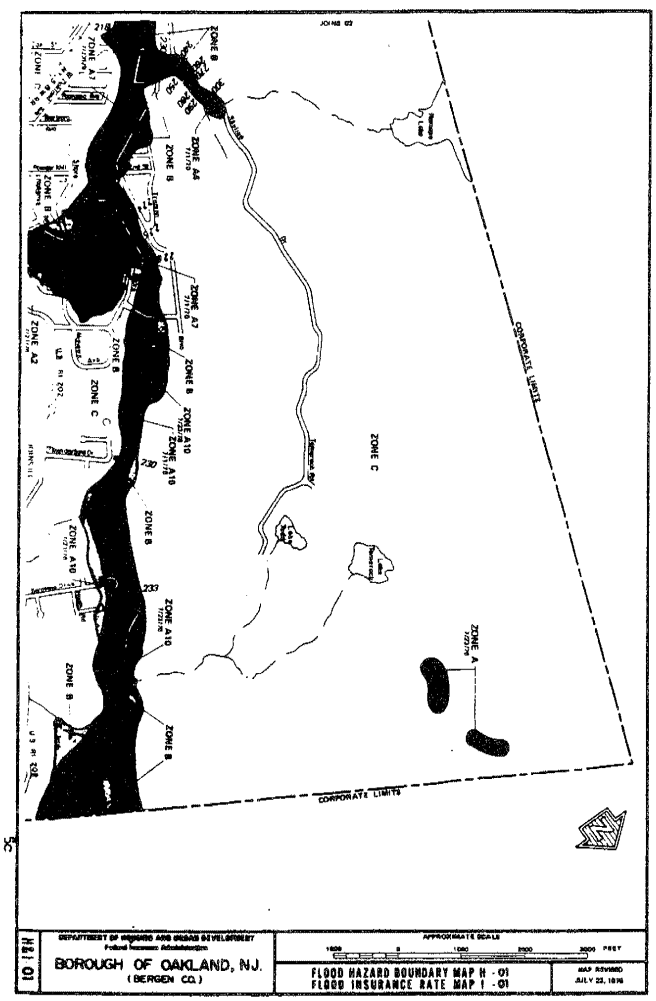
In the Central Basin and Highlands area, surface water and groundwater are used for public water supply. The Lower Valley has the greatest utilization of water and the water of poorest quality.

At present, the Army Corps of Engineers is working with the New Jersey Department of Environmental Protection on a Congressionally mandated Plan of Study for flood management and control. Both structural and nonstructural solution and interim measures are being developed for the basin. Floodway maps are being developed for all communities in the region. See figures 5, a, b, c, and d as samples.

In the Passaic River Basin, population now ranges from 147 people per square mile to 12,933 people per square mile. The population has been shifting to the flood prone Central Basin. As man-made structures intrude into this region, discharge peaks show a concurrent increase. Peak flood discharges would show a 56 % increase for the 100 year flood and a 44 % increase for a 25 year flood. The Corps of Engineers is charged with developing plans for retention of water and control of flow throughout the basin.







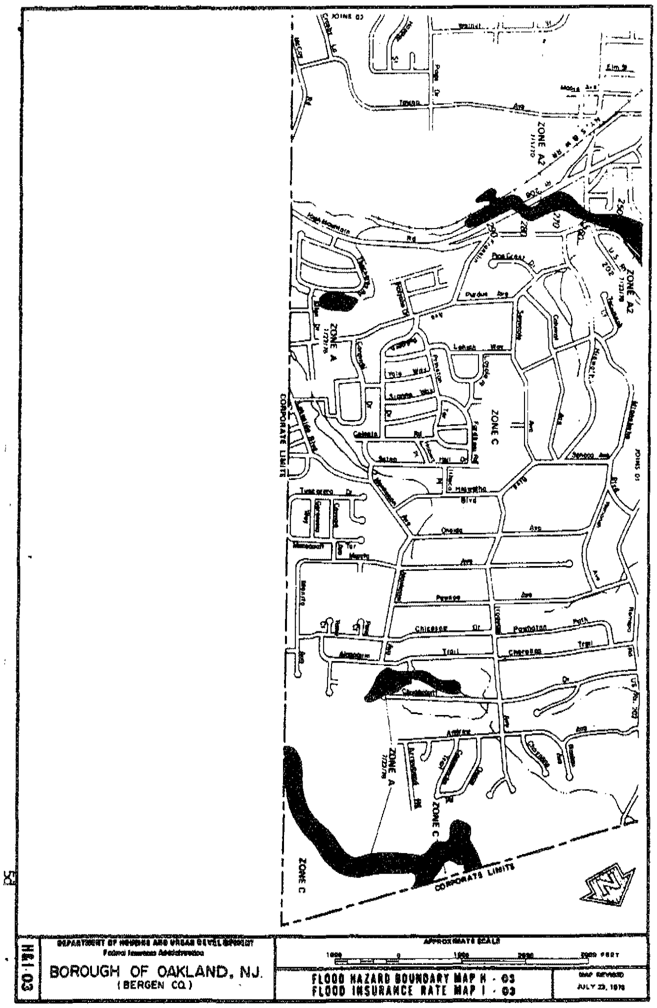
KEY TO SYMBOLS

Base Flood Elevation Line with elevation in feet	513
Base Flood Elevation where uniform within zone	
Elevation Reference Mark	RM7 x
River Mile	.M1.5

*Explanation of Zone Designations

A flood insurance map displays the zone designations for a community according to areas of designated flood hazards. The zone designations used by FIA are:

Zone	Explanation
A	Areas of 100-year flood; base flood elevations and flood hazard factors not determined.
AO	Areas of 100-year shallow flooding; flood depth 1 to 3 feet; product of flood depth (feet) and velocity (feet per second) less than 15.
A1 - A30	Areas of 100-year flood; base flood elevations and flood hazard factors determined.
A99	Areas of 100-year flood to be protected by flood protection system under construction; base flood elevations and flood hazard factors not determined.
B	Area between limits of 100-year flood and 500-year flood; areas of 100-year shallow flooding where depths less than 1 foot.
C	Areas outside 500-year flood.
D	Areas of undetermined, but possible, flood hazards.
V	Areas of 100-year coastal flood with velocity (wave action); base flood elevations and flood hazard factors not determined.
VO	Areas of 100-year shallow flooding with velocity; flood depth 1 to 3 feet; product of depth (feet) and velocity (feet per second) more than 15.
V1 - V30	Areas of 100-year coastal flood with velocity (wave action); base flood elevations and flood hazard factors determined.



ROAD LOG

Cumulative Mileage

0.0 Leave Rutgers Campus. Follow Rt. 21N to George St., Passaic. Trip parallels the Passaic River near the mouth in Newark Bay. Extending Northward to Dundee Dam in the Clifton-Garfield region the river is a salt-water estuary with about a four-foot tidal range. It is a navigable river with a 20 foot deep channel maintained in the lower estuary. Note the heavy industrialization and rotted piers and barges on either side.

10.0 Left onto George St.

10.1 Right onto Monroe St.

10.5 Over railroad trestle left onto River Rd. in Garfield. Note problem of debris build-up and desnagging needed.

13.9 Continue north on River Rd. to Rt. 46W. Dundee Dam is the area of demarcation between fresh water above and estuary below Garfield.

18.0 **STOP 1** Great Notch Rt. 46W Telephone Booth parking area. The roadway is located in an area that was formerly one of two spillways. The lithology is a basaltic flow of the First Watchung Mountain. This is the second water gap opened at the close of the Wisconsin glaciation.

20.9 Proceed West and turn right onto Rt. 23N. Continue North. Rt. 23N Rt. 46W and Rt. 80W mark the junction of Singac Brook and the Pompton River.

26.7 **STOP 2** Rear parking lot at Great Brake. Intersection of Rt. 23N and Pompton Plains Cross Road. Weir and flood marker are located at the junction of the Pequannock and Pompton Rivers. Note the bar deposits due to the curtailment of the stream energy by the bridge and pipeline. In this area the watershed traverses a setting of homes and ball fields. Return to bridge, proceed right on Pompton Plains Cross Road.

27.1 **STOP 3** Intersection of Pompton Plains Cross Road and Framingdale Ave. at John J. Baum Co. Old Feeder Dam above junction of the Pequannock and Pompton Rivers. Note changeable sign that keeps drowning record. This is a region of severe flooding after heavy rainfall despite the canal that can be followed from this region to Stop Two.

27.4 Follow Pompton Plains Crossroad and turn left onto Black Oak Ridge Rd. The ridge on the right is part of the First Watchung flow. Drainage on this side runs toward Pompton Lake, opposite is Wayne Township.

28.3 Continue to left turn onto Hamburg Turnpike.

29.1 Turn right onto Rt. 202N (Ramapo Valley Rd.) in Pompton Lakes and pumping station. Long term siltation and eutrophification has affected the retention ability of the lake. Dredging is to begin in mid-1980. Evidence of an abortive landfill can be seen in part of the lake shore along Rt. 202N.

31.3 **STOP 4** Turn left to Pleasureland Park at Doty Rd. and Rt. 202N, Oakland. This location is at the upper end of Terhune Park on Pompton Lake which receives the Ramapo River. It is named for Albert Payson Terhune, a dog breeder and author. It is also the site of boxer Joe Louis's training camp during the 1940's. Residential development lies on both sides of the river; note the undercutting of the retention wall. The area is connected by a small bridge to elevated Rt. 202N where residents park cars prior to flood events. Similiar bridges can be found east of this location. A major problem is that the flood plain is swamp woodland resulting in debris jams at many sites.

31.7 **STOP 5** Return to Rt. 202. Retrace route to Grand Union parking lot at left. Newark's Wanaque Reservoir pumping station has a persistant desnagging problem. The Ramapo Fault lies under the talus sloop (north) seen across the lake dam at the pumping station site.

Return to 202 and turn left onto Hamburg Turnpike.

32.1 Turn right over the Bridge at Dawes Highway. The Pompton River forms a meander near its junction with the Pequannock River. Two to four feet of water inundate four blocks of homes during severe flooding.

32.3 Follow Riveredge Drive to the left.

33.5 **STOP 6** Return to Dawes Highway and turn left at the stop sign; turning right at Riverdale Blvd.

33.7 Turn left onto Riverdale Rd. at intersection of Riverdale Blvd.

34.3 Follow Riverdale Rd. over the bridge crossing the Pequannock River to Rt. 23S and bear left. Note the sand and gravel pits associated with the Wisconsin glacial moraine. Rt. 23 dips in several locations leading to major flooding following heavy rain, especially near the sites of the Racquetball Spa and MacDonald's Beach and Lake adjacent to the road.

37.3 Turn right onto Pequannock Ave. at the Hofbrau Restaurant bear left to Pequannock Ave.

37.4 Note the drainage ditch that now enhances flooding near the elevated cottages.

37.9 Turn left at Newark-Pompton Turnpike (old Rt. 23S).

38.1 **STOP 7** Bridge at Riverside Drive. The bridge and pipeline are part of the water supply for the city of Newark. The siltation and build up of debris occur in several locations in a limited area.

38.7 Proceed on the turnpike and turn right at Haul Avenue.

39.2 **STOP 8** Dorsa Ave. is the designated flood parking area for area residents. Pia Costa Co. property is a natural retention basin extending into Fairfield, now being developed near Rt. 46E at opposite side of the basin. The railroad trestle shows much evidence of heavy siltation.

40.2 Continue to Ryerson Ave. at stop sign. Turn right onto Ryerson Ave.

40.7 **STOP 9** Park at Soccer Field. Note Pompton River undercutting banks and homes with retaining walls opposite the fields. This is Lincoln Park, the site of repeated flood problems during heavy rainfall. The soccer fields have been flooded to a depth of 3-4 feet during flood stage of the river. Make a U-turn in parking lot and return to the Newark-Pompton Turnpike. This road follows part of the flood evacuation route to emergency parking.

41.4 Turn right onto the turnpike and follow it into Rt. 23S.

42.7 Turn right onto Fairfield Rd. at Jim's Gems. Fairfield Rd. follows the course of the Pompton River. Elevated homes are built on the island and opposite bank. Raised bridges create access to the sites of housing.

43.8 **STOP 10** Two Bridges - Cross the bridge and park in the lot on the right. This is the junction of the Passaic and Pompton Rivers, a site of frequent flooding after heavy rain. Color differences noting the river junction is often obvious at the bridge junction.

44.5 Proceed over Two Bridges to the left and cross onto Rt. 46E at sign.

45.2 Proceed to Riverside Drive. Homes built on the flood way of the Passaic River between it and a former retention site. Minor flooding occurred with frequency prior to the development of the retention site.

45.4 **STOP 11** Willowbrook Mall. A mall developed on the former retention area elevated the region. The homes near Riverside Drive now receive drainage from this parking lot and flood water from the river. Flooding is more frequent and severe. The roadway is township property and not mall property and is designated a flood parking area.

60.9 Return to Rt. 46E for one brief "mystery" stop. Proceeding to Rt. 3E and Rt. 21S to the Newark Rutgers University Campus.

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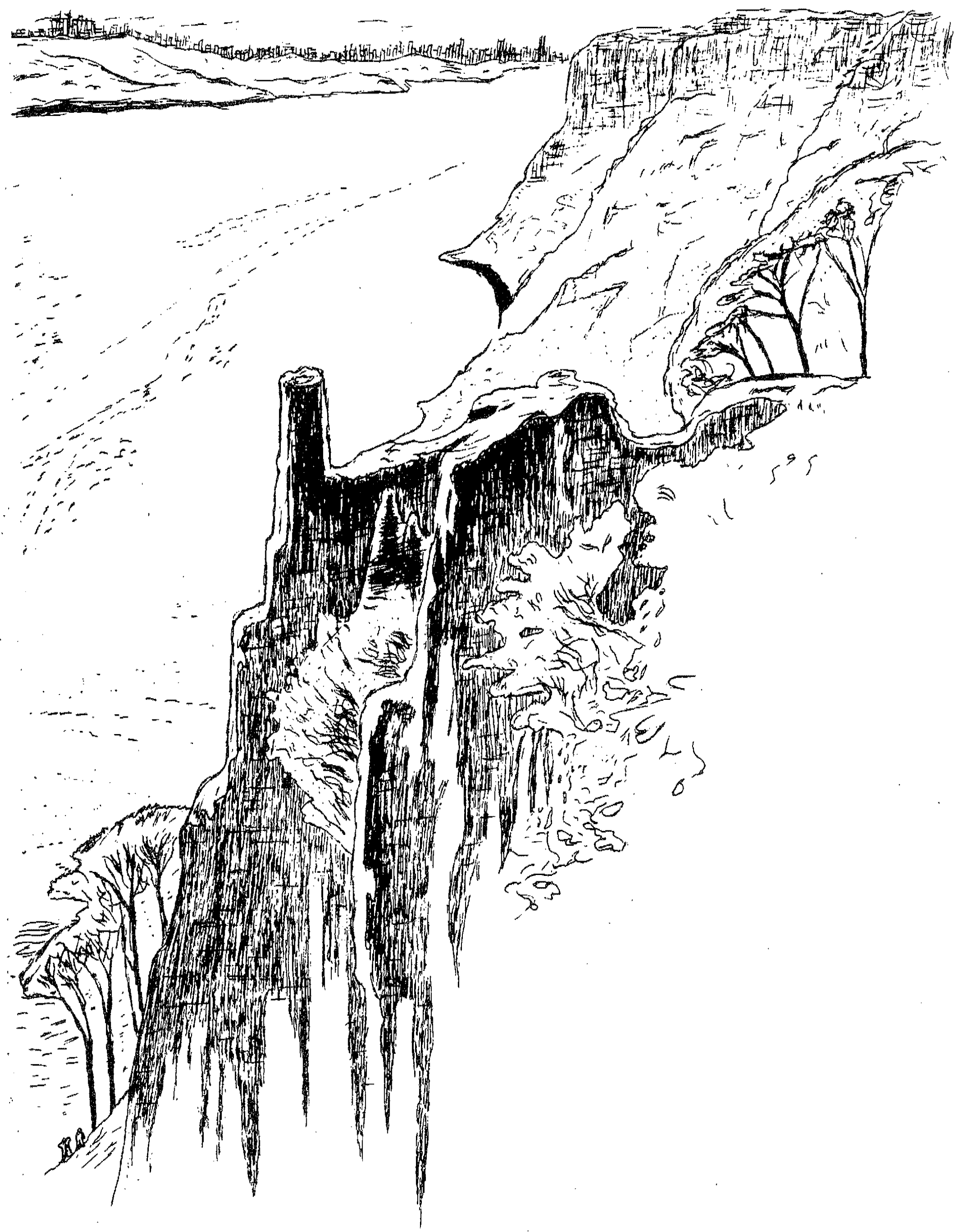

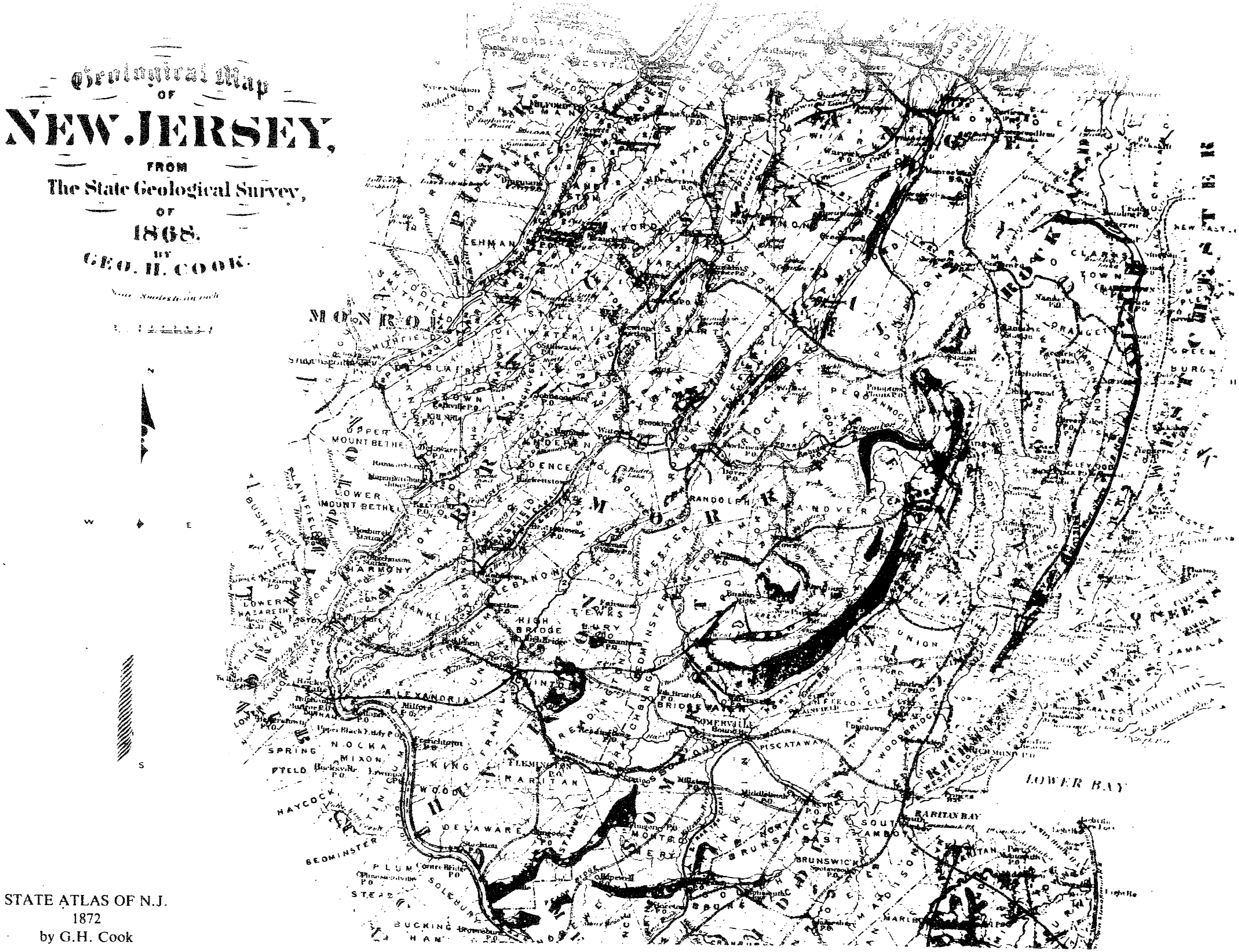

STATE ATLAS OF N.J.
1872
by G.H. Cook

LATE TRIASSIC PART OF NEWARK SUPERGROUP, DELAWARE RIVER SECTION, WEST-CENTRAL NEW JERSEY

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Introduction

The Late Triassic part of the Newark Supergroup exposed along the Delaware Valley (Van Houten, 1969) consists of as much as 6 km of nonmarine sedimentary rocks and an associated sill. Its strike generally parallels the northeasterly trend of the basin with a dip of 10-20°NW. Along the northwestern margin the sequence is bounded by Precambrian and Paleozoic rocks of the Reading Prong of the New England Upland. Most of this boundary is a system of high-angle faults (see Ratcliffe, this guidebook), but intermittently Newark border conglomerate overlaps on rocks of the upland terrane. Within the basin and along its southeastern margin Newark strata lie on Paleozoic and Precambrian rocks of the Blue Ridge and Piedmont provinces.

In the northeast (Fig. 3) the Newark Supergroup consists of a lower, locally conglomeratic Stockton Arkose (1840 m, 6000 ft), grading upward into reddish-brown Brunswick Mudstone (more than 1900 m and perhaps as much as 4000 m thick). Along the northwestern faulted border these deposits interfinger with the Hammer Creek Conglomerate. In the central part of the basin the widely-occurring Stockton and Brunswick formations are separated by and interfinger with the dark gray to reddish-brown Lockatong Formation (as much as 1145 m, 3750 ft thick). These major sedimentary rock types comprise rather uniform, widespread units. In the Delaware Valley area a diabase (dolerite) sill is intruded into Lockatong and lower Brunswick strata.

Across the central part of the basin, as seen along the Delaware River, the Newark formations are repeated in three large northwest-tilted blocks. The Flemington and Hopewell faults that bound them may be part of a transcurrent system involving those along the northwestern border as well. Geophysical and subsurface evidence of intrabasin faults near the present margin of the basin (Summer, 1977; Cloos and Pettijohn, 1973) indicates that it was not a simple half-graben.

The Newark Supergroup ranges in age from Karnian (Late Triassic, 215 my) to late Liassic (about 180 my), with Liassic sedimentation beginning about 100 m below the 1st Watchung basaltic lava flow in the middle of the Brunswick Formation (Cornet and Traverse, 1975; Olsen and others, 1980; Olsen, this guidebook). Along the terrane of extension in eastern North America basin development and igneous activity apparently peaked about 190 my ago. In the Delaware River section the Triassic-Liassic boundary presumably is above the preserved Brunswick strata.

Source Area

Soda-rich crystalline rocks in the faulted eastern and southeastern Piedmont upland were the source of most of the feldspathic Newark detritus. Its broad westerly paleoslope probably was broken by growth faults (Cloos and Pettijohn, 1973) covered by progressive outward spread of the proximal facies now stripped back from its original eastward extent. In contrast, northwestern highlands supplied mostly Paleozoic debris down a steep paleoslope to local fanglomerates and associated sandstones along the adjacent border of the basin.

Stockton Formation

Along the Delaware River the Stockton Formation is about 1525 m thick in the northern fault block. Here it consists principally of yellowish-gray to pale reddish-brown fairly well-sorted arkose and subordinary poorly-sorted conglomerate and reddish-brown mudstone distributed in rather distinct units (Fig. 1). Commonly these are as much as 15-20 m thick and can be traced for several kilometers. Persistent groups of beds as much as 100 m thick have been defined as members.

Yellowish-gray conglomeratic deposits in the lower part contain moderately rounded clasts averaging about

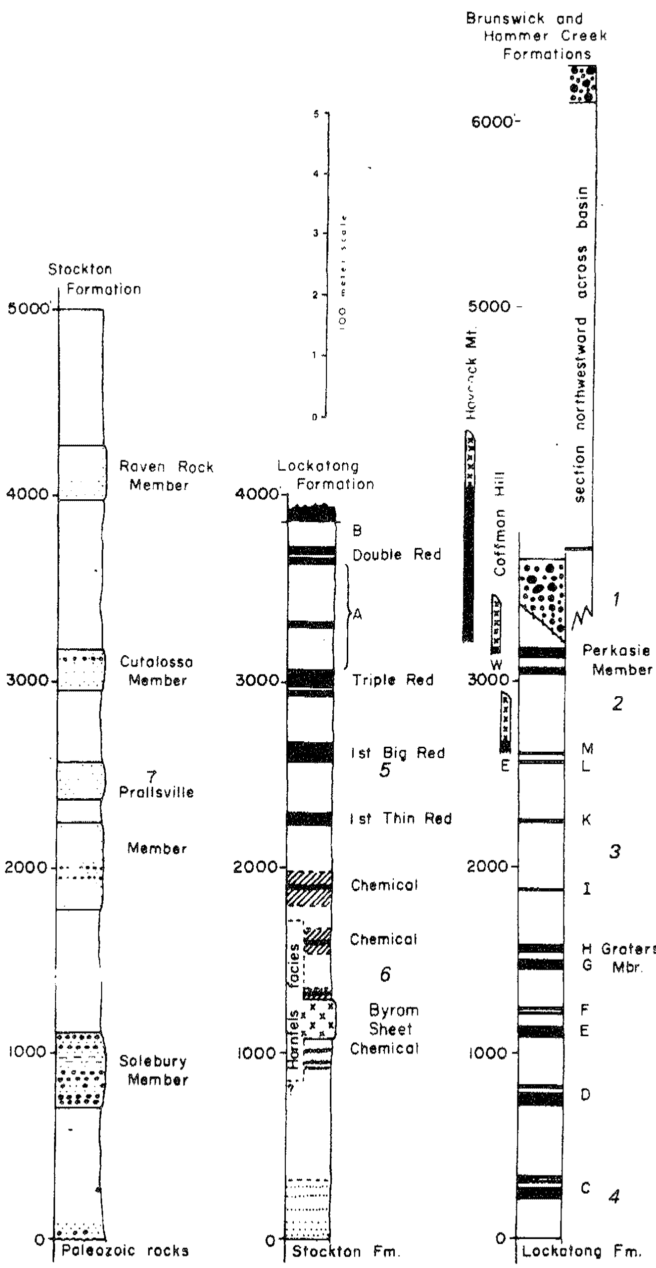


Figure 1. Stratigraphic section of Newark Supergroup along the Delaware River from Stockton northward to 3 miles of Milford, N.J. Subordinate units in gray Lockatong Formation are grayish-red to reddish-brown; those in reddish-brown Brunswick Formation are dark gray. Shows position of diabase sills, Lockatong gray chemical cycles and hornfels, and field trip stops.

2-3 cm in diameter and only locally more than 6-8 cm long, set in a poorly-sorted arkosic matrix. Most of the clasts are quartz, some are quartzite, and a few are feldspar, metamorphic rock, and shale fragments.

In the northwestern part of the basin well-sorted medium-to fine-grained arkose occurs in thick beds only locally with stringers of conglomerate and mudstone. Stratification commonly is outlined by films of reddish-brown clay, or locally by abundant grains of specular hematite (after magnetite). Planar bedding predominates. Cross-bedding and channeling are much more common in the eastern to southeastern proximal facies.

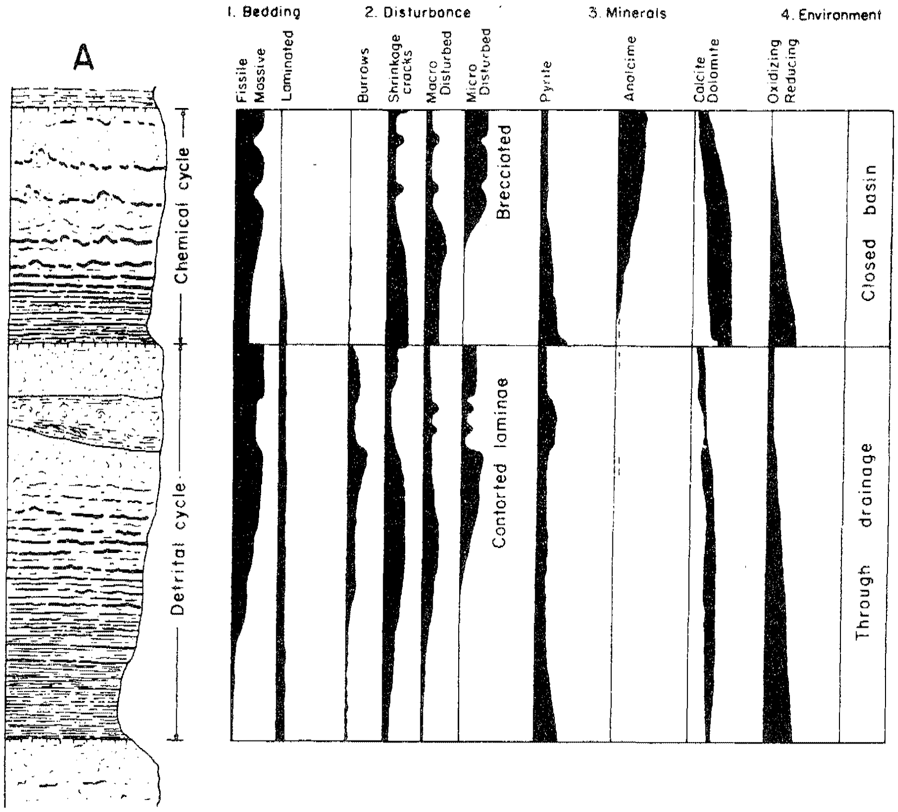
Most of the Stockton Arkose has a texture of interlocking grains produced by pressure solution presumably resulting from burial below an estimated 3000 m or more. Authigenic feldspar occurs locally as overgrowths and void fillings. In outcrop much of the well-sorted, fine-grained sandstone is speckled with yellowish-brown intergranular patches of limonite after iron-rich carbonate. Stockton Arkose contains 50-70 percent quartz, 15-40 percent feldspar which decreases in abundance stratigraphically upward and northward, and subordinate chert and metamorphic rock fragments, muscovite, biotite, and chlorite. Albite-oligoclase commonly is more abundant than K-feldspar.

Associated reddish-brown feldspathic mudstone is well-bedded, very micaceous, and burrowed. It contains abundant illite and muscovite, but very little kaolinite, and Na-feldspar predominates over K-feldspars.

Lockatong Formation

In the northwestern fault-block the Lockatong Formation is about 1145 m thick. It thins laterally to the northeast and southwest along the axis of the basin and toward the southeastern border. The lower 120-160 m consists of micaceous mudstone with subordinate ripple-bedded and mud-cracked fine-grained sandstone similar to that in the underlying Stockton Formation. Lockatong deposits grade upward into the Brunswick Formation through a succession of rather regularly alternating reddish-brown and dark gray units (Fig. 1) recurring at about 100 m intervals. Gray units above the main body of the formation are successively thinner upward whereas reddish-brown ones are progressively thicker.

Throughout much of its extent the Lockatong Formation is arranged in short " detrital" and "chemical" cycles averaging several metres thick (Fig. 2). Detrital cycles are most common in long gray intervals and at the northwestern and southwestern ends of the formation whereas chemical cycles are best-developed in the reddish-brown sequences recurring at about 100 m (300-325 ft) intervals. Short detrital cycles about 4-6 m thick comprise a lower black pyritic shale succeeded by platy dark gray carbonate-rich mudstone in the lower part, and tough, massive gray calcareous mudstone (argillite) in the upper. The argillite has a very small-scale contorted and disrupted fabric produced largely by crumpled shrinkage cracks and burrow casts. Some thicker detrital cycles contain a 0.5-1.5 m-thick lens of thin-bedded, ripple-bedded siltstone and fine-grained



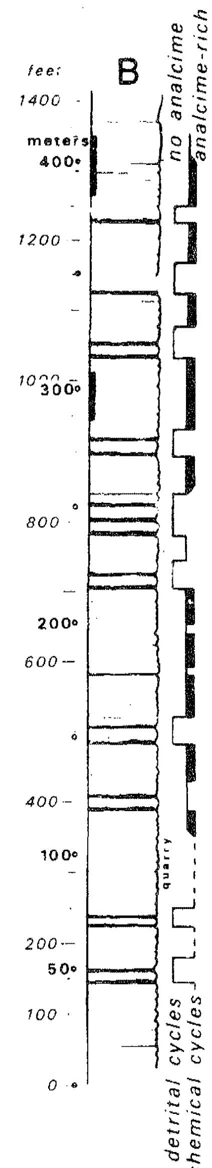


Figure 2. A. Model of detrital (average 17ft.) and chemical (average 10 ft.) short cycles in Lockatong Formation, showing estimated distribution of sedimentary features. **B.** Measured section of short cycles along NJ 29, 6 to 7 miles south of Frenchtown. Bundles of detrital and chemical cycles indicated at right of column. Thick lines along left margin mark 1st Thin Red and 1st Big Red units in pattern of long cycles shown in figure 1.

feldspathic sandstone with small-scale disturbed bedding. On average these deposits contain abundant Na-feldspar, illite and muscovite, some K-feldspar, chlorite and calcite, and a little quartz.

Short chemical cycles about 2-4 m thick are most common in the upper part of the formation and are limited to the central 100 km along the axis of the basin. Lower beds 1-8 cm thick are alternating dark gray to black platy dolomitic mudstone and marlstone disrupted by shrinkage cracks. Locally basal beds contain thin lenses of dolomite and pyrite. In the middle, more massive argillite encloses layers of the tan-weathering dolomitic marlstone extensively disrupted by shrinkage cracking. The middle part of many chemical cycles, as well as of reddish-brown ones in the lowest part of the Brunswick Formation, exhibit a pattern of upward-concave surfaces and thin zones of shearing in tent-like structures 15 to 30 cm high and recurring laterally in wave lengths of 0.5 to 1 m. The beds involved contain numerous small crumpled shrinkage cracks and have been fractured and brecciated (Van Houten, 1964, p. 518, Fig. 14). These structures resemble gilgai (Hallworth and Beckmann, 1969) produced by repeated wetting and drying of carbonate-rich clayey soils. The upper part of a chemical cycle is tough gray analcime- and dolomite-rich argillite brecciated on a microscopic scale. Tiny slender crumpled shrinkage cracks filled with dolomite and analcime produce a "birdseye" fabric. Some thinner chemical cycles are grayish red to reddish brown. In these cycles thinner dark red layers are disrupted by shrinkage cracks and broken into mosaic intraformational breccia with patches of analcime and dolomite in the cracks. Thicker massive beds are speckled with tiny lozenge-shaped pseudomorphs of dolomite and analcime after gypsum? or glauberite? (Van Houten, 1965), and locally marked by long intricately crumpled crack filling. Argillite in the upper part of chemical cycles contains as much as 7 percent of Na_2O and as little as 47 percent SiO_2. It is composed of a maximum of 35-40 percent analcime, together with albite, dolomite and calcite, and illite and minor chlorite.

Brunswick Formation

Throughout the central part of the basin the Brunswick Formation consists of a rather uniform succession of reddish-brown mudstone and siltstone with subordinate claystone and fine-grained feldspathic sandstone. Unlike normal nonmarine basin deposits, this central facies has no well-developed coarse-grained channel fill. Commonly two kinds of mudstone occur in alternating sequences (Fig. 6). One is crumbly, bright reddish-brown homogeneous claystone only locally well bedded, with thin persistent layers of siltstone. The other is tougher bioturbated silty mudstone locally scoured by broad channels filled with a succession of 2-5 cm-thick overlapping layers of fine-grained sandstone and mudstone, many of which have been burrowed and have a mudcracked upper surface. Brunswick strata also record large and small tracks and trails. Molds of glauberite filled with calcite or barite are abundant locally in 5-20 cm-thick lenses. Calcite casts of incomplete glauberite crystals also form rosettes 10 cm in diameter.

Widespread units of dark gray pyritic mudstone and marlstone recur in the formation at 120-135 m (400-450 ft) intervals, matching those in the upper part of the Lockatong Formation (Fig. 1, 7). Eight such gray units have been identified in the Brunswick Formation in the northwestern fault block.

The common feldspathic mudstone and micaceous siltstone in the Brunswick Formation contain abundant illite and subordinate chlorite, abundant quartz (50-75 percent in siltstone, 10-30 percent in mudstone), less than 15 percent feldspar (Na-feldspar normally predominates), and relatively rare lithic fragments except near the northwestern border. Hematite is the pigment mineral coating grains and staining the clay fraction. It is also the common opaque mineral grain.

Hammer Creek Conglomerate

Along the northwestern border of the basin very coarse fanglomerate projects southward several kilometers (Fig. 1, 4, 5). Most of it as now exposed interfingers with Brunswick mudstone; some interfingers with the Stockton and Lockatong formations as well. Throughout its lateral extent the Hammer Creek Formation varies from common poorly-sorted, rather well-rounded conglomerate to local angular breccia. In west-central New Jersey Hammer Creek deposits are arranged in lenticular, crudely fining-upward units (Fig. 5), with caliche-like carbonate concentrated in the sandy upper part. Clasts range in size from 10-20 cm cobbles to rare blocks 30 cm long. Most of them are Paleozoic quartzite, with fewer, smaller clasts of dolomite. The dark reddish-brown finer-grained fraction is very poorly -sorted lithic-rich sandstone containing abundant shreds of greenish-gray Paleozoic shale.

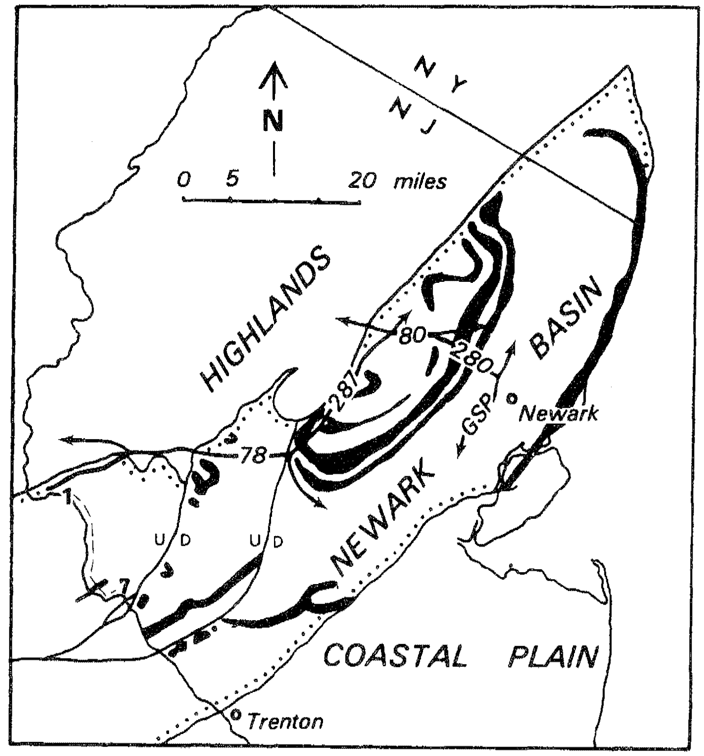


Figure 3. Route of one-day field trip from Newark, N.J. to Delaware River section of the Newark Supergroup. Sills and flows are black. Field trip stops are 1-7.

Newark Hornfels

Thermally metamorphosed rock produced by intrusion of diabase reflects both composition of the host deposit and distance from the contact (Van Houten, 1971). In west-central New Jersey hornfels developed in Brunswick hematitic mudstone and micaceous siltstone near the Lambertville Sill (Fig. 4). The least altered mudstone a few hundred metres from the contact contains nodules of epidote and chlorite. Nearer the sill the matrix is chlorite-sericite with patches of coarsely crystalline chlorite and sericite or epidote and magnetite pseudomorphic after cordierite. The characteristic pale lavender color is due largely to conversion of aphanitic hematite pigment to fine-grained specularite. Dark gray pelitic hornfels with magnetite developed no more than 15-20 m from the intrusion. This inner facies contains phaneritic patches and isolated crystals of tourmaline and cordierite. High-grade hornfels of calcareous and sandy deposits is a grossularite-diopside-prehnite-muscovite or chlorite-calcsilicate rock.

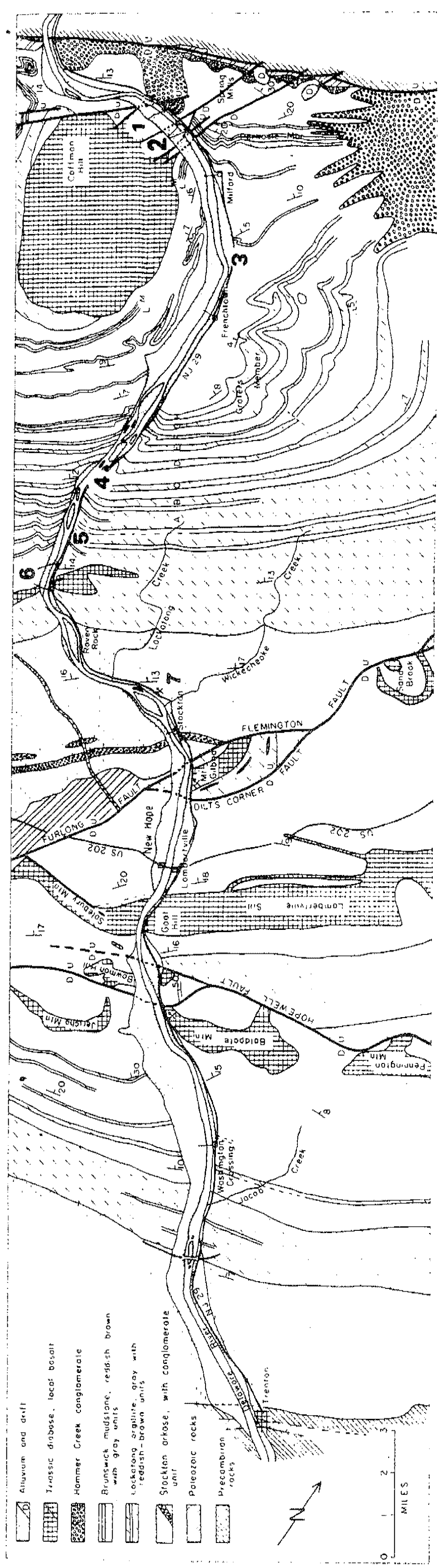


Figure 4. Geologic map of Newark Supergroup along Delaware River, west-central New Jersey and Pennsylvania. Shows field trip stops 1-7.

The Lockatong Formation was most susceptible to thermal metamorphism, and converted to varieties of very fine-grained calcitic biotite and Na-feldspar hornfels marked by an absence of quartz, a paucity of SiO_2, and an abundance of Na_2O. In spite of extensive mineralogical alteration these rocks still exhibit their characteristic sedimentary structures. The middle carbonate-rich mudstone of Lockatong short cycles within 100 m of the sill commonly contains analcime, grossularite, andradite, diopside, datolite, prehnite, sphene, calcite, biotite, and feldspar. The upper massive argillite of detrital cycles contains scapolite, aegirine, diopside, clinozoisite, K-feldspar, Na-feldspar, calcite, chlorite and biotite. The unique upper argillite of short chemical cycles (Fig. 8) contains nepheline, sodalite, cancrinite, thompsonite, calcite, biotite, and albite within 25 m of the sill; 25 m to 100 m from the sill cancrinite, thompsonite and increasing unaltered analcime predominate. In the uppermost part of the coarse-grained diabase at Mt. Gilboa (Brookville) a block of phaneritic nepheline and analcime syenites apparently was produced by reaction of a soda-rich Lockatong xenolith with the granophyre differentiate of the basic intrusion (Barker and Long, 1969).

Igneous Rocks

Intrusive and extrusive igneous rocks in the Newark Supergroup are olivine-poor quartz tholeiite characteristic of rift valley sequences on continental crust. In northeastern New Jersey a thick diabase (dolerite) sill intruded the lower part of the Newark Section. Along the Delaware River a sill in Lockatong and lower Brunswick beds locally transects the enclosing strata (Fig. 4). Only the thick (550 m) Lambertville Sill exposed in the middle fault block developed an early-formed olivine layer (Hess, 1956). Multiple basaltic lava flows such as those interbedded with upper Brunswick (Liassic) strata in the northeastern half of the basin are not present along the Delaware River.

Conditions of Deposition

Deep dissection of the Appalachian orogen and a late Permian and early Triassic hiatus reflect 20 to 30 my of broad uplift and erosion in eastern North America. Then a new framework of extension and rifting in late Triassic time produced a swath of faulted basins and uplands along the orogen. Newark deposits in New Jersey, like those in late Triassic-early Jurassic sequences throughout the belt, comprise the major facies of a piedmont-valley flat complex in rift basins (Van Houten, 1977, p. 89-93; 1978). During this episode of basin filling much of the sediment transported from flanking highlands was dispersed longitudinally by axial drainage. The path of exit of major through-flowing streams has not been determined, however.

In the principal eastern source area valleys incised in crystalline basement yielded a continuing supply of feldspar-rich detritus while deep weathering of the upland interfluves produced abundant clay. Streams flowing westward on a long, gentle foothill slope spread Stockton gravel, sand and minor mud across much of the basin, forming extensive sheets of feldspar-rich alluvium. Most of the muddy fraction was carried beyond the known sandy deposits and perhaps beyond the Newark basin. Well-bedded, well-sorted upper Stockton Arkose in the northwestern interior of the basin may be a deltaic facies deposited along the shore of a narrow lake (Turner-Peterson, 1980). This facies lacks abundant cross-bedding, repeated fining-upward sequences, and paleosol caliche characteristic of fluvial deposits like the New Haven Arkose in the Newark Supergroup in Connecticut (Hubert, 1978).

Active faulting along the northwestern flank of the Newark Basin and repeated flash floods generated short, vigorous torrents in the highlands. These eroded the Paleozoic bedrock and fed local debris flows, sheets floods, and steep-gradient streams that built Hammer Creek alluvial fans which projected several kilometers into the basin. Although the roundness of tough Paleozoic quartzite clasts suggests prolonged abrasion, the character and distribution of the deposit point to derivation of debris from source perhaps 15 to 30 km away. Construction of these northwestern fans presumably occurred throughout the basin filling, renewed by successive faulting and relative uplift along the border faults. During lulls in aggradation paleosol caliche developed in the fan deposits.

Widespread acculumation of Stockton sandy deposits ended with waning of detrital influx and widespread ponding along the axial drainageway. Eventually this produced a huge Lockatong lake with narrow marginal Brunswick mudflats and small deltas supplied largely from the distant southeastern upland. Along its northern margin the lake was fringed by alluvial fans. The cause of ponding is not known, but it may have been partly the especially active building of fans at both ends of the basin (Van Houten, 1969, Fig. 8; Turner-Peterson, 1980, Fig. 2), combined with continued slow subsidence. Once established, conditions in the long lake varied only within narrow limits for several million years. In this stabilized setting cyclic variation in climate exerted a major control on the lacustrine sedimentation. This was expressed in a succession of short detrital cycles during times of through-flowing drainage, and of chemical cycles when the lake was closed. Among the early Mesozoic basins flanking the Atlantic Basin, the Newark Basin was unique in producing a thick soda-rich silicate facies. In its late stage the Lockatong lake became a carbonate-clay playa with salts cystallizing in the mud and repeated wetting and drying producing extensive cracking, brecciation, and upward-concave patterns of shearing (gilgai). Based on the counts of assumed varves Lockatong short cycles may be the result of expansion and waning of the lake during 21,000 year precession cycles. Clusters of 20 to 25 cycles (Fig, 2b), either predominantly detrital or chemical, suggest another climatic control of 400-500,000 years duration.

The long-lived Lockatong lacustrine facies gradually gave way to broad oxygenated Brunswick mudflats and ponds with shallow water-courses and weak external drainage. In the eastern source most of the mud

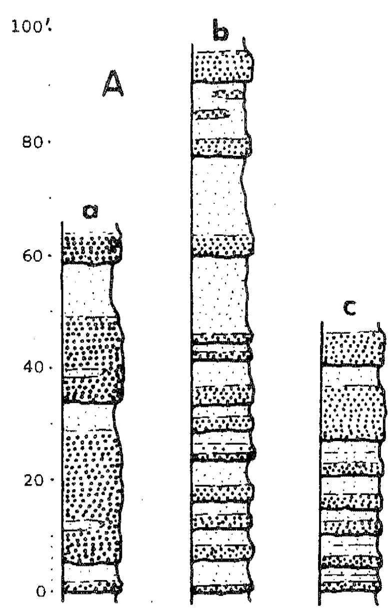
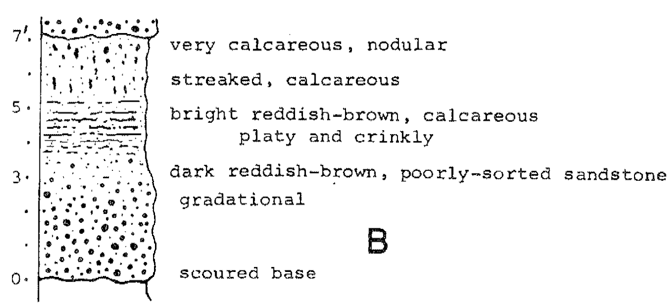


Figure 5. A. Sections of lenticular, fining-upward sequences in Hammer Creek Conglomerate; a. is about 0.5 miles northwest of c. Maximum clast size: **a** - about 30-35 cm long; **b** - about 20-25 cm long. STOP 1, Pebble Bluffs, Rt. 627, about 2 miles west of Milford, N.J. **B.** Model of fining-upward conglomerate-sandstone sequence with capping calcrete paleosol recording episode of non-deposition in warm, dry climate.



weathering was intense enough to convert crystalline basement in the upland into a continuing supply of ferric oxide-rich feldspathic mud. Along the northwestern border of the basin Brunswick mud interfingered directly with the fringing alluvial fans. Much of the basin regime may have been that of ephemeral clay-flat playas where sedimentation was largely from suspension (Friend and Moody-Stuart, 1972; Turner-Peterson, 1980). Here and there glauberite formed as scattered crystals in dried-out mud abundantly broken by shrinkage cracks, and both large and small reptile and small crustaceans left their tracks and trails on the mudflats.

Long (400-500,000 year) climatic cycles, in phase with those recorded in upper Lockatong deposits, produced prolonged periods of dry, oxidizing environment and thick sequences of ferric oxide-rich mud alternating with briefer, moist intervals and accumulation of thin units of pyritic dark gray mud and minor carbonate.

FIELD TRIP
Route and Objective

This one-day field trip (Fig. 3) crosses the Newark Basin and Watchung lava flows northwestward from Newark to the border fault, then turns southwestward to the Delaware River section of the Newark Supergroup in the northernmost of three major fault blocks in the central part of the basin. Stops along the 33 km (20 mi.) traverse southward down the section afford study of 1) the Hammer Creek Conglomerate near the northern border fault, composed of Paleozoic carbonate and quartzite clasts in fining-upward sequences marked by calcrete paleosols; 2) the lower part of the Brunswick Mudstone arranged in repeated alternations of reddish-brown silty mudstone and claystone mudflat deposits; 3) the cyclic lacustrine facies of the analcime-dolomite-rich Lockatong Argillite and its hornfels; 4) the small Byram diabase sill; and 5) the Stockton Arkose with a predominance of Na-feldspar, confirming derivation of most of the Newark basin fill from an eastern or southeastern source. This thick (6 km) sequence is the record of interior basin sedimentation in a major rift valley developed during the early stage of post-Appalachian-Variscan opening of the central Atlantic Basin. The return trip to Newark crosses the Brunswick mudflat lowland in the middle fault block (Fig. 3, 4), then continues northeastward along the south flank of the Watchung lava flows.

The focus of the field trip is on the principal sedimentary facies and the successive changes in sedimentation displayed in the Newark Basin. In this review particular significance is attributed 1) to the eastern upland as the source of the distinctive soda-rich basin fill, 2) to relatively intense weathering in the upland terrane required to produce the large supply of clay in the Lockatong and Brunswick formations, in contrast to the evidence of aridity in the basin reflected in many of the sedimentary features, 3) to a long interval of stability during development of the graben documented by the Lockatong lacustrine deposits, and 4) to several patterns of allocyclic sedimentation recorded in the Lockatong and Brunswick deposits.

ROAD LOG

Mileage

0.0 Enter I 280 at intersection with Garden State Parkway (exit 145). Head NW. Interbedded Brunswick (Passaic) reddish-brown arkosic sandstone and mudstone with thin layers of dark gray micaceous mudstone. Local exposures of fining-upward fluvial sequences. See Olsen, this guidebook for revised stratigraphic nomenclature.

Samples across this traverse to the border fault reveal that the 1250m section of Late Triassic Brunswick beds below the 1st Watchung lava flow contains many zones of reversed magnetic polarity. All of the Liassic strata (1750m) above the 1st flow are normally magnetized (McIntosh and Hargraves, 1980, ms; Cornet and Traverse, 1975).

3.5 1st Watchung lava flow (Orange Mountain Basalt) 50-65m thick. Basal contact covered. Very thin hornfels facies with small patches of copper minerals. Lower part displays well-developed colonnade with vertical columnar joints. Main

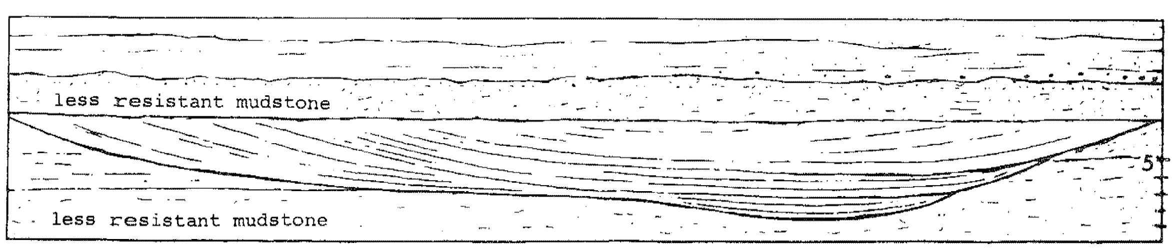


Figure 6. Sketch of rhythmic reddish-brown alternations in Brunswick Formation. Each consists of a more massive, resistant silty mudstone member and a less resistant hackly clay-rich member. Channel is filled with successive overlapping beds 2-8 cm thick, commonly grading upward from fine-grained feldspathic sandstone into mudstone. Tongue of dark reddish-brown poorly-sorted lithic-rich Hammer Creek Formation derived from the northwest. STOP 2, Rt. 627, about 1 mile west of Milford, N.J.

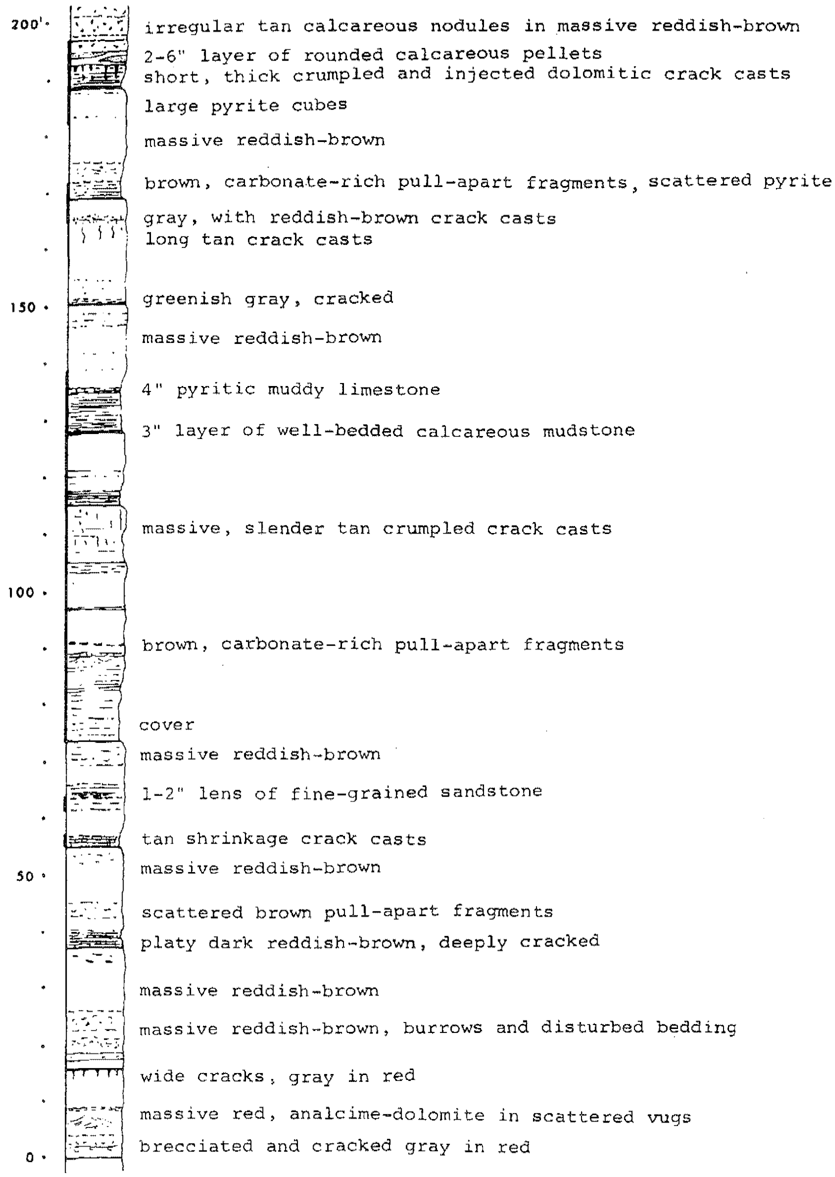


Figure 7. Section of upper 75 ft (20 m) of lowest reddish-brown unit in Brunswick Formation and overlying lowest gray unit C (see Fig. 1). STOP 4, Rt. 29, 5 miles south of Frenchtown, N.J.

body of flow is curvi-columnar zone with closely-spaced radiating joints. (See Manspeizer, this guidebook). Roadcut is 38m deep, said to be the deepest east of the Mississippi River.

4.5 Crossing Pleasant Valley Way in mudflat and lacustrine facies of Brunswick (Feltville) Formation between 1st and 2nd Watchung Mts.

4.75 2nd Watchung lava flow (Preakness Mountain Basalt).

7.2 Crossing lowland in reddish-brown fluvial and dark gray lacustrine Towaco Formation (37m). Rikers Hill (Roseland) Nat. Mon. (dinosaur tracks) to SW. Locally some of these lacustrine deposits contain traces of hydrocarbons.

8.4 Crossing 3rd Watchung lava flow (Hook Mountain Basalt). Each Watchung flow was extruded somewhat later than renewed faulting and differential uplift of the flanking highlands that produced fanglomerates (Faust, 1978).

Passaic River, drains Hatfield Swamp on broad expanse of uppermost Brunswick (Boonton) Formation to W.

11.3 Join I 80 W to I 287.

14.0 SW on I 287. Continue past Morristown.

21.5 North horn of New Vernon anticline in 3rd Watchung flow to S.

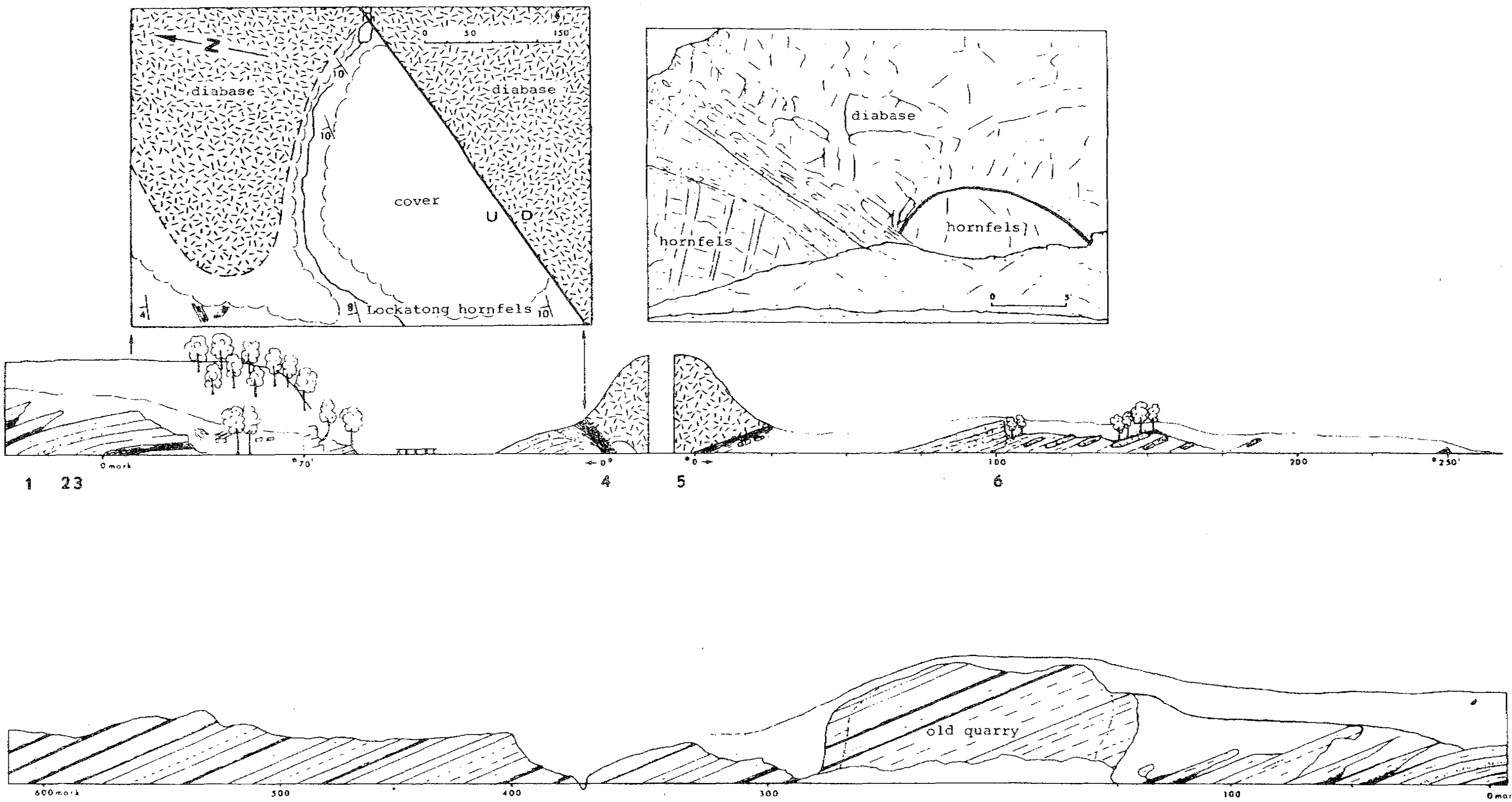


Figure 8. Sketch of roadcut through middle part of Lockatong Formation and Byram diabase sill. STOP 6, Rt. 29, Byram, N.J. 0*-*70 ft. and *0-*250 ft.- Lockatong hornfels above and below diabase. 0 mark about 70 ft above the sill is base of continuous section to north measured in feet. Lower profile - Lockatong Formation 70 to 715 ft (0-645 ft marks in measured section) STOP 6A. Heavy lines at base of detrital cycles (see Fig. 2B). Well-displayed analcime-rich chemical cycles between 450 and 550 ft marks. Cancrinite occurs as much as 425 ft (134 m) above sill. Upper profile - Lockatong hornfels. Enlargement (upper right) of upper faulted contact; sketch map (upper left) of diabase east of road. 1-6: items listed in road log.

23.5 Patch of Hammer Creek Conglomerate in low hill to SE.

24.5 Narrow gap between Ramapo border fault and west end of New Vernon anticline in 3rd Watchung flow. The fault continues for about 50 miles to the NE end of the basin (see Ratcliffe, this guidebook).

25.5 Crossing Passaic River. In its last stage Glacial Lake Passaic drained northeastward through gaps in the Watchung flows at Little Falls and Paterson. Great Swamp National Wildlife Refuge to S is a swampy remnant in broad syncline above the 3rd Watchung flow.

28.6 Narrow gap between 2nd and 3rd Watchung ridges.

30.5 Moggy Hollow (Mine Brook Road) between recurved 2nd Watchung Mt. to NW and 3rd Watchung (Long Hill) Mt. to ESE. Early drainage of Glacial Lake Passaic flowed westward through this notch to the North Branch of the Raritan River. West scarp of 2nd Watchung faulted against Brunswick Formation (Adams, 1980).

34.3 Intersection of I 287 and I 78. Watchung Mts. on skyline to E. Continue W on I 78.

40.7 Syncline in New Germantown flow in low hills a mile N.

44.7 Crossing NE end of Flemington Fault at junction with the border fault (near Lebanon). To S Cushetunk Mt. (diabase) encloses Round Valley Reservoir.

45.7 Complexly faulted Cambro-Ordovician strata and Precambrian gneiss that project S into the Newark Basin are limited on E by the Flemington Fault.

49.7 Reddish-brown and gray Early and Middle Ordovician shale with thin beds of chert and limestone. Apparently a remnant of a Taconic klippe (Perrisoratis, 1974).

51.2 Ordovician shale overlapped by Hammer Creek Conglomerate.

52.7 Leave I 78(22), SW to Pattenburg (1.1 mi) on northern edge of Hammer Creek Conglomerate covering Cambro-Ordovician strata faulted against Precambrian gneiss.

55.3 Cross Rt. 579 on border fault. Large fan of quartzite-rich conglomerate interfingers with Brunswick, Lockatong, and Stockton formations to E and SE. Evidence that movement on border fault occurred throughout episode of basin-filling.

57.7 Little York on border fault. Turn S (0.3 mi.) then SW (1.0 mi), then W in Brunswick Formation S of narrow belt of limestone-pebble conglomerate.

60.4 Spring Mills on Brunswick Mudstone between fanglomerates. Jog N then continue W on Church Road along border fault.

62.0 Quarry in Hammer Creek (Silurian quartzite clasts) Conglomerate to S. Clasts shattered by crushing in fault zone. Detailed map of Musconetcong Mt. to N and Newark Supergroup S to Frenchtown by Drake and others, 1961, 1967.

63.4 S on Phillips Road. Traverse crosses narrow belt of Cambrian limestone and border conglomerate, and the Brunswick Mudstone between lobes of Hammer Creek Conglomerate. Good exposures of border fault relations across the Delaware River at Monroe (0.5 mi S of Durham Furnace on PA 611).

64.3 S on Rt. 627 (River Road). Cliff on far side of river above power station shows patterned sequence of middle Brunswick deposits seen at Stop 2. Plateau capped by Coffman Hill diabase sheet (165 m) above gray Brunswick hornfels. The sill is estimated to be about 1400 m below the 1st Watchung lava flow.

65.6

Local Traverse

0.0 **STOP 1** Hammer Creek Conglomerate, Pebble Bluffs at culvert.

0.5 **Stop 1B** Conglomerate in steep roadcut at RR milepost 37 (0.5 mi S). Southward projecting lobe of quartzite-rich fanglomerate dipping 10-15 NW. Most clasts are less than 8 cm in diameter, a few are 13 cm long, the largest are 25 cm long. Some clasts are imbricated. Bedding is very poorly developed; cross-bedding is virtually absent.

The poorly sorted detritus is arranged in crudely fining-upward sequences about 7-9 m thick (Fig. 5) with a scoured base, multi-storied units of conglomerate, and calcareous patches and nodules (calcrete paleosol) in the upper sandier part.

Significant items:

1. Outcrop less than 5 mi from border fault.
2. Source probably less than 25-30 mi to N.
3. Clasts and matrix derived from Paleozoic rocks now stripped from the uplands.
4. Fining-upward sequence and calcrete common in alluvial fans.
5. Lensing and channeling well-displayed at south end of bluffs.
6. Rapid gradation southward into distal, finer-grained facies.
7. Fault in ravine between two major outcrops.

1.1 **STOP 2** Long roadcut in essentially horizontal middle Brunswick Mudstone south of Spring Valley Road. Bright reddish-brown mudstone in patterned sequences about 950 m above base of formation (Picard and High, 1963).

Items along 0.2 mi traverse:

1. Normal fault at E end of exposure down to E. Conspicuous jointing.
2. Succession of about 30 massive mudstone and hackly claystone alternations averaging 1.5-3 m thick (Picard and High, 1963). Few units with persistent 1-2 cm beds of siltstone.
3. Abundant burrowing has destroyed lamination in mudstone. Absence of bedding in claystone may be result of small-scale physical disruption.
4. Distinct 2-6 cm layers filling abandoned channel (Fig. 6). Fine-to-medium grained feldspathic sandstone in lower part of each layer derived from southeastern Na-feldspar-rich source area. Some layers are graded. Tops

are marked by burrows and shrinkage cracks. Abandoned channel may have been part of interfluvial drainage of extensive alluvial plain (Allen and Williams, 1979) or a shallow waterway in a clay-flat playa.

5. Hammer Creek tongue of dark reddish-brown Paleozoic quartzite-clast lithic-rich sandstone 3 m above road E and W of ravine and culvert.

1.8 Dark gray Perkasie and L and M members of Brunswick Formation 930 m above Lockatong Formation. These are highest of 8 recurring gray units in the Delaware Valley region, centered at 120-137 m intervals (Fig. 1). Several have been traced to NE into Hammer Creek Conglomate (Fig. 4), as well as 25 km to SW where they interfinger with reddish-brown mudstone. Gray units consist of black, pyritic platy muddy limestone and calcareous mudstone. The Perkasie Member apparently is about 1400 m below the 1st Watchung flow. Intervals of reversed magnetic polarization have been identified below both the Perkasie and L and M units, as well as just below and above the Graters Member lower in the formation (W.C. McIntosh and R.B. Hargraves, 1980, Ms).

2.5 Milford. Turn E on Main Street, then S at traffic light on Rt. 627.

4.5 **STOP 3** Middle Brunswick Mudstone, roadside excavation. Well-displayed bedding surface markings, including several sizes of shrinkage crack-patterns, burrows, and small tracks and trails, many probably made by small crustaceans (Boyer, 1979).

6.1 Frenchtown. Turn E on Main Street, then S on NJ 29.

9.5 Gray units E and F exposed in ravine and along side road. Gray units G and H above 100 m higher in section constitute the Graters Member (40 m thick).

10.05 Gray unit D exposed in ravine of Warford Creek.

10.7 to 10.9 **STOP 4** Lowermost Brunswick Formation, Tumble Falls. Ravine and high roadcut in lowest reddish-brown unit and lowest gray unit C (40 m thick) about 75 m above base of formation (Fig. 1, 7). Reddish-brown mudstone units exhibit three distinctive disruption features:

1. Thin greenish-gray beds with scattered shrinkage wafers.
2. Layers of light brown-weathering dolomitic mudstone 1-3 cm thick, in both pull-apart structures and widely dispersed fragments.
3. Upward-concave surfaces of shearing in tent-like structures 15 to 30 cm high suggestive of gilgai formed in soils by repeated wetting and drying.

The uppermost platy part of gray unit C consists of:

1. Black pyritic mudstone layers 2-3 cm thick with wide, completely crumpled composite and injected shrinkage crack casts of brown-weathering muddy dolomite and minor calcite.
2. Lenses of pyritic peloidal dolomite 10-20 cm thick, with silty round and flattened burrow casts and thin arcuate calcitic skeletal debris (ostracodes?) in the upper part. Many of the peloids are crudely concretionary dolomite with internal shrinkage cracks filled with sparry calcite. They may be algal oncolites.

The overlying massive reddish-brown mudstone contains tiny flecks of pyrite and irregular tan calcareous nodules 1-5 cm long that may be algal structures. Many of them have irregular patches of sparry calcite or are crudely concretionary.

11.1 Top of Lockatong Formation (top of gray unit B). Base of Brunswick Formation has been placed arbitrarily below the lowest thick reddish-brown unit (Fig. 1) even though its lower part is more like upper Lockatong deposits than the upper part of the Brunswick Formation.

11.4 Double Red unit exposed in creek to E is uppermost reddish-brown sequence of analcime-rich chemical cycles assigned to the Lockatong Formation. Thin reddish-brown intervals of this sort are the most analcime-rich and recur in a 105-120 m pattern of long cycles in phase with thick reddish-brown units in the Brunswick Formation (Fig. 1).

12.0 Triple Red unit in abandoned building-stone quarry to E about 1000 m above base of Lockatong Formation. Red units were favored for building blocks because of their more interesting variegated colors.

12.25 **STOP 5A** First Big Red unit about 35 m thick, Lockatong Formation, roadside outcrop, north end of Byram road cut. Short chemical cycles consist of lower platy dark lavender analcime-rich argillite with intraformational breccia and conspicuous shrinkage cracks with large white patches of analcime and dolomite. Upper massive part is reddish-brown, and spotted with tiny specks of analcime and dolomite locally arranged in rosettes of radiating skeletal crystal casts.

Profile of ledges in long Byram roadcut to S (395-730 m above base of Lockatong Formation) outlines succession of short cycles (Fig. 2B).

12.4 **STOP 5B** Short detrital cycles in gray sequence of Lockatong Formation. Easily eroded black shale in lowest part and feldspathic (Na-feldspar predominates) siltstone and fine-grained sandstone in the upper part (Fig. 2A). Essentially a very fine-grained distal facies of Stockton Arkose.

12.5 First thin Red unit in Lockatong Formation. Lowest of the several red units in the Newark section (Fig. 1).

12.8 **STOP 6A** Short chemical cycles in gray unit of Lockatong Formation between 450-550 ft marks (Fig. 8). Gray analcime-rich chemical cycles 2-4 m thick (Fig. 2) are characterized by:

1. Platy lower part of alternating black mudstone and tan-weathering dolomitic layers disrupted by shrinkage cracks and pull-aparts.
2. More massive middle part with extenisvely disrupted dolomitic layers.
3. Upper more homogeneous analcime-rich part,

commonly speckled with tiny patches of analcime and dolomite distributed in a pattern of minute shrinkage cracks. Locally analcime and dolomite occur in sprays of skeletal crystal casts.

13.1 Large abandoned quarry in Lockatong cancrinite-rich hornfels (chemical cycles; Fig. 8). Cancrinite is present 130 m (425 ft) stratigraphically above the faulted contact with the Byram diabase to the S. Two well-defined detrital cycles at top of quarry wall.

13.3 to 13.5 **STOP 6B** Lockatong hornfels and Byram diabase sill, south end of roadcut (Fig. 8).

1. White sprays of cancrinite, albite, and calcite at 21 ft mark developed from analcime-dolomite crystals in a chemical cycle, as seen in First Big Red units (stop 5a).
2. Nepheline developed in hornfels 25 m (11 ft mark) above Byram Sill.
3. Metal disk 2 m above road at 10 ft mark records flood level in Sept. 1955.
4. Faulted upper contact with diabase sill (Fig. 8) and essentially undisturbed contact with xenolith. Lockatong chemical cycles metamorphosed to nepheline cancrinite, calcite, pyroxene and amphibole, biotite-albite hornfels (an aphanitic syenite!).
5. Extenisvely fractured coarse-grained diabase with abundant joint minerals including calcite, epidote, prehnite, tourmaline, and amphibole. Conspicuous horizontal lineations marked by concentrations of joint minerals are not related to compositional layering in the sill.
6. Vague cyclic pattern of ledges of albite-biotite hornfels S of sill. Nepheline occurs about 30 m (100 ft) below the sill.

13.6 Southernmost roadside outcrop of Lockatong hornfels, about 80 m below Byram sill.

14.4 Crossing estimated Lockatong-Stockton contact.

14.8 Well-bedded reddish-brown sandy mudstone and sandstone in uppermost Stockton Formation.

15.1 Raven Rock. Upper arkosic member 100 m thick (Fig. 1).

16.3 Lockatong Creek. Quarry in Cutalossa Member of Stockton Formation (Fig. 1) high on west bank of river.

17.5 **STOP 7** Middle Stockton Arkose. Quarry 1 mi N of Stockton. Upper Prallsville Member (Fig. 1) 61 m thick, 760 m above base.

1. Yellowish-gray, well-sorted, medium-grained arkose with only minor reddish-brown micaceous mudstone.
2. Horizontal bedding predominates, with local micro-placers of specular hematite (after magnetite) on bedding planes.
3. Large- and small-scale cross-bedding rare.
4. Intraformational mud-chip conglomerate common.
5. Isolated burrows in arkose and on bedding planes. Micaceous mudstone extensively burrowed.
6. Small yellowish-brown patches common in arkose are limonite after altered iron-rich carbonate cement.
7. Na-feldspar almost twice as abundant as K-feldspar.
8. Very coarse-grained, kaolinized arkose along upper rim of quarry with clasts of quartz, feldspar, quartzite, and gneiss.

17.8 Wichecheoke Creek. Bear right to Stockton on NJ 29.

18.65 Conglomeratic Solebury Member (115 m thick) of Stockton Formation in schoolyard to E.

19.1 Roadcut in arkosic conglomerate of Solebury Member. Clasts as large as 8 cm mostly quartzite, rare feldspar and gneiss.

19.2 Crossing Flemington Fault at Brookville (Fig. 4). To W in Pennsylvania uplifted Cambro-Ordovician limestone is overlain by conglomeratic limestone-clast facies of Stockton Formation.

19.5 Lockatong nepheline-cancrinite hornfels above Mt. Gilboa diabase. Nepheline and analcime syenites at top of sill probably formed by reaction of a xenolith of Lockatong chemical cycles with a granophyric differentiate of the coarse-grained diabase (Barker and Long, 1969).

20.1 Mt. Gilboa trap-rock quarry in unusually coarse-grained diabase (gabbro). Lockatong hornfels along south edge of quarry.

20.3 Crossing southern branch of Flemington Fault (Dilts Corner Fault).

22.0 Join US 202 to NE across Brunswick Formation north of Lambertville sill.

Return Trip

6.0 Ringoes.

12.0 Flemington. Continue to US 202.

26.0 Somerville. Join US 22 to NE, south of Watchung lava flows.

46.0 Enter Garden State Parkway at exit 140. N to exit 145.

52.0 Exit 145 to Newark. End of trip.

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RAMAPO RIVER.

RAMAPO RIVER
by Jules Tavernier
from Picturesque America, Vol. II, 1874

BRITTLE FAULTS (RAMAPO FAULT) AND PHYLLONITIC DUCTILE SHEAR ZONES IN THE BASEMENT ROCKS OF THE RAMAPO SEISMIC ZONES NEW YORK AND NEW JERSEY, AND THEIR RELATIONSHIP TO CURRENT SEISMICITY

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Introduction and rationale for investigations

Field investigations at the northern end of the Newark basin begun more than 10 years ago led to the publication of several articles (Ratcliffe, 1971; Ratcliffe and others, 1972) in which a case was made for long continued fault activity in the vicinity of the border fault (Ramapo fault) in New York and New Jersey. These articles also called attention to the observation that a series of low-level earthquakes appears to be spatially associated with these ancient faults (Fig. 1).

Since that time, seismic-detention capabilities of the Lamont-Doherty network have been greatly improved and further supplemented by a dense array of stations located on the northern extension of the Ramapo fault in the vicinity of Consolidated Edison's nuclear-generating plants at Indian Point (Fig. 2)[1].

Aggarwal and Sykes (1978) document a pattern of seismicity (Figs. 1 and 2) that illustrates that numerous low-level events (Nuttli magnitude 1.5 to approximately 3) are occurring throughout a 30 km-wide zone roughly centered on the trace of the Ramapo fault at depths of 0 to about 10 km. Fault-plane solutions (Fig. 2) obtained by them and by Yang and Aggarwal suggest that motion is currently taking place on northeast-striking steeply southeast-dipping surfaces. First-motion studies indicate southeast-to-northwest compression and therefore a reverse-faulting mechanism. They conclude that currect seismicity in the Ramapo zone is being controlled by reactivation of the northeast-striking steeply southeast-dipping faults which make up the predominant structural grain in this area. They further suggest that the Mesozoic border fault, the Ramapo fault, and its northern splays (Fig. 1) are the actual surfaces being reactivated.

The geologic framework of the Ramapo seismic zone, however, is extremely complex. A multitude of faults of different ages have different physical characteristics and contrasting histories. The northeast-trending structural grain of this zone is accompanied by faults of Proterozoic, Paleozoic, Mesozoic and possibly Tertiary and recent age.

Despite the abundant evidence for reactivation of older faults in the Mesozoic, (Ratcliffe, 1971) the Mesozoic and younger faults are not uniformly distributed and do not everywhere coincide with the traces of older faults. Unfortunately, it is not presently possible to produce a tectonic map of this area that accurately shows the distribution of Mesozoic as opposed to older faults. In general, previous studies have not attempted to differentiate Mesozoic faults except where Mesozoic rocks are actually offset. The geologic-tectonic template, therefore, is quite incomplete at present, and any plan to test the hypothesis that geologic structures of Mesozoic age are responsible for current seismicity is severly limited by the lack of appropriate geologic data. Figure 1 shows a new preliminary compilation of fault features.

Tectonic framework and fault distribution in northern New Jersey and southeastern New York

Figure 1 shows the distribution of major tectonic features in the Ramapo seismic zone. Two classes of faults are distinguished:

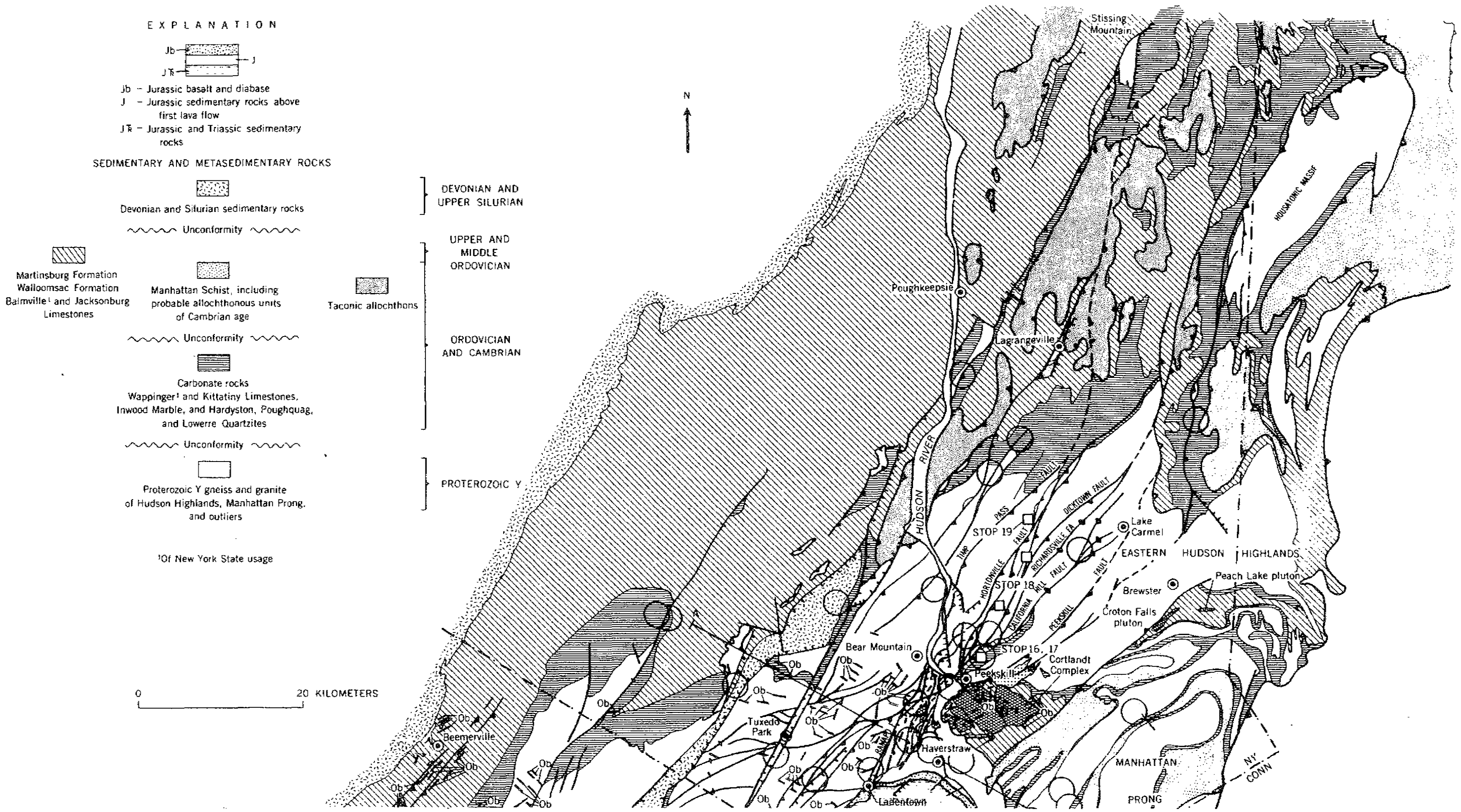
a) faults with associated semiductile fabric in adjacent rocks, and phyllonite or blastomylonite at fault contacts;

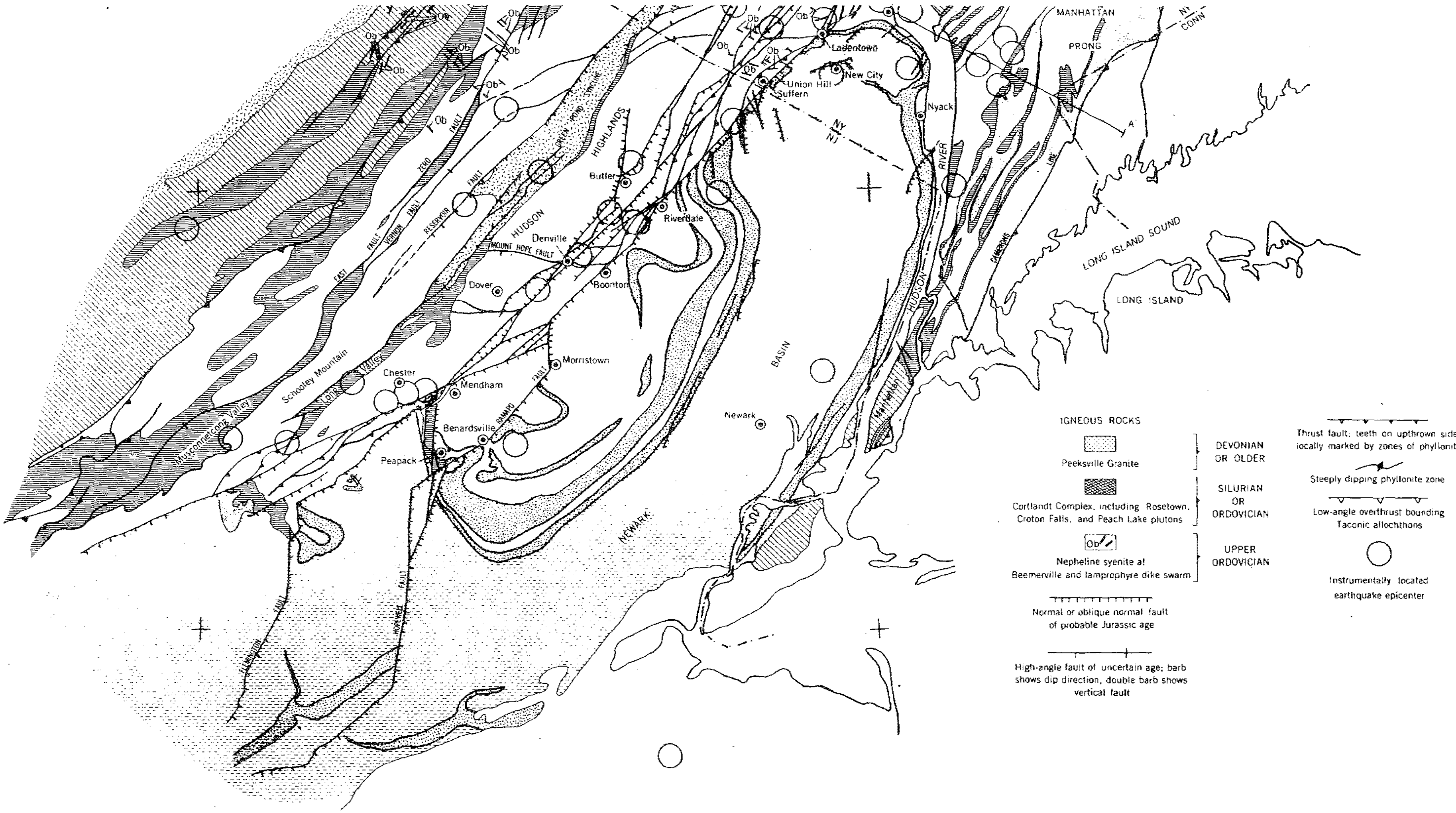
b) more brittle faults characterized by discrete breaks and cataclastic fabrics.

This grouping of faults by and large also serves to distinguish thrust faults, largely class (a), from normal or oblique dipslip faults, class (b).

[1] Figure 2 is reproduced with permission of the authors from a paper by Jin-Ping Yang and Y.P. Aggarwal, Seismotectonics of northeastern United States and adjacent Canada, submitted for publication to the Journal of Geophysical Research.

Fig. 1. Preliminary tectonic map of the Reading Prong, northern Newark basin, and Manhattan Prong, showing distribution of "brittle" versus more ductile style fault zones and earthquake epicenters. Compilation uses data of Drake, Lyttle, and Owens (1979), New York State geologic map (Fisher, Isachsen and Rickard, 1971) New York State brittle fracture map (Isachsen and McKendree, 1977), New Jersey Geological Survey maps at 1:62,500, and new data (Ratcliffe, unpub. data) principally along the Ramapo-Canopus fault system. Locations of U.S. Geological Survey drill holes along the Ramapo fault are identified. This map is preliminary and is likely to be altered substantially as dating of faults and examination of fault-zone materials continue. Line A-A identifies the location of cross section (Fig. 4). Epicenter locations from data of Lamont-Doherty Geological Observatory published in Regional Seismicity Bulletin of the Lamont-Doherty Network, Palisades, N.Y. Horizontal errors are less than 2 km (diameter of circles).





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Butler
Riverdale
Denville
MOUNT HOPE FAULT
Dover
Boonton
Morristown
Chester
Mendham
Benardsville
Peapack
Newark
BASIN
NEWARK
HUDSON
RIVER
LONG ISLAND SOUND
LONG ISLAND
Schooley Mountain
Musconetcong Valley
Long Valley
ZERO FAULT
VERNON FAULT
RESERVOIR FAULT
EAST FAULT
RAMAPO FAULT
FLEMINGTON FAULT
HOPEWELL FAULT
CAMERONS
LINE
Manhattan
IGNEOUS ROCKS
Peeksville Granite
DEVONIAN OR OLDER
Cortlandt Complex, including Rosetown, Croton Falls, and Peach Lake plutons
SILURIAN OR ORDOVICIAN
Nepheline syenite at Beemerville and lamprophyre dike swarm
UPPER ORDOVICIAN
Normal or oblique normal fault of probable Jurassic age
High-angle fault of uncertain age; barb shows dip direction, double barb shows vertical fault
Thrust fault; teeth on upthrown side; locally marked by zones of phyllonite
Steeply dipping phyllonite zone
Low-angle overthrust bounding Taconic allochthons
Instrumentally located earthquake epicenter

On this map, numerous faults of both kinds are present within the Ramapo seismic zone. Definition of faults in New York State is somewhat better than in New Jersey, especially within the Reading Prong, because of recent mapping in a tier of quadrangles extending from the Hudson River west to Greenwood Lake. Recent geologic mapping is somewhat limited in the New Jersey Highlands, and investigations specifically on faults have not been conducted except locally.

A series of previously unrecognized, interconnected Mesozoic faults are now recognized as a result of reconnaissance studies over the past several years. The probable interconnection of the Flemington and Hopewell faults with the Ramapo fault system is worthy of note. Investigations in the Morristown-Bloomingdale to Chester area suggest that individual splays of the main Ramapo fault extend southwestward from a point just north of Morristown to interconnect with the Flemington fault south of Mendham. This zone of faulting coincides with a zone of concentrated earthquake activity in the Bloomingdale-Denville area (Fig. 1).

Faults bounding the Green Pond syncline are interpreted to be Triassic and Jurassic, although reactivation of older faults is likely, especially on the Reservoir fault. The Tuxedo Lake valley, however, is bordered by abundantly block-faulted rocks that have zeolite-chlorite mineralization and irregular wear grooves typical of Mesozoic faults. These rocks almost certainly mark a zone of Jurassic faulting. A similar zone extends northeastward to Sebago Lake from the Sloatsburg area.

The Ramapo fault itself extends from the Peapack-Gladstone area northeastward to Thiells, N.Y., where it bifurcates into the Thiells and Mott Farm Road faults (Figs. 8, 9). A possible zone of Jurassic faulting may extend through Timp Pass, although the bulk of the fault fabrics here are mylonite associated with class B faults of probable Paleozoic age and Proterozoic age.

North of the Hudson River, evidence for Mesozoic faulting along the Ramapo N. 40° E. trend is absent, but a zone of Mesozoic faulting does extend northward along the Hudson River. The tracing of these Mesozoic faults northward is uncertain.

The Peekskill fault, which forms the boundary of the Manhattan Prong, is largely a Paleozoic fault, although some Triassic and Jurassic reactivation is possible with a south-side-down sense of motion.

Mesozoic fractures show characteristics of brittle surface breakage such as wear grooves, irregular indentations, and polished surfaces that are indicative of stick-slip behavior commonly ascribed to movements that produce earthquakes. Therefore, it may be logical to assume that classes of faults showing these features at the surface in a seismic area are the faults most likely associated with the current activity. The obverse argument is that healed, more ductile faults that do not show evidence of movement in an earthquake-generating mode are probably not responsible for producing present-day earthquakes.

Acceptance of this premise has profound significance because it suggests that present-day seismicity in crystalline terranes such as the northeastern United States should be occurring in tectonic areas only where brittle fractures have in the proper attitude for reactivation by present stress fields.

My present feeling is that we have not yet demonstrated either from experiment, theory, or empirical observation that the premise restricting seismic activity to surface brittle fracture zones is at all valid. The Ramapo seismic zone is the best locality, but perhaps the most complex area in the eastern U.S. in which to empirically test this premise.

Semiductile shear zones, expressed by phyllonite or diapthoritic phyllonite-blastomylonite are common throughout the Proterozoic rocks of the Hudson Highlands. A zone of especially intense concentration of these faults is located in the Canopus zone north of Peekskill. Detailed mapping has allowed tracing of these faults northwestward toward Carmel, N.Y., and southwestward to near Boonton, where ductile shear zones are truncated by the Ramapo fault. Throughout this belt, metamorphic mineral fabrics found in fault zones indicate progressive increase in grade northeastward in sympathy with increasing Ordovician isograds. This prograde character of the retrogressive shear zone minerals in these faults suggests that these faults are Ordovician or older.

Independent evidence for the age of these sheared rocks comes from the age of igneous rocks that crosscut or intrude along these faults. Igneous plutonic rocks of the Rosetown outlier of the Corlandt Complex and a swarm of lamprophyre, andesite and rhyodacite dikes intrude across the fault zones that include rocks as young as Middle Ordovician. K-Ar, $^{40}Ar/^{39}Ar$, and Rb/Sr age determination indicate that these dikes and plutonic rocks are roughly the same age as the regional Taconic dynamothermal metamorphism at 440-460 m.a. or Taconic (Dallmeyer, 1975; Dallmeyer and Sutter, 1976). A swarm of dikes extends S. 80° W. from Cortlandt to Beemerville, N.J., where the strongly alkalic "Beemerville" nepheline syenite of Ordovician age crops out. The uniqueness of the structural grain has just recently been recognized as a result of study of the dike systems in the highlands of New Jersey and New York and is of regional importance.

These semiductile shear zones are found west of the Ramapo border fault in New Jersey as far south as the Gladstone-Peapack area and invariably show steep southeast-dipping attitudes. To the west in the Reading Prong, shear zones are less well known, but many dip more gently southeast and appear to form at the soles of overthrust that carry Proterozoic Y rocks northwestward over Paleozoic strata.

Without doubt, these major semiductile fault zones are present in the basement rocks beneath the Mesozoic Newark basin. I believe that these faults are major tectonic features of Ordovician and Proterozoic age that have localized fault activity throughout geologic time. Current seismic activity may be more strongly controlled by the presence of these through-going crustal structures than it is by the more superficial Mesozoic faults.

On this trip, we will examine the cataclastic-mylonitic rocks associated with Mesozoic, Paleozoic, and Proterozoic faults throughout the Ramapo seismic zone. Special attention will be given to the complex geologic history that produced the tectonic grain in Proterozoic Y and Cambrian and Ordovician rocks up-plunge from the Newark basin in the Hudson Highlands. The role that these faults played in the Taconic orogeny will be stressed. I hope to demonstrate by examination of several exposures the spatial association of Paleozoic phyllonite zones (that encorporate slivers of Cambrian and Ordovician metasedimentary rocks) with later zones of Mesozoic reactivation.

Fault Reactivation: structural control of Mesozoic faults by older Tectonic grain and current seismicity

Semiductile shear zones such as the Canopus faults, Thiells, and unnamed shear zones subparallel to the Ramapo fault, dip steeply into the crystalline basement of the Newark basin. The N. 40° E. tectonic grain along which these faults trend, was formed in the "Grenville" deformation approximately 1 b.y. ago. Subsequent reactivation in the Ordovician produced right-oblique thrust faults and intense zones of phyllonitization.

Field studies and results of drill coring of the Triassic border fault (Ramapo fault) have shown that these more ductile zones are not manifestations of Triassic and Jurassic cataclasis, but metamorphic mylonites formed under greenshist-grade regional metamorphism. Results of isotopic studies also support the old age of these shear zones. Figure 3 shows the schematic relationship of depth of formation and age of some of these features.

The steeply dipping shear zones served to localized Triassic and Jurassic faulting along the Canopus trend. Cataclasis associated with these faults is characteristically brittle and has resulted in gouge and cataclasite.

A generalized cross section across the Reading and Manhattan Prongs (Fig. 4) shows the general steepening of that phyllonite shear zone in the vicinity of the Ramapo fault zone. Earthquake hypocenters (Fig. 4) in the vicinity of this section tend to be deeper in the southeast than in the northwest. Fault-plane solutions for events as deep as 10 km within the Ramapo fault zone indicate steep dips of 60° - 70° coinciding with the attitude of both the ductile shear zones and the Triassic and Jurassic faults (Fig. 2). Current seismicity appears to be controlled by attitude and distribution of the older shear zones, that in turn have localized Mesozoic faulting.

The current stress sytem requires southeast-northwest compression (Aggarwal and Sykes, 1978). Detailed examination of drill cores of the actual Ramapo fault have revealed no evidence of reactivation as a thrust fault along the actual Ramapo fault surface. In addition, no data has yet been discovered of offset glacially polished surfaces or of surficial deposits where they have been trenched across the Ramapo fault. Studies of surficial deposits near the fault trace are in progress.

Regional geology and major tectonic problems in the Reading Prong

Proterozoic Y rocks form the basement of the Reading-Hudson Highlands and of the Manhattan Prong. These terrains are part of the 1 b.y. old North American basement consolidated prior to onset of Appalachian tectonics that began with late Proterozoic rifting and initiation of oceanic spreading of the Iapetus ocean. Cover rocks of these areas are also distinctly North American and consist of Lower Cambrian through Middle Ordovician shelf and exogeosynclinal sediments formed on the foundered edge of the North American continent.

Basement gneisses of charnokitic affinities crop out in the Hudson Highlands west to the Canopus fault zone. Available geochronologic data suggest that regional dynamothermal metamorphism and plutonism may have occurred between 1139 ± 10 m.y. ago and 914 ± 12 m.y. ago based on Rb/Sr ages for metamorphic rocks, syntectonic and late tectonic granites (Helenek and Mose, 1976). Polyphase folding and plutonism are widely recognized by Helenek and Murray (*in* Hall and others, 1975).

A major tectonic zone of highly faulted rock, the Canopus fault zone (Ratcliffe, 1971) (Fig. 1) effectively separates the western Highlands block from the eastern

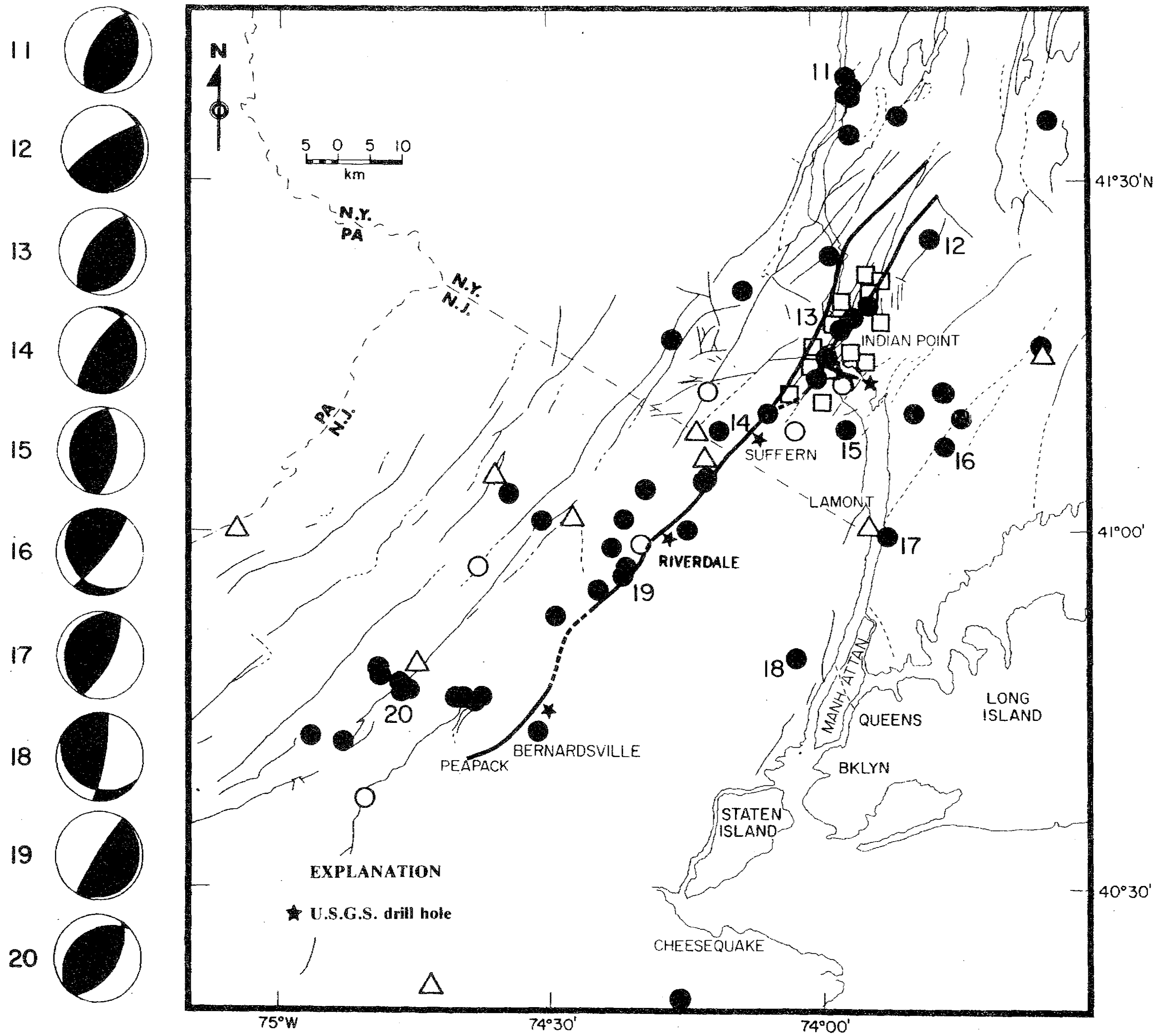


Fig. 2. Location of earthquake epicenters and fault-plane solutions for Ramapo seismic zone reproduced from Yang and Aggarwal [4]. Location of U.S. Geological Survey drill holes along Ramapo fault are shown. Stereograms show upper hemisphere projections for individual fault-plane solutions identified on map. Triangles show location of Lamont-Doherty stations, small boxes Consolidated Edison network. Open circles, events 1951-1972; closed circles, events 1973-1979.

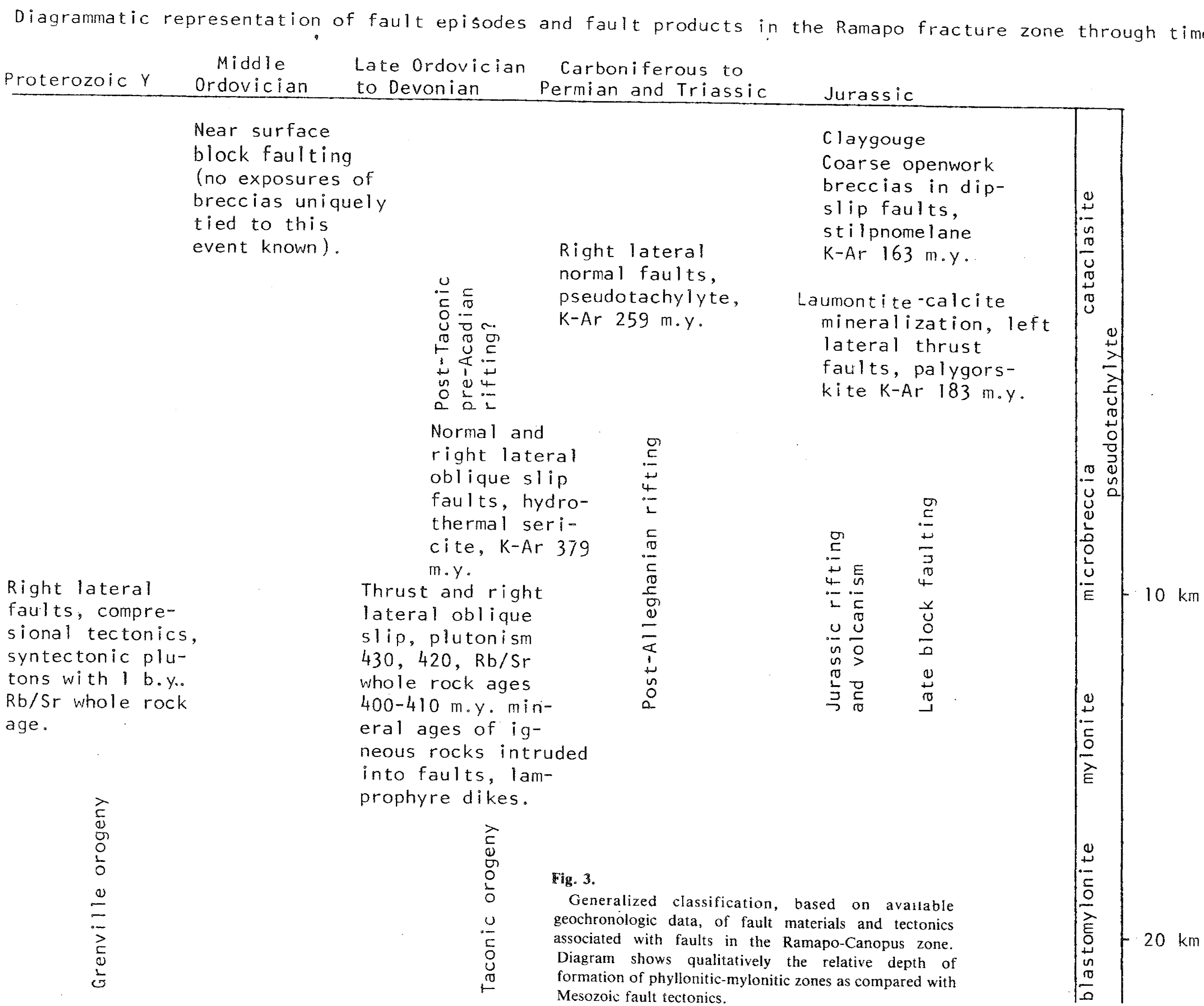


Fig. 3.
Generalized classification, based on available geochronologic data, of fault materials and tectonics associated with faults in the Ramapo-Canopus zone. Diagram shows qualitatively the relative depth of formation of phyllonitic-mylonitic zones as compared with Mesozoic fault tectonics.

Hudson Highlands. Hall and others (1975) have suggested that Proterozoic Y rocks east of this fault zone are unlike rocks of the western Highlands block. The Canopus zone has been the locus of fault activity in the Proterozoic, Ordovician, and possible Triassic (Ratcliffe, 1971) and plutonic rocks of the Canopus pluton dated at about 1070 m.y. by Armstrong (Ratcliffe and others, 1972) are syntectonically deformed in the fault zone. The lack of correspondence of Proterozoic rocks across this zone led to the suggestion that the two terrains are of considerably different parentage and that the eastern block may be allochthonous with respect to the main Reading Prong (Hall and others, 1975). This difference is also expressed in differing aeromagnetic patterns for these two areas of basement. West of the fault zone, the aeromagnetic patterns are characterized by linear, high-amplitude anomalies. East of the fault, the patterns are broad, low-amplitude features without strong linear pattern (Harwood and Zeitz, 1974).

The linear magnetic belt characteristic of the Beacon-Copake anomaly west of the Canopus zone is approximately 25 km wide. The western boundary of this zone is marked by exposure of biotite-rich paragneiss amphibolite, calc-silicate rocks, and associated magnetite deposits (Dodd, 1965). The eastern boundary is also marked by northeast-trending linear belts of magnetite deposits, the Sprout Brook, Canopus Hill "ore ranges" of Colony (1921). The internal structure of this zone is dominated by northeast-trending limbs of steep isoclinal folds in which the distribution of steeply dipping highly magnetic calc-silicate and paragneiss units are adjacent to weakly magnetic granitic and leuocratic rocks. The distinctive aeromagnetic pattern, therefore, appears to result from the presence of near-vertical belts of highly magnetic rocks on the limbs of regional folds. At the Canopus zone the structural style in Proterozoic rocks changes from one of steeply dipping linear belts of Proterozoic rocks to one of a swirled pattern of more open folding with shallow northeastern plunges. East of the Canopus belt broad aeromagnetic anomalies greater than 1300 gammas are associated with amphibolite and calc-silicate rocks locally bearing magnetite deposits as at Brewster, Mahopac, and Sprout Brook belts (Colony, 1921).

This leads to the conclusion that the linear aeromagnetic pattern described by Harwood and Zeitz (1974) may result largely in part from the configuration of magnetic rock units rather than from an inherent difference in the rocks. The magnetic grain or signature of the western Highlands was produced by the structural imprint of Proterozoic Y age, which terminates at the Canopus zone. West of this zone, Proterozoic Y rocks contain N. 40° E.-trending isoclinal folds that have steep axial surfaces and vertical limbs. In the Canopus zone, superposition of strain-slip folds and shear zones

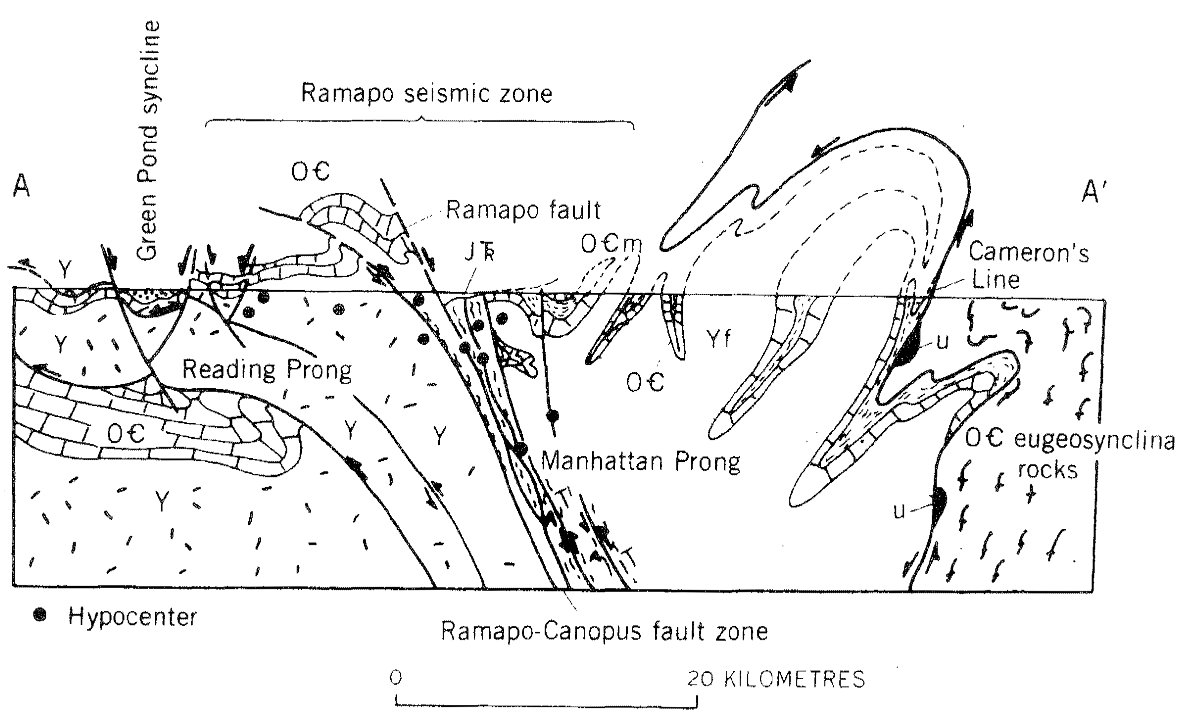


Fig. 4. 1:1 cross section across the Reading and Manhattan Prongs showing inferred deeper crustal structure and approximate hypocenters for earthquakes within the Ramapo seismic zone near line of section. Note increasing depth of hypocenters near ductile Ramapo-Canopus zone. Earthquakes as deep as 10km yield fault-plane solution indicating movement on steeply southeast-dipping faults in Ramapo-Canopus zone.
Y = Proterozoic rocks; Yf = Fordham Gneiss; OЄ = Ordovician and Cambrian miogeoclinal rocks; OЄm = Manhattan Schist; u -ultramafic rocks east of Cameron's Line. See figure 1 for location of section.

disrupt this older "Grenville" structure. Some evidence suggests that folds of Proterozoic Y age east of the Canopus zone are oriented differently and represent a different tectonic belt east of a Proterozoic shear zone. The difference in tectonic style and in consequent aeromagnetic patterns is probably the result of juxtaposition of two structural domains in Proterozoic time.

An alternate hypothesis is that the rocks east of the Canopus zone have a different structural style because of intense Paleozoic overprinting. The problem is not easily resolved, and most probably Proterozoic and Paleozoic tectonism are involved and the eastern Highlands undoubtedly do contain a complicated composite structural fabric. Figure 16, A, B, C shows schematically the structural evolution of the Ramapo-Canopus fault zone.

A major unresolved tectonic problem is the nature and extent of overthrusting of basement rocks of the Reading Prong. Field workers in the Hudson Highlands regard the northern part of the Reading Prong as mantled by a continuous shelf cover on the western edge with limited thrust faulting.

Two recent articles by Dallmeyer (1974) and Harwood and Zeitz (1974) have dealt with structural interpretations of the northern end of the Reading Prong. Their results appear to confirm the basic conclusion of field workers in this area that the northern end of the Reading Prong from Beacon northeastward may not be allochthonous in the sense proposed by Isachsen (1964). Isachsen advocated total allochthony of the Reading Prong with respect to the Paleozoic shelf-sequence rocks to the northwest and to the Manhattan Prong to the southeast.

Harwood and Zeitz (1974) have shown that linear magnetic patterns in exposed Proterozoic rocks project N. 30° - 40° E. from Beacon, N.Y., to Copake, N.Y. (Beacon-Copake magnetic anomaly), beneath overlying Cambrian and Ordovician cover rocks. This observation suggests that basement rocks of the Reading Prong are not allochthonous with respect to the cover rocks of the Hudson River Valley area.

Detail mapping of the Ramapo-Canapos zone and of the contact between the Hudson Highlands and the Manhattan Prong (Ratcliffe, 1971 and unpub. data) reveals that no trailing edge is preserved near this southern and eastern border in the Proterozoic rocks. Instead, structural data suggest that faults within crystalline core of Reading Prong steepen as this contact is approached. I prefer the interpretation, shown schematically in figure 4, that the Reading Prong, at the latitude of New York is dominated by deeply rooted wedges of basement rock thrust westward and southwestward during Taconic deformation.

Mesozoic faults of the Ramapo fault zone

The Ramapo fault forms the western border of the Newark basin (Fig. 1), and extends as a discrete structural feature from Ladentown, N.Y., south to Peapack, N.J. North of Ladentown, the fault may bifurcate into two branches, one trending N. 20° E. and the other N. 60° E. connecting northeastward with the Thiells fault, although this connection is not verified. The projection of the Ramapo fault northward into the Hudson Highlands is complex. One arm, the Mott Farm Road fault, extends northeastward and rejoins the main border fault north of Tomkins Cove, N.Y. Northeast of Tomkins Cove, Mesozoic faults are not abundant, although a zone of typical Mesozoic faults extend northward along the Hudson River at least as far as Cold Spring, N.Y.

South of Suffern, N.Y., the Ramapo is moderately straight until the Pompton Plains area where splays and a series of en echelon faults passes into the Hudson Highlands. Major faults, previously unrecognized, trend southwestward from Morristown, N.J., toward the Denville-Chester area and may connect to the south with the Flemington fault.

The Ramapo fault is easily recognized as far south as Bernardsville, N.J. South of Bernardsville the Ramapo fault appears to branch into a series of more southerly directed splays and to connect with the Hopewell fault. The likelihood of this connection has not been recognized until recently (Adams, 1980; Manspeizer, personal commun., 1980; Olsen, personal commun., 1980). Mapping in the Gladstone area suggests that previously drawn maps showing the Ramapo curving westward to join with the Flemington fault appear incorrect on the basis of my remapping of the Gladstone area.

The major pattern of Mesozoic faults is shown on figure 1. All cores examined show evidence of right-lateral slip which produced minor folds and dragging of older cataclastic fabrics.

Fault breccia, cataclasite, and gouge predominate in the Ramapo drill cores. Cataclasite with a strong fluxion structure is present and gives the fault rock a mylonitic fabric. Neomineralization consists of chlorite, calcite, and laumontite.

Magnitude and movement history of the Ramapo fault

The Ramapo fault offsets rocks as young as middle Early Jurassic (Sinemurian) in the vicinity of Riverdale, N.J. (Boonton Formation of Olsen, this publication).

From Ladenton, N.Y. to Peapack, N.J., the fault truncates approximately 1400 m of basalt and sedimentary rock on the western limb of the Watchung syncline, on the basis of thickness estimates of Olsen (this publication). If the fault connects northward with the Thiells fault, stratigraphic throw of approximately 4 km is possible if we assume that the sedimentary deposits do not thin northwestward. Alternately, most of the movement on the Ramapo fault could have been taken upon its northern extension, the Mott Farm Road fault, and the 1400 m of probable stratigraphic separation cited above could be used as an estimate. The actual displacement of the Ramapo fault is unknown. Folding of the Triassic strata in the Watchung syncline prodated faulting or was produced by drag folding during faulting. Data do not appear to support the concept that deeper strata in the northern end of the Newark basin have undergone greater rotation than younger deposits, an argument used to support syndepositional faulting.

I have examined the outcropping fault fabric associated with the Ramapo fault over its entire length

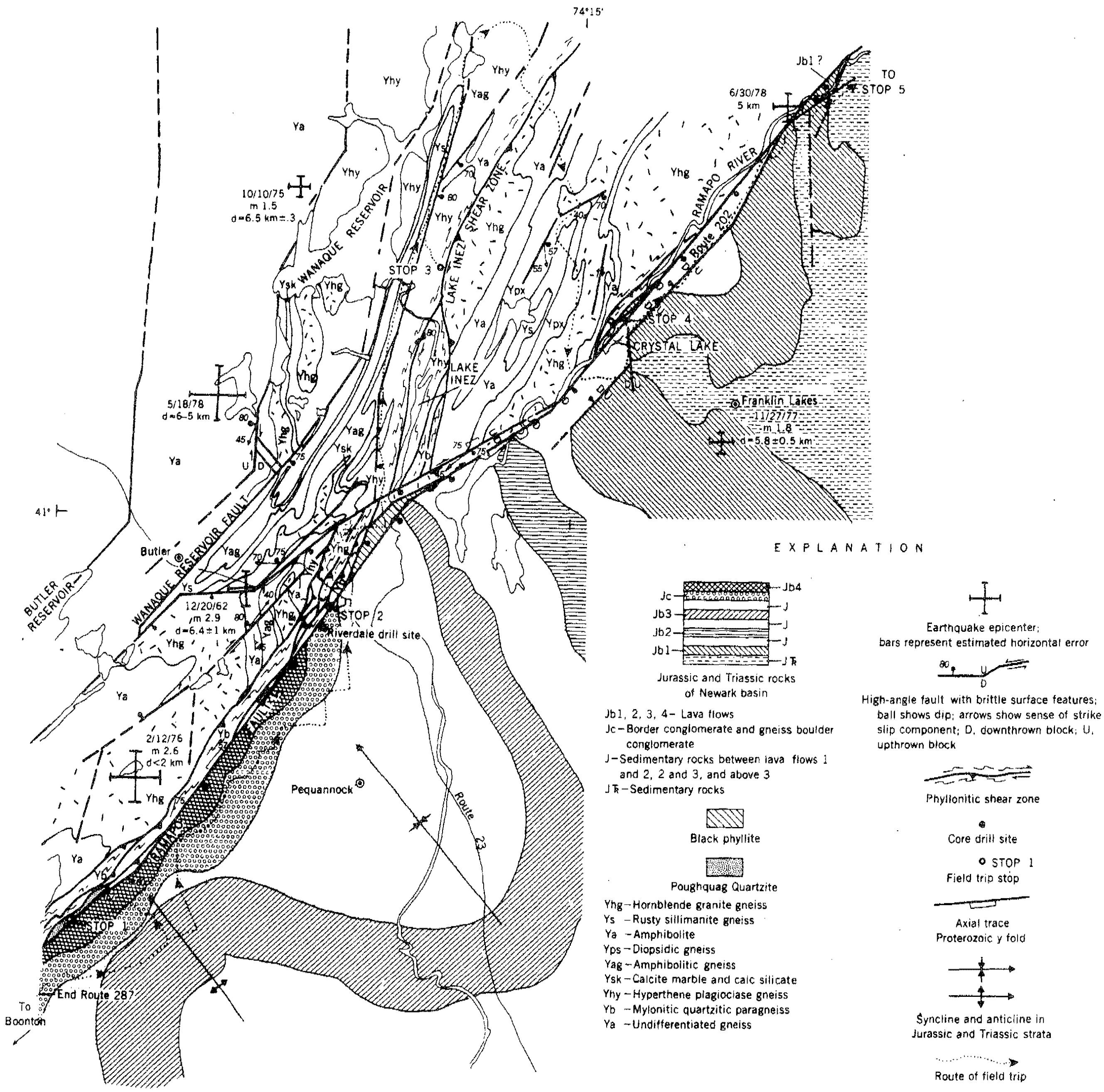


Fig. 5. Generalized geologic map of the Ramapo fault between Boonton, N.J., and Suffern, N.Y., showing distribution of semiductile shear zones with associated slivers of Paleozoic rocks and more brittle faults of probable Mesozoic age. Location of earthquake epicenters are shown. Geology of fault zone based on new data (Ratcliffe, unpub. data). Stop locations and location of Riverdale drill core figures 6 and 7 are shown. North of Riverdale, a splay of the Ramapo fault offsets Proterozoic structure and phyllonite zones 1.5 km in a right-lateral sense.

and examined continuous cores obtained at four major sites distributed along its length (Fig. 2).

The results of all these observations are reasonably consistent. Steep conjugate normal-fault fracture patterns dominate in the footwall block with extensive fracturing limited to within 100-200 m of the fault. Rusty weathering, chlorite-coated and slickensided and grooved surfaces are common. Calcite and laumonite fill extension fractures. Evidence for multiple movement with a significant component oblique slip is common. The primary movement plan for the border fault appears to be right-oblique normal movement on southwest-dipping surfaces and left-oblique movement on northwest-dipping surfaces.

Attitude of the Ramapo fault

The results of drill core information from three drill sites along the length of the Ramapo fault are shown in figures 6, 10, and 13. The dip of the fault is variable: 70° SE. at Stony Point, 55° SE. north of Suffern (Sky Meadow site), 50° - 55° at Riverdale, 50° - 45° at Bernardsville. At each of these localities, the actual fault contact is marked in drill cores by nonhealed unconsolidated rock gouge 1-5 cm thick. Details of some of the actual contacts are shown in figures 5, 7, and 11.

The footwall block at these localities is predominantly hornblende granite gneiss in the north and dioritic or amphibolitic gneiss at the two southern sites. Examination of fracture patterns, and slickensides, and micro-offsets indicate a predominant, down-to-the-southeast sense of movement with evidence for both right-lateral and left-lateral movement. The dominant sense of movement is right oblique normal faulting. Folding and plication of fluxion banded cataclasite is commonly found immediately above the fault attesting to some reactivation. The drag sense of deflected fluxion banding is consistent with right-oblique normal faulting.

Evidence for syndepositional faulting

Carlston (1946) and previous writers have suggested that active faulting occurred during sedimentation. The arguments that favor this are:

1. Coarse border conglomerates and fans localized near border fault.
2. Very local sources of material in basin suggesting high local relief.
3. Fragments of pillow basalt in the fanglomerate suggesting that lava flows overstepped the basin and were fed back into basin as a result of renewed faulting (seen in conglomerates below the two higher lava flows).
4. Fragments of mylonitic or cataclastic rocks of footwall in the border conglomerate (these have been seen at Boonton, Ladentown, and Tomkins Cove).
5. Large blocks of cataclastic rock in fan deposits (to be seen at Union Hill, Stop 6).
6. Progressive unroofing of highlands block as recorded by abundant detritus of Proterozoic Y age in the youngest conglomerates of the basin. (Proterozoic gneiss fragments are abundant in the youngest deposits but rare in Upper Triassic rocks).
7. Relationship of the lava flows at Ladentown to underlying folded rocks. The Ladentown lava flows (Stop 7) show evidence of having flowed along a stream channel incised into previously folded Triassic strata. The lava may have ponded against the fault escarpment.

Although all of these arguments do suggest fault activity during sedimentation, the magnitude of this activity is quite uncertain. It is my feeling that estimates of probable displacement on the border fault are greatly exaggerated and are not more than 500 m along the northward extension of this fault into the Hudson Highlands near Stony Point and on the Mott Farm Road faults. These estimates are based on correlation of Proterozoic and Paleozoic structures across Mesozoic faults at the north end of the basin where the possibility of large (greater than 500 m) displacements here on Mesozoic faults are precluded.

Examination of the clasts found in the border conglomerate suggest that extremely local sources existed in or near the border fault in Sinemurian and older time.

1. At Riverdale, fragments of phyllonitic hornblende granite gneiss, veined with epidote, are traceable to outcrops several hundred meters west of the conglomerate and must have been very locally derived (Stop 2).
2. At Stony Point, fragments of Cambrian quartzite traceable to local outcrops 400 m southwest are found in this fanglomerate at Stop 10.
3. At the north end of the basin, distinctive clasts of hornfelsed Manhattan Schist from the contact aureole of the Corlandt Complex less than

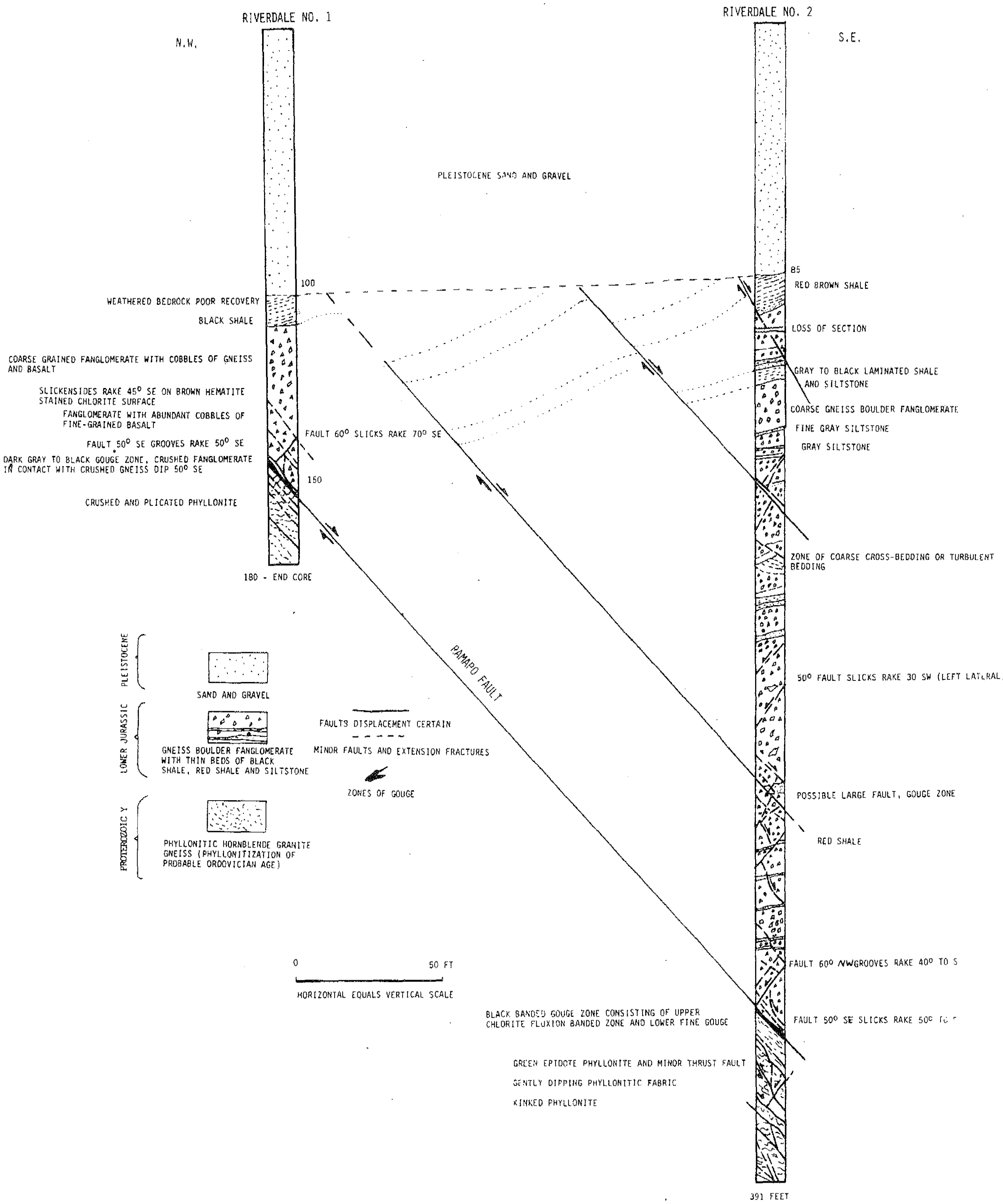


Fig. 6. Cross section showing attitude of Ramapo fault at Riverdale drill site Two continuous cores penetrated the fault between Jurassic fanglomerate and phyllonitic gneiss of footwall.

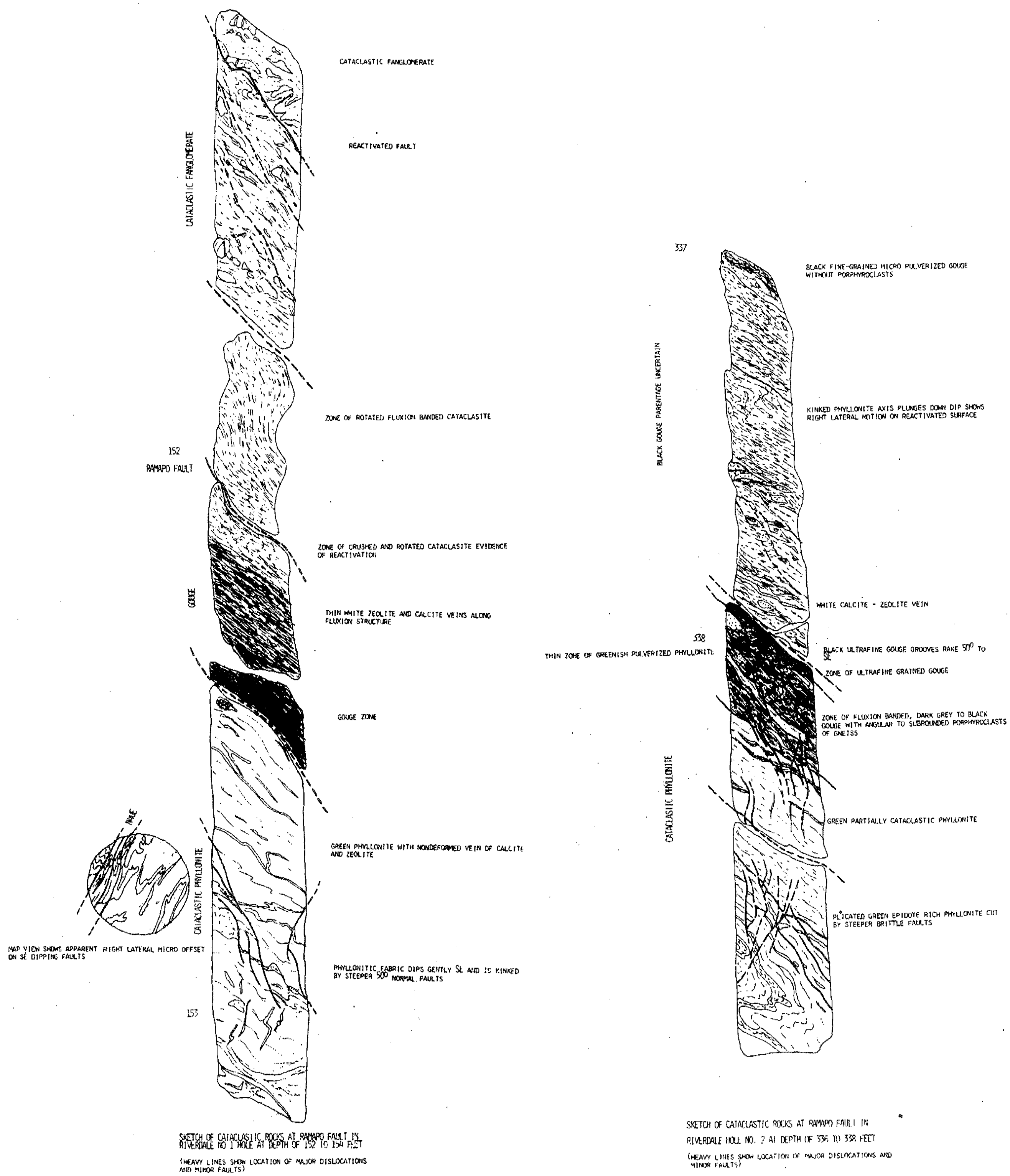


Fig. 7. Detailed sketches of cataclastic rocks from Ramapo fault at Riverdale drill site showing physical character of rock materials. Phyllonite penetrated below fault is material cropping out at ledges at Riverdale, Stop 2, and is traceable northward to next stop at Wanaque. The phyllonite is disrupted by post-Sinemurian faulting. The last recorded movement was of a normal kind. No evidence of reactivation as a reverse fault is seen. Cores are 2 in. in diameter.

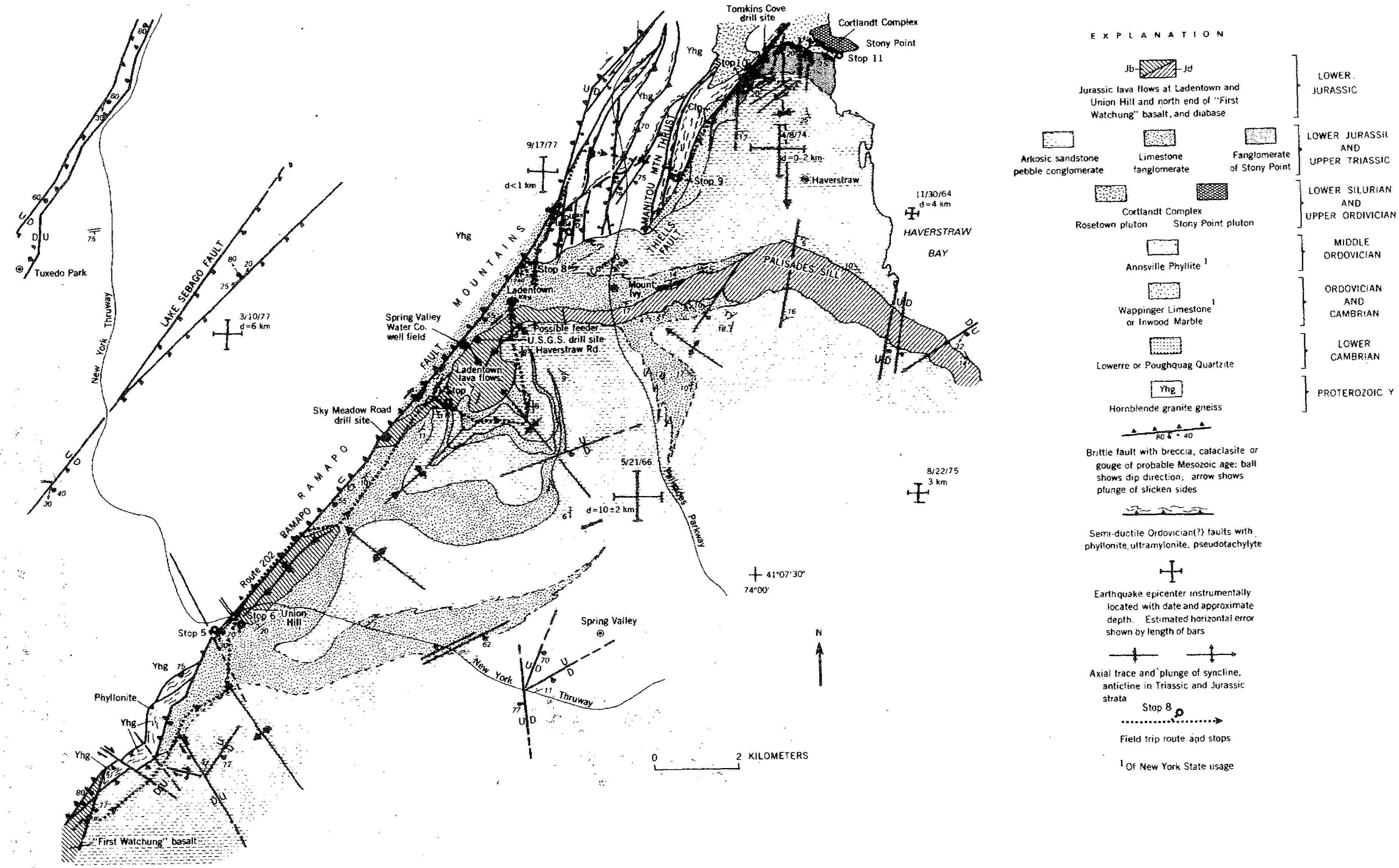


Fig. 8. Generalized geologic map of the northern part of the Newark basin showing probable physical connection of Palisades sill with lava flows of Ladentown and the apparent truncation of folded Triassic and Jurassic rocks by the flows. Brittle faults within and adjacent to basin record both right-lateral and left-lateral movements with northwest-trending faults the latest. Two sets of folds in the Triassic and Jurassic rocks have produced additional strain in Newark basin sedimentary rocks.

100 m north of the northern edge of the basin are found in the fanglomerate (Stop 11).

4. Boulders of local dike rocks from the Rosetown extension of the Cortlandt Complex have been found at three localities in the fanglomerate.

These observations suggest that the rocks now exposed at the surface in the footwall and hanging wall blocks could not have been separated greatly following Sinemurian deposition.

Intrusive activity in the northern Newark basin and origin of the lava flows at Ladentown

The Palisades sill (Walker, 1969) is intruded into Upper Triassic rocks of the Newark basin and has been dated by $^{40}Ar/^{39}Ar$ technique at 193 ± 9 m.y. (Dallmeyer, 1975). The Palisades sill crosscuts rocks as young as the basal part of the Lockatong Formation of late Carnian Age at the Hudson River but cuts up section possibly into rocks of Norian Age near Mount Ivy. Basaltic lava flows constituting the Watchung Basalt are Hettangian in age (Early Jurassic) based on palynomorphs (Cornet, 1977) and fish zonations (Olsen, this publication). Whole-rock K-Ar ages for the Watchung Basalt lava flows range from 193-136 m.y. (Houlik and Laird, 1977), but the ages younger then 193 m.y. are treatable only as minimum ages.

Pillow basalts and pahoehoe-type lava are exposed at Union Hill (Suffern) and at Ladentown at the north end of the Newark basin. Kummel (1898, p. 41) suggested that the Ladentown flows might be the result of a fissure eruption. Aeromagnetic, outcrop, and drill data suggest that the western end of the Palisades sill might extend westward as a feeder to the Ladentown lava flows. A gravity and ground magnetic survey done by students at Lehigh University working with Ken Kadoma in the critical area of possible connection, suggests that two near-vertical feeder dikes extend westward from the Palisades termination at the Palisades Parkway. Either one or both of these join with a possible feeder located at Camp Hill (see discussion Stops 6 and 7).

Mapping of the Ladentown exposures reveals abundant evidence for multiple flows, pahoehoe lava, and composite lava flows. Three main flow units separated by vesicular zones, are recognized. The basaltic rocks extend southwestward to the Ramapo fault where the lavas have been cored in two holes that document a thickness greater than 450 feet.

The Ladentown exposures are especially significant because of the apparent crosscutting relationship of the flows to structure in the underlying Triassic fanglomerate. Ladentown flows fill a structural basin produced by intersection of two fold systems, a longitudinal northeast-trending syncline parallel to the Ramapo fault and a transverse northwest-trending syncline (Fig. 8).

The base of the lava flows appears to decrease in elevation from northeast to southwest and to cut across, flowing in an apparent channel, northeast-dipping strata on the western limb of the longitudinal syncline. Pahoehoe tongues and lobate bulges suggest flow directions to the southwest down the apparent channel.

One possible interpretation of the data is that the Ladentown lava flows are a surface representation of the Palisades magma that was erupted from a fissure feeder onto already folded strata. Flowage of lava in a southwesterly incised drainage pattern resulted in ponding against the border fault in the vicinity of the Sky Meadow drill site. Pre-flow rotation of the Triassic strata could have been produced by drag on the border fault, causing the longitudinal northeast-trending syncline.

Subsequent northwest and additional northeast folding postdated the flows as the border fault was reactivated as a right-oblique normal fault as documented by core drilling at the Sky Meadow site.

Drill coring at the western edge of the Ladentown flows showed composite flows resting on black organic siltstone. This organic siltstone may have been deposited in sag ponds locally developed near the border faults.

If the above interpretation proves correct, then faulting and folding of Triassic strata preceded eruption of the lava flows at about 193 m.y. or earliest Jurassic time. These are the first observations that suggest that longitudinal folding near the border fault may have developed during sedimentation.

The presence of cobbles of basaltic pillows in association with the coarse boulders of brecciated dolostone seen at Union Hill (Stop 6), just beneath the lava flows suggests that basaltic activity preceded eruption of the flows at Mount Union. Boulder and cobbles of rhyodacite dikes found in alluvial gravels associated with fanglomerate from Ladentown south to the New York Thruway at Suffern can be traced to the Rosetown dike swarm found to the north in the Proterozoic and indicate that a southerly-directed drainage system was present near the border fault prior to eruption of the Mount Union-Ladentown lava flows.

Speculations regarding the folding of pre-Hettangian (lowermost Jurassic) strata adjacent to the border fault suggest that growth tectonics may be applicable to the Newark basin and that faulting and folding began before 193 m.y. ago or 20 m.y. before initiation of coherent, large-scale ocean-floor spreading estimated to have begun from ages of extensional dikes (May, 1971; Sutter and Smith, 1979). In the Hartford basin rotation of 191 m.y. old lava flows, sills and strata as young as Toarcian-Bajocian (late Early to early Middle Jurassic) preceded intrusion of the Fairhaven dikes at 175 m.y., or late Early Jurassic, which are not rotated (Sutter and Smith, 1979). Uncertainties in age assignments for stratigraphic units and dikes lead to the possible overlap in ages.

Despite extensive hydration of the Ladentown basalt, table 1, the TiO_2, Fe_2O_3, and SiO_2 values are comparable with values for the Palisades chill dolerite and to pigeonite dolerite corresponding to Palisades magma types 1 and 2 of Walker (1969). Total iron oxide for the Ladentown is distinctly lower than third Watchung basalts (Faust, 1975, table 2). The TiO_2 content and major-element chemistry of the basal flows of the Ladentown resemble magma types of Pennsylvania at Rossville and York Haven and the "First" and "Second Watchung" flow units (Black and Piburn, 1972; Smith, Rose and Lanning, 1975). Chemical analyses of Ladentown basalt (Geiger, Puffer, and Lechler, 1980) reportedly resemble closely the second Palisade magma type. They suggest, as did Savage (1968, p. 90), that the Ladentown flows are Palisades magma that erupted on the Early Jurassic land surface.

The available geophysical, geochemical and geologic data suggest that the Ladentown lavas represent a fissure-flow eruption fed by the Palisades sill or an offshot of the same magma chamber that fed the Palisades. The indications are that the lava extruded across previously folded and dissected Triassic strata.

If we can assume that the lava is 193 m.y. old (coeval with the Palisades sill), then we are looking approximately at the same level of erosion with respect to Palisades sill as existed in earliest Jurassic time.

If the sediments at the base of the lava flows are earliest Jurassic in age, then the total stratigraphic thickness of the sedimentary rocks at the north end of the Newark basin (northeast of Ladentown to Stony

Table 1 Chemical analyses of lava flows at Ladentown from base of lava flows, compared with Palisades magma and "Third Watchung" basalt.

	Palisades sill (Avg. chill dolerite) Walker 1969	Pigeonite dolerite	Ladentown lava flows from Haverstraw Road core: Center HR78*	Top of flow HR74	Pillow basalt HR31**	Pillow basalt HR23	"Third Watchung" basalt (Avg. 36 samples Faust 1975 Table 2)
SiO_2	52.0	50.18	49.2	46.3	49.9	51	49.4
TiO_2	1.2	1.57	1.1	1.3	1.2	1.1	1.3
Al_2O_3	14.5	14.63	14.2	16.3	14.7	13.3	13.58
Fe_2O_3	1.35	2.58	3.8	4.6	4.5	4.9	5.08
FeO	8.9	7.77	6.2	4.1	5.6	5.3	9.54
MnO	.15	.14	.23	.21	0.24	.22	.24
MgO	7.6	8.04	7.7	6.7	6.8	7.2	5.65
CaO	10.3	10.29	10.6	9.6	10.1	9.8	9.15
Na_2O	2.0	2.05	2.1	2.8	2.9	2.5	2.96
K_2O	.85	.60	.18	.37	.18	.39	.51
P_2O_5	.15	.25	.14	.16	.15	.15	.17
H_2O	1.05	1.66	4.0	.7	3.8	3.1	2.59
CO_2		nd	.03	2.2	1.1	.38	

* Sample taken for $^{40}AR/^{39}Ar$ dating by John Sutter

** Sample taken for $^{40}Ar/^{39}AR$ dating by John Sutter at 26 ft.

Point) is probably only 1,000-2,000 m thick and markedly thinner than equivalent age sedimentary rocks in the center of the basin. Olsen (this publication) estimates that approximately 5,000 m of Upper Triassic sedimentary rocks underlie the central part of the Newark basin and that this section thins to about 2,500 m at the eastern edge of the basin at the Hudson River near Jersey City.

If the Ladentown flows do correlate with the Palisades sill and with the "First Watchung" lava flow as shown on figure 1 then no rock younger than earliest Jurassic occurs in the Newark basin north of the Watchung syncline.

ROAD LOG

Field log begins from intersection of Route 78 and Garden State Parkway headed north from Newark on the Garden State Parkway.

Mileage

3.5 Turn onto 280 W. at E. Orange exit 145

7.5 Excellent crops of "First Watchung" basalt (Orange Mountain basalt in Olsen this guidebook) Minor faults strike N. 20° E. and dip 80° SE. and have broad shear zones with gouge and subhorizontal slickensides.

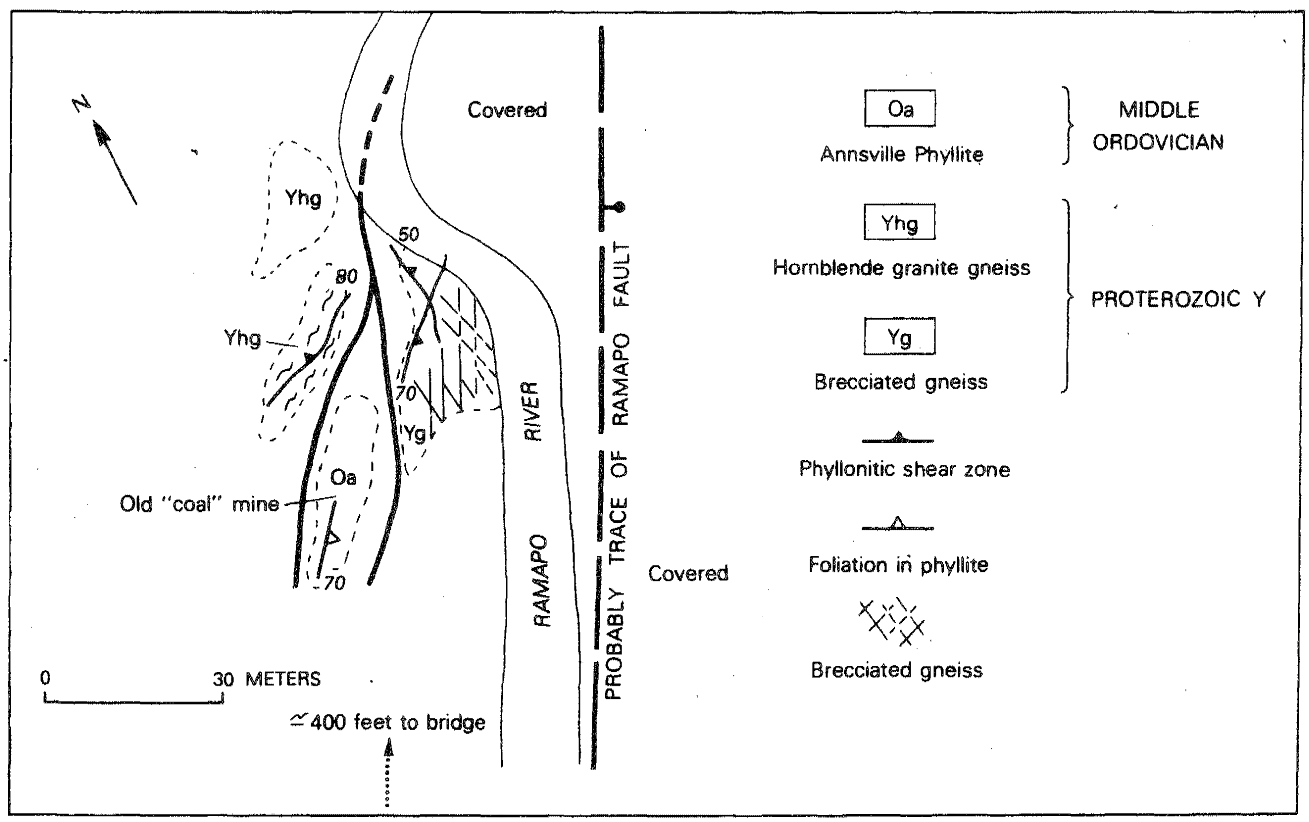
9.3 Crops of platy jointed basalts of Second Mountain (Preakness Mountain basalt of Olsen, this guidebook)

10.3 View in distance of Hudson Highlands and Ramapo fault escarpment.

16. Follow 287 to Boonton; watch for right turn.(See Fig. 5 for start of route).

23 Excellent crops of the conglomerate at Montville of Carlston (1946) here contain cobbles of hornblende granite gneiss, epidote veined cataclastic gneiss, "Franklin Marble", and abundant clasts of basalt. These deposits are the youngest rocks in the Newark basin.

23.8 End 287; take Route 202 to left.



[1] Of New York State usage

Fig. 9. Sketch of field relationship seen at Stop 4 where a sliver of "Annsville Phyllite" is enclosed between mylonitic shear zones. Brittle fractures, microbreccia and cataclasite at the east edge of the exposure illustrates Mesozoic fault fabrics.

25 Turn left on Waughaw Road in Towaco.

25.8 Turn left on Old Lane and crops of gneiss boulder conglomerate.

26.8 Stop at entrance to Mulbrook Lane.

Stop 1. Mulbrook Lane. Stop at end of circle - **Sliver of Cambrian quarzite phyllonite and Ramapo fault breccia**

At east side of circle is brown, very shattered, dioritic gneiss(?). To west up slopes by house are crops of vitreous quartzite of probable Cambrian age. Farther west, across small swale, are excellent crops of pale-green, phyllonite gneiss typical of the more ductile deformation zones in the Hudson Highlands.

Sericite, epidote, and needles of actinolite are found in the phyllonite which exhibits strong right-lateral strain slip folds. Ductile deformation is characteristic of these zones along the western edge of the Mesozoic basin.

This quartzite forms one of a series of similar slivers of Cambrian and Ordovician cover rocks that are found west of the Ramapo fault from Boonton north to Tomkins Cove and are interpreted as fault slivers within the ductile shear zones of pre-Mesozoic age. The phyllonite zone forms a continuous belt along the Ramapo to Riverdale where the shear zone may bifurcate with part of the zone extending northward into the Proterozoic rocks along the Lake Inez shear zone.

The cataclastic rocks east of the circle are more typical of cataclastic rocks associated with Mesozoic faulting on the Ramapo.

Return to bus.

27.8 Return to intersection Old and Waughaw Road; turn left.

28.2 Turn right on Indian Lane - low crops of what may be the 4th Watchung lava flow; excellent crops in gas pipeline.

28.6 Left on Jacksonville Road; follow road to right.

30 Turn left at intersection with Sunset Road.

31 Crops of fanglomerate. Optional Stop 1b.

1b. Optional stop. Roadcuts at entrance to golf course at Jacksonville.

Grey to greenish-grey coarse conglomerate (Jc) that contains fragments of "Franklin Marble", detrital graphite, coarse cobbles fragments of hornblende granite gneiss and epidote-veined phyllonite from the older phyllonite west of the Ramapo fault. To the south, a lava flow younger than the "Third Watchung" lava flow overlies fanglomerate. A waterwell drilled in 1979 penetrated 50 feet of basalt and bottomed at 130 feet in grey and red shale conglomerate near this site.

These sedimentary rocks and the lava flows are the youngest rocks known in the Newark basin, based on the palynology of Cornet (1977) who identified these rocks as Sinemurian (middle Early Jurassic).

The nonfolded outcrop pattern of these Sinemurian deposits as compared with the marked northwest-trending folds affecting the Watchung lava flows is notable. This suggests to me that the northwest crossfolds may have formed prior to cessation of fanglomerate deposition.

32 Turn left at stop sign, West End Road.

32.4 Mountain Avenue, turn right then left onto Boulevard Avenue.

33.6 Intersect Route 23, cross over, head west to traffic circle.

34.3 Just after traffic circle pull over to right. Stop 2 - cross over highway with caution to large sandpit. Bus will turn around and meet us on east bound side of Route 23.

Stop 2. Large sandpit southwest of traffic circle at Riverdale. (See Fig. 5,6,7).

Discussion of core drilling at Riverdale site and bedrock exposures of phyllonitic shear zones and epidote veined cross faults.

Excellent pavement exposures of phyllonitic hornblende granite gneiss and quartzite paragneiss can be seen. Isoclinal folds with axial planes of N. 35° E., 72° E. are crossed by crossfaults locally marked by epidote veins cross-faults N. 65° E., 72° SE., N. 30° W., 90°, N. 25° W., 85° NE. show predominant left-lateral and reverse movement.

At the south end of pit, a mylonitic grey, quartzose gneiss is crossed by small crenulations and down-to-east faults. Along the entire border fault, phyllonite where present near the Ramapo is crenulated and micro-faulted with veins of calcite and laumontite. This is typical of Mesozoic mineralization. The phyllonite predates the epidote-rich crossfaults that are of unknown age.

In the sand pits to the south, two continuous core drill holes penetrated the Ramapo fault, see figures 6 and 7. The fault offsets fanglomerate of probable Sinemurian Age of the hanging wall against phyllonitic gneiss of the ductile shear zone.

The actual fault is expressed by 1 cm of soft gouge, consisting of pulverized rock material. Below the fault, green phyllonite, like that seen in the exposures here, is crenulated and displaced on normal faults. Excellent recovery of the fault zone material has permitted thin section examination of the actual fault. The sawtooth contact is preserved showing down-to-the-southeast sense of movement with no evidence for reactivation since this last normal movement. Chlorite-coated surfaces, microbreccia and cataclasite, and "mylonitic" cataclasite with a pronounced fluxion structure are common in the cores. The actual fault is remarkably sharp and well defined in each core. The fault dips 50° SE. assuming a N. 40° E. strike as indicated from outcrop data to the south.

Sections of the actual core will be available for inspection. PLEASE DO NOT REMOVE CORE FROM BOXES.

Route 23 east, enter traffic circle, 270° to left; take Newark Boulevard north toward Riverdale.

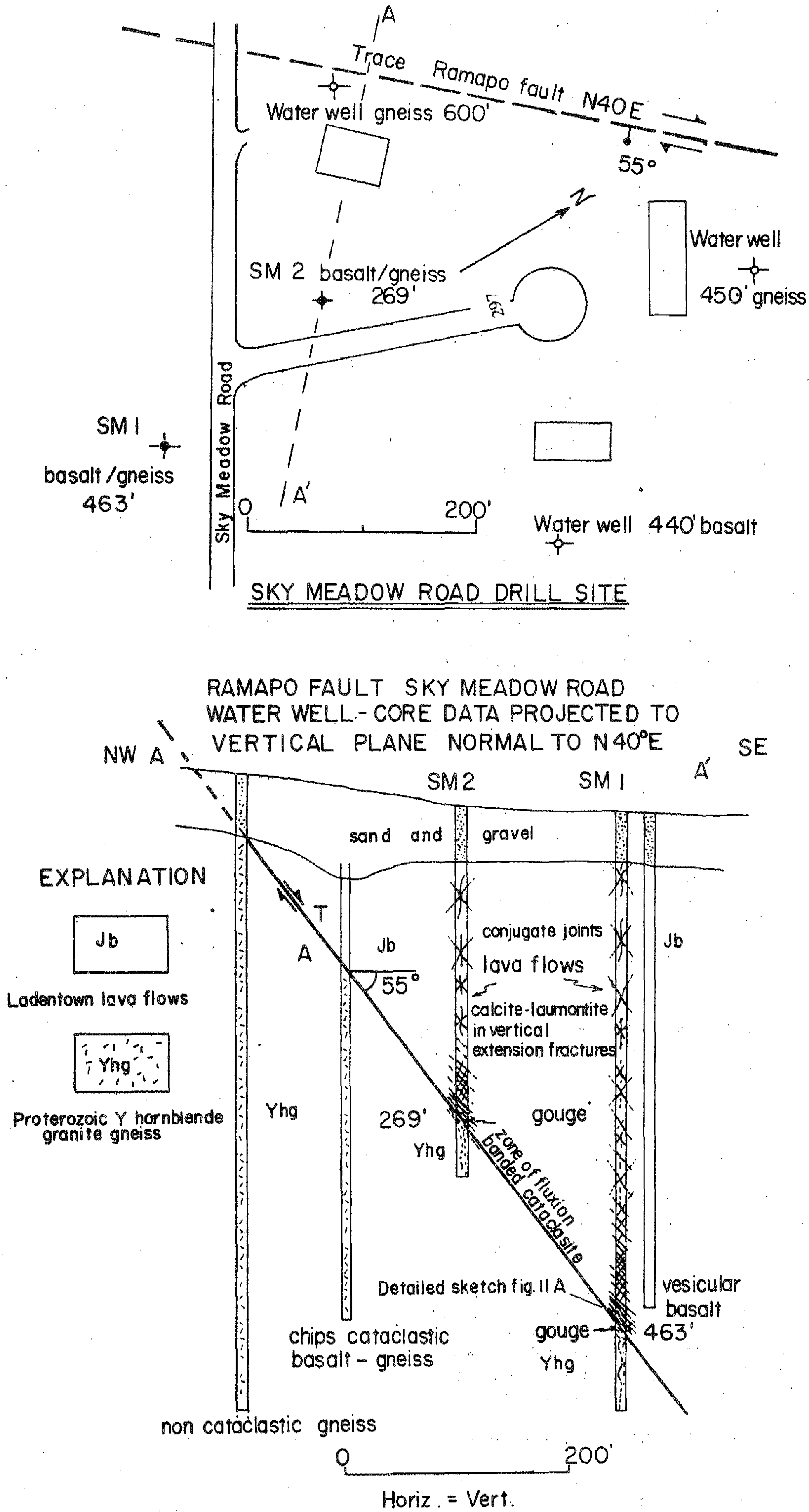


Fig. 10. Generalized diagram showing location of drill holes and water-well data penetrating Ramapo fault at Sky Meadow Road site.

35.6 Turn right at intersection for Pompton Lakes.

36.4 Turn left on Riverdale Road to Wanaque.

40.0 Turn right on Belmont Avenue just after WANA-Q Pizza, follow circuitous route to small cottage at north end of sand pit. Walk east from cottage to opening in sand pit.

Stop 3. Lake Inez shear zone exposures in abandoned sandpit.

Pavement exposures of phyllonitic, amphibolite gneiss and pink pegmatite show right-lateral displacement of pegmatite on N. 15° E., 30° SE. dipping shear zones. Chlorite, epidote and sericite mark phyllonite zones. Later cross faults N. 65° W., 60° SW. show left-lateral displacement of shear zones and are marked by veinlets of epidote. This is the northerly extension of the same shear zone seen at Stop 2.

Up the hillside to the east, exposure of gneiss show reactivation of gneissic layering. Within this area, all suitably oriented surfaces, gneissic layering, mylonite zones and more brittle thrust faults all show evidence of reactivation in the Mesozoic movement sense. Widespread reactivation in this area follows the steep northeast-trending structural grain developed in "Grenville" and Taconic tectonism.

Log resumes at Belmont and Riverdale Road, turn right on Riverdale Road.

43.1 Turn right on Skyline Drive - excellent crops in Erskine area show abundant brittle faults as well as more ductile ones. Reactivation has been widespread.

45.8 Near crest of hill at gas pipeline epidote-filled cross fractures with excellent wear grooves suggest Mesozoic reactivation.

48.2 Stop sign; turn left and cross River; follow signs to 202 north.

50.1 Exposures of faulted basalt, turn left on Navajo Road, bend around south shore of Crystal Lake and turn right on Lenape Street.

50.3 Park at bridge west shore. Stop 4.

Stop 4. (Optional stop) "Coal Mine"

Reports from a desultory mining operation in the late 1800's refer to small coal prospect on the west bank of the Ramapo River ¼ mile north of Crystal Lake.

This exposure is a sliver of coal black graphitic phyllite ("Annsville Phyllite") similar to the exposure along the border fault at Riverdale. Sketch map figure 9 shows the relations. The sliver of black phyllite is found between two outcrops of gneiss. Very mylonitic gneiss is located to the west. Gneiss exposed east of the sliver has a composite fabric with brittle fractures and abundant microbreccia. The relationships seen here are similar to those seen at Stop 1 and those to be seen at Stop 9 on the Thiells fault. The brittle fractures are spatially related to Mesozoic faulting; the more ductile shears are associated with thrust and strike-slip faulting of probable Ordovician age and represent the southwestward extension of the Canopus zone fault exposed north of the Newark basin. Drill holes for water wells about 400 feet north of this site penetrated granite gneiss in holes 500 feet east of this locality. The "Annsville Phyllite" inclusion does not occur within the Mesozoic border fault but lies west of it as part of the footwall block.

50.5 Return to Route 202, turn left.

58 Turn left under RR tracks; follow Route 202 north to Suffern.

58.6 Stop opp[illegible] Room Restaurant. (See fig. 8 for location).

Stop 5. Optional Stop. **Cataclasite and fault fabric in cataclastic gneiss at Ramapo fault, Suffern.**

These small exposures of black, chlorite-coated, cataclastic, hornblende-granite gneiss are much more instructive than the exposures north of Suffern commonly visited by field trips. Excellent chlorite-slick surfaces dip in conjugate fashion northwest and southeast and exhibit down-to-the-south right-oblique slip on southeast-dipping surfaces and down-to-the-west and left-oblique movement on southwest-dipping surfaces. The near-vertical attitude of the extension fractures here and in the Sky Meadow drill core suggests that the rocks of the footwall block have not undergone rotation after formation of the cataclastic fabric.

58.9 Right on LaFayette Avenue, continue past circle to entrance to N.Y. telephone building - park in lot.

59.2 Stop 6 - Plaza Stone Quarry - Union Hill

We are permitted entrance with the clear understanding that we will not attempt to enter the quarry proper. Please respect the owners' wishes. Use extreme caution near steep cliffs on west side of exposure.

Stop 6. Union Hill trap quarry and contact of lava flows with fanglomerate.

Superb exposures at the south end of the quarry near the rock crushers show a vertical wall of coarse fanglomerate, enclosing a large boulder of brecciated dolostone in an apparent channel that, in turn, is overlain by an upward-fining cycle ending in fine red shale with greenish slate chips. Vesicular pillow lava directly overlies this shale.

Clasts in the fanglomerate include epidote-rich hornblende granite gneiss, Silurian Green Pond conglomerate, dolostone clasts, and several cobbles of basalt pillows. I interpret the large boulder as a block of breccia from the border fault, and the clasts of pillow basalt as blocks eroded from the southward-advancing Ladentown lava flows.

In the Ladentown-Suffern area, alluvial deposits such as those seen here contain boulders of felsic dikes uniquely traceable to the Rosetown dike swarm. These data indicate, as do the observations at the next stop, that a southerly-directed Jurassic drainage system was present near the border fault prior to eruption of the flows at Ladentown and Mount Union. Perhaps the debris flow material seen here are earthquake-activated deposits formed immediately prior to extrusion of the Ladentown basalt. The basalts seen here are correlated with basalts of the "First Watchung" on the opposite limb of the Suffern cross anticline.

59.7 Return to traffic circle on LaFayette; turn right on 202.

63.0 Sky Meadow Road - drill site is at base of mountain to left.

63.6 Limekiln Road; turn right; stop at top of hill.

63.8 Stop 7

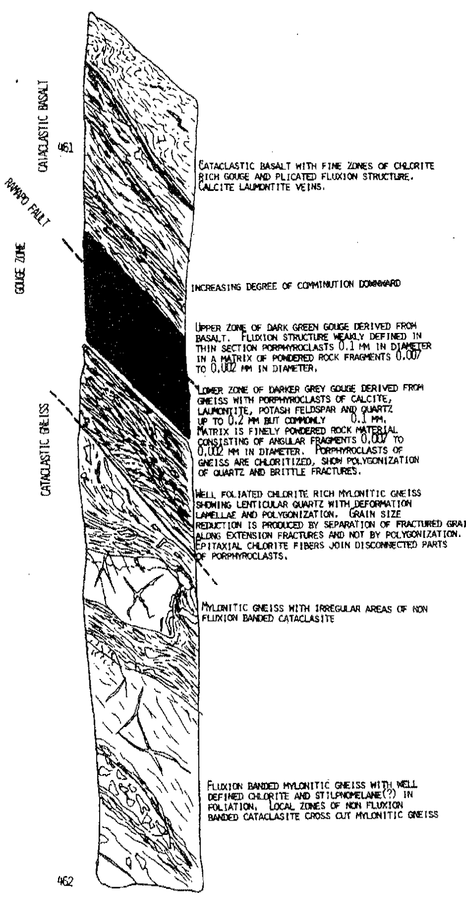
Stop 7. Basalt at Ladentown and discussion of drill data from the Ramapo fault.

Note exposures and attitude of red quartz-pebble arkose by road and walk north to ridge behind house. Multiple basaltic lava flows with pahoehoe tongues and snouts as well as small pressure ridges may be seen. BE VERY CAREFUL NOT TO DISLODGE BLOCKS THAT WOULD TUMBLE INTO THE BACKYARDS OF THE HOUSES BELOW. Flow direction obtained from similar exposures suggest that the lava flows were flowing southwest toward the border fault and that the base of the lavas flows are at lower elevations to the southwest.

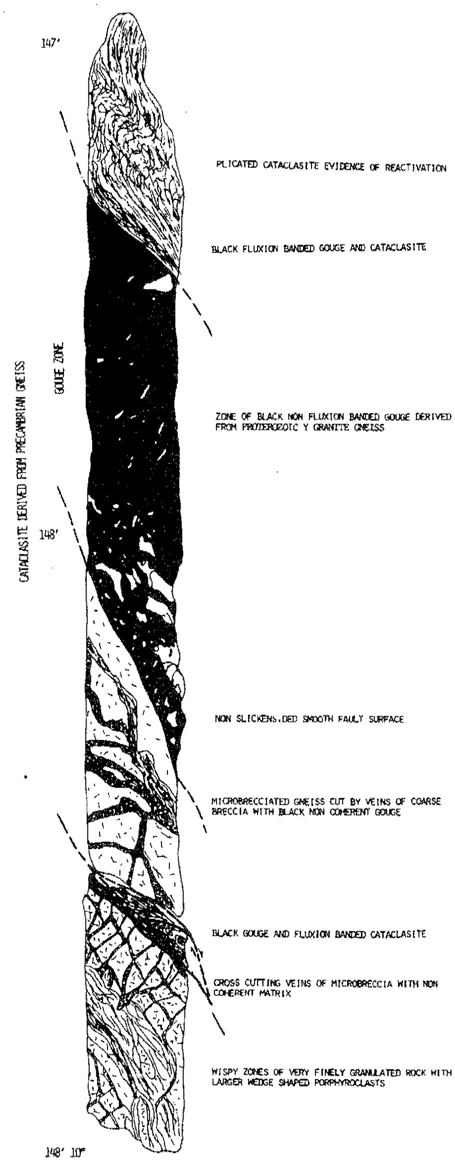
Drill-core data from Sky Meadow Road suggest that vesicular lava and multiple flows of lava more than 450 ft. thick accumulated near the border fault. These speculations would require a local relief in the basin adjacent to the border fault of approximately 450 ft.

Results of the drilling of the border fault will be discussed (see text).

Continue east on Limekiln.



DETAILED SKETCH OF CATACLASTIC ROCKS IN SKYMEADOW CORE HOLE 1
AT RAMAPO FAULT (DRAWN TO SCALE)



SKETCH OF CATACLASTIC FANGLOMERATE AND GRANITE GNEISS FROM TRIASSIC BORDER FAULT AT DEPTH OF 146 TO 199 AT HOYT CEMETARY, STONY POINT

Fig. 11. Detailed sketches of cataclastic rocks seen in drill cores across Ramapo fault at Sky Meadow Road and at Hoyt Cemetery, Stony Point drill core 2 in. in diameter. A - Sky Meadow Road; B - Cem. No. 1, Stony Point.

Excellent pavement outcrops of limestone.

64.2 Fanglomerate found immediately below Ladentown lava flows (optional stop) just past intersection.

65.0 Light turn right on Route 306.

66.5 Route 202 continue straight across to Ladentown.

66.7 Bear right then left on Call Hallow Road.

68.0 Turn right on access road leading up to watertank. Stop 8.

Stop 8. (Optional stop). **Excellent exposures of Mesozoic fault features on Cheesecoate Mountain north of Newark basin and view of Newark basin.**

This block of Proterozoic gneiss lies east of the Ramapo fault but west of the Thiells fault. It may represent a horst of basement rock that was structurally high during Triassic sedimentation. The principal argument in favor of this contention is the dominance of northeast-striking faults that appear to pass into the basin but do not disrupt the continuous belt of intrusive and extrusive lava.

Continue north on Call Hallow Road to Willow Grove.

69.7 Turn right on Willow Grove Road, pass under Palisades Parkway. We are traversing a belt of gneiss that possibly forms a horst block between the Ramapo fault and the Thiells fault.

71.0 Turn right on Hammond Road.

71.7 Stop at intersection of Suffern Lane at Thiells. Stop 9.

Stop 9. Thiells fault.

This small but significant exposure (Fig. 12) illustrates well the difference between Mesozoic faults as seen in drill record and the older mylonitic faults of probable Ordovician age. The Thiells fault is an oblique-thrust fault that juxtaposes the Manhattan Prong rocks against those of the Reading Prong. Abundant ultramylonite, pseudotachylite, and mylonite with metamorphic mineralization affects Proterozoic Y and Paleozoic rocks everywhere along the fault. Figure 12 shows the structural relationship exposed in the small quarry behind the houses.

K-Ar data on sericite that replaces mylonitic quartzite yields an age of 379 ± 13 m.y. (386 m.y. using newer constants). K-Ar data on pseudotachylite from a locality to the north gave an age of 259 ± 9 m.y. (264 m.y.). The mylonitization and sericitization associated with the fault are totally unlike that found on any proven Mesozoic fault.

Fracturing in the quartzite at the east side of the exposure may be related to Mesozoic faulting. The similarity of this exposure to that seen at Stop 1 is striking.

Return north on Hammond Road to stop sign.

72.4 At Willow Grove Road, turn right.

72.6 Turn left on Goethius Bridge Road.

73.3 Continue north to Route 210 intersection and Stop 10.

Stop 10. Triassic quarzite-rich fanglomerate and cataclastic Annsville at Cedar Pond Brook, Stony Point. (See fig. 14 for location).

Exposures of black cataclastic "Annsville Phyllite" may be seen at the banks of the small pond west of the dam. Thin-section examination of the east-dipping fabric reveals up-from-the-southeast microdisplacements and abundant clinozoisite and sericite replacement veinlets. This fabric is associated with the Thiells fault that crops out to the west.

A light-colored conglomerate of uncertain origin overlies phyllite and contains fragments of brecciated "Wappinger Limestone" and "Annsville Phyllite". This conglomerate may be a basal triassic conglomerate deposited unconformably on the cataclastic "Annsville Phyllite". Light-grey carbonate-rich conglomerates similar to this are found along the unconformity at Tomkins Cove to the north.

Large crops of coarse fanglomerate are seen at the dam to the northeast. Quartzite clasts dominate. Cambrian Poughquag Quartzite crops out 1,000 ft to the west where it forms an unconformable cover on the gneiss of the Hudson Highlands west of the Thiells fault. This suggests very local source area for the fanglomerate and further suggests that little post-depositional separation has occurred in this area.

Drill data from cores and trenches 800 ft to the north are shown in figures 13 and 11. A normal fault dipping 70° SE. was intercepted in two vertical drill holes. Cataclasite and gouge typical of other Mesozoic faults marked the fault zone. Unexpectedly, gneiss forms the footwall in Cem. 1. A possible interpretation of the data is shown in figure 13. It is notable that none of the distinctive ultramylonitic rocks seen at the Thiells fault (Stop 9) were found at the border fault. This illustrates the difference between Mesozoic brittle fault products and ductile fabrics of Ordovician faults.

Turn right on Route 210.

74.3 Route 9 W turn left.

74.9 Turn right at sign marking entrance to Stony Point Battlefield.

76.0 Continue to entrance to park at RR tracks and park. Stop 11.

Stop 11. Fanglomerate at Stony Point at northern end of Newark Basin.

Limestone fanglomerate unconformably overlies Inwood Marble and "Annsville Phyllite" along the east-west Triassic outcrop belt at Tomkins Cove. Exposures in the railroad cut along the slopes contain inclusions of dolostone traceable to the immediately adjacent dolostone in the Tomkins Cove quarry. Small chips of distinctive biotite-rich hornfelsed Manhattan Schist typical of the contact facies bordering the Cortlandt Complex have been found in the fanglomerate at this locality. Very local sediment sources are suggested by these data.

END SATURDAY TRIP

ROADLOG FOR SUNDAY TRIP

Assembly point is entrance to Stony Point Battlefield; same location as end of Saturday trip. (See fig. 14 for location).

For early arrivers, a brief tour of the exposures of the Cortlandt Complex in the park will be possible.

Mileage

Leave Stony Point Battlefield

0.5 Turn right on 9W

1.0 Turn right at entrance to Hudson River Aggregates Tomkins Cove quarry - drive to entrance and wait for guard to open gates.

Hard hats are required - no climbing of talus slopes and *please* stay away from overhanging walls.

Stop 12 Tomkins Cove quarry in "Wappinger Limestone" (Inwood Marble) and fault exposures north of the Newark basin.

This large quarry in "Wappinger Limestone" (Fig. 14) forms the axial portion of a westward overturned anticline bordered by "Annsville Phyllite" on the west and Manhattan Schist unit A on the east.

Well-layered beige-to-tan weathering quartzose dolostone with phyllite partings forms the central part of the quarry and is bordered on the west by southeast-dipping overturned but highly folded light gray nonquartzose dolostone and black phyllite.

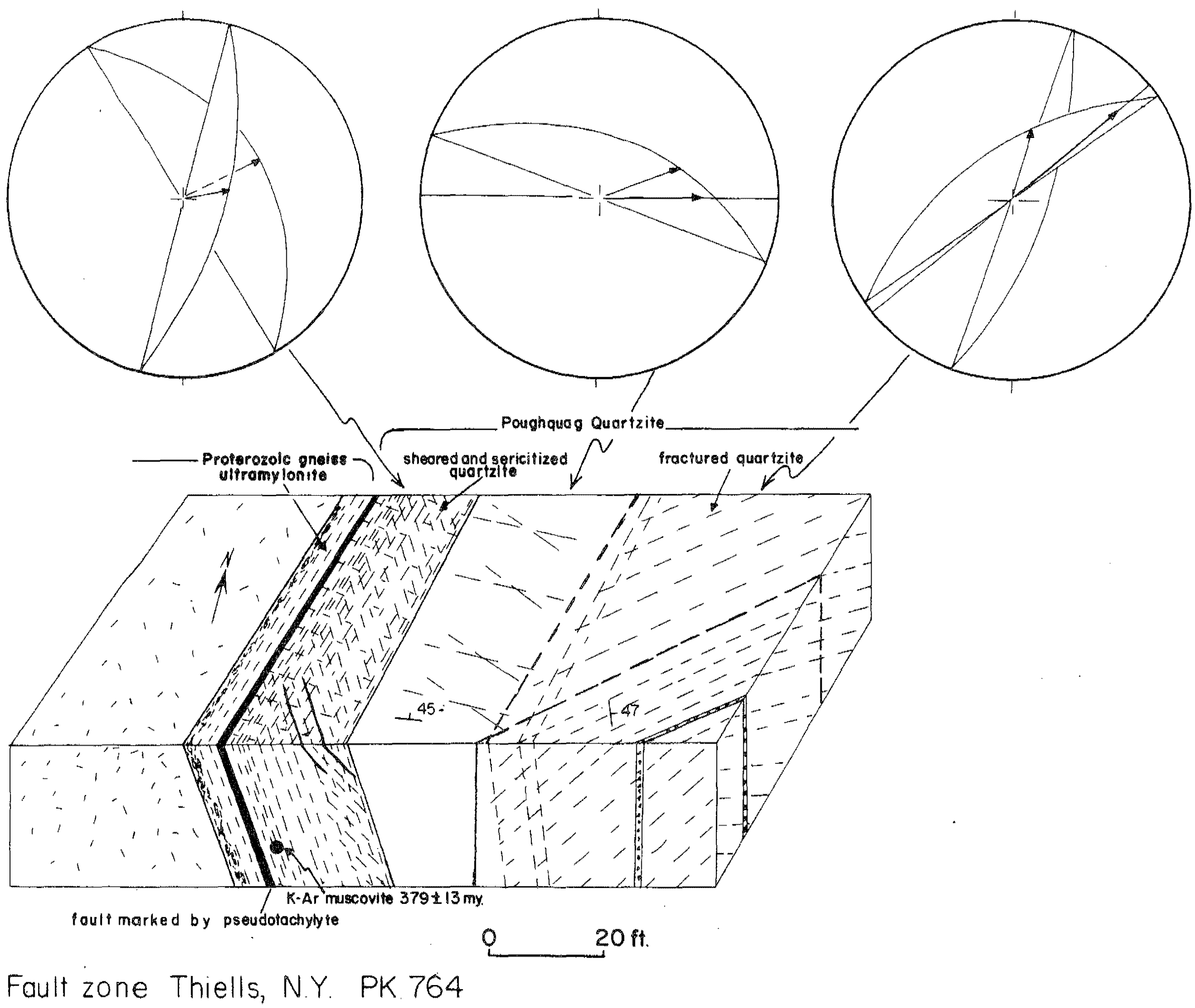


Fig. 12. Block diagram of fault at Thiells, N.Y., showing intensely developed zone of ultramylonite, and pseudotachylite at contact of Cambrian Poughquag Quartzite and Proterozoic Y hornblende granite gneiss. Sericitization is pronounced in ultramylonite and in Poughquag immediately east of fault. Nonaligned muscovite replacing quartz in the fault zone yields a K-Ar mineral age of 379±13 m.y. Lower hemisphere equal-area projections of dominant shears in three areas, and some lineations are shown.

The muscovite age yields a minimum age of the faulting at this locality. Because the same fault offsets rocks as young as Middle Ordovician to the north, the fault is Late Ordovician to Devonian in age and is regarded as a Taconic fault.

Planetable mapping of the quarry at 1″=200 with structural geology students at City College has shown that straight forward correlations of units across the quarry is not possible because of eight major fault zones that disrupt the structural continuity. These faults are expressed by red or green zones of clay gouge and phyllonite. Several of these features can be seen on the south face of the quarry exposed in all three levels.

Structural analyses of the fabric associated with these faults indicate that most are southeast-dipping reverse faults with left-lateral or right-lateral components of movement. Minor folds within shear zones plunge steeply down the dip of fault surfaces, commonly normal to slickensides. Faults are located on the limbs of isoclinal overturned folds exhibiting excellent metamorphic fabric and ductile fold styles.

Despite the young looking nature of these faults they appear to be compressional features formed during Taconic dynamothermal metamorphism. Reactivation may have produced the clay gouge and slickensides locally.

Within the quarry, at the extreme west in corner of level 2 and near the southeastern corner of level 3, N.S. steep north-trending faults offset the older clay gouge zones and produce drag folding of older slickensided surfaces.

The western fault is coated with fibrous palygorskite that forms an excellent slickenside lineation. K-Ar dating of this mineral by H. Kruger yielded an age of 183 ± 31 m.y. These data suggest that the prominent clay gouge seams seen in the quarry are older than 183 ± 31 m.y., The palygorskite-coated fault probably is Mesozoic. The fact that the red claygouge thrust fault zones are not recognized in the Triassic rocks immediately overlying the dolostone to the south also suggests that the main faults seen here are pre-Mesozoic in age.

From these observations, I conclude that the faults seen here are (1) Ordovician thrust faults possibly reactivated in Triassic time to produce gouge, and (2) steep Mesozoic normal and strike-slip faults.

If it were not for the K-Ar age from the palygorskite one might suggest that the clay-gouge zones represent zones of current thrust reactivation in the present compressive stress field related to present-day seismicity. This stop illustrates well some of the complexities in correlation of seismic events with fault surfaces. Any one or all of the faults seen in this area (Stop 9, 10, 12) and shown on figure 14 might satisfy the available fault plan solutions (see fig. 2) available for this area.

Turn right on Route 9W. Log resumes.

Continue north past outcrops of mylonite biotite gneiss and amphibolite of Ordovician fault zones.

2.8 At swale, trace of Mott Farm Road fault and cataclastite typical of Mesozoic faults trending N. 70°-80° E. View of Indian Point reactors to east.

Long up-grade traverses hornblende granite gneiss and abundant semiductile faults with associated lamprophyre dikes on Dunderberg Mountain.

5.8 In swale, trace of Timp Pass fault zone of a composite fault zone with evidence of Proterozoic Y, Paleozoic and possible Mesozoic fault activity. This is a major fault that is traceable northeastward through the Hudson Highlands as a metamorphic semiductile fault zone. Very distinctive blastomylonite and a zone of intense folding accompanied by injection of pegmatite mark this fault in many localities. Excellent exposures here of tectonic breccia with inclusions of calcsilicate rocks in a ductile matrix of marble.

6.5 Take Bear Mountain Bridge and turn right south on Route 6 and 202. Note excellent exposures of rusty paragneiss and calc-silicate rock with typical Mesozoic fault fabrics. Exposures of quartz plagioclase gneiss, amphibolite and white alaskite gneiss. Numerous semiductile faults are present in this area.

8.8 Pull off at overlook - view of Hudson River, Dunderberg Mountain and discussion of regional fault patterns.

Stop 13

In the nearly continuous exposures along Route 206 from the Bear Mountain Bridge south to Camp Smith numerous faults have been mapped. These faults are predominantly the semiductile type with excellent phyllonite zones and abundant evidence for right-lateral oblique thrust faulting. Correlation of tectonic features across the Hudson to Dunderberg Mountain is excellent and northeast-trending Mesozoic faults are largely absent. Mesozoic faults are predominantly north- and northwest-trending suggesting that the left-handed bend in the Hudson River here is controlled by brittle fractures of Mesozic age.

These outcrops of biotite granite gneiss are not clearly either "Storm King Granite" or "Canada Hill Granite". However, intrusive relationship in amphibolite can be seen in the roadcuts. A comparison of this rock with the "Reservoir Granite" seen at the next stop is in order.

9.7 Excellent exposures of amphibolite, alaskite, and hornblende granite gneiss ("Storm King Granite") may be seen at sharp bend in road.

11.2 Entrance to Camp Smith and trace of a major semiductile fault--Wallace Pond fault.

At traffic circle bear right on Route 6 and 202; follow 202 and 6 right after bridge. Annsville Creek.

12.3 Pull off at overlook. Stop 14.

Stop 14. "Reservoir Granite" and mylonite zones

The "Reservoir Granite" (Berkey and Rice, 1919) is a widespread granitic rock type east of the Canopus fault zone. Doug Mose has dated a collection of rocks from this locality and from northeast of here and obtained an Rb/Sr isochron of approximately 1250 m.y. for both collections (Helenek and Mose, 1976). The granite has intrusive contacts with amphibolite with which it is commonly associated and may represent either remobilized felsic volcanic rocks (interlayered with amphibolite) or truly intrusive granite.

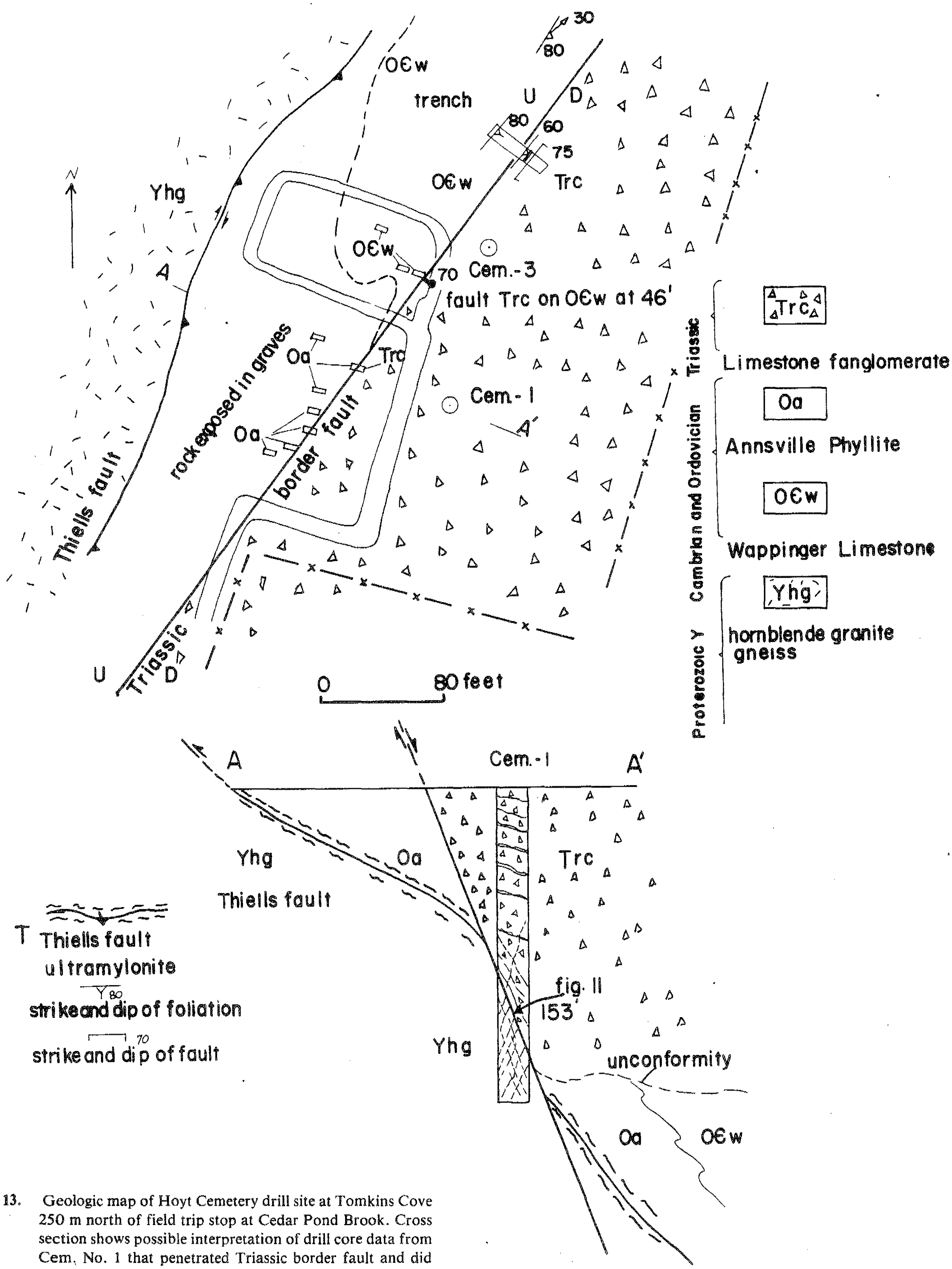


Fig. 13. Geologic map of Hoyt Cemetery drill site at Tomkins Cove 250 m north of field trip stop at Cedar Pond Brook. Cross section shows possible interpretation of drill core data from Cem. No. 1 that penetrated Triassic border fault and did not cross ultramylonite or mylonite such as that seen at Stop 9.

Excellent mylonite zones cut this garnet-bearing granite. Biotite-rich blastomylonite zones contain syntectonic garnet and intrafolial folds indicating right lateral movement. "A" lineations are subhorizontal. The granite gneiss has biotite and muscovite growing in ductile shear zones and garnet is retrogressively altered to biotite. This tectonic fabric probably represents Ordovician retrogression. The regional grade in Middle Ordovician rocks at this locality is between biotite and garnet zone.

12.5 Exit for Route 35 turn left and return north on Route 6 and 202, continue north to traffic circle and follow Route 9 north.

16.0 Low road cuts of phyllite.

Stop 15. Optional **Annsville fault - tectonic breccia**

Exposures of marble with rounded inclusions of gneiss were cited by Bucher (1957) and by Ratcliffe (1971) as evidence for Middle Ordovician erosion beneath the "Annsville Phyllite". I have changed my opinion of this strange rock and interpret this polymict breccia as a tectonic-mylonitic breccia resulting from large-scale extension and flowage in Proterzoic shear zones. Dismembered calc-silicate rocks form the inclusion within the strongly flow-banded marble. Breccias like this are present throughout the Hudson Highlands and are not restricted to zones of Paleozoic faulting.

A fault between "Annsville Phyllite" and this marble is exposed on the north side of these cuts, where the flow-banded marble is dragged in right-lateral sense into the N. 40° E.-trending Annsville fault. Right-lateral minor folds in fluxion banded rocks and minor thrust faults suggest right-lateral, oblique thrust faulting. Exposed contacts in the sand pits to the north, reveal ribbon-quartz mylonite and diapthoritic phyllonite. Syntectonic muscovite, tremopite, actinolite, epidote, and phlogopite are formed in sheared rocks of appropriate composition.

I interpret the Annsville fault as a post-Middle Ordovician, probably Late Ordovician fault, perhaps equitable with the Thiells fault.

Numerous earthquakes have been recorded in the Annsville area, most recently in January 1980 (Fig. 1). Despite the repeated activity, faults of probably Mesozoic age are largely absent. Faults seen at the surface are all characterized by mylonitic-ductile deformation. The northeast-striking, southeast-dipping phyllonitic shear zones satisfy the available fault-plane solutions.

Turn right for Annsville and turn left after light onto Spout Brook Road and follow this north to intersection with Gallows Hill Road. Turn left. Continue north to Continental Village, take right fork.

19.0 Park at aqueduct crossing

Stop 16. Canopus pluton and western Canopus fault: a probable Proterozoic Y fault zone. (See figs. 16a,b,c and 17

Road cuts of quartz monzonite and granodiorite of the Canopus pluton. Large rectangular microcline-perthite phenocrysts, showing Rapikivi-like mantles. produce a striking igneous lamination trending north to northwest. Ductile shear zones related to the Canopus fault show right-lateral drag of the older fabric. Locally small pegmatite dikes crosscut augen, gneiss and sheared igneous rocks.

The Canopus pluton has been interpreted as a Proterozoic Y syntectonic pluton on the basis of Rb/Sr and K-Ar dating by Dick Armstrong (Ratcliffe and others, 1972). The pluton is deformed in a right-lateral shear couple.

19.5 **Stop 17 Mylonite gneiss in western Canopus fault**

Strongly mylonitic gneiss at the eastern border of the Canopus pluton are exposed in the road cuts. Biotite-rich blastomylonite and more felsic, mylonitic, quartz-feldspar layers produce a strikingly well-layered rock. Reclined, right-lateral, isoclinal folds plunge steeply southwest in the N. 20° E., 80° SE. dipping shear fabric. A strong lineation is produced by the intersection of compositional banding and mylonitic foliation. The tectonic fabric seen here is restricted to local shear zones of Proterozoic Y age.

Continue north.

21.2 Turn right, follow sharp bend in paved road.

21.3 Turn left on dirt road.

22.3 Turn right on paved road.

22.5 Park on shoulder opposite H. Abrams house.

Stop 18 Eastern Canopus fault and overprint by probable Paleozoic fault fabric of the Dicktown fault. (See fig. 17)

Walk east to base of small cliffs.

This is a complex fault zone, consisting of pink and black biotite-rich augen, gneiss, biotite-rich blastomylonite and intrusive pegmatite. Excellent right-lateral folds, adjacent to ductile shear zones, plunge S. 45° E.

A dark-gray mafic dike crosscuts sheared gneiss and blastomylonite. Metamorphosed dikes like this one are common throughout the Hudson Highlands and are possibly of Proterozoic Z age. Chemically these dikes are distinct from lamprophyres and from Triassic diabases and are currently being studied. No definitive age data are currently available. However, K-Ar whole-rock dates range from 900 m.y. to 240 m.y. in six samples. The fact that they are metamorphosed, locally foliated, and confined to rocks of Proterozoic age suggests that they are old dikes. A series of small mafic stocks, dikes and small plutons are recognized in the Highlands in the vicinity of the Canopus pluton. Those igneous rocks are mafic to ultramafic and always are strongly metamorphosed. These mafic rocks and plutons represent a very obscure period of igneous activity in the Hudson Highlands but appear to be post- to very late syntectonic in the Proterozoic Y deformation. Locally they are extremely abundant.

A traverse up the hill from this point is instructive and shows increasing progressive overprinting of the Canopus fault fabric by the Annsville-Dicktown fault. In the Dicktown fault zone biotite and garnet are retrograded to chlorite and chlorite rich phyllonite is common. The contrast in the metamorphic grade of a retrogressive mineral assemblages within mylonite rocks may be useful in distinguishing Proterozoic Y faults from Ordovician ones in this area. To the east the Paleozoic grade increases to sillimanite zone and mineral assemblages within mylonites of both Proterozoic Y and Paleozoic age are not distinguishable. Outcrops at this stop, however, are well within the area of relict Proterozoic Y Ar^{40}/Ar^{39} biotite ages obtained by Dallmeyer and Sutter (1976). These data suggest that the Proterozoic rocks of this area never were heated above the biotite blocking temperature of approximately 350°C since the late Proterozoic. These data are consistent with the assignment of the biotite-rich blastomylonites seen here and at Stops 15 and 16 to Proterozoic Y fault zones. Chlorite-rich phyllonite associated with the Dicktown fault, however, is probably Ordovician.

Throughout the Canopus zone east to the California Hill fault (Fig. 1), no faults having Mesozoic fault characteristics have been recognized, despite detailed mapping. However, as at Annsville, earthquakes are recorded from this zone. The event near the California Hill fault (Fig. 1) is associated with a zone of very ductile, probably Proterozoic faulting.

Faults commonly dip 80° SE. or NW. but locally may dip 60° SE. These tectonic features (Figs. 1 and 4) probably extend through the continental crust and must be present as significant inhomogeneous (weak) zones at depths of 1-10km where earthquakes are occuring. I interpret this highly faulted zone as the ancestral grain that localized Mesozoic faulting in the area to the south traversed on the first day of this field trip. (See fig. 16c)

Turn around and return north on Dennytown Road.

23.5 Bear left on Dennytown Road at Y intersection.

27.5 Intersection Route 301 at Fahnestock Corners. Turn right. Exposures of "Canada Hill Granite" and rusty biotite-sillimanite paragneiss typical of the western block of the Hudson Highlands.

29.5 Canopus Lake - crossing Dennytown fault that marks the beginning of Canopus fault zone, crops of rusty paragneiss, amphibolite marble, calc-silicate rock, and magnetite-bearing quartzite.

30.5 Entrance to Canopus Lake beach area, park at swimming area north end of lake.

Stop 19. Dennytown fault, Poughquag Quartzite inlier (See figure 1 for location)

This exposure marks the southwestern limit of a series of faulted slivers of basement gneiss and Poughquag Quartzite that extend southwest from the front of the Hudson Highlands along the Dennytown fault. These inliers are surrounded by phyllonite zones marked by chlorite-sericite-epidote mineralization and ductile fold styles. Fold axes, within phyllonite plunge southeast in 80° to 60° SE. dipping surfaces. Excellent right lateral offsets and folds are seen in thin section and outcrop. A northeast plunging "a" lineation defines the probable slip direction.

I interpret this fault as an Ordovician, right-lateral, oblique thrust fault parallel to the Proterozoic Y fabric in the gneiss. The northward extension of these fault zones is uncertain but they probably extend out into the Paleozoic cover rocks north of the Hudson Highlands.

Participants from Saturday's trip may be struck by the similarity of these exposures to the quartzite-phyllonite zone seen on Stop 1 near Boonton, N.J. This similarity should drive home the point that phyllonitic shear zones of probable Paleozoic age are regionally important features within the Ramapo seismic zone. Earthquake activity here seems to be more associated with semiductile features such as the Dennytown fault than with brittle-type Mesozoic faults.

END OF TRIP

The Taconic State Parkway intersects Route 301 0.3 miles east of this stop. I-84 intersection with the Taconic Parkway is approximately 5 miles north of that point.

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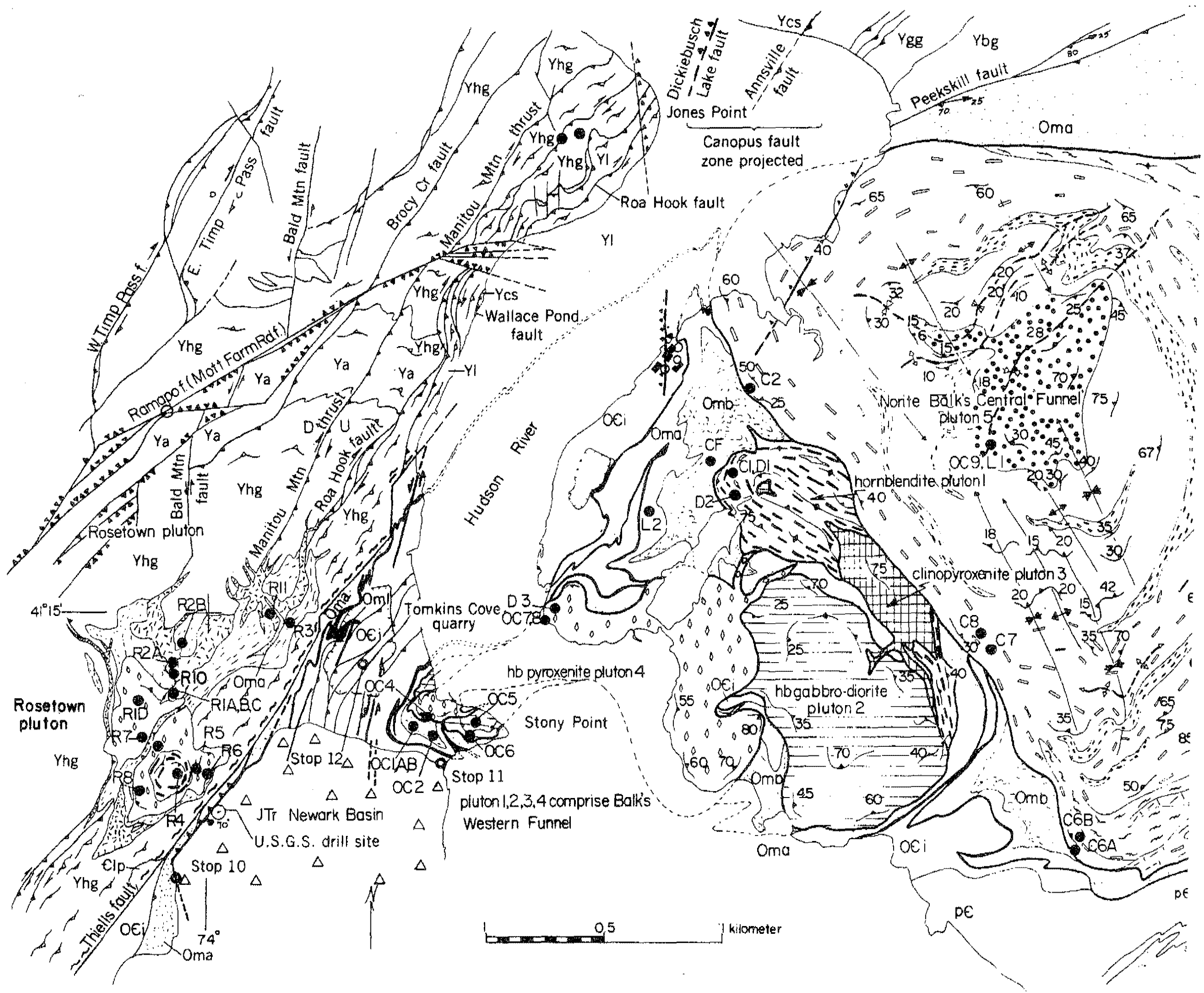

Fig. 14. Generalized geologic map of the Tomkins Cove area showing the northward extension of the Ramapo fault (as the Mott Farm Road fault) and the Thiells fault. Semiductile shear zones of the Ramapo-Canopus zone are truncated by intrusive rock of the Rosetown pluton and lamprophyric dikes. Circled stations refer to localities for K-Ar and Rb/Sr studies by Armstrong, Dallmeyer, Mose and this report (Ratcliffe and others, in press). Yhg -hornblende granite gneiss; Ya - amphibolite; Yl-leucogneiss and quartzose paragneiss; Ygg-"Reservoir"-type granite gneiss; Ybq - biotitic paragneiss; Ycs - calcsilicate gneiss. (figure reproduced from Ratcliffe and other, in press).

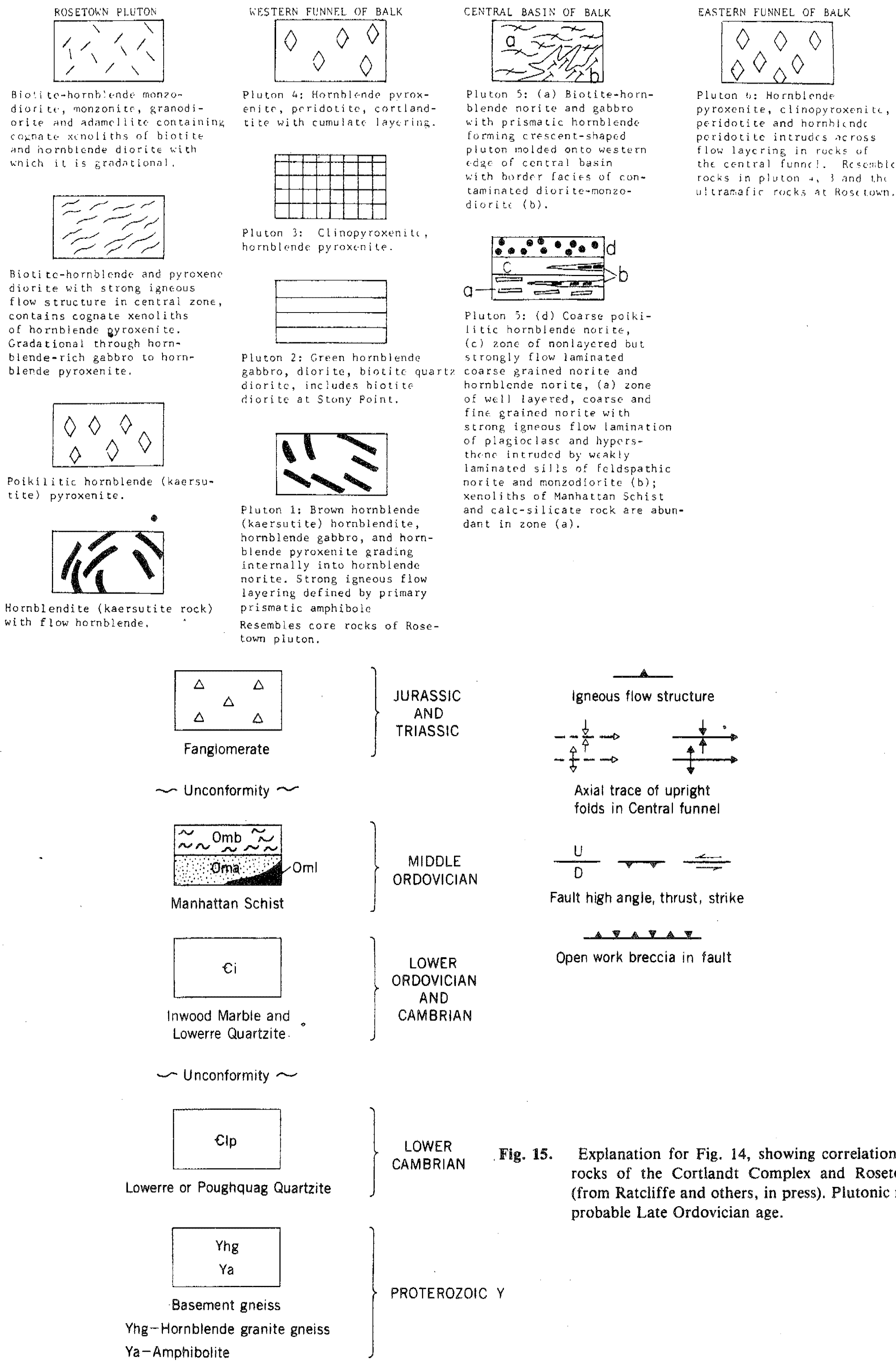

Fig. 15. Explanation for Fig. 14, showing correlation of igneous rocks of the Cortlandt Complex and Rosetown pluton (from Ratcliffe and others, in press). Plutonic rocks are of probable Late Ordovician age.

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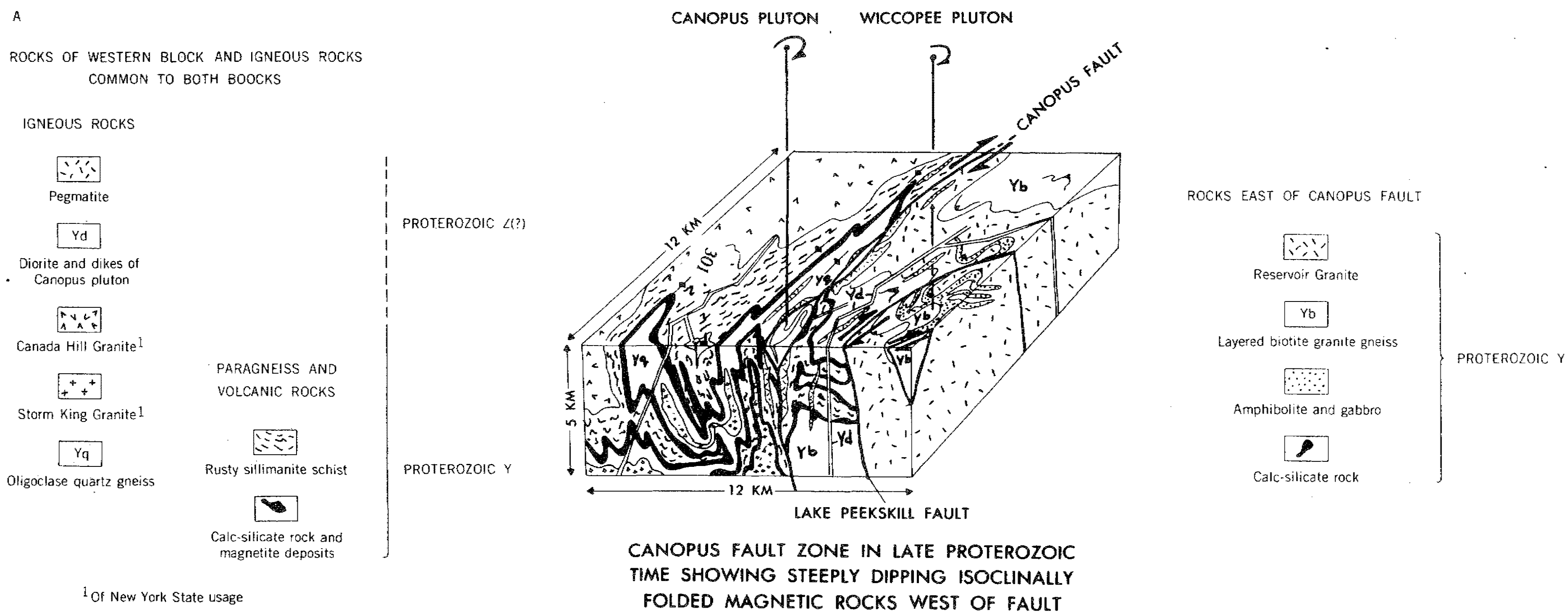

Fig. 16. Generalized block diagrams showing the structural evolution of the Ramapo-Canopus fault zone and location of earthquake epicenters.

A. Canopus fault zone in Proterozoic time showing two mafic plutons, Canopus and Wiccopee, that are intruded syntectonically with respect to Canopus and Lake Peekskill faults. Crosscutting mafic dike of metadiabase or ferrodolerite are probably of Proterozoic Z age and post-date "Grenville" deformation.

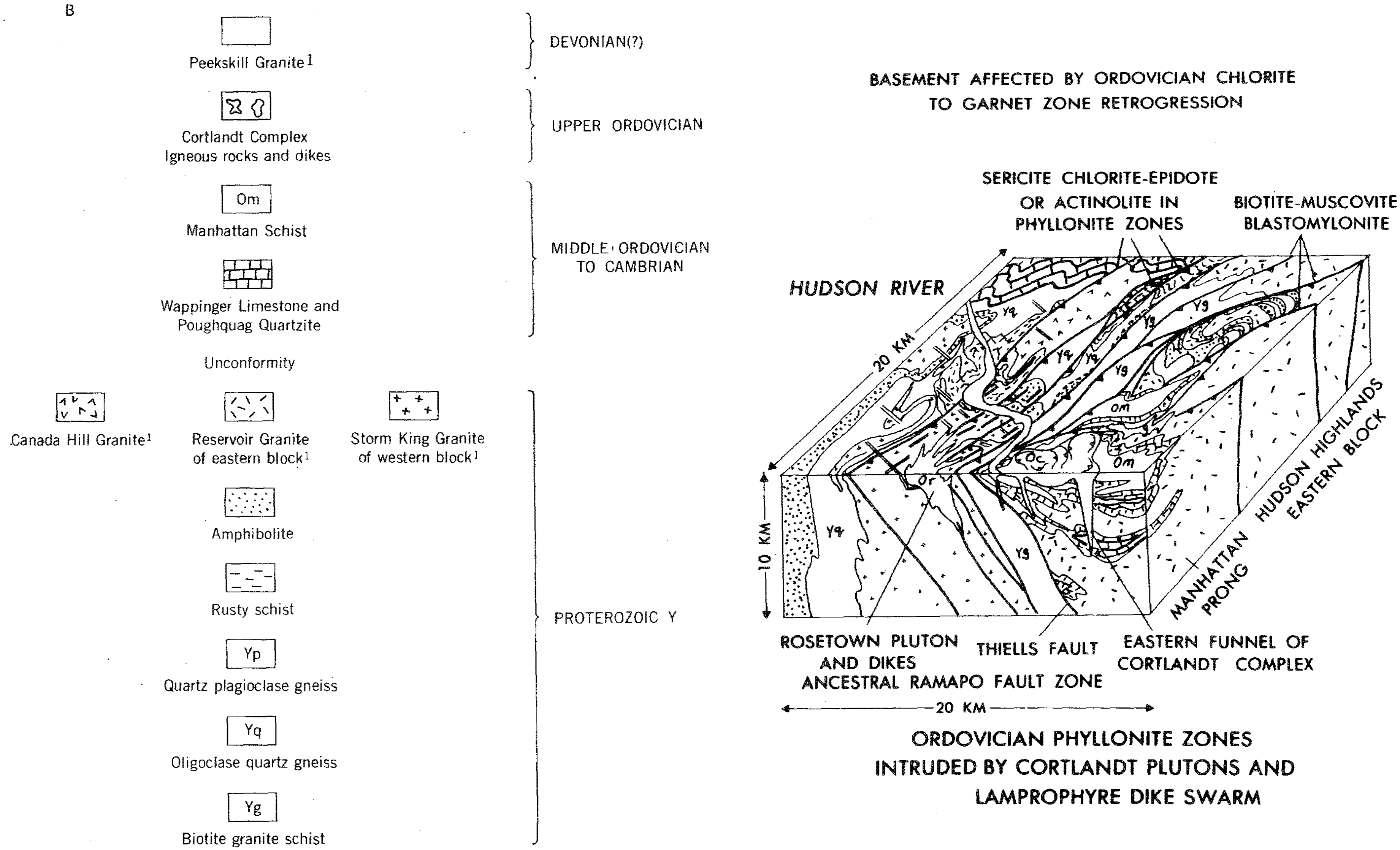

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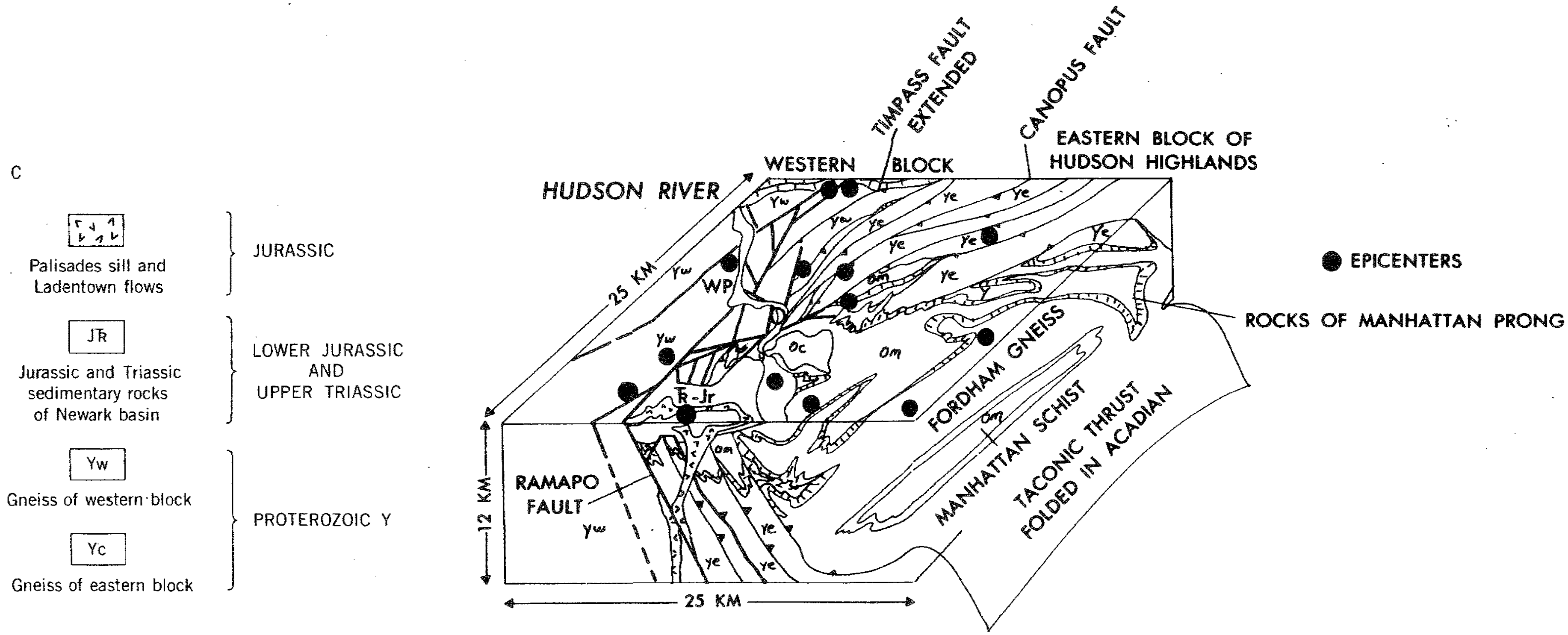
Fig. 16. Generalized block diagrams showing the structural evolution of the Ramapo-Canopus fault zone and location of earthquake epicenters.

B. Ramapo-Canopus zone in Late Ordovician time showing retrogression of Proterozoic Y rocks in semiductile fault zones to produce phyllonite and mylonite. Dike and plutons of the Cortlandt Complex intrude along or crosscut these faults.



RAMAPO-CANOPUS FAULT ZONE IN MESOZOIC TIME SHOWING STEEPLY DIPPING OLD STRUCTURAL GRAIN OF PROTEROZOIC AND ORDOVICIAN AGES

Fig. 16. Generalized block diagrams showing the structural evolution of the Ramapo-Canopus fault zone and location of earthquake epicenters.

C. Ramapo fault zone in Early Jurassic time showing steep attitude of older grain and distribution of earthquake epicenters. Heavy lines represent Mesozoic faults. Note absence of Mesozoic faults in area of epicenters northeast of Hudson River where earthquakes appear to be spatially related to steep zones of semiductile faulting.

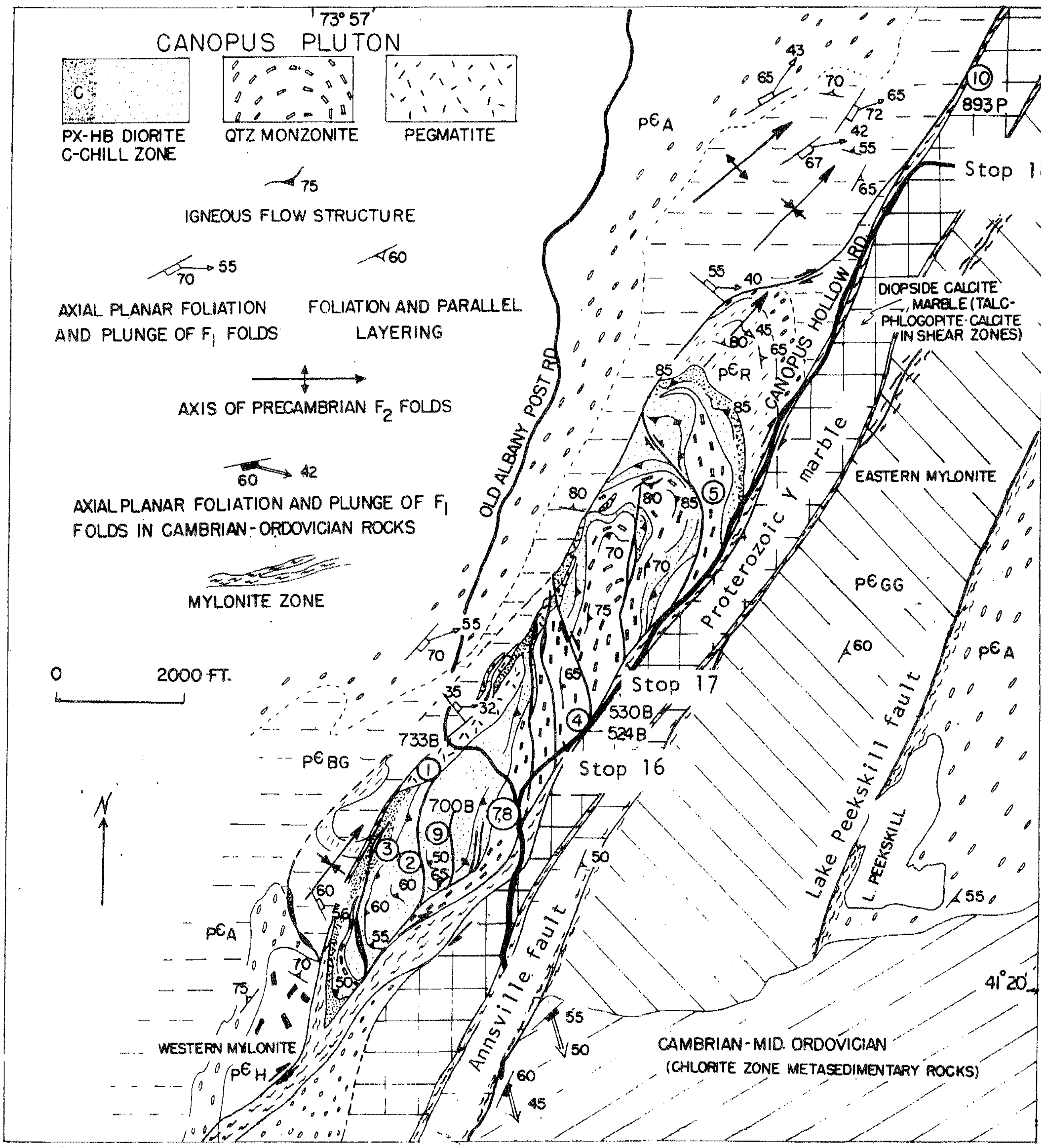
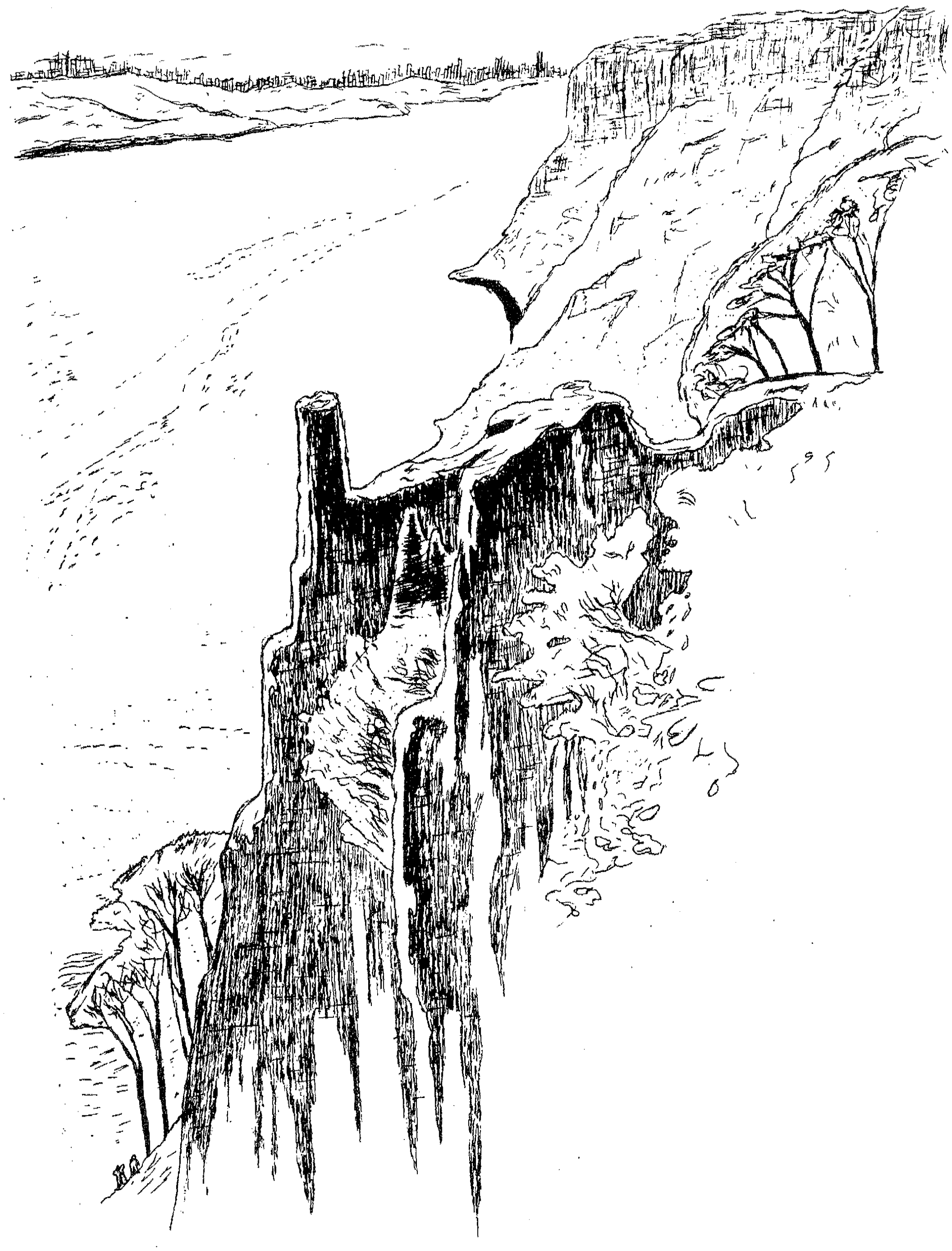


Fig. 17. Geologic map of the extension of the Ramapo-Canopus fault zone showing location of Stops 16, 17, and 18. Generalized geologic map of the Canopus pluton, showing internal igneous flow structure and relationship of pluton to F_1 and F_2 structure in Proterozoic gneisses. Key to Proterozoic lithologies; pCA = amphibolitic gneiss, pCGG = granodioritic gneiss, pCBG = biotite quartz plagioclase paragneiss, pCR = rusty weathering granitic gneiss, pCH = hornblende-biotite granitic gneiss. K-Ar and Rb-Sr ages are shown on map. (B = biotite, P = phlogopite). Numbered localities on sample sites for whole rock and mineral data. Underlined dates refer to K-Ar, other date Rb-Sr from Ratcliffe and others (1972). Figure reprinted from Ratcliffe and others (1972).



The "GIANT'S CAUSEWAY"
at Orange, N.J.
by
Charles Graham, 1884

RIFT TECTONICS INFERRED FROM VOLCANIC AND CLASTIC STRUCTURES

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INTRODUCTION

Tholeiitic basaltic lava flows and intrusives of Late Triassic and Early Jurassic age clearly mark and distinguish the upper part of the rift-valley stratigraphic sequence in the onshore and offshore basins of eastern North America and northwest Africa. These igneous rocks were emplaced over a vast area, perhaps 2500 km long and 1000 km wide, during an episode of crustal extension and sea-floor spreading and hence exhibit a variety of structures reflecting the complex history of the basin at that time. Where these volcanics are interbedded with sediments having paleocurrent and/or paleo-environmental attributes, important conclusions may be deduced about the tectonic behavior of the basin from each rock type.

The objective of this field trip is to study a typical rift facies of interbedded volcanics and sediments, thereby providing a frame-work for interpreting the tectonics of the basin during crustal extension and sea-floor spreading. Figure 1, a diagrammatic sketch through the section, shows the kinds of structures and facies that we shall observe on the field trip. Many of these features, such as tumuli, subaqueous flow lobes and palagonite forset bedding have not been reported from rift volcanics of eastern North America. Figure 2 shows the route of our field trip.

A Stratigraphic Perspective: Geologic Setting

Field studies (Manspeizer and others, 1978) in North America and Morocco show that the major elements of Triassic-Jurassic stratigraphy in basins marginal to the Atlantic Ocean are: (1) Mesozoic rocks resting with profound unconformity on Autunian sandstones (Upper Carboniferous and Lower Permian) and Paleozoic metamorphics; (2) Rifting and syntectonic clastic deposition began in the Carnian Stage (Lower Upper Triassic), along a zone marginal to the axis of the proto-Atlantic Ocean; and (3) Vulcanism began about 195 m.y. ago, i.e. about 10-15 m.y. after the onset of rifting and the accumulation of 3-5 km of clastics in the rift valleys. (Fig. 3)

On the bases of these studies we infer (Fig. 4) that : (1) crustal thinning (through erosion, necking and extension) was very long-lived, perhaps 50-75 m.y., and followed an episode of Late Paleozoic Hercynian crustal thickening and mountain building through continental collision; (2) rifting and clastic deposition was widespread by the beginning of the Late Triassic in many small rift basins marginal to the proto-Atlantic Ocean; and (3) a second phase of crustal extension resulting primarily from horizontal shear developed at the beginning of the Jurassic Period and was accompanied by vulcanism, sea-floor spreading and collapse of the continental margins (Manspeizer and other, 1978).

The largest of these onshore basins in North America is the combined Newark-Gettysburg Basin, which extends from Rockland County, New York through central New Jersey to Lancaster, Pennsylvania. The basin, a half-graben, is step-faulted in the subsurface (Sumner, 1978). The rift fill consists of 5 to 6 km of continental sediments interbedded with tholeiitic lavas of the Watchungs and intruded by diabases of the Palisade Sill-Rocky Hill Complex. The sequence, resting unconformably on Paleozoic metamorphics and dipping westward towards the east-facing high angle border fault, is folded and faulted with considerable vertical and strike-slip displacement (Sanders, 1962).

STRATIGRAPHY

Intrusive sheets, such as the Palisade Sill and the Rocky Hill-Lambertville sheets, extend collectively throughout the basin while the volcanics are restricted to its northern end. Paleoflow data (Manspeizer, 1969) and geochemical data (Puffer and Lechler, 1980) show that these lavas, now preserved as erosional remnants in the north, originally extended 80-150 km south to their probable source in the eastern part of Pennsylvania. Field studies also indicate that the lava flows extended west of the Ramapo border fault. The lavas, intercalated within the sediments of the "Brunswick" For-

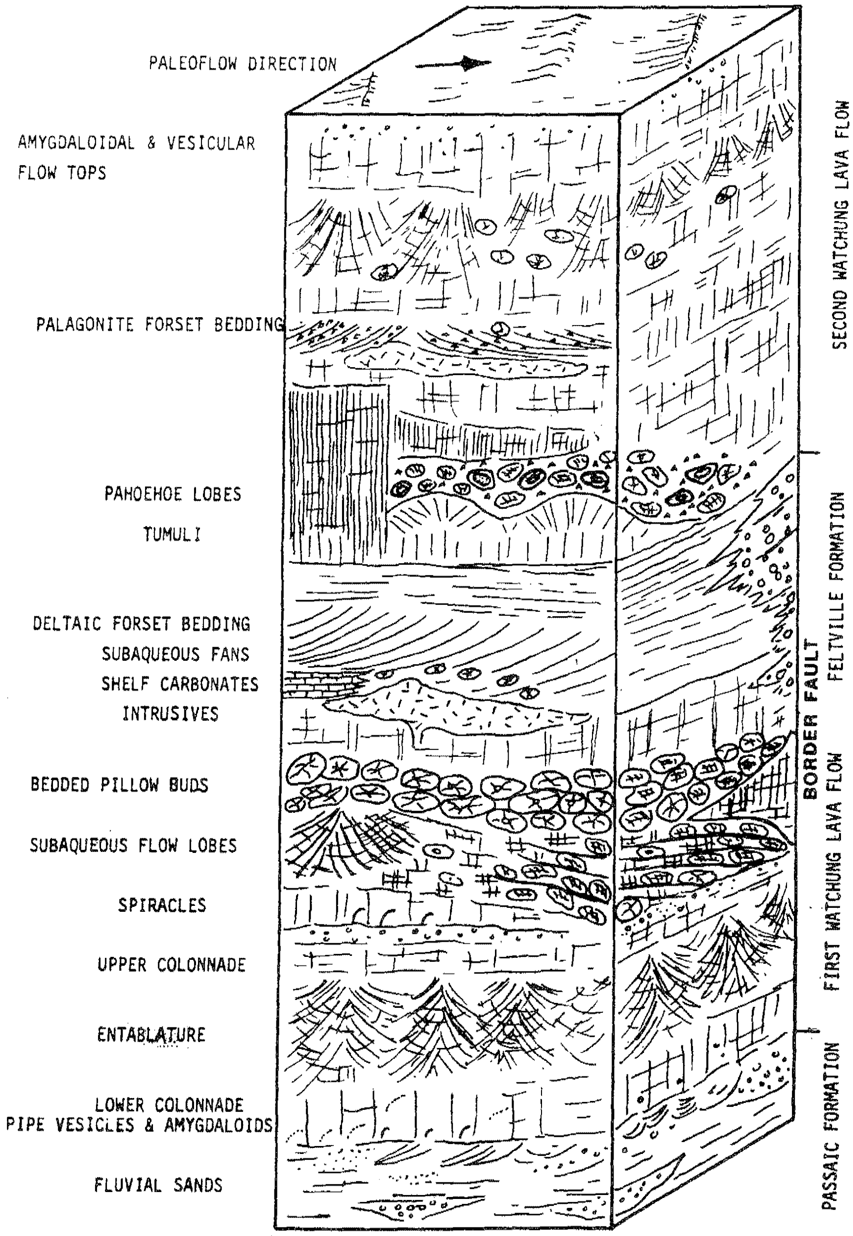


Fig. 1 Schematic diagram of the volcanic and sedimentary structures to be studied on the field trip.

mation, form three marked stratigraphic units: the First, Second, and Third Watchung basalts, which average about 185, 230 and 90 meters thick respectively (Kummel, 1898; Darton and others 1908; Faust, 1975). Although these names are well established in the geologic literature, cogent arguments are presented by Olsen (see the guidebook) for dropping the names Watchung and Brunswick in favor of the following which are listed in stratigraphically ascending order: Passaic Formation, Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation (Fig. 5). The writer, adopting Olsen's as formal stratigraphic names, uses the Watchung nomenclature as informal designations in the same way that researchers use the name Columbia River Basalt. The introduction of new names, although bothersome to some, actually helps to elucidate complex stratigraphic relationships and is in the spirit of the Code of Stratigraphic Nomenclature (1961). This will be evident throughout the field trip.

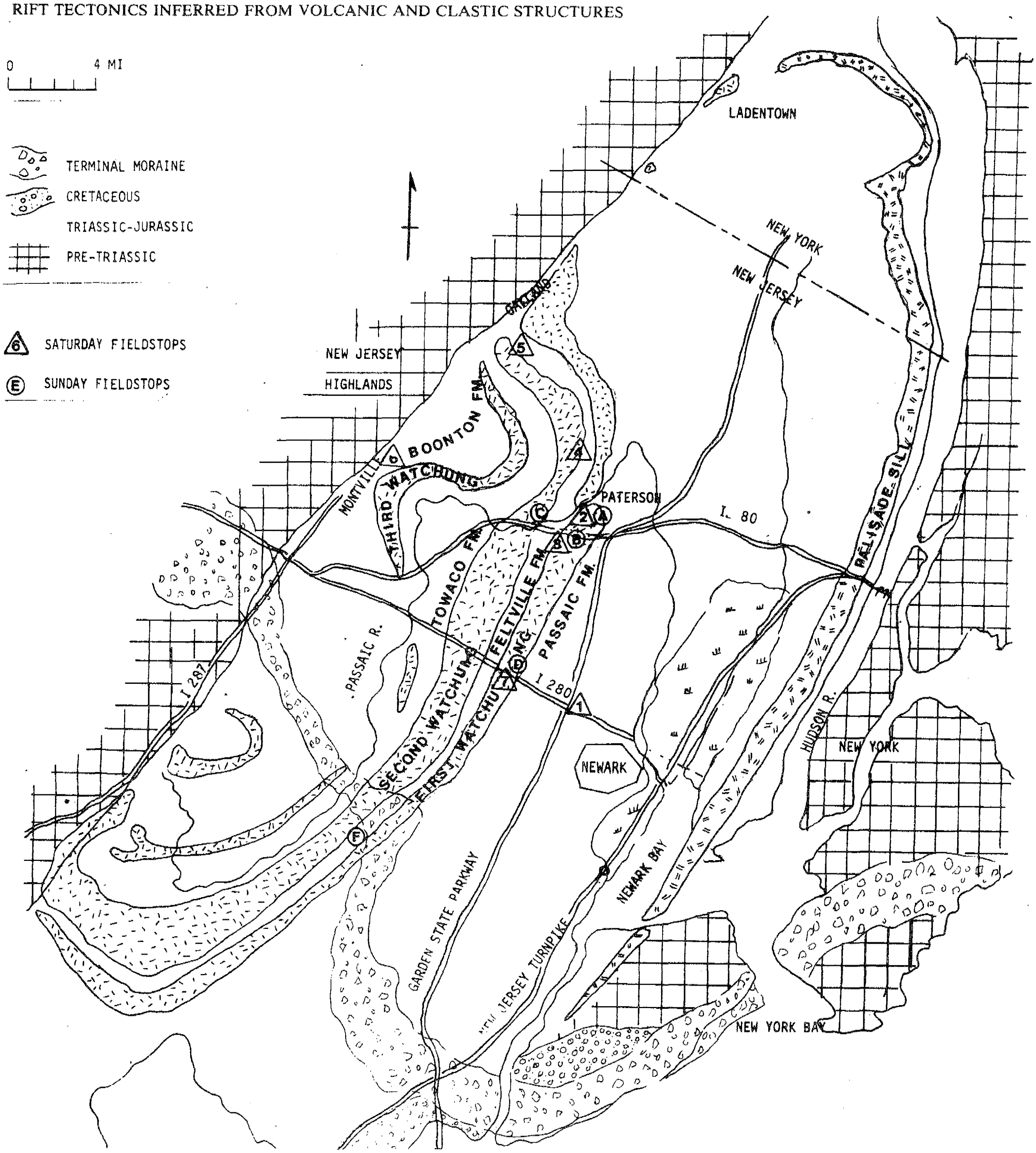


Fig. 2 Location map, showing generalized geology and field stops.

Each lava flow consists of multiple flow units. At least two, and perhaps three, flow units are recognized in each of the First and Second Watchungs, while at least three flow units are recognized in the Third Watchung. The lateral extent of individual flow units may not be as great as anticipated by early investigators (Johnson, 1957), although Van Houten (1969) states that the Watchung lavas flowed at least 60 km as a single unit 450 to 500 m thick. Where the exposures are good, each flow unit may exhibit: (1) a flow top of vesicular, amygdaloidal and/or ropy pahoehoe lava; (2) a flow base of massive columnar basalt with pipe vesicles and pipe amygdaloids; and (3) an advancing flow front of pillow lavas and palagonite tuff in forset beds. Some of the lava, however, originated as fissure eruptions within deep-water, fault-bounded lakes, and did not flow any appreciable distance. Individual flows are separated by thin lenses of red tuff at Millington,

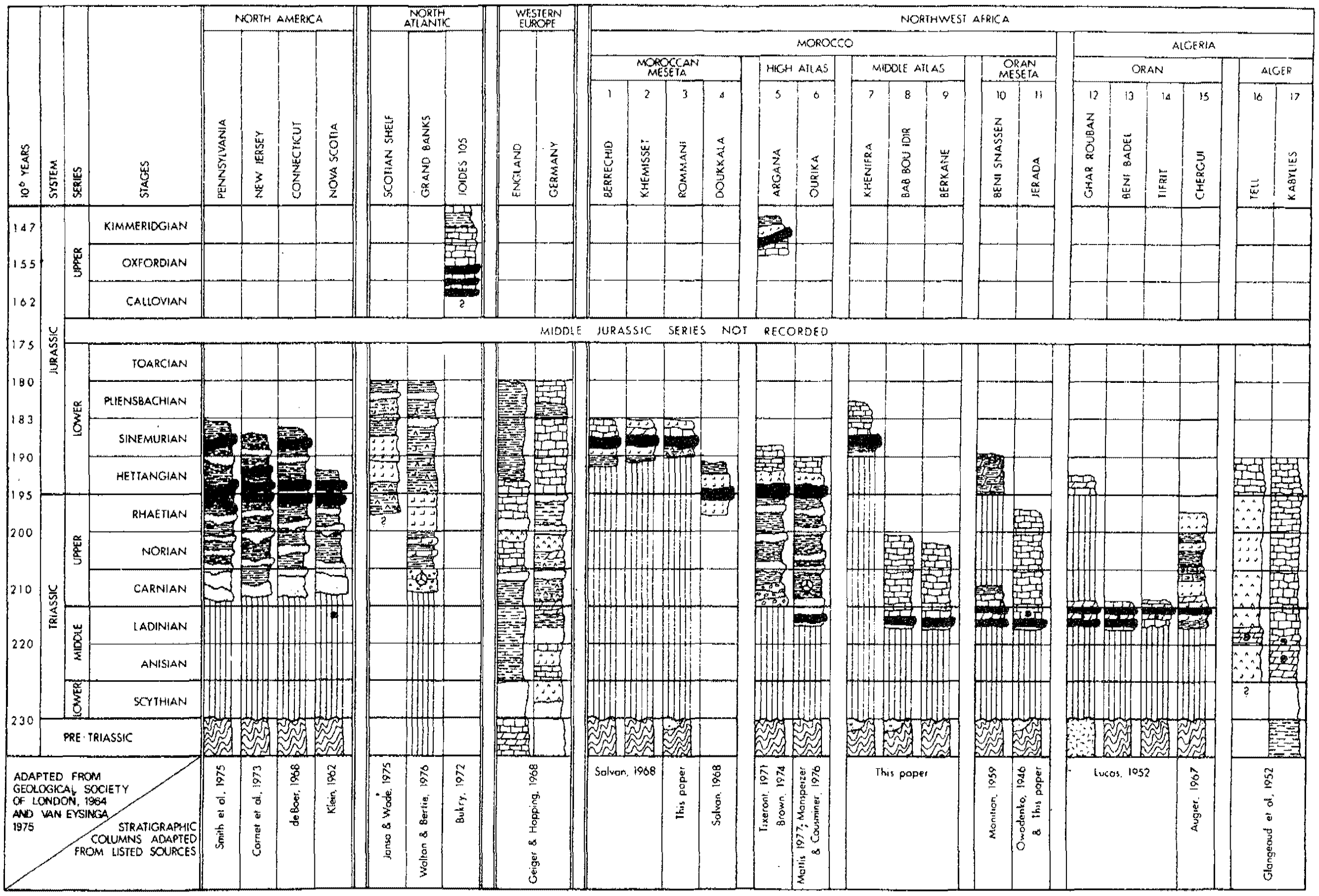


Fig. 3 Intercontinental correlation chart. Conventional symbols depict time - and rock - stratigraphic units (Manspeizer and others, 1978).

Summit and Oldwick (Johnson, 1957), New Street Quarry in Paterson (Van Houten, 1969), siltstone at Prospect Park Quarry near Paterson (Bucher and Kerr, 1948), and sandstones at Caldwell (Faust, 1975).

Paleoflow Structures in Rift Volcanics (Field trip stops 2 and A)

The application of paleocurrent structures in sedimentary rocks is well-known and has been used to resolve important questions on the dispersal systems, basin geometry and provenance. Primary directional structures also occur in volcanic rocks and have been used effectively by Brinkman (1957), Waters (1960), Schmincke (1967), and others to resolve important questions about the tectonic history of various basins. Except for preliminary observations on Triassic-Jurassic volcanic structures by Walker and Parsons (1922) in Nova Scotia, Bain (1957) in Massachusetts, Chapman (1965) in Connecticut, and Iddings (1906), Fenner (1908), Bucher and Kerr (1948) and Manspeizer (1969) in New Jersey, none of these features has been systematically mapped or studied in detail. Among the most useful paleoflow structures for determining flow direction are pipe vesicles, pipe amygdaloids, and pillow-palagonite forset bedding. Other structures, such as tumuli and pillow lavas provide important information about the paleoenvironment.

Pipe Vesicles and Pipe Amygdaloids (Du Toit, 1907) commonly occur in the lower colonnade, near the sole of the flow, in sets of parallel-to-sub-parallel, straight-to-bifurcating cylindrical tubes surrounded by chilled lava. The vesicles measure about 0.5 cm in diameter and 10 cm long. Vesicles probably form when the heat of the lava vaporized water from the underlying sediment. As the vapors rise into the overlying flow, their leading ends are bent in the direction of the lava flow (Figs. 6 and 7). Pipe vesicles have been used effectively for basin analyses by Brinkman (1957), Waters (1960), and Schmincke (1967).

Vesicle Cylinders (Du Toit, 1907) are cylindrical zones of vesicular basalt that often occur in the upper part of the lower colonnade (Fig. 6). They are considerably larger than pipe vesicles, measuring about 2

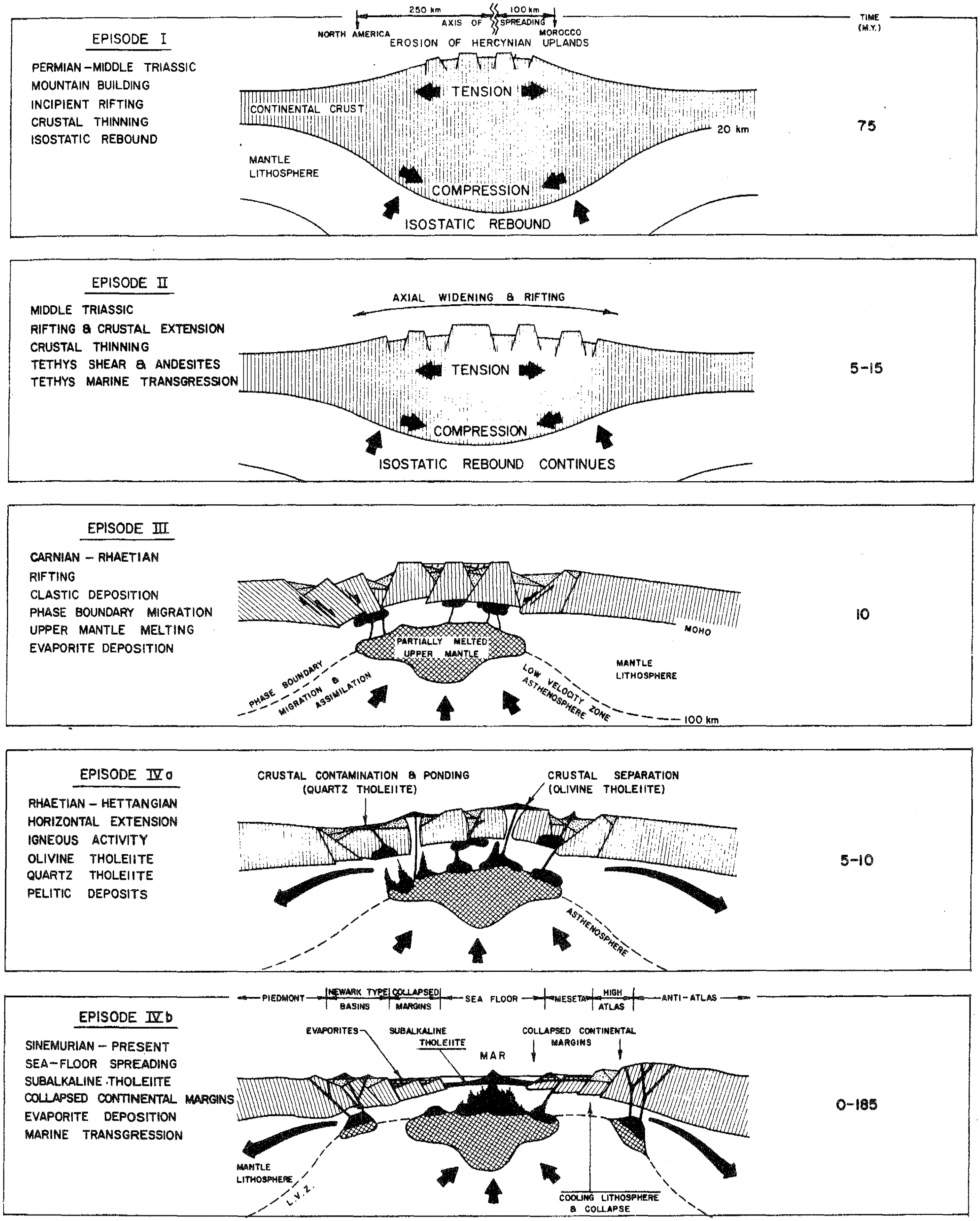


Fig. 4 Conceptional model showing tectonic episodes from initial crustal thinning and rifting to sea-floor spreading. (Manspeizer and others, 1978).

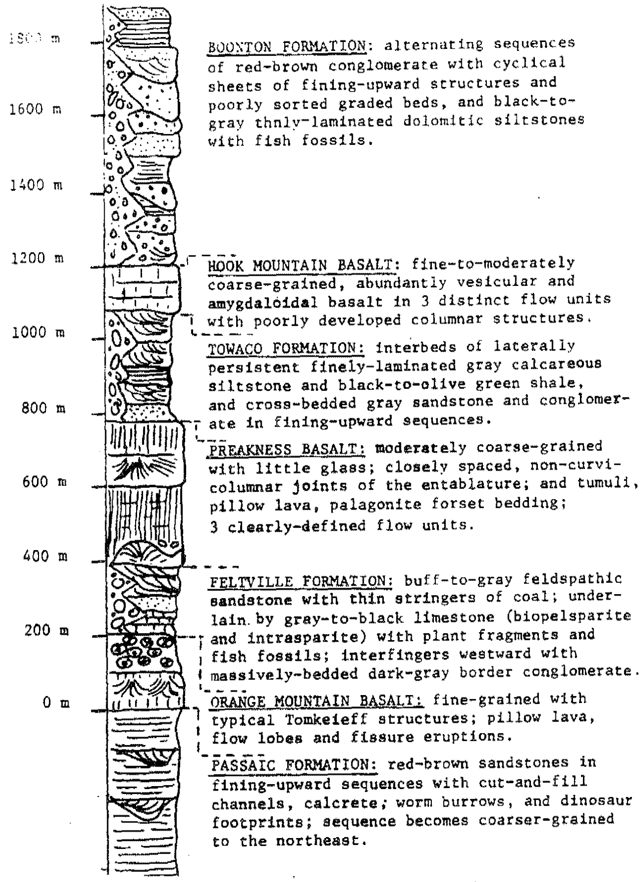


Fig. 5 Schematic composite column for the latest Triassic-Jurassic rocks, Newark Basin.

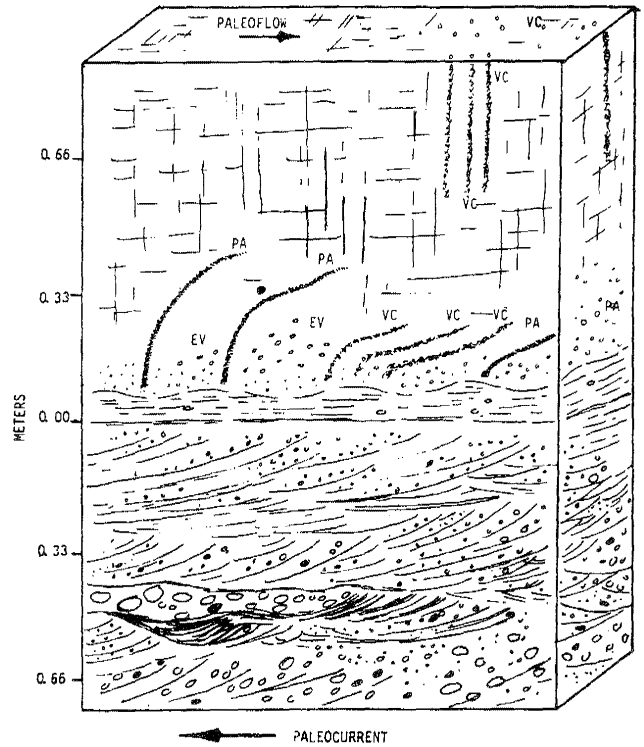


Fig. 6 Field sketch showing contact of the Orange Mountain Basalt with oriented pipe amygdaloids (pa), pipe vesicles (pv) and vesicle cylinders (vc), and underlying cross-bedded pebbly sandstone of the Passaic Formation, McBride Ave., Paterson. Structures indicate that the lava flowed towards the northeast, although the sedimentary paleoslope was inclined to the southwest.

cm in diameter and 30 cm long. Because many vesicle cylinders are essentially straight and perpendicular to the flow surface, they probably originate as a late phase gaseous stage entirely within the basalt.

Palagonite Forset Bedding (Fuller, 1931) are common in the flows, and were probably widespread along the advancing front of the Watchung lavas. This structure consists of steeply dipping to gently inclined, poorly stratified forset beds of brecciated basaltic glass, tongues of basalt and chaotic and kneaded blocks of redbeds or tuff. The basaltic glass, or sideromelane, is commonly altered to yellow earthy palagonite which alters to zeolites and clay minerals (Waters, 1960). This structure forms when lava, flowing into a marginal lake or pond, congeals and granulates into finely brecciated glassy slag that is deposited with pillow lavas and tongues of chilled basalt on the forset slope of lava-originated deltas. The paleoslope and paleoflow direction may be inferred from the attitude of the forset beds.

Tumuli, Pressure Domes or schollendomes (Wentworth and Macdonald, 1953) (Field trip stop C) are domal upbowings of the flow surface that are typically elliptical in plan view and grade into elongate structures termed pressure ridges. In the Newark Basin, tumuli (observed only in cross section) are about 7 m high, about 15 m wide and spaced about 15 m apart. In cross section, they exhibit a well-defined set of vertical joints of the lower colonnade, radial joints fanning upward in the entablature, and a thin vesicular and brecciated upper colonnade (Fig. 8). At Little Falls, N.J., they are overlain by a pillow-pahoehoe complex that thins along the tumulus crest and thickens along its flanks and in adjacent troughs (Fig. 9). The joint fans of the entablature are perpendicular to the cooling surface and, therefore, perpendicular to the isotherms.

Tumuli apparently form above clogged distributary tubes (Swanson, 1973). Where the lava continued to feed into these tunnels and tubes, pressure from the advancing flow bowed upward the roof of the tunnel at its weakest point, ultimately breaking through the roof and flanks and feeding the pillow-pahoehoe complex. Continued extrusion of the lava, either through the tumuli or through new fissures, thickens the complex between tumuli creating a surface of low relief (Fig. 9).

Pillow Lavas and Subaqueous Flow Lobes (Field trip stop 3 and B)

One of the most striking features of moderately deep-water Recent basaltic vulcanism is its abundance of pillow lavas (Jones, 1966). Current investigations on the FAMOUS expedition (Heirtzler and Bryan, 1975; Choukrone and others, 1978) show that pillow lavas and pillow rubble comprise an important component of the Mid-Atlantic Rift facies. While the main deeps of the rift are often buried by considerable rubble, pillows form on adjacent highs away from the center of tectonic activity from flows erupting from volcanic vents and fissures.

Pillow lavas occur extensively throughout the upper flow unit of the Orange Mountain Basalt and in the lower flow unit of the Preakness Basalt. They are best exposed in several trap quarries in the Paterson region, where according to Fenner (1908), they formed in the lacustrine setting of Lake Paterson. In the New Street Quarry of Paterson, long a favorite collecting site for mineral hobbyists, pillow lavas are abundant, occurring in two distinctively different facies: (1) a subaqueous flow lobe, and (2) bedded pillow lavas. (Fig. 10)

The subaqueous flow lobe, sketched in figure 11 from the walls of two adjacent quarries and a roadcut, is about 400 m long and 35 m high with an apparent long axis oriented east-to-west. Its upper surface slopes gently westward 5° - 10°, while its distal front and flanks are extremely steep and slope 35° - 40°. Its shape is a broadly flat-topped tongue or lobe that flares out along its distal end to the west. The lobe overlies the vesicular and tuf-

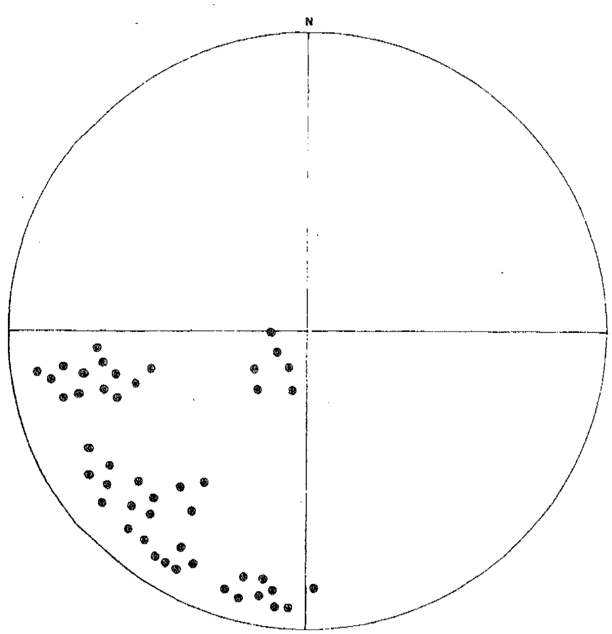


Fig. 7 Stereographic projection of pipe amygdaloids and pipe vesicles, Orange Mountain Basalt, McBride Ave., Paterson.

Fig. 8 Tumulus with a massive central core and curved upper vesicular and brecciated zone that is overlain by columnar basalt of a second flow unit (left side of photograph); Little Falls.

faceous upper surface of the lower flow unit and appears conformably overlain by an extensive horizon of bedded pillows and massive columnar basalt (Fig. 11). In longitudinal section (Fig.11), the flow lobe consists of three components: (1) a proximal eastern zone of massive columnar basalt of entablatures and colonnades; (2) a transitional medial facies of columnar basalt with isolated pillows and some collapsed lava tubes that become more abundant to the west; and (3) a distal facies of steeply dipping, overlapping ellipsoidal pillows whose long axes are primarily perpendicular to the long axis of the lobe along its crest and flanks and parallel to the lobe axis along the flow front (Fig. 13). These observations provide insight into a vexing problem relating the elongation of the pillows to the paleoflow direction (see Jones, 1969a; Johnston, 1969).

What appears to be a subaqueous volcanic neck, or fissure eruption, can be seen in the lower New Street quarry. There a massive diabase with columnar and entablature structures overlies the distal end of the westward advancing flow lobe and is overlain by a younger set of bedded pillows (Fig. 12). The diabase feeds a second flow lobe of pillows and columnar basalt that also advances to the west. A transverse section of overlapping arcuate lobes of pillow lavas may be seen on Route 80. The geometry and stratigraphic relations of these units suggest that the bedded pillow lavas may have formed on the steep flanks of a subaqueous volcanic slope (Fig. 13).

Pillows of the bedded and lobe-type form interconnected ellipsoidal masses that are distorted, kneaded and flattened like half-filled sacks in a tight structural framework without matrix but with open interstices (Fig. 14). The interstices have irregular shapes and are filled with small angular fragments of basaltic glass that are completely surrounded by and cemented with secondary zeolites, calcite and quartz (Fig. 15). It is clear that the clasts were derived from the glassy and checkered rind of the pillows by circulating secondary solutions

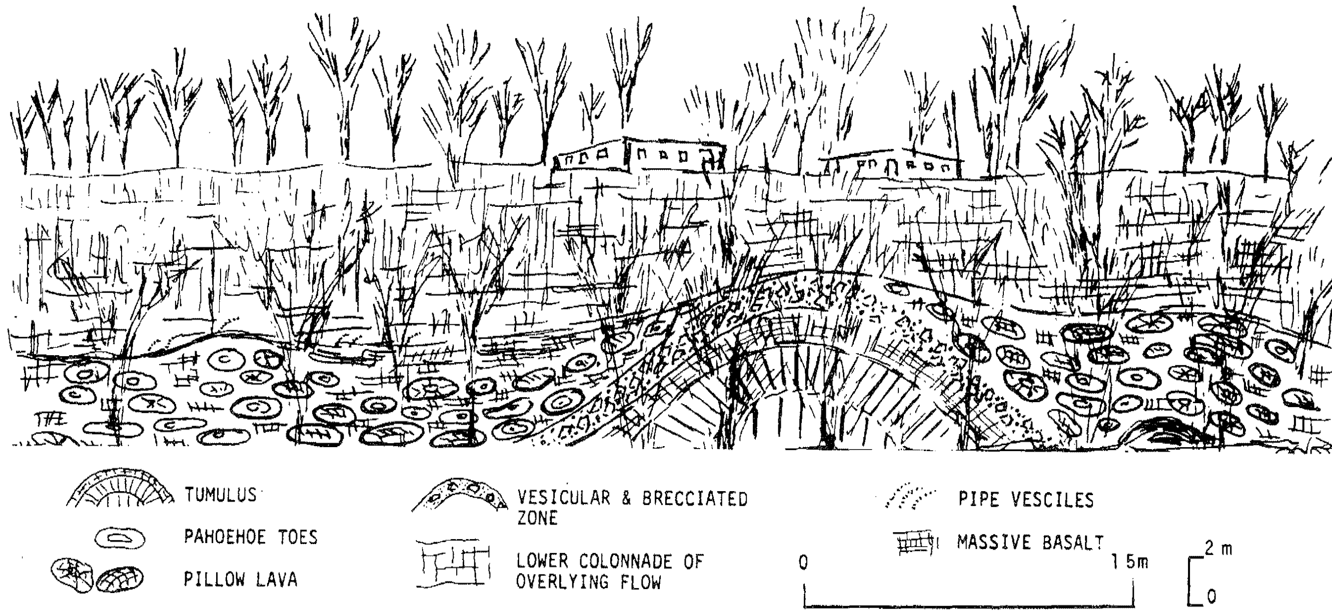


Fig.9 Field sketch of tumulus with overlying pillow-pahoehoe complex that thins along the crest of the tumulus and is overlain by columnar basalt of the second flow unit; Little Falls.

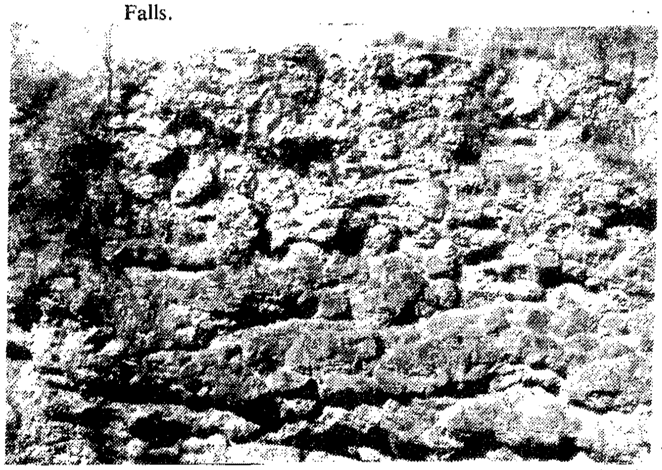


Fig.10 Pillow buds of the subaqueous flow lobe in longitudinal view, overlain by bedded pillow buds in cross-sectional view; Upper New Street Quarry, Paterson.

that displaced the glassy rind by their mineralizations. In transverse section the pillows are almost circular and display well-developed radial and/or concentric joints. Concentric layering and blocky joint patterns accompany longitudinal sections, which are markedly elliptical with long axes to short axes ratios in the order of 3:2 (Fig. 16). While the exterior rind of the pillows are cracked in the form of checkered glass selvage, the interior is generally massive and only very slightly and minutely vesicular. At Feltville and Little Falls, New Jersey, however, the pillows commonly are vesicular with long pipe amygdaloids at right angles to an outer concentric shell of alternating vesicular and solid glassy basalt. Vesicularity and vesicle size, according to Moore (1965) and Jones (1969), is an index of the depth of water in the formation of pillows. The pillows of Lake Paterson have few microvesicles and may have formed in moderately deep water. This avenue of research is currently being investigated.

The absence of rubble is an important and notable attribute of the pillows of Paterson, suggesting to this writer that the waters of this basin were deep and well-agitated and that the finely comminuted clasts were washed into the deeper part of the basin perhaps along the border fault. (See Choukroune and others, 1978, Fig. 6).

Fenner (1908) determined that the minimum size of the lake basin was in the order of 8 km long, that is from Montclair to North Haledon where the beds are con-

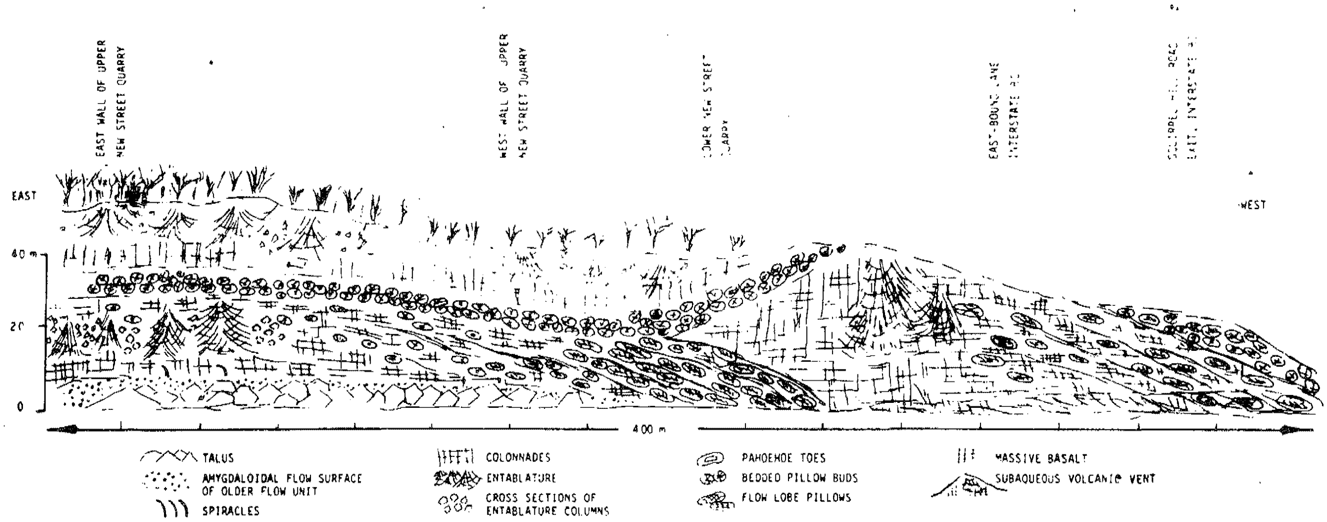


Fig. 11 Field sketch of volcanic structures studied in the second flow unit of the Orange Mountain Basalt in the Upper and Lower New Street Quarries and along I-80; note: longitudinal section of the subaqueous flow lobe, volcanic vent, bedded pillow lavas, an overlying Tomkeieff sequence and underlying amygdaloidal flow top.

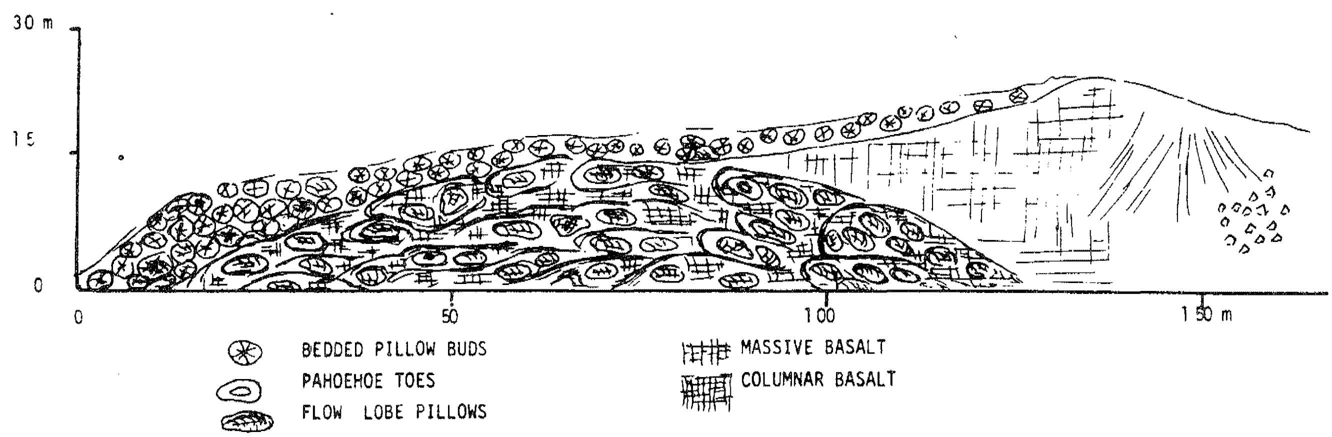


Fig. 12 Field sketch of the lower New Street Quarry, showing transverse section of the subaqueous flow lobe, volcanic vent, and overlying bedded pillow lava.

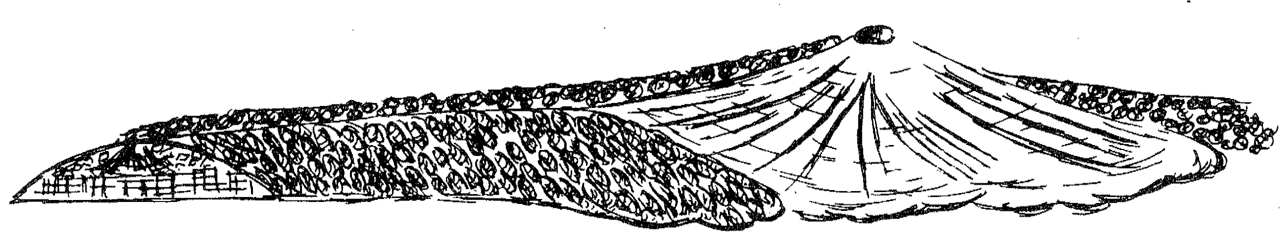


Fig. 13 Conceptual view of subaqueous flow lobe, volcanic vent and bedded pillow lavas; New Street Quarries, Paterson.

cealed by glacial cover. Field data, however, show that similar rifting and vulcanism may have occurred concurrently in isolated basins from Ladentown, New York (See Ratcliffe this guidebook) south to Feltville, New Jersey, a distance of about 75 km. The presence of volcanic vents, subaqueous flow lobes, deep-water pillow lavas within down-dropped crustal blocks causes one to speculate about whether a short-lived juvenile ocean basin hadn't formed for a brief moment here during the Early Jurassic.

Pahoehoe Flows and Toes

According to the pioneering studies of Wentworth and Macdonald (1953) and Macdonald (1953) on the Hawaiian lavas, pahoehoe lavas are characterized by a smooth, hummocky, ropy surface with spherical vesicles and lava tubes. After the initial eruption of lava, the upper surface of the flow becomes crusted over by congealed rock and the advancing lava fills the resulting lava tubes which subdivide and feed smaller lobes or toes along an advancing lobate front. In cross section an advancing pahoehoe flow unit often consists of stacked filled lava tubes or toes that resemble pillow lavas. It is worthy of mention that the bulbous budding hypothesis was first presented by J. Volney Lewis (1915) almost seventy years ago to explain the pillow lavas of the First Watchungs. Recent studies by Jones (1967), Swanson (1973) and Moore and others (1973) support this conclusion.

Apart from the obvious environmental and tectonic differences under which these lavas are erupted, Macdonald (1967) points out that the eruption of pahoehoe flows is related to the repeated eruption of small outpourings of magma, while the formation of pillow lavas forms widespread flows of large volumes and high eruptive rates.

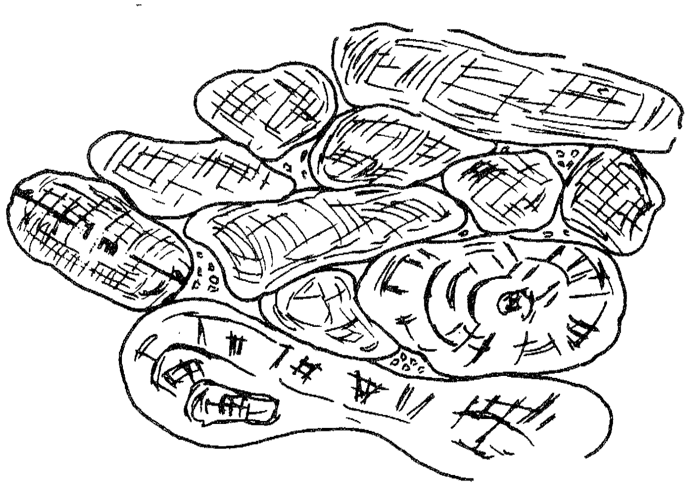


Fig. 14 Field sketch of pillow buds of the subaqueous flow lobe, Upper New Street Quarry. Pillows are elongate ellipsoidal masses that form a tight structural framework with open interstices and without volcanic breccia.

Both pillow lavas and pahoehoe toes occur in the Watchung basalts and, perhaps because of loading and/or tectonism, are difficult to distinguish one from the other. The writer, largely using criteria established by Macdonald (1953), recognizes the following characteristics:

Pahoehoe toes

Major axis of the ellipsoid 3 or 4 times the cross sectional axis.
Concentric structures in cross section
Moderately to highly vesicular or amygdaloidal
Vesicles elongate tangentially to edge or not at all.
Lava tubes are common, resulting in central cavities.
Radial joints are poorly developed or absent.

Pillow lavas

Major axis of ellipsoid less than 3 or 4 times the cross sectional axis.
Radial structures well developed.
Moderately to poorly vesicular or amygdaloidal.
Vesicles elongate radially, especially near the edge.
Lava tubes are rare.
Radial joints are well-developed and co spicuous in cross section

Zeolites (Field trip stops 3 and B)

The trap rocks of the Paterson region with their spectacular array of zeolites and associated minerals have been favored by mineralogists and hobbyists for over 150 years. These minerals enrich museums and private collections throughout the world and their quality and diversity rank with similar collections from Nova Scotia, Iceland and the Deccan of India (Mason, 1960). As early as 1822 Nutall recorded the occurrence of prehnite, natrolite, chabazite, stilbite and datolite from quarries in the First Watchung Basalts (Mason, 1960). Among the zeolites, Bucher and Kerr (1948), report that stilbite, analcime, natrolite, laumontite, thaumasite, chabazite and heulandite are probably the most frequently found, and that they occur most often with quartz, calcite, datolite, prehnite, pectolite and apopyllite. Of the sulphides, pyrite and chalcopyrite occur more frequently than galena and bornite. Among the sulphate, gypsum occurs rarely.

In the past, as basalt quarries were actively worked for the trap rock, good crystals could be found in newly opened quarry faces. Today there are no operating trap quarries in Paterson, therefore, mineral collecting is almost non-existent.

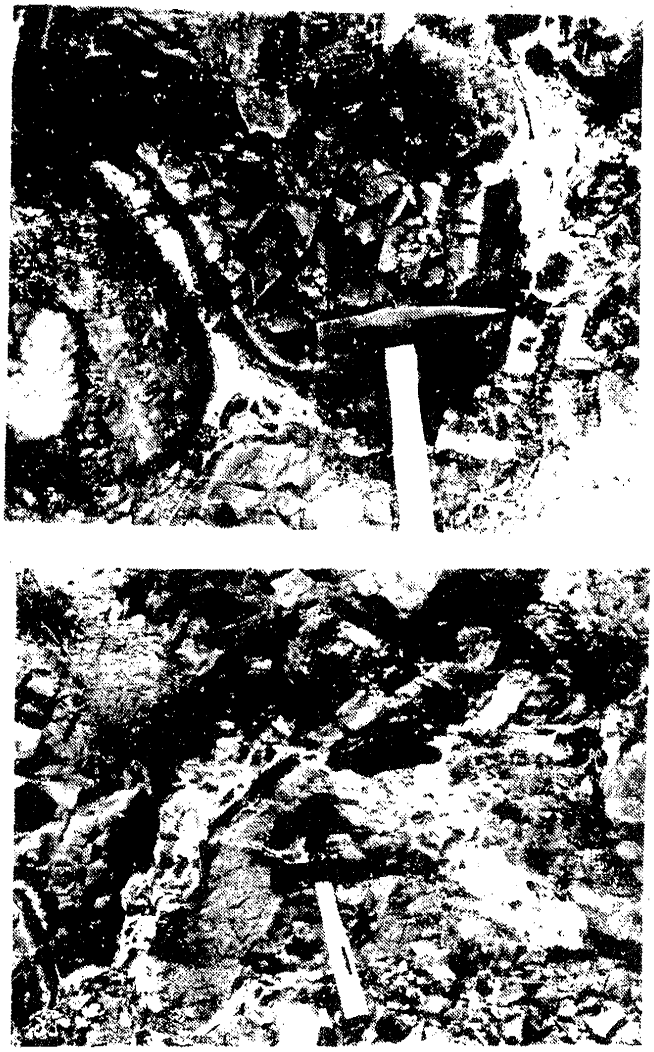


Fig. 15 Pillow buds with massive pillow cores, checkered exterior glassy rind, interstitial angualr clasts of basaltic glass surrounded by and cemented with calcite, quartz and zeolite. Note: that the clasts are displaced from the pillow rind by secondary mineralization.

In the Paterson region, zeolites and associated minerals occur in cavities in the uppermost vesicular zone of the lower flow unit and in the interstices between pillows of the overlying second flow unit. Fenner (1910) and Schaller (1932) have shown that cavities after glauberite and anhydrite within these interstices served as the primary host cavities for the subsequent crystallization of the zeolites and other minerals. Crystals of glauberite and anhydrite, first encrusted with quartz, prehnite or datolite, were dissolved leaving rhombic (after glauberite) and rectangular (after anhydrite) crystals that were partially filled by first prehnite, then zeolites, and finally by calcite.

The presence of cavities and pseudomorphs after glauberite and anhydrite within the pillow complex at Paterson and in the mudstones below the lavas led Schaller (1932) to suggest that the zeolites formed only when the second flow unit entered into a saline lake. Van Houten (1969), however, suggests that the pillowed lava and underlying vesicular lava at Paterson were mineralized after burial by circulating ground water, perhaps derived largely from the compaction and dewatering of the underlying mudstones.

Pillow lavas and pillow-derived debris are important rock components in modern oceans. The absence of debris in the interstices of pillows suggests that it was washed away, leaving open channels for subsequent mineralization by ground water solutions. Therefore, it seems unlikely that the zeolites formed in shallow water playas.

Columnar Jointing (Field trip stops 7 and D)

A spectacular columnar joint system, marked by a lower and upper colonnade with a central entablature, is the single most consistent and prominent feature of the lower flow unit of the First Watchung basalts (Fig. 17). It is remarkable that this three-fold joint pattern may be observed for a distance of almost 80 km along strike. It marks a uniform flow condition and cooling history over a vast area, suggesting that the lava was ponded. It is unlikely that these ponded lavas could have reached far beyond the northern limits of the current basin. First described almost 100 years ago by Iddings in 1886, these structures are equal in prominence to those described by Bailey (1924) of the Mull Province, Tomkeieff (1940) of the Devil's Causeway, and Waters (1960) of the Columbia River basalts.

This joint system is most completely exposed along Interstate Route 280 in West Orange, near the site of the O'Rourke Quarry described by Iddings in 1886 (Manspeizer, 1969). The structure, overlying a fluvial red bed sequence of shales and sandstones, consists of: (1) a lower colonnade; (2) an entablature; and (3) an upper colonnade. The lower colonnade, about 15 m thick, is composed of massive 4-5 or 6-sided polygonal subvertical joint prisms up to 13 m high and 0.5 - 1.2 m wide. The entablature consists of long (20 to 30 m), slender, slightly undulating curved polygonal columns that pinch and swell, and radiate from the apices of wide-angle cones that form upright, inverted and oblique fans and chevron structures (see Spry, 1961, p. 195.) Sheafs of curved downward radiating fans and chevrons are significantly more abundant than upward radiating structures by a factor of perhaps 10:1. Cross joints, intersecting the radiating columns at high angle, appear concentrically distributed about the apex of radiation. The density of joints, as manifested by the long slender prismatic columns, is the key factor differentiating the entablature from the colonnades. While the entablature of the First Watchung is curvi-

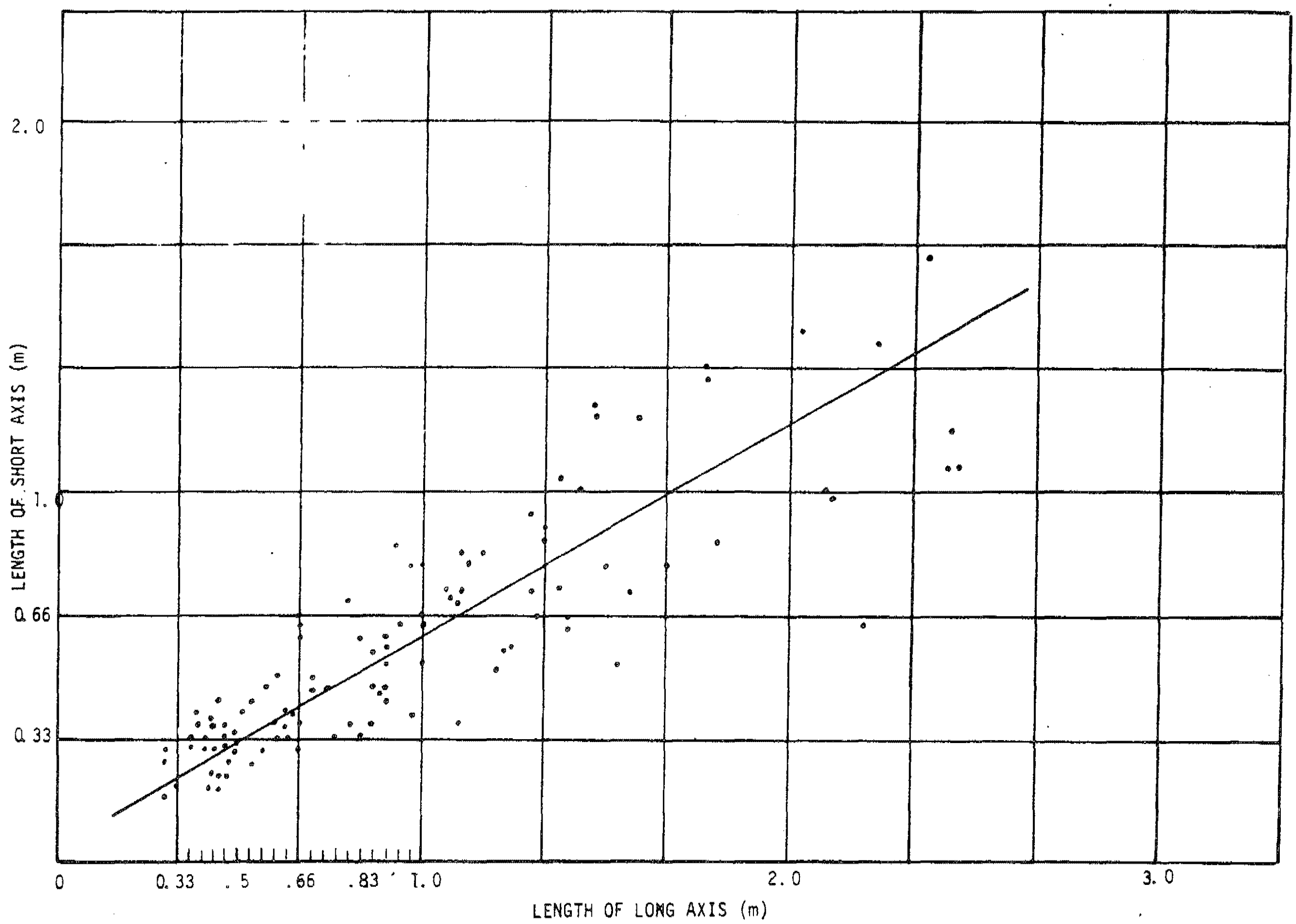


Fig. 16 Shape of pillow buds; plot of long axis vs. short axis of pillow buds; Upper New Street Quarry, Paterson (Data, D. Bello, pers. comm.).

columnar, in the Second Watchung it is characteristically composed of very long (about 25 m) and fairly continuous, slender (about 10 cm in diameter), non-radiating, parallel columns that are perpendicular to the flow surface. Poorly developed blocky columns and massive basalt of the upper colonnade overlie the entablature in most areas.

Petrographic studies of these structures in the First Watchung show some correlation between texture and mineralogy and the joint type (Fig. 18). The grain size is aphanitic throughout the flow but tends to increase from the lower contact to the base of entablature, remaining constant through the entablature, and reaching a maximum in the lower part of the upper colonnade. Microphenocrysts of plagioclase and augite occur in all three units.

The mineralogy includes pigeonite, augite, labradorite, and olivine (serpentinized) with few accessory minerals. Glass with magnetite is present in the interstices of almost all the samples. Six to ten percent olivine is present in the entablature and in the lower few feet of the upper colonnade, but only traces occur more than a few feet above or below the entablature. Pigeonite is absent from the entablature. The relative proportions of glass, total pyroxene and labradorite vary little in the upper two units. Glass and total pyroxene content in the lower colonnade show an inverse relationship. The amount of glass increases from 10% at the lower contact to 38% below the entablature. The pyroxene content decreases from 43% at the lower contact to 12% below the entablature. Glass and pyroxene content in the entablature and the upper colonnade are respectively 27 to 32% and 25 to 35% of the rock. Neither the anorthite content nor the total percentage of the labradorite shows any relationship to the joint structures of the flow.

Petrographically the curvi-columnar joint pattern of the entablature is characterized by an increase in grain size, an increase in the abundance and size of the interstitial glass, and the virtual restriction of olivine to this zone. These relationships suggest that although the rate of cooling of the hot flow interior may have proceeded slowly, once a ground mass capable of transmit-

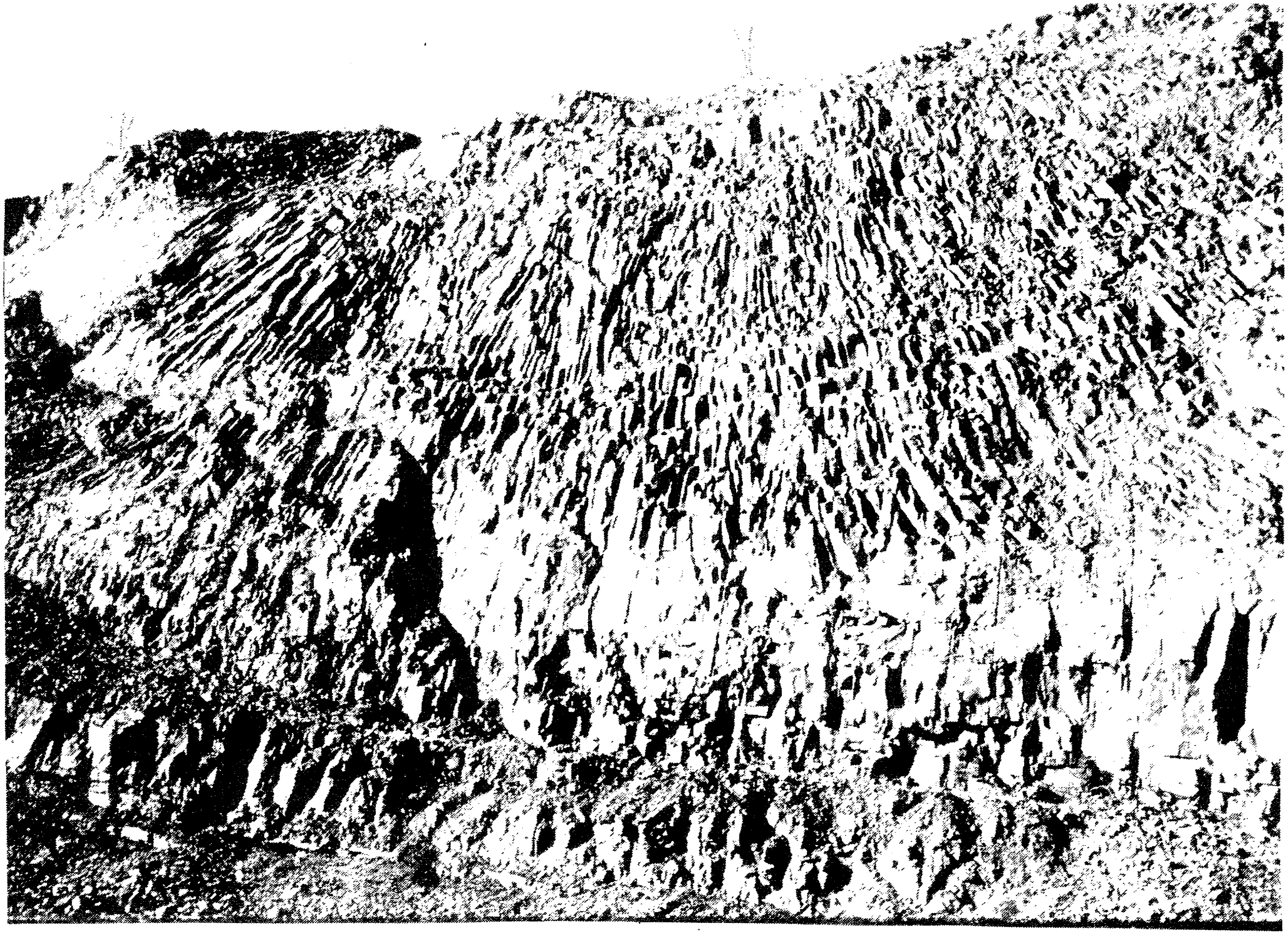


Fig. 17 Tomkeieff structural sequence of lower colonnade, entablature and partially exposed upper colonnade. Note radiating and bifurcating columnar joints and cross joints which are concentric about the apex of radiating; refraction of joints into the lower colonnade; and conformable sequence of sedimentary rocks below the igneous sequence. Orange Mountain Basalt, I-280, West Orange.

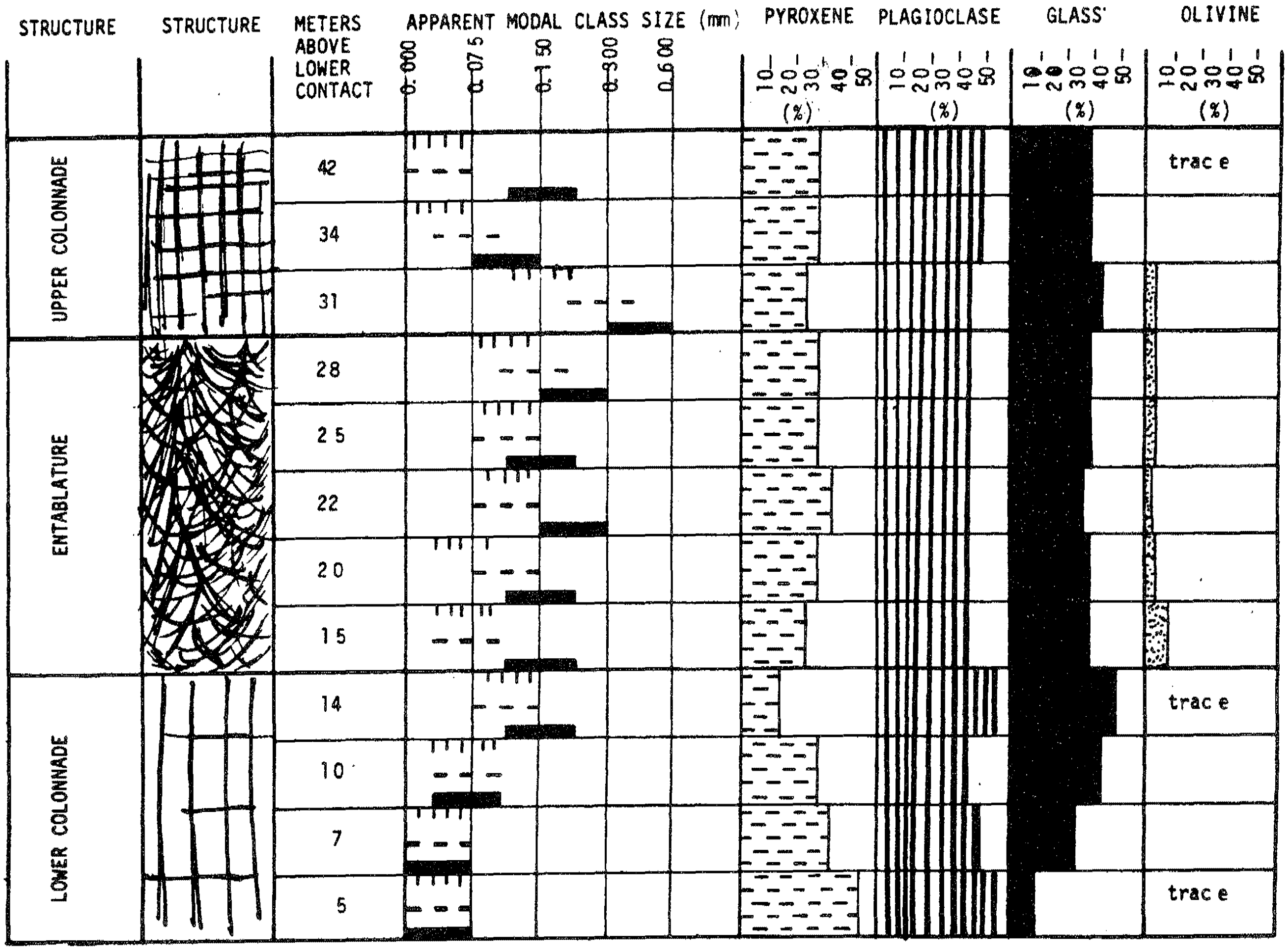


Fig. 18 Plot of mineral and glass content and texture against the Tomkeieff sequence of colonnades and entablature, Orange Mountain Basalt, I-280, West Orange.

ting stress was established the remaining silicate melt cooled almost instantaneously. The greater rate of cooling near the center of the flow would produce more fractures per unit volume and a greater release of the total energy in the system (Spry, 1961). The clarity of joint reflection from the lower colonnade into the entablature indicates that joint propagation proceeded along master joints, as suggested by Spry (1961). The obscure joint pattern observed almost everywhere in the upper colonnade may be the result of convective heat loss near the upper part of the flow.

Other explanations offered for the origin of the curvicolumnar jointing in the entablature of the First Watchung basalts include: (1) an undulatory upper surface (Iddings, 1886; Manspeizer, 1969); (2) varying rates of cooling at the upper contact (Iddings, 1886); (3) the occurrence of feeder dikes (Bucher and Kerr, 1948); (4) the effects of master joints upon stress in the entablature (Spry, 1971), and a fracture-controlled quenching process whereby temperature and stress distribution are altered by water introduced through joints (Justus and others, 1978). This issue, and the observations by Ryan and Sammis (1978) are further discussed in the Road Log.

Paleoslopes and Source of Lava

Vector means calculated from oriented pipe vesicles of the First and Second Watchung are respectively N 49°E. and N 70°E. indicating that these lavas erupted from tholeiitic dike swarms near the narrow neck of the Newark-Gettysburg Basin and flowed northeast along the axis of the basin (Manspeizer, 1969). Field and map data show that the lavas were not fed by dikes intruding along the border faults, since dike intrusions do not occur along the border fault but occur instead cutting across the border fault, the marginal highlands, and folded and faulted Triassic sediments. While both the dike swarms and border fault activity represent an Early Jurassic extensional phase of the crust, it appears that feeder dikes cannot penetrate the established border fault at times of active sedimentation and concomitant vertical displacement of the hanging wall (Manspeizer,

Fig. 19 Photomicrograph of entablature showing feldspar lathes, augite and glass; 22 m above the lower contact, Orange Mountain Basalt, I-280, West Orange.

and others, 1978). Recent geochemical studies by Puffer and Lechler (1980) support this view and show that the likely source for the Orange Mountain and Preakness Basalts was to the south, near the neck of the basin.

Vector means calculated from paleocurrent structures in sedimentary rock in contact with the lower lava flow surface show that the prevailing sedimentary paleoslope was to the southwest. This is supported by facies studies showing that the First Watchung is underlain by a fluvial-playa sequence that becomes progressively finer to the southwest, and that the Second Watchung is underlain by a lacustrine deltaic sequence that progrades to the southwest. Clearly the regional sedimentary paleoslope was inclined in a direction opposite to the regional paleoflow direction of the lava.

The paradox of two opposing regional slopes is a characteristic of flood basalt geology. See White (1960) and his discussion of the Keweenawan lavas, and Schmincke(1967) and his discussion of the Columbia River basalts of Washington. It appears unlikely that the basin behaved like a seesaw with a fulcrum along the longitudinal midpoint of the basin.

It is believed that the lower flow unit was ponded against an opposing regional paleoslope. Using an average sedimentary paleoslope of about 5m/km for the underlying fluvial and playa sedimentary sequence, we may conclude that the lava at its source in Pennsylvania, about 70 km away, had to be in the order of 350 m thick before it even could reach the northern end of the basin.

The dike swarms of the Gettysburg area may have fed low sloping shield volcanoes whose summits rose in the order of 1 km above sedimentary surface. Lavas issuing as summit or fissure eruptions on the flanks of the volcanoes could flow to the northern end of the basin and perhaps slightly beyond. Daneš (1972) has shown that tholeiitic lavas, like those of the Columbia Plateau, could spread over distances in the order of hundreds of kilometers over nearly horizontal surfaces with negligible head, even when their thicknesses are only on the order of meters.

While First and Second Watchung lavas erupted from sources in the southwestern end of the basin, vector means calculated from pipe vesicles indicate that the Third Watchung erupted from an unknown area to the northeast of the basin and flowed to the southwest in the direction of the regional sedimentary paleoslope (Manspeizer, 1969). These flows may have fractionated from a typical Mid-Atlantic Ridge basalt magma (Puffer and Lechler, 1980).

Emplacement of the Watchung Lavas (Field trip stop E)

During the middle of the 19th century a lively debate occurred in the geologic community over the origin of the trap rocks of New Jersey. Accounts taken from N.H. Darton (1889; 1890) indicate that Rogers (1840), Cook (1868) and Russel (1878) all argued that the Watchungs, like the Palisade Sill, are intrusive as evidenced by the baked sediments overlying the Watchungs at Feltville. Although Davis (1882) agreed with previous observations by Emmons (1846), Cook (1868) and Russel (1878) that the Palisades is an intrusive body, he concluded that the Watchung traps were extrusive and similar to the extrusive sheets that he had studied in Connecticut. At Feltville, Davis found that the trap was vesicular, slag-like and brecciated, and overlain by mottled shales without any signs of alterations. In his paper, "Triassic Traps and Sandstones of Eastern United States", Davis considered the occurrence of the breccia strong evidence that the Watchung traps are extrusive, stating that "...it is difficult to understand how it would have formed except on the surface of a pre-existent sheet of lava." (Darton,1890, pg. 26). Citing Feltville and other localities, Darton (1889; 1890) concurred with Davis that the Watchung traps were emplaced as lava flows.

Central to this issue are observations at Feltville, one of the very rare places where the upper contact may be studied. The section should be interpreted in light of our observations of the upper flow unit at the New Street Quarry in Paterson. The sections are fundamentally isochronous. At Feltville the shales and sandstones overlying the irregular contact of the upper flow unit, although poorly exposed, appear to be intruded by diabase and interbedded with pillow lavas that probably formed when the magma was injected into the con-

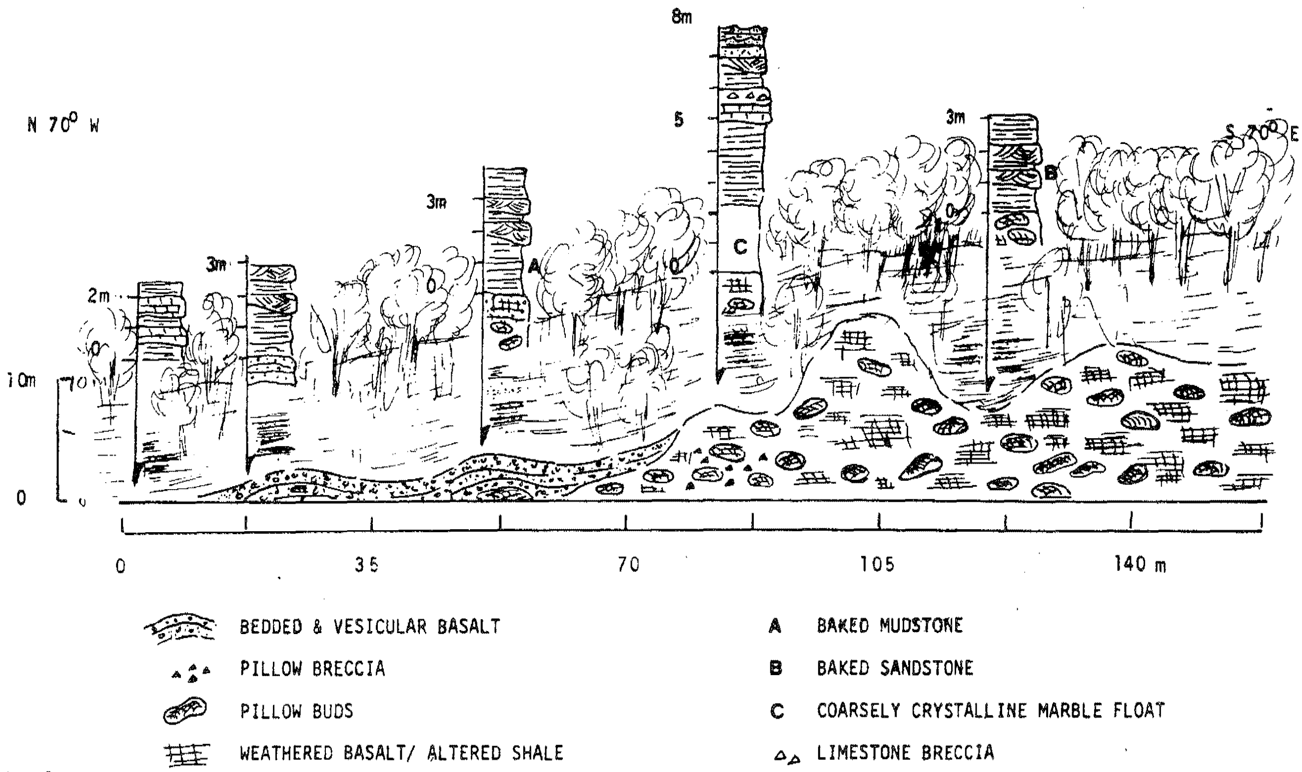


Fig. 20 Field sketch of the Orange Mountain Basalt in contact with the overlying Feltville Formation, ravine near the old copper mine, south side of Blue Brook, Watchung Reservation, Union County.

siderably younger non-lithified lacustrine sediments (Fig. 20). Coarsely crystalline, ripple-marked marble with basalt apophyses occur as float above the intrusion in horizons otherwise containing limestone. Russel (1878) also reported the occurrence of marble above the igneous rock. Thin sections of baked mudstone show many free floating quartz grains surrounded by thin wisps of basalt and iron oxide "cement" which looks like the basaltic glass found in lavas. The rock is very hard and appears similar to the Lake Superior iron ores. It is often difficult to place the upper contact of the igneous rock, since it is bedded on the same scale as the overlying sedimentary rock. There is reason to believe that these structures represent relict sedimentary bedding. Some may advance the possibility that this represents an ancient soil horizon. This and other possibilities are under investigation.

Currently, however, the data seem to indicate that the second flow unit of the Orange Mountain Basalt was emplaced at a time of considerable crustal extension and block faulting primarily along the axis of the basin with large isolated fault-bounded lakes developing in the regions of Paterson and Feltville and perhaps Ladentown. Fissure eruptions along these fractures produced the pillow-flow lobe complex and subaqueous volcanic eruptions at Paterson, and the pillow-intrusive complex at Feltville. Although the volcanic processes are complementary in the two basins, they may not have occurred at the same time. At Feltville, the volcanics are partly younger than the Feltville Formation. At Paterson, however, the Feltville Formation is not exposed.

Although the upper flow unit of the Orange Mountain Basalt is intrusive resulting from fissure eruptions, most of the Watchungs were emplaced as lava flows. Some basalt flowed below the cooled surface in an underground series of lava tunnels and tubes that occasionally arched up and pierced the thin overlying pahoehoe shell. In this manner, the heated subterranean system of lava might bake, intrude and engulf the overlying younger sedimentary rock which occasionally collpased into a chasm of magma.

Paleoflow Environment

As we have seen, the Watchung lavas exhibit a variety of paleoflow structures that indicate their flow direction and environment of formation. Paleoflow maps of the lava show that the lava flowed to the northeast (along the rift axis) on the surface and in lava tunnels below a marked hummocky surface of tumuli, pressure ridges and collapsed depressions. Where the lava issued from lava tubes, it built out pahoehoe toes and sheet basalts on land and pillow-palagonite forset beds of lava deltas in lakes. Where the lava issued from fissures in

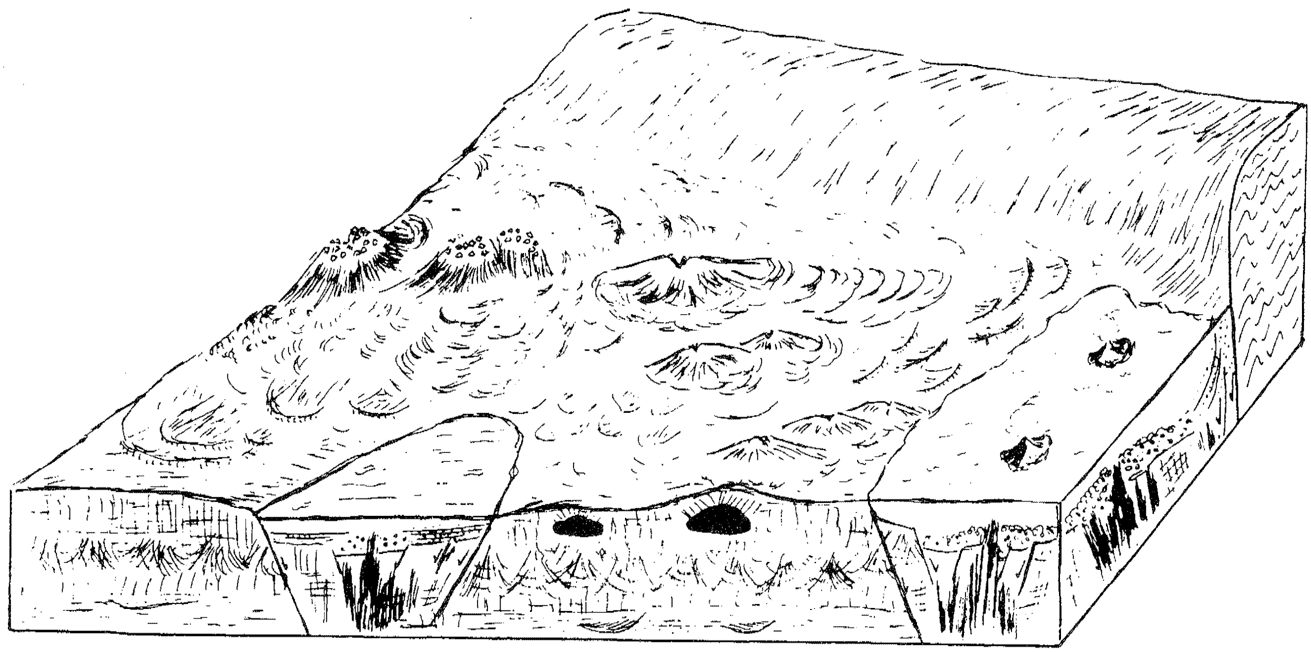


Fig. 21 Schematic block diagram illustrating volcanic structures and paleogeography of the Newark Basin during the extrusion of the First and Second Watchung lavas.

moderately deep water fault-bounded lakes, it built out volcanic cones and flow lobes and was injected into semi-lithified lacustrine sediment forming pillow complexes. In places it appears that the lava may have risen to the surface where it rafted and assimilated older supradjacent and lithified sedimentary rock. (Fig. 21).

Sedimentary Facies

Recurrent normal faulting along the western border fault and concomitant uplift and westward tilting of the eastern highlands established the tectonic framework of the basin and created a rift climate that influenced sedimentation pattern within the basin. Adiabatic uplift of warm maritime air from the Tethys Sea to the east produced seasonal storms in the higher western Highlands with torrential streams carrying coarse detritus onto eastward prograding alluvial fans. Most of the fill, however, came from the eastern metamorphic source, and was transported to the basin by perennial streams draining a weathered terrain and transporting sands and clays across a regional paleoslope inclined to the southwest. As continental and maritime masses descended to the floor of the rift valley, they warmed adiabatically creating arid conditions under which continental sabkhas developed along the valley floor. During humid climatic episodes (and aided by vulcansim, faulting and alluvial fan encroachment onto the valley floor), the drainage became deranged and large lakes occupied much of the rift valley (see Van Houten, and Olsen, this field book).

Horizontal extension resulting in vulcanism, however, substantially altered the tectonic framework of the basin so that moderately deep water lacustrine fans and deltas were deposited in the Early Jurassic where fluvial and playa red beds had accumulated in the Late Triassic.

The thick prism of sediment discussed in this paper may be divided into two megafacies: a central basin facies and a marginal rift facies. The central basin facies includes: (1) a pre-volcanic, Late Triassic, fluvial-playa facies; and (2) an intravolcanic, Early Jurassic, fluvial-deltaic facies. The marginal rift facies is similarly subdivided into: (1) a Late Triassic alluvial fan facies; and (2) an Early Jurassic shelf margin fan-delta. The geographic distribution of these facies indicates that the major source of the basin fill came from the east and north. Although a considerable amount of sediment was derived from the western source, it was restricted to the basin margin. Vector means, calculated mainly from cross bedded sandstones of the central basin facies and pebble imbrication of conglomerates of the marginal rift facies, support this view. Each facies is described more completely below with emphasis given to the features observed at each field stop.

Central Basin Facies: Fluvial-Playa (Late Triassic, Passaic Formation (Field trip stop 1)

Sedimentary rock in contact with the lower surface of the First Watchung lavas forms an isochronous surface

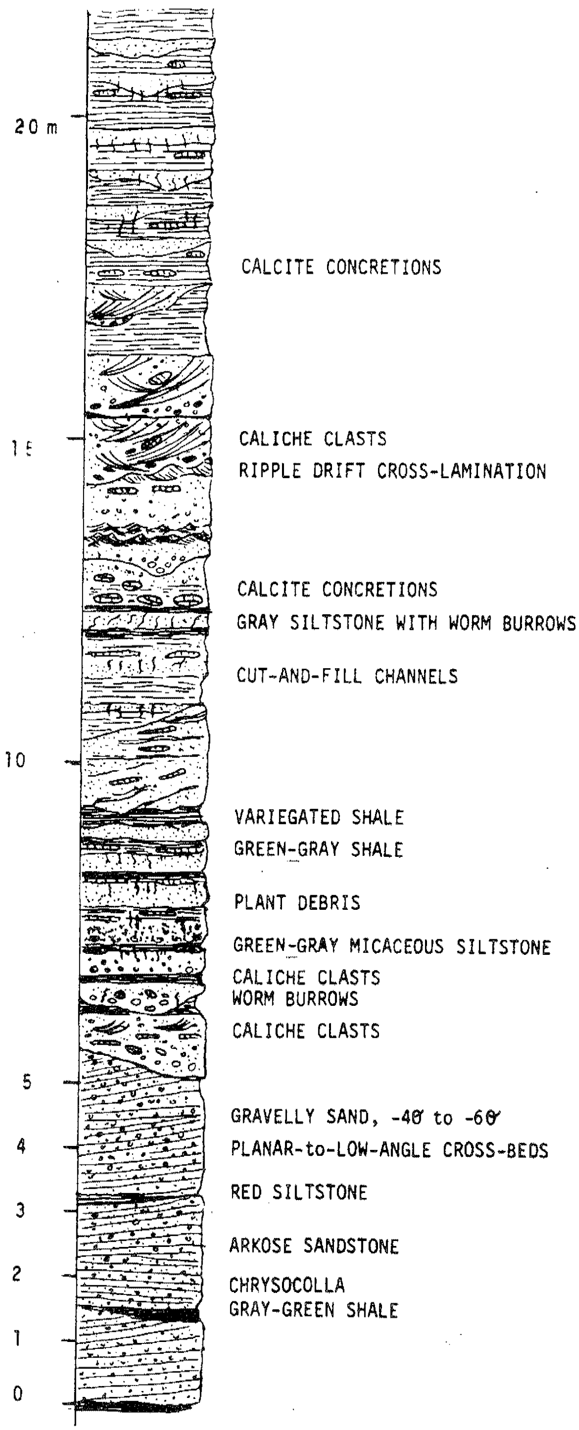


Fig. 22 Columnar section through part of the Passaic Formation, an inferred fluvial-playa sequence; I-280, East Orange.

of braided stream conglomerates to the northeast, fining-upward cycles of meandering stream in the central part of the basin, and playa muds with occasional casts of glauberite to the southwest. Along with these facies changes there is a concomitant decrease of: bedding thickness, average and maximum grain size, and size of cross-bedding sets.

Fining-upward sequences, characteristic of meandering stream deposits, are common in the central part of the basin. There they consist predominantly of cross-stratified pebbly sandstones, filling well-defined cut-and-fill channels, and sandy mudstones with rootlets of the overbank deposit (Fig. 22). Facies changes are abrupt, and cross-stratifications, ripple marks, pebble lag concentrates, mudcracks, and worm burrows and trails are common. Carbonate concretions, measuring several inches in diameter, occur in the overbank clays and silts, and occasionally in channel lag deposits. The sandstones are commonly arkosic to feldspathic with a carbonate cement, and polycrystalline quartz grains. While the overbank clays are primarily illite-rich, occasionally they are black, palynoliferrous and include chrysocolla.

The data (supported by paleocurrent studies by the writer) indicate that the sediment was transported to the basin across a gentle and broad southwest-sloping pediment by perennial streams that drained a deeply weathered metamorphic terrane to the north and east and occasionally overflowed its banks to support a moderate fauna on the floodplain. As these streams flowed to the southwest, they terminated in playa lakes or, after losing their flow by evaporation or infiltration terminated in mud flats.

While a southward regional paleocurrent direction does not rule out tectonic activity along the border fault with concomitant fanglomerate deposition along the basin margin, it gives reason to question whether the basin actively subsided as a unit or as individual blocks at this time. A clue to the question comes from isolated outcrops of "border" conglomerates along the western border fault near Ladentown, New York. The conglomerates show typical alluvial characteristics, namely: (1) cyclical bedding; (2) cut-and-fill channel deposits of braided streams; (3) fining-upward sequences of meandering streams; and (4) non-sorted pebbly mudstones and sandstones characteristic of debris flows and mudflows.

On the basis of geochemical studies, Geiger and others (1980) suggest that the Ladentown lavas were fed by a second pulse of Palisade magma and, therefore, are time equivalents of the Second Watchung lavas (see also Savage, 1968). Ratcliffe (this field book) traced unique felsite clasts in the conglomerate north to the Rosetown dike swarms and inferred that the conglomerates were transported to basin across a southerly-inclined paleoslope. This is compatible with paleocurrent studies through the Newark and Hartford Basins and may support a modified broad terrane hypothesis (see Hubert and others, 1978), showing that this segment of the border fault was inactive and that the western highlands stood low at this time. This is further supported by the studies of Ratcliffe and Olsen (this field book), who respectively estimate the thickness of the Triassic section along the border fault from Ladentown to Stony Point at 1000 to 2000 m, and in the Watchung Syncline at 5000 m.

Central Basin Facies: Lacustrine-Deltaic Facies (Early Jurassic, Feltville Formation) (Field trip stop 4)

The Feltville Formation is an isochronous horizon that lies between the First and Second Watchung basalts. Facies changes within this 200 m section may be worked out to a fair degree of accuracy, albeit it overlies the probable intrusive horizon of the Orange Mountain Basalt. Substantial stratigraphic data show that the section consists of fluvial-deltaic sandstones and shales prograding to the southwest, along the tectonic axis of the basin, over a lacustrine shelf carbonate and black shale facies. A marginal rift fanglomerate is also present within this horizon, but will be described in the following section. The depth and level of the lake was controlled by vertical displacement along the border fault, slope of the lake floor, and climate which had become more humid since the beginning of the Jurassic Period.

Typical distributary channel sands of the lower delta plain dominate the upper part of the lithosome to the northeast, where they are moderately sorted, laminated, angular, feldspathic, cemented with sparry calcite, and show pressure solution and clasts of monocrystalline quartz and metamorphic rock. Long-sloping, high-angle, unidirectional planar cross beds with parting lineations and occasionally convolute bedding characterize these beds. They commonly overlie woody debris and thin lenses of coal with underclay of the interdistributary channels, and give way upward in section to finely-textured ripple drift cross-laminations. To the south many of these sand horizons show flaser bedding, indicative of tidal flats. At places underlying shales of the delta front are convoluted, fissile, black to green, interbedded with sole-marked siltstones, and include isolated multistoried sandstone lenses.To the north these deltaic sands interfinger with typical fluvial sands (Fig. 23).

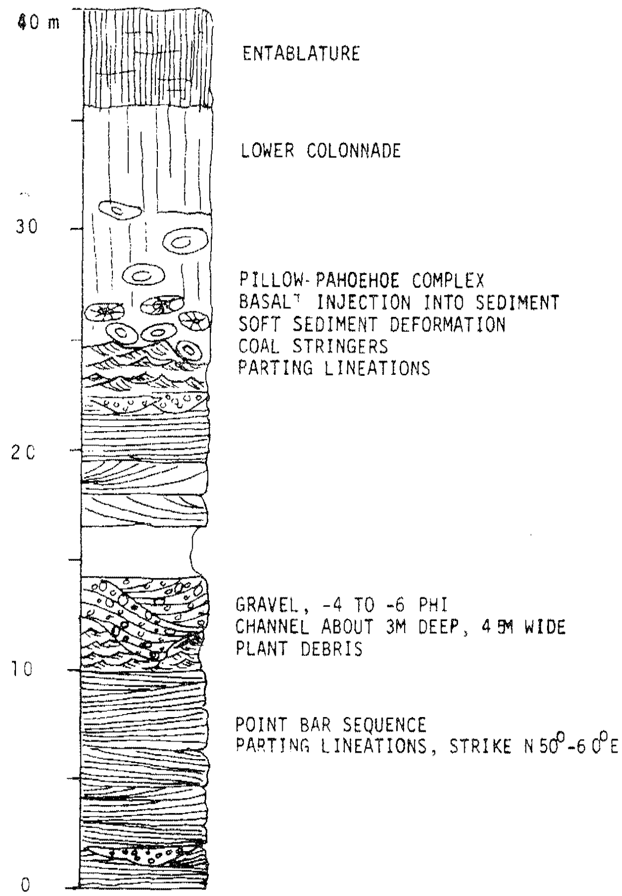
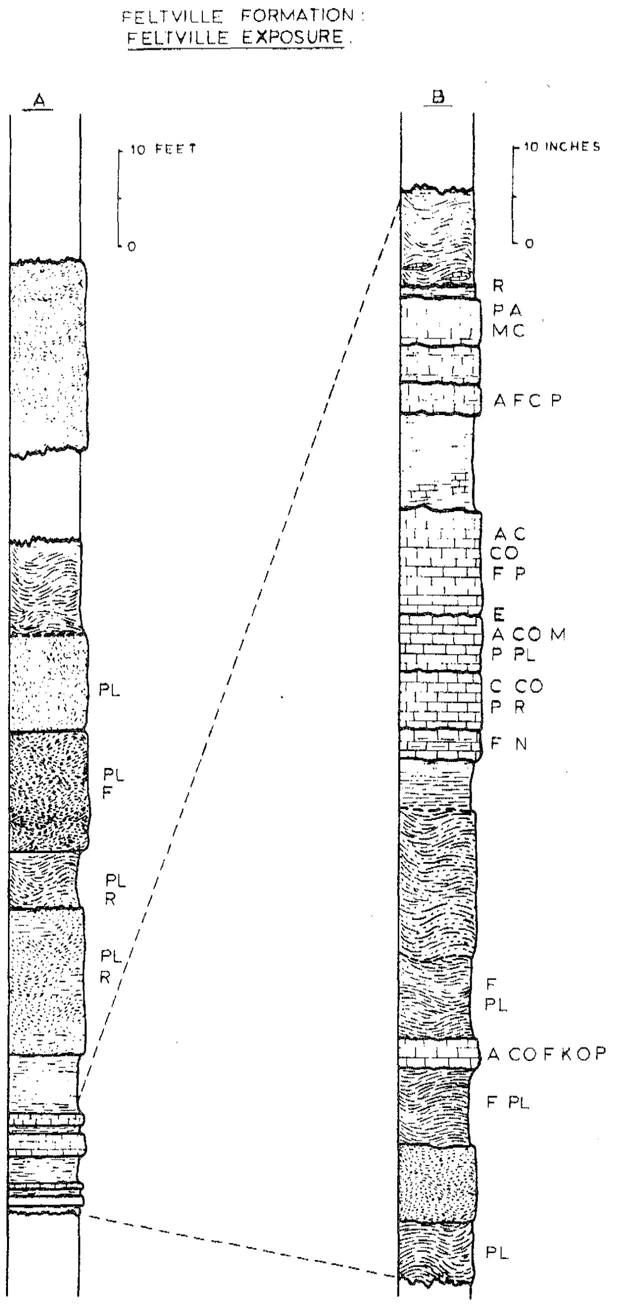


Fig. 23 Columnar section through part of the Feltville Formation, an inferred fluvial-deltaic sequence; small ravine near Belmont and Overlook Avenues, Haledon.

Thin discontinuous limestone lenses, in a shelf carbonate sequence of calcareous siltstones and shales, crop out from 5-25 meters above the upper contact of the First Watchung lava flows in small isolated stream sections at, the old and once-deserted village of, Feltville (now part of the Watchung Reservation). This facies dominates the basal part of the time-stratigraphic unit to the south and is overlain by ripple-marked calcareous siltstone with ripple drift cross-laminations, flaser bedding and parting lineations (Fig. 24). The precise stratigraphic position of the carbonates varies with respect to the very irregular contact of the underlying intrusion. The carbonates are interbedded with gray and reddish-brown shale, and with gray, calcareous, thinly laminated and finely cross-stratified siltstones that, according to Olsen (1975), contain reptile footprints and *Semionotus* fish fossils. The limestone lenses measure about 10 cm thick and about 100 m long, and display many shallow water features, such as: sedimentary breccias with ripped-up clasts up to 3 cm in diameter, cross bedding, abraded and broken fossils and intraclasts, ripple marks, dessication cracks, and minor disconformities with cut-and-fill channels (Fig. 24). In some sections the limestones are thinly laminated, and in others they are bioturbated. Rounded and abraded algal debris, micritic intraclasts and pellets comprise the bulk of the allochems, and are cemented with fine-textured sparry calcite. Dahlgren (1975) reports the occurrence of algal mats, ostracods, plant fragments, one branchiopod, and one possible mollusc shell. The rock contains no significant detrital component. Quartz is commonly found only in trace quantities. Euhedral crystals and abraded grains of authigenic feldspar occur in minor amounts in some thin sections.



Explanation:

Figure shows only those units found on the slope just east of Feltville.

Column A shows the entire exposure and begins approximately 35 feet above the top of the Orange Mountain Basalt.

Column B is a detail of the carbonates at the base of the exposure.

A - Algae
C - Clay Clasts and/or Partings
CH- Channeling
CO- Collophane
E - Erosional Surface
F - Fish Scales
K - Kerogen
M - Mudcracks
N - Nodular Micrite
O - Ostracods
P - Pellets
PL - Plant Fragments
R - Rippled Surface

Fig. 24 Stratigraphic section, Feltville Formation, an inferred carbonate shelf sequence; north side of Blue Brook, Watchung Reservation, Union County, (Data, McGowan, 1980).

Today algal stromatolites are the most diagnostic organic feature of the tidal-flat environment, and are found primarily in the high intertidal and low supra tidal environment (Lucia, 1972). The abundance of algal debris associated with many shallow water structures indicates that these limestones were laid down on a broad shallow shelf that was periodically submerged by tidal waters, becoming shallower with time. In the absence of clearly defined marine fossils (acritarchs and dinoflagellates; Olsen, oral comm.), one may speculate that these carbonates are lacustrine. Olsen (this field book) also reports that this shelf carbonate sequence is underlain by thinly laminated carbonates of deep-water facies.

Marginal Rift Facies: Alluvial Fan (Late Triassic, Passaic Formation)

Conglomeratic beds, termed fanglomerates by Lawson in 1913, "for cemented deposits of angular pebbles and cobbles which were formed in alluvial fans" (Carlston, 1946), occur in scattered exposures along the length of the northwest border of the Newark Basin. The areal distribution of these conglomerates is markedly more sparse and discontinuous in the Late Triassic beds north of the Watchung Syncline than in the Late Triassic beds to the south, near Pennsylvania. Eastward the conglomerates interfinger with typical Stockton, Lockatong and "Brunswick" beds. Although well-rounded quartzite clasts dominate the conglomeratic suite at most sites, angular-to-rounded carbonate clasts dominate the suite near Annandale, New Jersey and near Ladentown, New York. Gneissic clasts occur in abundance only at the Montville section where they crop out in some of the youngest beds of the Watchung Syncline, leading Kummel (1940) to conclude that the New Jersey Highlands must have been largely covered by Paleozoic beds with only few streams cutting into the basement. Arkose sandstones of the older Stockton Formation, however, show that the eastern highlands were mantled with weathered granitic debris in the Late Triassic. Moreover, feldspar clasts in the younger "Brunswick" Formation near the New York-New Jersey state line dated at 870 my and 930 my by Abdel-Monem and Kulp (1968), indicate that other Precambrian rocks were exposed to the northwest at this time.

A vertical stratigraphic section may be constructed of the conglomerates by "walking out" the section along the western margin of the basin, from Ladentown, New York southwest to Montville and Boonton, New Jersey. Although much of that section is concealed with glacial deposits, analyses of sedimentary facies and stratigraphic relations of these scattered exposures provide insight into the complex processes attending episodes of deposition. The section at Ladentown has been discussed previously in this paper under the central basin facies.

Marginal Rift Facies: Fan Delta (Early Jurassic, Feltville, Towaco and Boonton Formations).

South along the border fault the conglomerates become progressively younger, and in the Watchung Syncline they are interbedded with black shales or occur in lacustrine-dominated horizons. A composite, drawn from isolated exposures within the syncline, suggests that these fanglomerates form a fan delta depositional complex of interfingering, time-transgressive megafacies (Fig. 25). Three major facies of the fan delta are identified, representing the following depositional environments: (1) subaerial delta plain and alluvial fan with braided streams, meandering channels, flood plains and marshes; (2) moderately deep water lakes (see Olsen, this field book); and (3) moderately deep water subaqueous fans of resedimented conglomerates. The absence of well-defined beach deposits in the sequence suggests that fan-delta sedimentation occurred on a narrow coastal zone with a steep offshore profile.

Holmes (1965, p. 554) describes a fan delta as an alluvial fan that progrades into a standing body of water from an adjacent source area. Fan deltas occur today at the edge of tectonically active continental margins where high gradient braided streams debouching from mountainous terrane deposit their sedimentary load on a narrow coastal plain with a steep offshore slope (Wescott and Ethridge, 1980). Along the Dead Sea Rift Holocene fan deltas prograding across a narrow shelf also feed deep water lacustrine fans (Neev and Hall, 1976; Sneh, 1979; and Manspeizer, in press). Slumping, fluctuations in base level due to climatic changes, and tectonic activity are some of the processes initiating movement of sediment across the shelf and onto the subaqueous fans.

Each megafacies is diachronous and each lava flow is fundamentally isochronous. The lower alluvial fan sequence of Late Triassic age is not properly part of the fan delta sequence, and is included here only for the completeness of the fanglomerate record. The line of section, along the Ramapo border fault, also shows the

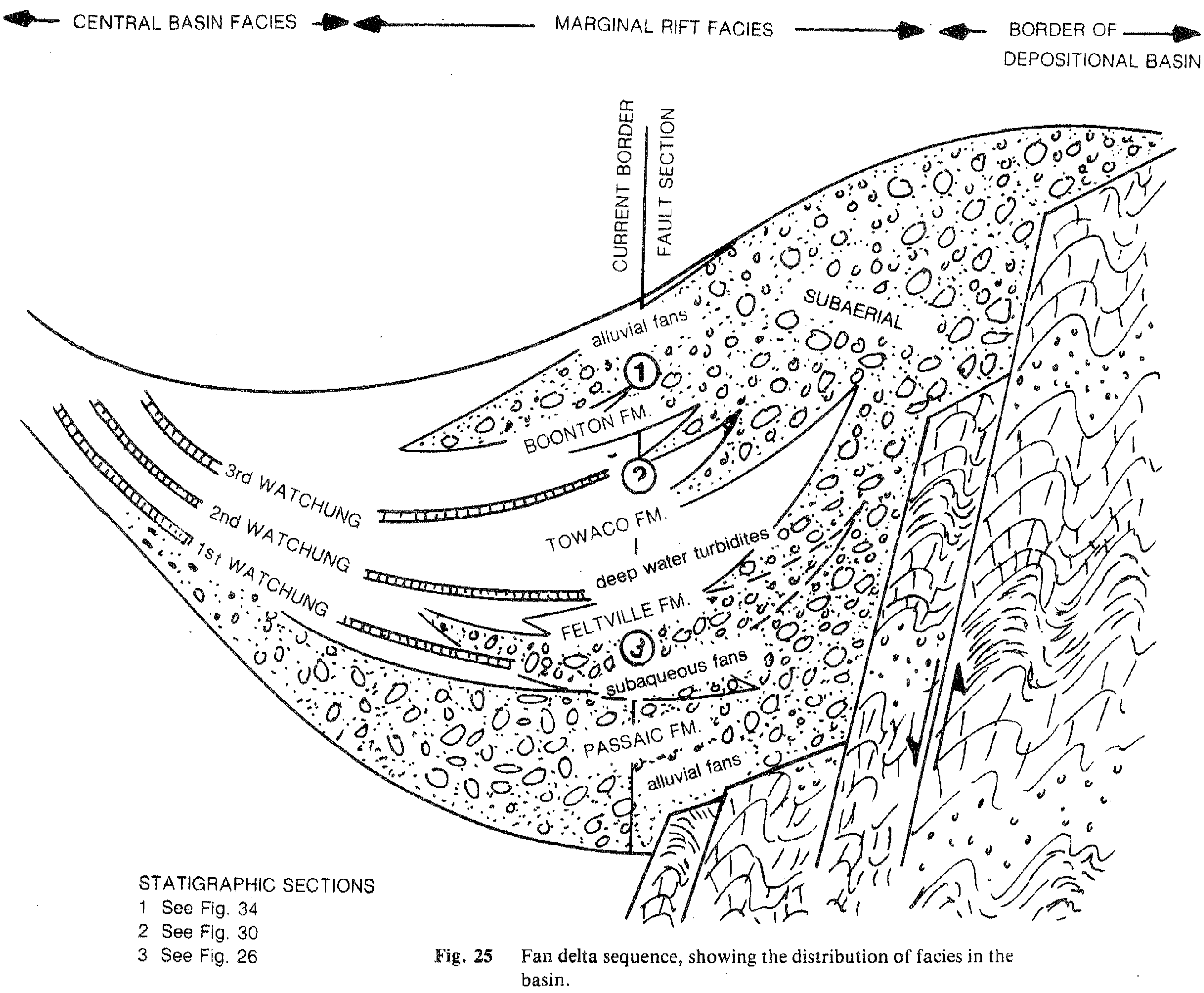


Fig. 25 Fan delta sequence, showing the distribution of facies in the basin.

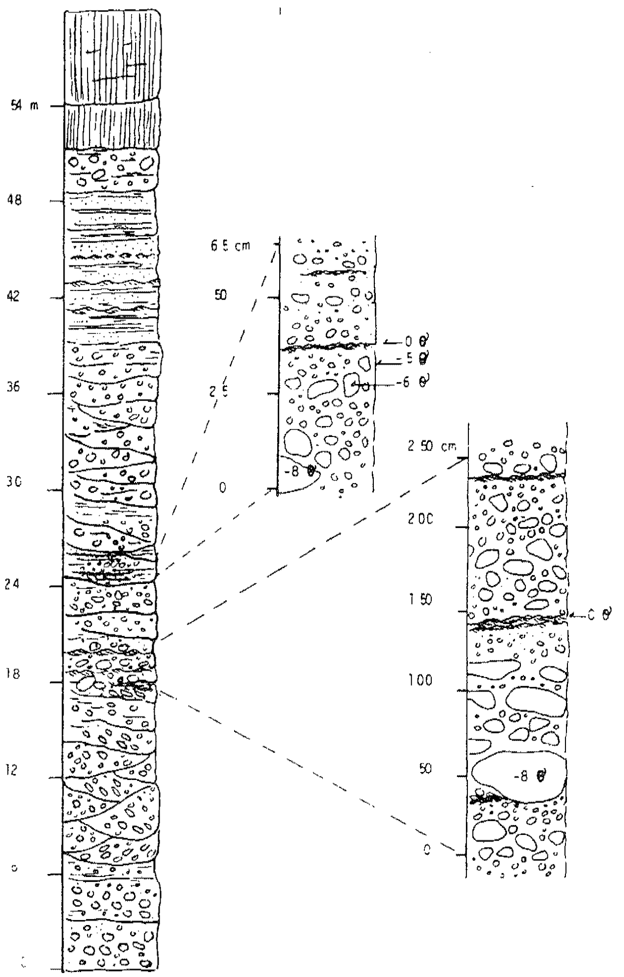


Fig. 26 Stratigraphic section through part of the Feltville Formation, inferred to represent a subaqueous fan deposit of the marginal border facies; beneath Preakness Basalt, behind shopping center off route 202, Oakland.

approximate location of the stratigraphic sections of figures 26, 30, and 34. Note: (1) the hypothetical extent of the depositional basin to the west; (2) that vulcanism corresponds to periods of shale deposition and low coarse-clastic input; and (3) that the depositional package becomes progressively more terrestrial with time.

Subaqueous Fans (Field trip stop 5)

The oldest part of the fan delta sequence is a uniquely exposed massively bedded, dark gray, largely clast-supported conglomerate that crops out near the border fault in Oakland, New Jersey (Fig. 26). Except for a small outcrop of feldspathic sandstone near the southern end of the Watchung Syncline, this site is the only exposure of this horizon along the border fault. The conglomerate, about 50 m thick, has characteristics similar to those described by Walker (1975; 1978) for feeder channels in deep-water subaqueous fans. Notable among them are: abundance of channeling, abundance of massive and poorly stratified gravels, and presence of large scale cross-stratification, graded bedding and imbrication (Fig. 27). While these features are common to both the fluvial and deep-water environment, the section at Oakland distinctively lacks associated features commonly found on other fluvial beds in the section, notably: rootlets, caliche deposits, plant fragments, dessication cracks, red beds, dinosaur footprints and fining-upward sequences terminating in overbank clays. Fischer and Mattinson (1968) relate inverse grading and other similar structures in the Wheeler Gorge Turbidite-Conglomerates of California to high density and high fluid underwater flow into deep water.

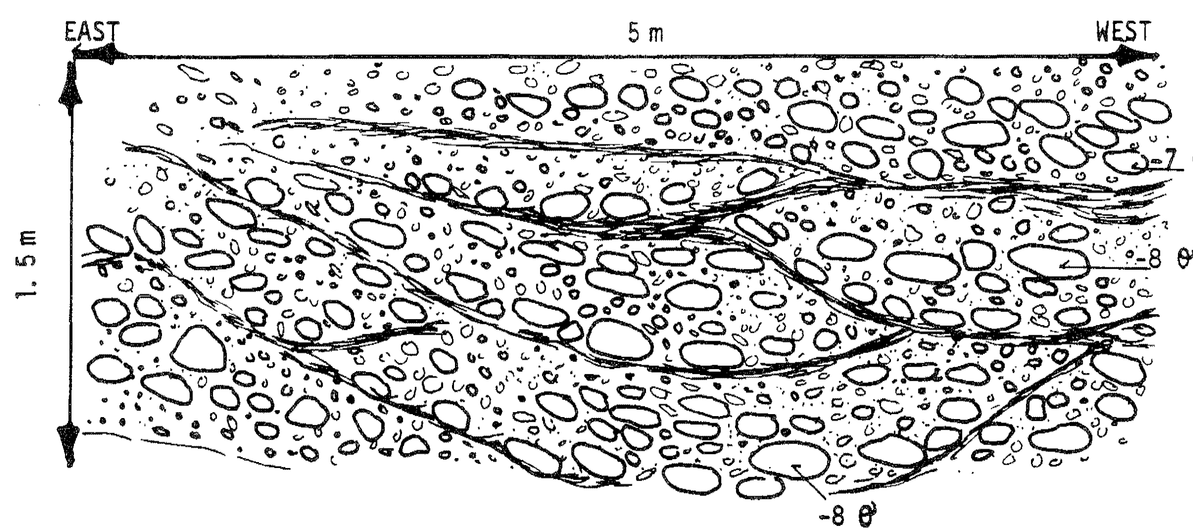


Fig. 27 Field sketch of cut-and-fill channel deposits, Feltville Formation, behind shopping center off route 202, Oakland.

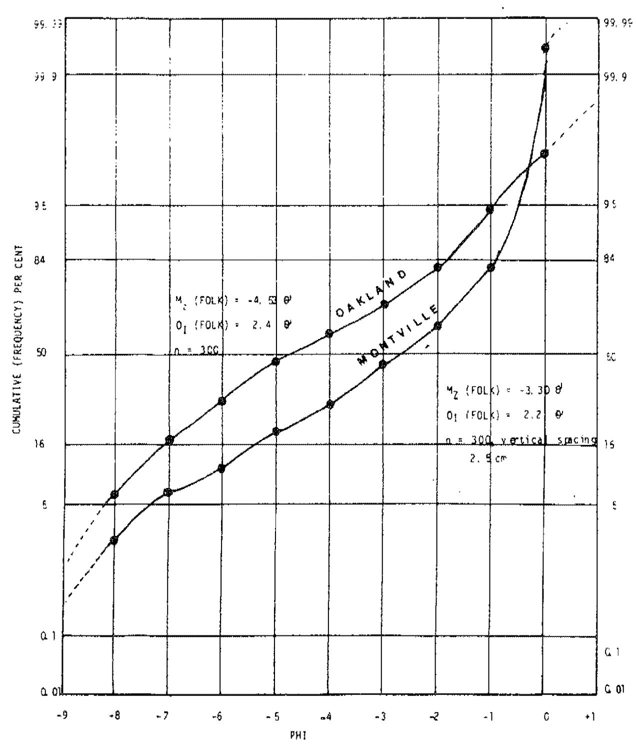


Fig. 28 Cumulative-frequency curve; grain size data in phi units and plotted on probability paper. Data for Oakland and Montville sections obtained from stratigraphy class exercise, Spring, 1980.

The conglomerates in this part of the section consist primarily of very poorly sorted carbonate, quartzite, vesicular basalt and low-rank metamorphic clasts. Cobbles and boulders are common. The average grain size is about - 4 to - 6 phi and the clasts have a graphic mean (Folk, 1974) of - 4.5 phi, and a graphic standard deviation (Folk 1974) of 2.4 phi (Fig. 28). . Most of the larger clasts are well rounded. Imbrication is common with a prevailing imbrication direction of S40°W, i.e. towards the border fault. A subtle stratification pervades the conglomerate and is enhanced by both inverse and normal grading (Fig. 29). Graded bedding is one of the most distinctive aspects of these beds. Although cut-and fill channels are abundant in the lower part of the section and measure about 3 m wide by 2 m deep, cross bedding is obscure. The conglomerate, virtually devoid of clay minerals and clay-size particles, contains "fines" of finely comminuted phyllitic and slaty clasts, which may be rounded and cemented with sparry calcite.

The beds become finer grained upward in section, where they are markedly cyclical and stratified. Each complete cycle consists of an inverse and normal graded component that is topped with ripple drift cross-stratification (Fig. 26). Many of the cycles are incomplete, having been subsequently eroded and filled with couplets of graded beds.

Higher in the section and directly beneath the Second Watchung lava flow, these conglomerates, although poorly exposed, become slightly finer grained and interfinger with reddish-brown, cross-bedded and micaceous pebbly sandstones. Since the overlying basalt does not show any evidence that it flowed into water, it is inferred that the upper part of the conglomeratic sequence is perhaps fluvial-deltaic.

Deep Water Lakes and Deltas

The border facies of the overlying Towaco depositional episode consists of several sedimentation couplets including: (1) laterally persistent, finely laminated gray calcareous siltstones and/or black-to-olive green shales with slump structures and thin interbeds of graded sandstones; and (2) cross-bedded gray pebbly sandstones and conglomerates with scoured lower contacts, fining-upward sequences, convolute bedding, worm burrows, plant fragments and ripple marks (Fig. 30). Olsen (this field book) also reports the occurrence of reptile footprints, roots, pollen and stromatolites from the sand-

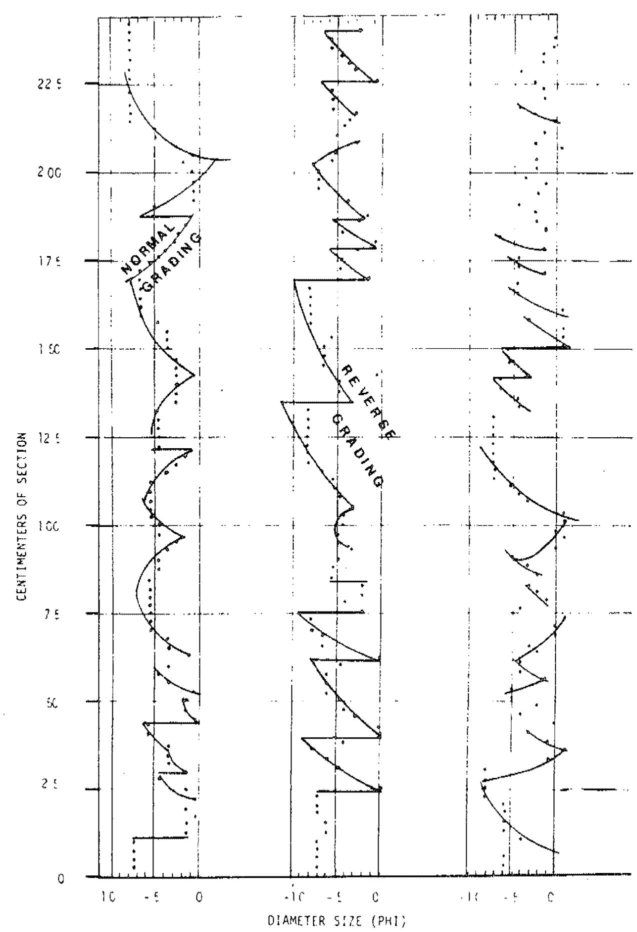


Fig. 29 Patterns of sedimentation reflected in grain-size variation through part of the Feltville Formation, inferred to represent a subaqueous fan deposit. Grain-size data (in phi units) was obtained in vertical section on 2.5 cm sampling grid. Section studied behind shopping center off route 202, about 40 m below Preakness Mountain Basalt, Oakland.

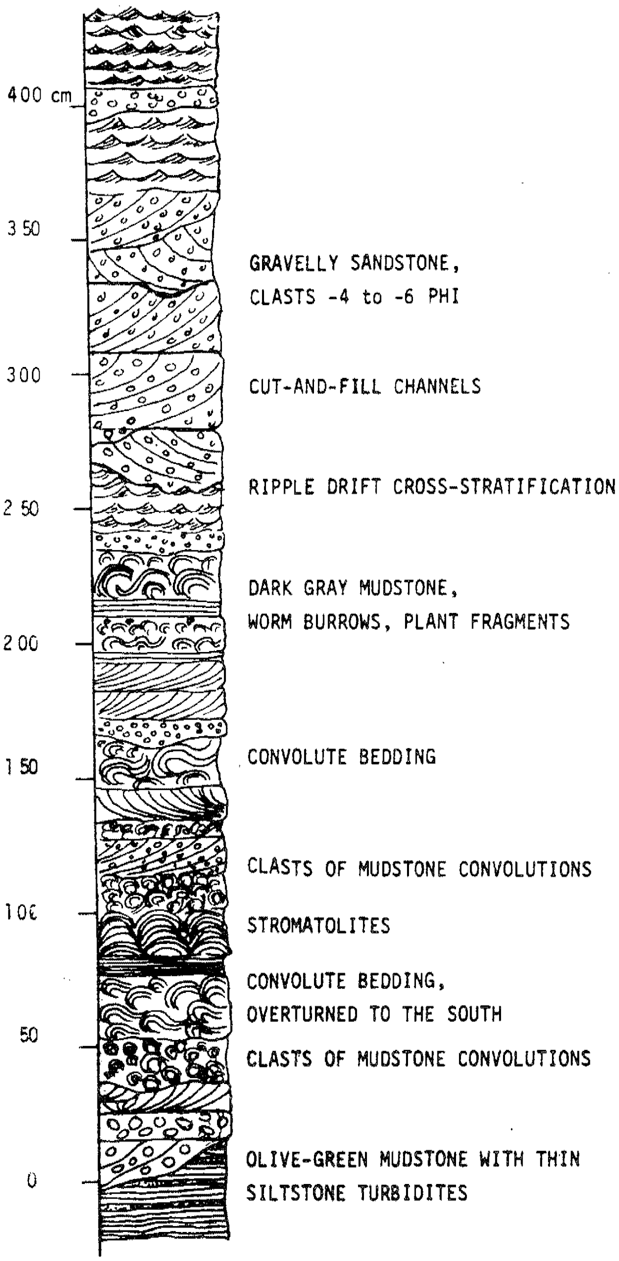


Fig. 30 Columnar section through part of the Towaco Formation deposited on a subaqueous slope over deep water turbidite deposits; Wayne.

stone facies, and fish fossils and scales from the shale and siltstone horizons.

The stratigraphic juxtaposition of two distinctively different facies, a moderately deep-water basinal facies with turbidite aspects, and a fluvial-deltaic facies with slump structures and terrestrial biogenic structures, suggests that these beds formed near a break in slope as fan deltas prograded across a narrow coastal margin onto the subsea floor.

Alluvial Fans (Field trip stop 6).

The youngest beds of the rift sequence crop out along the border fault and consist primarily of two markedly different time-transgressive shelf facies: (1) an alluvial fan facies of red sandstones and conglomerates, and (2) a deltaic-lacustrine facies of gray thinly laminated siltstones (containing the famous Boonton fish fossils) alternating with gray cross-bedded sandstones with fining-upward sequences and dolomitic concretions. Since the latter facies is largely the subject of Paul Olsen's paper (this field book) and is not seen on this field trip, attention will focus on the alluvial fan deposits.

The section at Montville, N.J., highly polished by glacial scour, is a superb section showing detailed sedimentary features. The fan formed at the foot of the upthrown Highlands, where streams flowing east off the steep escarpment spread as sheets infiltrating the coarse apron with a concomitant decrease in velocity, depth and carrying capacity (Figs. 31 and 32; Hall, pers. comm.). Where sheets of water incorporated sufficient sediment, entrainment occurred and the flow behaved like a plastic mass rather than a Newtonian fluid, creating debris flows of high density, viscosity and carrying capacity (Bull, 1972). Because each transport mode (traction and debris flow) yields a different set of sedimentary features, cyclical bedding is the most striking aspect of the alluvial fan deposit at Montville. While uniformity of bedding thickness is common to both

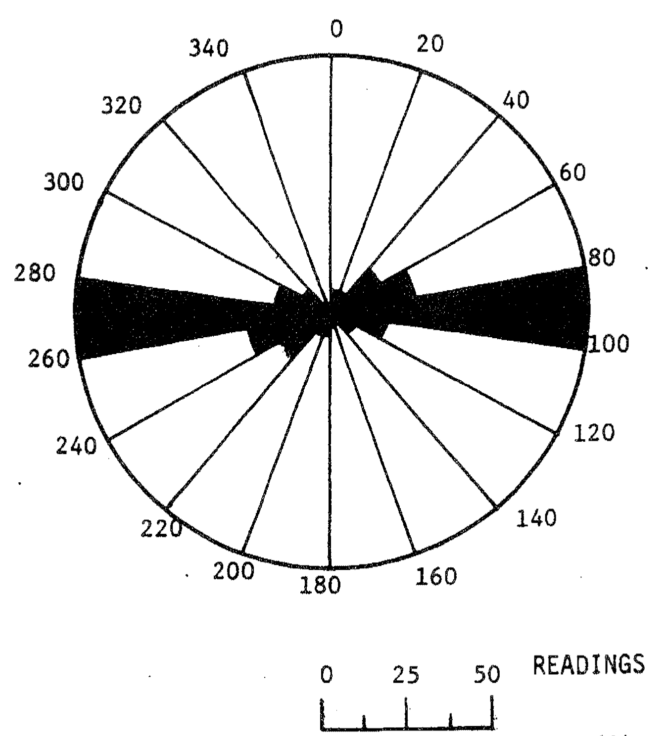


Fig. 31 Current rose diagram: azimuth of elongate pebbles, Boonton Formation, alluvial fan facies, Montville (Data, S. Hall, pers. comm).

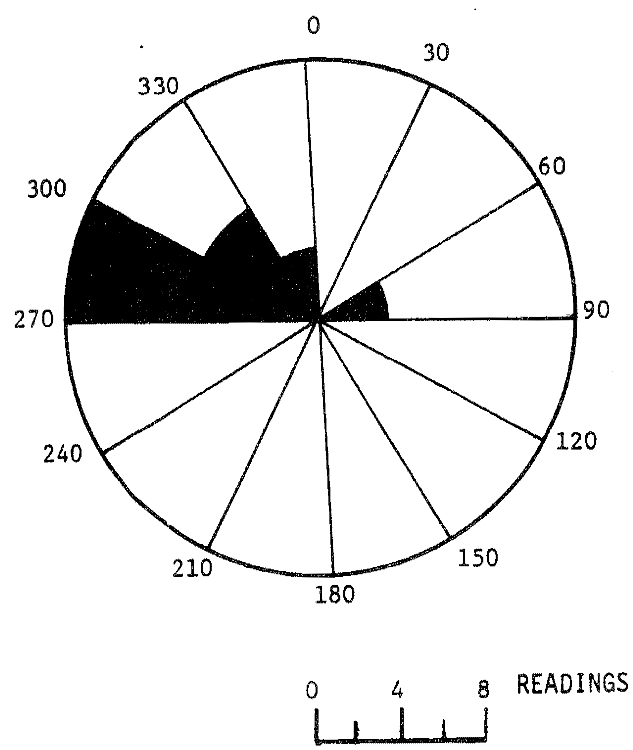


Fig. 32 Current rose diagram: azimuth of imbricated pebbles, Boonton Formation, alluvial fan facies, Montville (Data S. Hall pers. comm.) west-to-east paleocurrent.

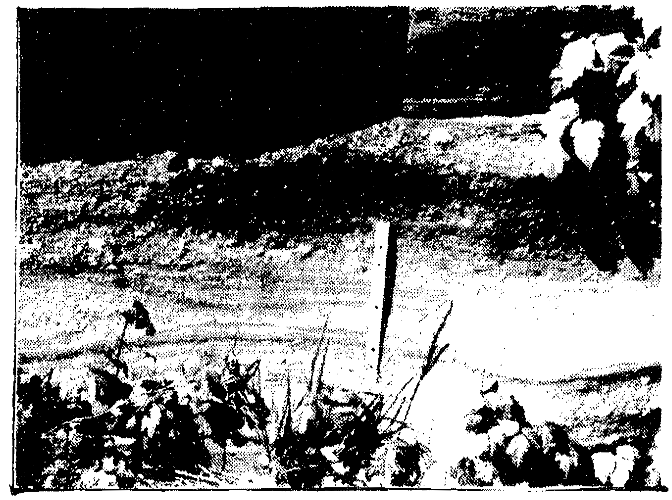
deposits, the poorly sorted and graded beds of the debris flow stand in marked contrast to the stratified, rippled, cross-bedded and scoured bedding of the water laid deposits (Fig. 33). The sheet-like dimensions of the beds are a function of sheet-flood and debris flow sedimentation. Beds in the lower part of the section have attributes of low-viscosity debris flow deposits or sediment-charged water laid deposits. Bedding is cyclical (on the order of 2-3 cm), graded, and fines upward from fine gravel to fine sand with ripple drift cross-laminations (Fig. 34). Incomplete cycles are common with the upper part of the cycle having been eroded and subsequently filled with graded beds of the overlying cycle. As there was little transport from their nearby largely crystalline source, the sediments tend to be poorly sorted, angular and composed of gravels and boulders of gneiss, vesicular basalt and quartzite with subordinate amounts of amphibolite, shale and greenstone schist.

Some Thoughts on Basin Tectonics

From a plate tectonic viewpoint, Newark-type basins formed along the margin of a plate boundary and in a zone essentially of east-to-west extension. Older faults were activated at this time, creating rift basins whose axes were generally at right angles to the extension direction. One of these, the Ramapo Fault, currently forms the western margin of the basin and has had a long tectonic history dating back to the Precambrian (Ratcliffe, 1971). Recurrent vertical motion and normal faulting along the fault zone was the dominant dynamic factor influencing the distribution of sediments and volcanic facies, tectonics and morphogenesis along most of the basin. The deepest and tectonically most active part of the basin was along the western border fault, particularly in the Watchung Syncline where the youngest and thickest rift sediments are preserved. North of the Watchung Syncline the basin was relatively stable and only a thin stratigraphic record is preserved (see Ratcliffe, and Olsen this field book).

Stratigraphic data indicate that the basin was strongly asymmetric at this time, taking on characteristics of en-echelon tilted blocks. We may infer from the rock record that the eastern fault block gently "tilted" towards the western border fault, where it was broken by high angle faults that step down rapidly to the up-thrown blocks on the west and tilted to the south. Marked by its unique preservation of substantially thick Jurassic sediments and volcanics, the Watchung Syncline most likely represents the site of greatest subsidence. It is also the site of the Feltville deepwater lacustrine fans marked by coarse border conglomerates that are restricted to a very narrow geographic zone near the border fault. These conglomerates do not overlap the central basin facies and, therefore, accumulated in the deeper parts of the subsiding trough. Note that the volcanic clasts of this border facies are not found in the central basin facies to the east, which was largely influenced by a more gentle paleoslope inclined or tilted to the west and southwest. While lacustrine-deltaic sedimentation is characteristic of both the central basin and marginal rift facies in the overlying Towaco Formation, the latter facies is clearly coarser grained and thicker with more turbidites and deep water lake deposits. Evidently the rate of subsidence and step faulting in the basin governed the paleoslope and bathymetry of the lake floor.

Subsidence along the western border fault may have also effectively sealed the fault to rising magma. Paleocurrent data (Manspeizer, 1969) and geochemical data (Puffer and Lechler, 1980) show that the First and Second Watchungs were largely derived from intrusives in Pennsylvania while the Third Watchung was derived from a source to the northeast of the basin. There is no body of data in support of the notion that the magma rose along the Ramapo border fault, either at the surface or even at depth. Indeed Ratcliffe (this field book) shows that the Ladentown lava, issuing from a Palisade magma flowed west into and down the subsiding Ramapo Fault. A review of the literature, including maps, indicates quite convincingly that neither Triassic-Jurassic feeder dikes nor volcanics lie along the border fault. Many of the dikes actually cut across the border



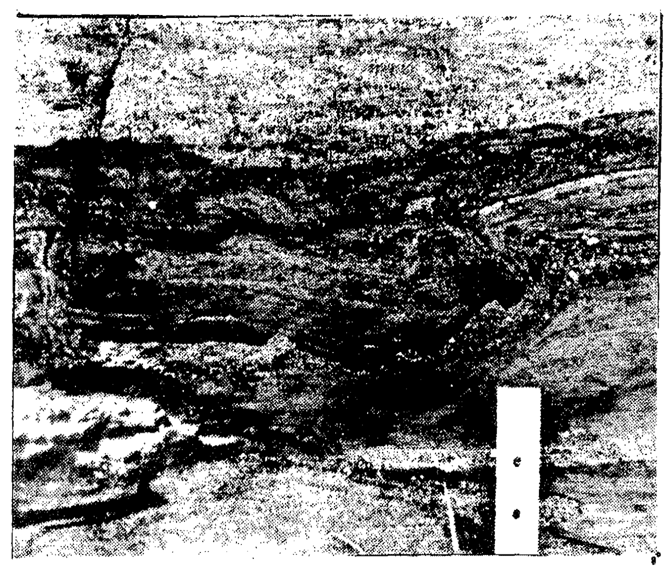
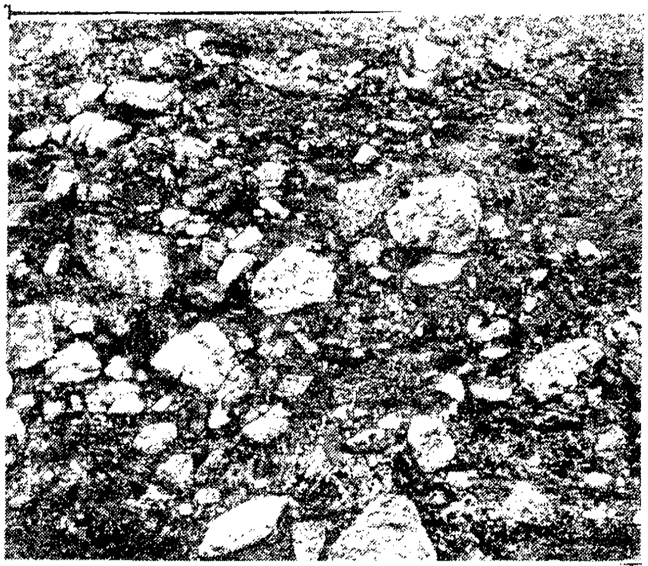
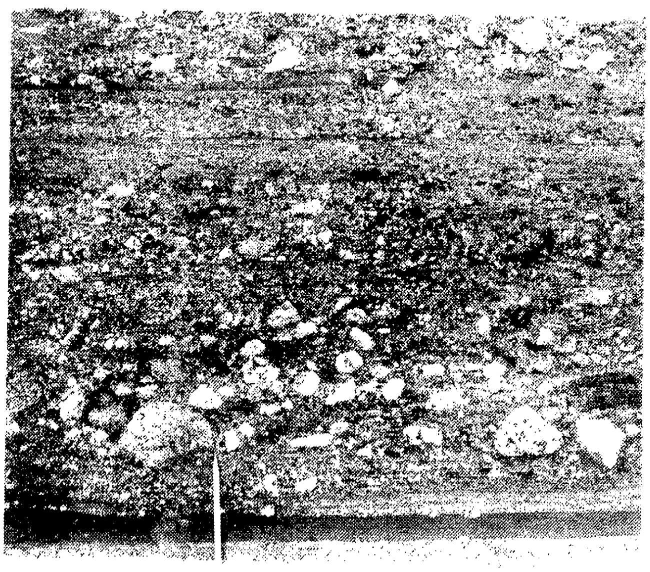
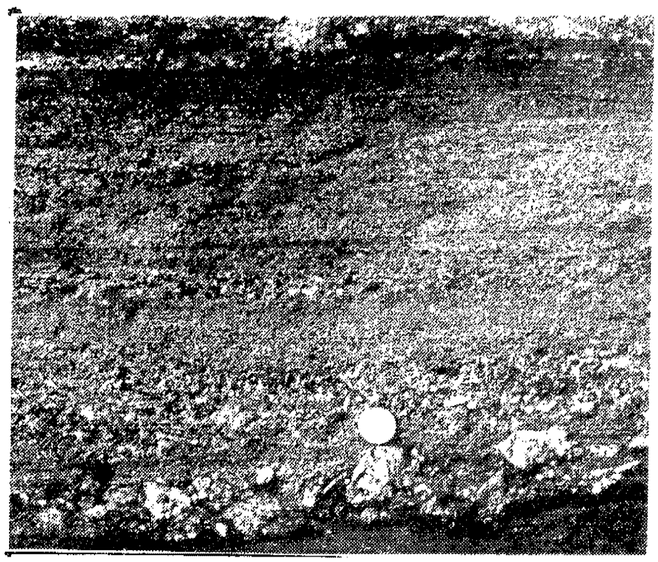


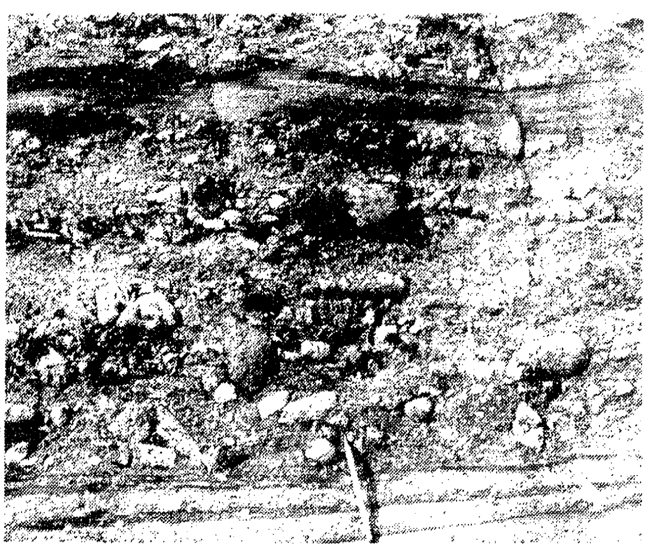
Fig. 33 Sedimentary structures of the Alluvial fan facies, Boonton Formation, near the intersection of River Road and Dahl Ave., Montville.

a) Aligned dreilkanters,sandblasted ventifacts; quarter for scale.
b) Sand wave (left side) and antidunes (lower right side); current left to right 25 cm rule for size.
c) Clast orientation, note glacial striations.
d) Convolute bedding; 10 cm of scale exposed.
e) Cut-and-fill channels, 10 cm of scale exposed.









f) Random isotropic fabric; largest clast about 15 cm diameter. Note size of matrix.
g) Non-graded cyclical beds of conglomerate overlain by fine sandstone beds with ripple drift cross-stratification.
h) Graded Beds, three cycles present.
i) Graded beds, five cycles present.
j) Cycles of moderately sorted and stratified fine gravel and sand, and poorly sorted massive gravels with subtle stratification.

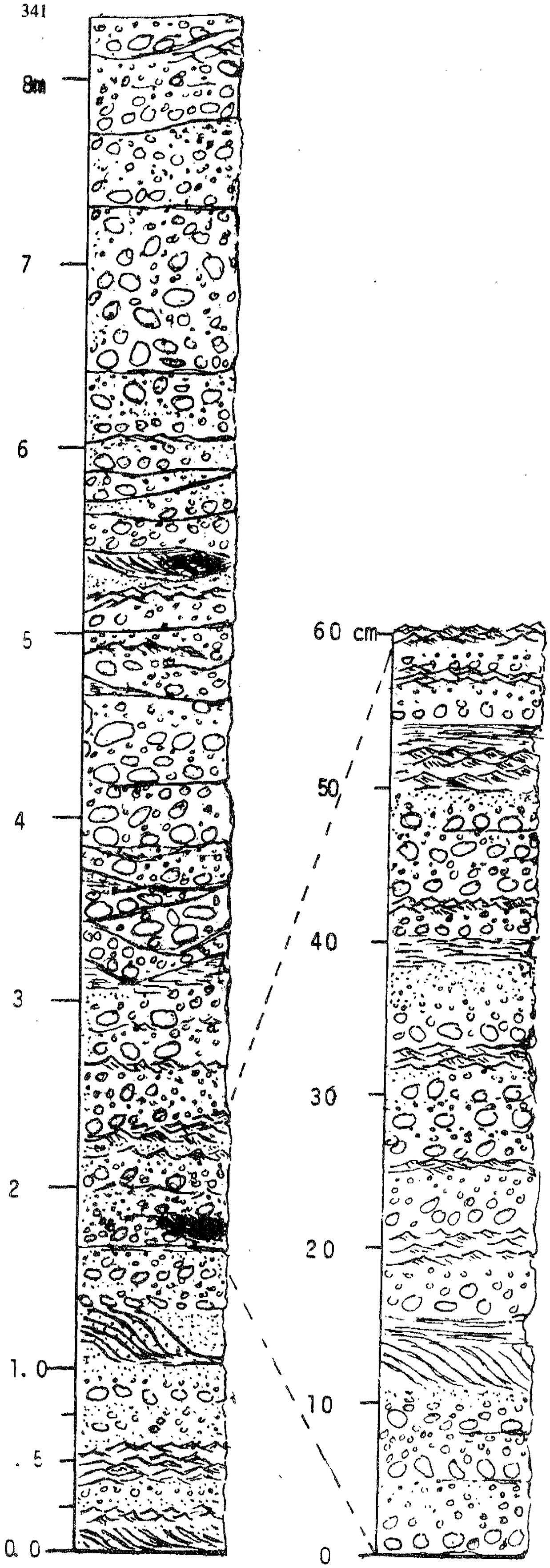


Fig. 34 Stratigraphic section through that part of the Boonton Formation inferred to represent an alluvial fan prograding eastward from the western border fault.

fault, as well as the folded and faulted rift sediments. Although feeder dikes did not follow the main fault zone during active subsidence and sedimentation, fissure eruptions intruded broken crustal blocks of the basin near its axis (at Paterson and Feltville), at a distance of about 15 km from the border fault. Similarly the York Haven intrusives of Pennsylvania, the source of the First and Second Watchungs, crop out up to 15 km from the border fault. The Palisade Sill - Rocky Hill - Lambertville igneous complex, a time-stratigraphic equivalent of the First and Second Watchungs also was intruded in a zone about 30 km from the border fault.

The data appear to indicate that as crustal extension occurs under plate separation, rising magma will be emplaced along "rising" crustal blocks near the rift axis, and not along subsiding troughs of the rift margins. These conclusions are compatible with those of Hamilton (1980), who found that in the New Madrid Rift Zone the main zone of seismicity and igneous intrusions occur along the rift axis.

In conclusion, Early Jurassic time was marked by considerable crustal fragmentation, yielding tilted horsts and grabens. The occurrence of isolated synclines with Jurassic rock (at Oldwick, Hopewell, and Jacksonwald) along the Ramapo and the Hopewell faults (both of which show considerable strike slip) suggests that, like the Watchung Syncline, they may represent deep Jurassic structural troughs. This interpretation is compatible with a Dead Sea Rift model, showing the presence of many isolated structural basins (e.g. the Dead Sea) within the Dead Sea Rift, a transform fault zone extending for more than 1000 km with left-lateral displacement of 105 km (Freund, 1965). That model provides the requisite compressional and tensional segments along the Ramapo Fault, which is notably offset by en-echelon, oblique-tending strike-slip faults that cut the basin into rhomb-shaped grabens (Fig. 35). Strike slip along an irregular margin creates an horizon of structural troughs or basins and folds or welts (Fig. 35) This is compatible with Ratcliffe's statement (this field book) that the major pattern of Mesozoic faults is right-lateral slip, and that the Watchung lavas flowed across previously folded and dissected strata. Accordingly, the opening of rhomb-shaped grabens in the Early Jurassic may have resulted from the propagation of conjugate shears to the west, as sea-floor spreading occured to the east.

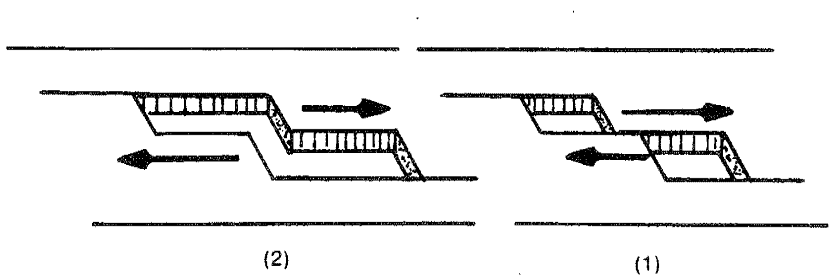


Fig. 35a Coalesces of 2 rhomb-shaped grabens to produce a composite graben

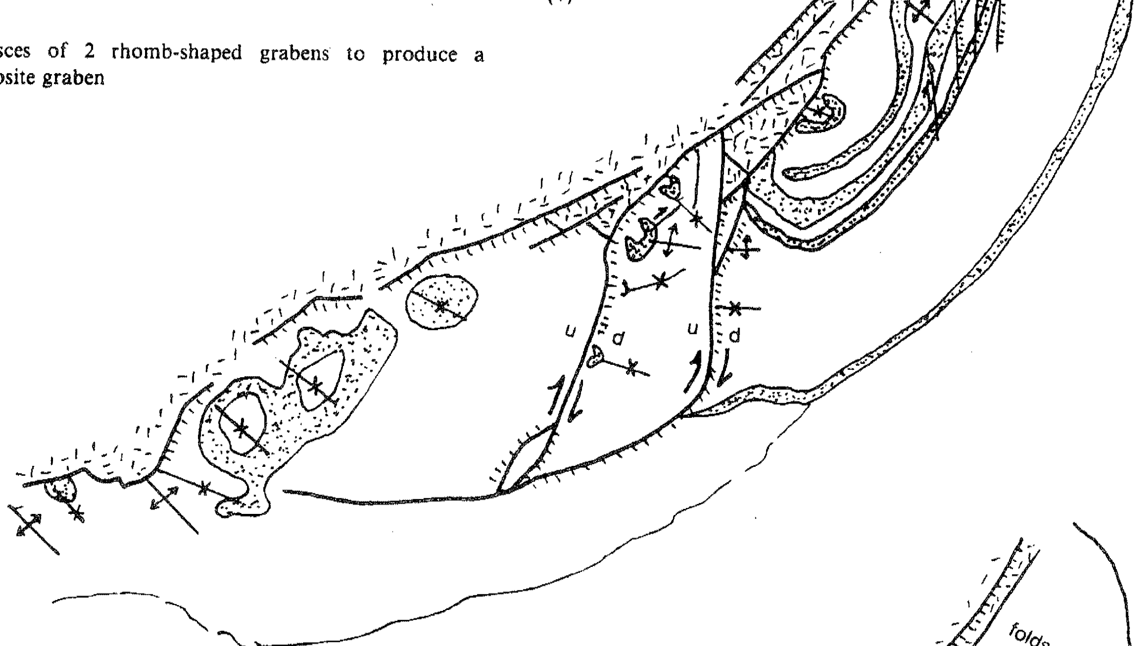


Fig. 35b Generalized stuctural geology map of the basin

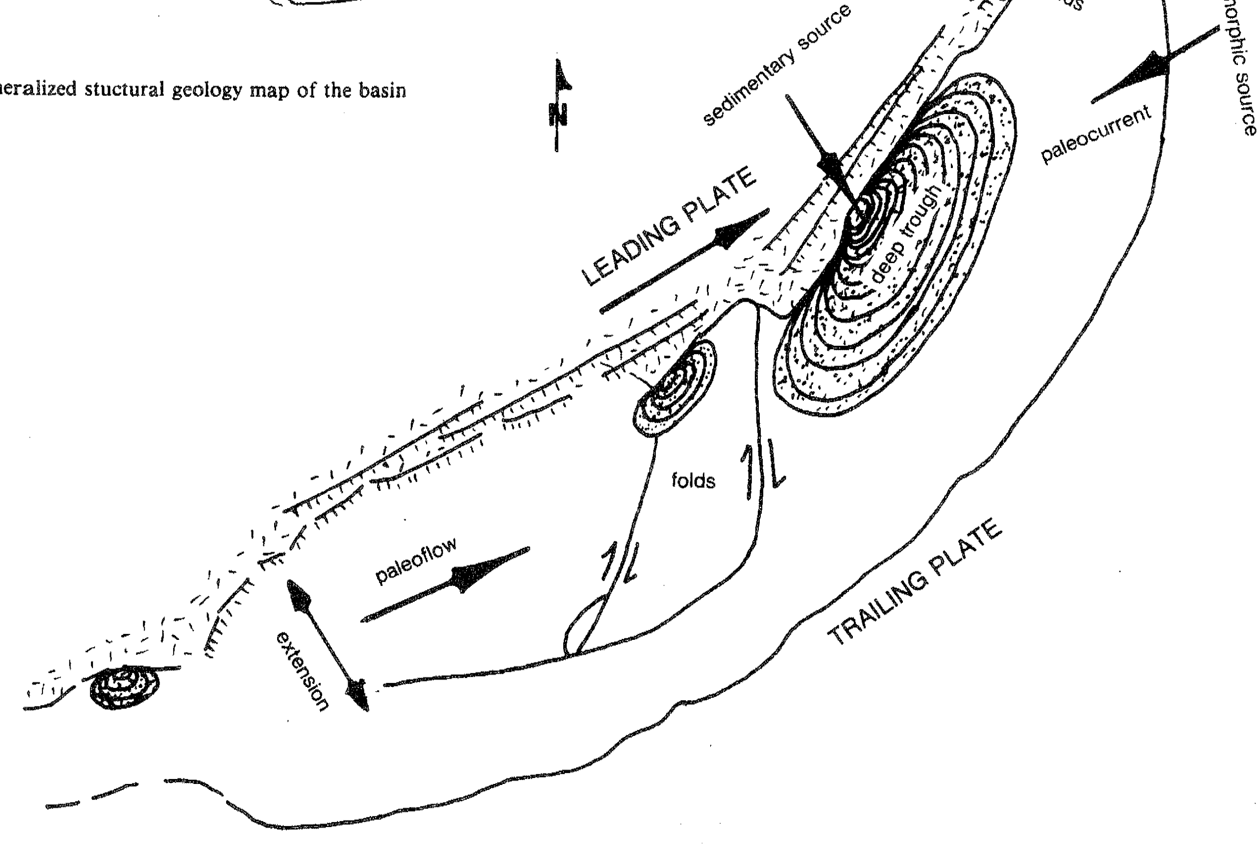


Fig. 35c Tectonic Model for the Early Jurassic

ROAD LOG (Saturday)

Mileage

0.0 Turn right onto Warren Street, leaving University parking lot.

0.1 Right turn at traffic light onto High Street. Continue for 0.5 miles north on High Street.

0.6 Left turn at traffic light onto Orange Street.

0.7 Right turn at first traffic light onto Nesbit Street.

1.0 Left turn at "T" intersection (glass apartment building directly to the north.) Proceed straight across the intersection, going west, onto the ramp leading to the Interstate Highway 280 and the Garden State Parkway.

1.6 Alternating beds of red sandstone and mudstone with a few thin interbeds of gray siltstone and dark gray to black micaceous shale, occurring below the first overpass. These siltstones yield a probable Upper Norian palynoflorule and occur about 1100 m below the First Watchung Mountain Basalt (Cornet and Traverse, 1975, p. 27). Sporadic exposures of sandstones and mudstones with fining-upward sequences, chacteristic of meandering streams, occur along Interstate 280 for the next 4.4 miles.

2.3 Bear right for the Garden State Parkway.

2.5 Park in service lane approaching East Orange Exit, and walk west to outcrop in exit ramp.

STOP 1. Passaic Formation: Central Basin Facies

Objective: to examine a fluvial sequence of the central basin facies.

Background: information for this stop is found in the text under, 'Central Basin Facies: Fluvial-Playa.'

Figure 22, a stratigraphic section of this stop, shows characteristics of the fining-upward sequence, namely: cut-and-fill channels, channel lag concentrates, cross-bedded arkosic sandstones, overbank deposits of reddish-brown mudstone with calcrete paleosols, gray-green to green shales with plant fragments, worm burrows, roots (?) and copper mineralization (chrysocolla and malachite.)

Petrographic and paleocurrent studies along this highway, and elsewhere in this stratigraphic horizon, indicate that the sediment was derived from a deeply weathered metamorphic terrane to the north and east, and transported to the basin across a broad southwest-sloping pediment.

2.8 Enter Garden State Parkway, northbound.

11.1 Great Notch, on the western horizon, is a 'wind gap' cut into the First Watchung Mountain by streams draining Glacial Lake Passaic.

12.1 Exit at 155P to Route 80 W and Paterson.

14.0 Bear left onto entrance ramp Route 80 W.

14.7 Contact of the Passaic Formation with the overlying Orange Mountain Basalt. The columnar basalts of the lower flow unit is well exposed as is the contact with reddish-brown ripple-marked sandstones of the Passaic Formation.

14.9 Beginning of the upper flow unit with its characteristic ropy pahohoe-pillowed surface.

15.3 Transverse cross section of subaqueous flow lobes. Note the arcuate pattern of the pillow lava complex. These structures will be examined in the lower and upper New Street Quarries at Stop 3.

15.4 Exit at Squirrel Woods Road, bearing right at exit.

15.6 Turn left at stop sign onto Glover Ave.

15.9 Turn right at light onto McBride Ave.

16.8 Bear right at "T" in road (Spiegel Ave.).

16.9 Left turn onto McBride Ave.

17.0 Left turn into Parking Lot.

STOP 2, and A. Contact of the Orange Mountain Basalt with the underlying Passaic Formation.

Objective: to determine the paleoflow direction of the lava and the paleocurrent direction of the underlying sediments.

Background: see the text under, 'paleoflow structures in rift volcanics: pipe vesicles and pipe amygdaloids.'

Figure 6 is a composite sketch of the structures found at the outcrop. The section shows the lower flow unit of the First Watchung basalt with southwest plunging pipe amygdaloids and vesicles, overlying an irregular surface of cross-bedded (southwest dipping) pebbly arkosic sandstones and conglomerates with large clasts of rounded quartzite, carbonate and shale chips. Figure 7, a stereographic projection of the paleoflow and paleocurrent data, indicates that the lava flowed to the northeast transgressing a regional sedimentary paleoslope inclined to the southwest.

This site is also of some historical importance. Alexander Hamilton, inspired by the power of the Passaic River as it cascaded over the Great Falls of Paterson, informed the New Jersey legislature that he had found the ideal site for industry in the new nation.

17.0 Right turn out of parking lot.

17.1 Right turn at stop sign (Spiegel Ave.)

17.2 Left turn at light onto McBride Ave.

18.1 Left turn onto Glover Ave.

18.4 Turn right to Squirrelwood Road, following signs to Route 80.

18.7 Bear left at road signs onto Route 80 overpass.

19.7 Left turn into New Jersey Bank parking lot. Drive east through the lot, exiting on New Street.

20.2 Left turn onto New Street. Park in the Richardson parking lot.

STOP 3 and B. Orange Mountain Basalt: Upper Flow Unit, New Street Quarry.

Objective: to examine subaqueous volcanic structures including: pillow lavas, flow lobes, fissure eruptions, a volcanic cone (?), and zeolite mineralization. Caution should be exercised in the quarry and participants should not climb the upper quarry walls.

Background: An extensive text is developed for this stop and found under 'pillow lavas and subaqueous flow lobes'.

The walls of this quarry and an adjacent quarry, long favorites of mineral collectors for their beautiful and diversified suite of zeolites, also exhibit a splendid array of subaqueous volcanic structures (see Fig. 11). Participants should first examine the structures of the east (or far) wall, noting the amygdaloidal and vesicular upper contact of the lower flow unit and the overlyng Tomkeieff sequence, which is overlain by bedded pillow lavas and a second Tomkeieff sequence. Note also spiracles in the lower colonnade and cross-sections of polygonal joint sets of the entablature. Follow the structures along the south wall, walking west, and note the increase in pillow lavas with a concomitant decrease in massive basalt. On the west wall we may observe the characteristic concave-downward arcuate form of overlapping flow lobes in transverse section. Pinching and swelling pillow buds elongated N-S in arcuate bundles distinguish the flow lobes from the overlying bedded pillows which appear to be stacked one on the other and elongated E-W.

Although the contact between the two types of pillows appears to be unconformable, the absence of eroded pillows along the contact indicates that they are comformable. Note the manner in which the younger pillows cascade off the flow lobe, building up slopes of about 40°. In general, the pillow buds are very dense with radial joint structures and few minute vesicles, indicating that they formed in deep water.

The absence of pillow-derived debris within the interstices of pillow complexes indicates that the debris was washed out of these pockets in a well-agitated lake. The occurence of interstitial angular basaltic fragments (surrounded with quartz, calcite, perhnite and other zeolites) indicates that the fragments were derived from the checkered exterior rinds of the pillows by circulating fluids, perhaps ground water. The original debris was probably redeposited in a deeper part of the basin, along the border fault.

The flow lobe appears to flare out and to plunge westward, where it may be studied in the walls of the lower New Street Quarry. At some appropriate time, we shall enter that quarry as a group. Figure 12, a field sketch of its east wall shows three distinct episodes of vulcanism: (1) an older episode of flow lobes; (2) a medial phase of massively bedded, moderately coarse-grained igneous rock that slopes away from a central point and overlaps the distal and advancing end of a flow lobe; and (3) a younger zone of bedded pillow buds that overlie both the steep slope of the subaqueous volcano (?) and the flow lobe. The origin of these features should encourage a lively discussion.

20.2 Turn right leaving the parking lot.

20.3 Turn right into New Jersey Bank parking lot. Drive west through the lot exiting onto Squirrel Wood Road.

20.9 Right turn onto Squirrel Wood Road, go straight and take overpass to stop sign at Glover Ave.

21.5 Left turn onto Glover Ave.

21.9 Cross Passaic River, then turn right onto River Terrace, which becomes Totowa Ave.

23.8 Left turn onto West Broadway.

24.1 Right turn onto Belmont Ave.

26.2 Left turn onto Overlook Ave., making a quick left turn into Suzuki-Honda parking lot. Walk to western end of parking lot and enter small stream where the section begins.

STOP 4. Feltville Formation in contact with the overlying Preakness Basalt.

Objective: Primarily to have lunch in a pleasant setting, and secondarily to examine a fluvial-deltaic (?) facies.

Background: A stratigraphic section of this site is found in figure 23, and shows two fairly complete fining upward sequences of point bar deposition, overlain by the Second Watchung lavas along an irregular contact with pahoehoe structures, pillows, soft sediment loading structures and injection features into the underlying mud.

Note the typical fining-upward sequence with its channel deposits of coarse clastics, overlying planar beds of sandstone, which is overlain by large, low angle cross-bedded sets and then by a thick sequence of ripple drift cross-laminations with shale interbeds that are cut through by a very large channel with cross-bedded pebbly sands, plant debris and thin stringers of coalified plants. The channel sands are overlain by low angle planar cross-beds, trough cross-beds and finally by fine-textured ripple drift cross-lamination. Convolute bedding and parting lineations are common with the prevailing trend of the latter striking N 50° E. Parting lineations, in conjunction with the cross bedding, indicate that the paleocurrent was to the southwest. We can easily follow these beds to the south (using the basalt as a marker bed) where they interfinger with distributary-type channel sands of the deltaic sequence.

Look for evidence of strike-slip movement on the far wall. The pockets of pillow lavas indicate that the lava flow dammed an existing lake or stream. The pillows are perhaps best exposed in the roadway adjacent to the lunch stop, where they may be examined against the fine-splintery columnar jointing so diagnostic of the Second Watchung lavas.

26.2 Left turn leaving parking lot onto Belmont Ave.

27.6 Belmont Ave. merges with High Mountain Road (North Haledon Reservoir ahead on right.)

29.6 Three quarter turn around traffic circle to Oakland via Franklin Lakes Road (Bergen County Road 502). The road is underlain by basalts of the First Watchung lavas. Glacial lakes are abundant in the area. As we proceed west onto Long Hill Road we will descend the backslope of the First Watchung.

32.6 Turn left at light into Shopping Center at bottom of steep hill (backslope of the First Watchungs). Park in upper parking lot, southwest corner.

STOP 5. Feltville Formation: subaqueous fan, marginal border facies.

Objective: to determine the provenance and depositional setting of these massively bedded conglomerates.

Background: field descriptions of this stop are found in the text under 'Marginal rift facies: fan delta'. Note figures 26 and 27. The section, about 45 m thick of coarse-grained and poorly sorted clasts with average grain size of about -4 to -6 phi (16 mm to 64 mm), occurs immediately below the base of the Second Watchung lava. The clast population has a graphic mean (Folk, 1974) of -4.5 phi and is very poorly sorted with a standard deviation of 2.4 phi (Fig. 28). The clasts are composed principally of carbonate, quartzite, low-rank metamorphics and most notably, vesicular basalt. Many of the clasts are reasonably well-rounded, imbricated, and show subtle grading which is perhaps one of the most distinctive - but elusive - aspects of this facies. In order to determine grading patterns of sedimentation, we measured the grain sizes of all clasts with a phi-ruler on a 2.5 cm sampling grid drawn perpendicular to bedding. The data, included on representative graphs of that exercise (Fig. 29) show: (1) the cyclical pattern of deposition and subtle stratification; (2) each cycle seems to begin with an inverse grading sequence, marked by a subtle increase in grain size upward in section, and followed by an abrupt decrease in grain size; (3) reverse grading is repetitive with each episode transporting slightly coarser components; and (4) many cycles are symmetrical.

Each complete depositional cycle consists of an erosional basal contact followed by a depositional couplet of inverse grading, followed by normal grading and an upper contact marked by finely comminuted particles in ripple drift cross-stratification (Fig. 26). Complete cycles are rare, and much of the section is marked by subtle and shallow cut-and-fill channels, (Fig. 27).

At the western end of the outcrop, the beds are graded and the bedding planes have a slightly arcuate pattern. Are we looking at a transverse section of a fan, or is this a drag structure along a fault?

Note that the section lacks features commonly associated with Triassic-Jurassic fluvial deposits, namely: rootlets, caliche deposits, plant fragments, dessication cracks, red beds, dinosaur footprints, worm burrows and overbank deposits.

Observe clast rounding, imbrication and composition. Although quartzites, carbonates, and low rank metamorphics are fairly common, perhaps the most significant clasts are the vesicular basalts. Together with the imbrication direction, it suggests that the lavas of the First Watchungs flowed westward over a low-lying fault escarpment.

33.0 Left turn out of parking lot onto Route 202 S.

34.6 Left turn at light onto Hamburg Turnpike (Route 202 S) at Pompton Lakes.

35.3 Most of the lakes in the area resulted from glaciation. Bear right onto 202 S, (Black Oak Ridge Road).

36.2 Right turn onto Pompton Plains Corner Road.

37.9 Three-quarter turn around traffic circle to Route 23; going south for 1.8 miles.

39.7 One-quarter turn around second circle onto Black Oak Ridge Road.

40.0 Right turn onto Newark Pompton Turnpike.

40.7 Left turn at Exxon Station onto Oak Road.

40.8 Left turn at stop sign onto Lincoln Park Road.

41.3 At stop sign, continue straight onto Alt. 511 (Ryerson Rd.).

41.7 Bear right at "V" in road onto Comly Road.

42.8 At traffic light turn right onto Main Street, which becomes 202 South.

47.4 At Montville Inn, bear left and enter onto River Road. Caution--this is a dangerous intersection!

47.7 Park car on "paper" street on left-hand side of road (opposite Dahl Ave.). Walk east to outcrop.

48.4 **STOP 6.** Boonton Formation (Fanglomerate). Marginal Border Facies

Objective: To examine an alluvial fan facies within the border fault zone.

Background: Field descriptions and photographs of this section are included in the text under, 'Boonton Formation: Marginal Border Facies'.

Because the section has been polished by glacial scour, conglomeratic structures are displayed in great detail. Cyclical and laterally continuous beds of poorly sorted debris flows grading upward into cross-bedded and ripple marked sheet-flood deposits are characteristic of the section (Fig. 34). Many of the cycles are incomplete, having been partially eroded by a subsequent debris flow. Each section is about 2 to 3 cm thick and occurs within larger cyclical units of about 1.5 m thick. The clast population has a graphic (Folk, 1974) mean size of -3.3 phi, and an inclusive graphic standard deviation (Folk, 1974) of 2.2 phi (Fig. 28); it is, therefore, very poorly sorted. In general, the grains are angular and primarily composed of a quartzite, gneiss and vesicular basalt with subordinate amounts of amphibolite, slate and greenstone schists. They appear to have been derived from a local source.

Some of the primary structures seen at the section include: ripple drift cross-lamination, dessication cracks, cut-and-fill channels, normal and inverse grading, sand waves, parting lineations, antidunes (?), random fabric, sand shadows, dreikanters and oriented clasts (Fig. 33).

Particle orientation was determined from clasts having a length to width ratio of at least 1.3:1. The prevailing long axis orientation is west-to-east with clast imbrication to the west (Figs. 31 and 32). This is compatible with a preliminary paleocurrent study showing that the clasts were transported to the basin by east-flowing streams. The occurrence of aligned ventifacts indicates that the wind was an effective agent of erosion, and may explain the deficiency of fine sand and clay size particles on the alluvial fan.

Turn around and go back to 202 northbound (right-turn at Montville Inn).

49.1 Enter Route 287, southbound. Boonton Formation pebbles along roadbank.

53.6 Boonton Reservoir on left—site of famous Boonton fish fossils.

54.4 Enter Route 80, eastbound.

56.5 Bear left onto I-280 towards Newark. We are traveling on the lake bed of glacial Lake Passaic, which formed as the meltwaters became empounded between the N.J. Highlands on the west, the Second Watchungs to the east and south, and the moraine to the south. At its greatest extent, the lake was 30 miles long, 10 miles wide and 240 feet deep (Kummel, 1940).

59.8 Passaic River

60.3 Third Watchung lava flow on the southern horizon (see Olsen, this field book).

62.2 Backslope of the Second Watchung lava flow. Coarse-grained diabasic texture may be examined near upper part of the exposure.

64.2 Contact of lava flow with the underlying Feltville Formation. Note the fine-textured joints of the entablature. When exposed during road construction, the formation consisted of cross-bedded feldspathic sandstone (10 m) underlain by thin stringers of coal with underclay. A similar section may be studied in the parking lot of the Daughters of Israel Nursing Home, 1155 Pleasant Valley Way, West Orange (about 3/4 mile south).

64.5 Backslope of the first Watchung lava flow; outlines of pahoehoe toes may be studied in roadcut.

65.2 **STOP 7 and D.** Orange Mountain Basalt; lower flow unit.

Objective: To examine a Tomkeieff sequence of colonnades and entablatures near the classical site of O'Rourke's Quarry. (See photograph facing the title page of this article.)

Background: This structure is described in the text under 'Columnar Jointing'.

When built in 1969, this road cut was the deepest federally-financed highway cut east of the Mississippi River. About 33 m deep, the cut exposes a complete section of the lower flow unit of the Orange Mountain Basalt, and a broad array of joint patterns that formed as the basalt cooled. The large "basin" structure on the southeast wall was first described about 100 years ago by J.P. Iddings (1886) of the U.S. Geological Survey in John O'Rourke's Quarry, about 300 m souh of the roadcut. While such complete structures have not been observed elsewhere in the Watchungs, similar joint structures, e.g. chevrons, oblique and reverse fans and rosettes (terminology of Spry, 1962) may be studied in this roadcut and in almost every quarry along strike for a distance of 80 to 100 km.

This structure (about 33 m thick) conformably overlies a fluvial red bed sequence of shales and sandstones and, when first exposed, displayed a complete Tomkeieff sequence of: (1) a lower colonnade (10-15 m); (2) entablatures (20-30 m); and (3) an upper colonnade (1-2 m) (Fig. 17). While the lower colonnade is composed of massive 4-5 or 6-sided polygonal and subvertical prisms, the entablature is composed of long (25-30 m) slender narrow joint prisms that radiate from an apparent focus. Several juxtaposed bundles or sheafs of radiating prisms may be observed in the roadcut, comprising fan and chevron-like features. Cross joints, intersecting radiating prisms at high angles, are prominent and appear to be concentrically arranged about the apex of radiation. An incomplete section pseudo-columns overlie the entablature.

Figure 18, depicting mineral and textural variations within the structure, shows an increase in grain size, an increase in the abundance and size of the interstitial glass, and an increase in the olivine content in the entablature (Fig. 19). This suggests that although cooling may have proceeded very slowly from the sediment-volcanic interface, once a groundmass capable of transmitting stress was established the remaining melt cooled almost instantly. The obscure joint pattern in the upper colonnade may form from convective heat loss near the upper part of the flow.

The early cooling history of the magma is manifested by well-developed horizontal striations observed on the joint surfaces of the lower colonnade. While Iddings (1886) may have been the first to report horizontal striations on joint surfaces (from O'Rourke's quarry), James (1920) speculated that these striations represent successive stages or pulses in which the rock broke and the columns formed. Recent studies by Ryan and Sammis (1978), and Justus and others (1978) at this site show that the striations are records of discrete thermal events, characterized by sudden periods of crack advance in the cooling basalt. Features such as chisel marks, pinch and swell and kink structures on the curvi-columnar joints may also represent an episodal cooling history. Each of these features may be observed on the walls of the highway cut.

The striations reported by Iddings (1886) show up on joint surfaces of the lower colonnade as cyclical bands of smooth and rough zones, about every 5-7 cm. Ryan and Sammis (1978) report that as the crack growth procedes, the first-formed zone is smooth and associated with a thermal shock event; the second zone is rough, has positive relief, and is associated with the halting of each crack advance.

Joints of the entablature are also cut by concave-upward "dish-like" joints that are cut by strike-slip faults. While the origin of this structure is debatable, it trends N 50° E and evidently formed after the basalt cooled and before faulting occurred.

66.0 Dike intrusion into fluvial channel sands.

End of Saturday field trip.

Return to the University via I 280.

ROAD LOG (Sunday)

Mileage

Several stops on Sunday's field trip are the same as Saturday's, and, therefore that part of the itinerary will not be duplicated. Instead the road log will be modified and reference will be made to the Saturday log.

0.0 Follow Saturday's road log from the University to Stop 2, which is Sunday's Stop A.

17.0 **STOP A.** Contact of the Orange Mountain Basalt with the Underlying Passaic Formation (see description for Stop 1, Saturday Road Log).

20.2 Follow Saturday's Road Log to Stop 3, which is Sunday's Stop B. Orange Mountain Basalt, Upper flow unit.
Stop B. (see description for Stop 3, Saturday Road Log).

20.2 Turn to the right leaving parking lot.

20.3 Turn right into New Jersey Bank Parking Lot. Drive west through the lot exiting onto Squirrel Wood Road.

20.9 Right turn on Squirred Wood Road, and go straight onto the overpass to stop sign at Glover Ave.

21.5 Left turn on Glover Ave.

21.6 Left turn at light onto McBride Ave.

22.5 Bear right at "Y" in road.

23.1 Right turn onto Lackawanna Ave., and cross the small bridge over the Passaic River.

23.3 First left turn onto River View Drive.

STOP C. Lower Flow Unit Preakness Basalt.

Objective: To examine tumuli (also known as pressure domes or schollendomes, Macdonald, 1953).

Background: Information about this structure is found under Tumulus, also figures 8 and 9 . The exposed tumulus structure, about 7 m high and 15 m wide, consists of a central core of massive basalt with columnar joints (1-1.5 m wide), an overlying zone of radiating entablature joints (0.5-1.0 m wide), and an upper colonnade with poorly defined columnar joints and vesicular to brecciated basaltic glass. The structure is overlain by a pillow-pahoehoe complex that thins along its crest and thickens along its flanks and adjacent troughs. A second flow unit overlies both structures and consists of massive colonnades with bent pipe amygdaloids, indicating that the lava flowed towards the crest of the tumulus. Although this tumulus did not feed the second flow unit, it appears to have fed (through the overlying brecciated zone) the pillow-pahoehoe complex.

The section also shows an interesting assemblage of ellipsoidal bun-like structures, including: pahoehoe toes with concentric layers of vesicular and non-vesicular basaltic glass, and with flat bottoms and rounded tops; (2) flattened lava tubes (?) with concentric structures and hollow interiors in transverse cross section; and (3) pillow buds with circular transverse sections and ellipsoidal longitudinal sections, vesicular cores and pipe amygdaloids elongated radially near the bud edge, and radial and concentric joints in cross section. Moreover, note: the variety of bun shapes and sizes; the volcanic debris separating these bun-like structures; the occurrence of several tumuli crests at different heights along the exposures; and the surface topography of the lava flow as expressed by the tumulus surface.

Did this structure form in water? When did it form relative to the pillow-pahoehoe complex? How do these bun-shaped structures compare to those at the New Street Quarry? Are the buds a tangled mass of independent sack-like structures or a tangled mass of cylindrical interconnected pillow buds, lobes and pahoehoe toes? What does the structure tell us about the relationship between topography, isotherms and the formation of columnar joints. We shall continue our discussion of this point at our next stop.

24.2 Left turn at light onto River View Drive. Cross the Passaic River at Little Falls.

24.5 Left turn onto Main Street in Little Falls.

24.8 Right turn at Shell Station (Stevens Ave.).

25.7 Left turn onto route 23, Southbound (Pompton Ave.).

28.1 Vesicular pahoehoe flows of the 2nd flow unit of the First Watchungs behind stores on right.

28.9 Crossing Bloomfield Ave. A wind gap cut into the First Watchung Basalts.

30.8 Left turn onto Eagle Rock Ave., Eastbound

31.1 Left turn into Eagle Rock Reservation. Park Buses -Lunch Stop.

31.9 Left turn, leaving reservation, onto Eagle Rock Ave., Eastbound.

32.1 Trap rock quarry, entablature structures may be seen from the road.

32.2 Llewellyn Park, site of Thomas Edison's house.

32.7 Bear right at light entering Main Street, West Orange.

33.5 Thomas Edison's laboratory and Black Mariah, site of first movie studio.

33.9 Right turn onto Mt. Pleasant Ave.

34.2 Bear right onto entrance of I-280.

34.6 Red beds with fining upward cycles.

40.0 Contact of the First Watchung lavas with the underlying red beds.

STOP D. Orange Mountain Basalt, lower flow unit. (See description for Stop 7, Saturday Road Log).

41.0 Continue west on I-280, exiting at Pleasant Valley Way (exit 7), bear left at exit onto Pleasant Valley Way, West Orange.

43.5 Continue south, entering the South Mountain Reservation; back slope of the First Watchung Mountains on the left (east); the Second Watchung Mountain on the right (west).

46.8 Paper Mill Playhouse.

47.0 Left turn at light onto Old Short Hills Road.

47.1 Right turn onto County Road 527 (Essex Street), bear left at turn.

47.4 Right turn at stop sign onto Millburn Ave.

48.3 Right turn at light onto Morris Turnpike (Route 24).

48.7 Bear left at Shop-Rite onto Broad Street and follow signs to Overlook Hospital.

49.7 Left at light onto Ashwood Ave.

49.8 Right at light onto Morris Ave.

49.9 Left onto State Highway 22.

50.0 Bear right at intersection onto Glenside Ave.

52.7 Left turn onto secondary road leading to Feltville.

STOP E. Feltville Formation in contact with the underlying Orange Mountain Basalt.

Objective: Primarily to determine whether the second flow unit is intrusive or extrusive. And secondarily to examine the carbonate sequence near the base of the Feltville Formation.

Background: This section is discussed in the paper under 'Emplacement of the Watchung Lavas', and 'Central Basin Facies: Lacustrine-Deltaic Facies', see figure 20. The issue before us at this site is the same as the one confronted by a group of emminent geologists more than 100 years ago, including: Cooke (1868), Russel (1878), Davis (1882) and others. Figure 20 will be helpful in your examination. Note the irregularity of the contact, the 'baked' mudstones and sandstones, vesicular sandstones, the occurrence of marble float along the carbonate horizon, the occurrence of pillow lavas, and the stratification in the basalt. Moreover, note pillow vesicularity, pipe vesicles and amygdaloids elongated radially near the bud edge, and brecciated clasts of basalt and red beds within pillow interstices.

Are the pillow buds independent sack-like structures or are they interconnected cylindrical-to-sack-like masses? Do they rest directly upon each other, or are they separated by baked sediment, weathered sediment or basalt, or an old soil horizon? Is the basalt stratification a relict sedimentary structure or a primary volcanic structure? Is the irregular sedimentary-igneous contact an old soil horizon or an intrusive-baked contact? Recall that this horizon is stratigraphically equivalent to the section that we studied at the New Street Quarry.

Upstream the pillow buds become larger, more numerous, bedded, and overlain by a complete Tomkeieff sequence. This part of the section is quite similar to the upper part of the section at New Street.

The second reason for examining this section is to study the sequence of shelf carbonates and siltstones that unconformably overlie the basalt, and crop out sporadically from Feltville to Pluckerman's Ravine.

The carbonates occur as thin discontinuous limestone lenses, about 5-20 meters above the igneous contact, and interbedded with gray and reddish-brown shale and gray calcareous thinly laminated siltstone. A trench dug into the hillside exposes the section (Fig. 24)(McGowan, 1980). The limestones, about 10 cm thick and 100 m long, display a variety of shallow water structures including: cross-bedding, dessication cracks, rounded intraclasts cemented with sparry calcite, ripple marks, abraded algal debris and erosional lower contacts. Although some of these features are ambiguous with respect to environments of deposition, the assemblage of structures point to a shallow water carbonate bank. See also McGowan (1980), who has made an extensive study of this formation. Olsen (pers. comm.) also reports the occurrence of thinly laminated deep-water carbonates with whole fish fossils stratigraphically beneath the shelf carbonates. Plant fragments, dinosaur footprints, fish fossils, algal mats, ostracods, and one branchiopod shell are reported from this section (Olsen, 1975; Dahlgren, 1975; McGowan, 1980). Flaser bedding, ripple drift cross-laminations, parting lineations and small scale trough cross beds may be observed in the overlying siltstones and sandstones. The average direction for the trough cross beds and parting lineations is 180° and 145° respectively (McGowan, 1980).

Right turn leaving Feltville and head back to Newark Campus via Interstate 280, stopping at the exposure of the First Watchung Basalt on the east-bound lane where we will examine structures in the lower colonnade before continuing to the University.

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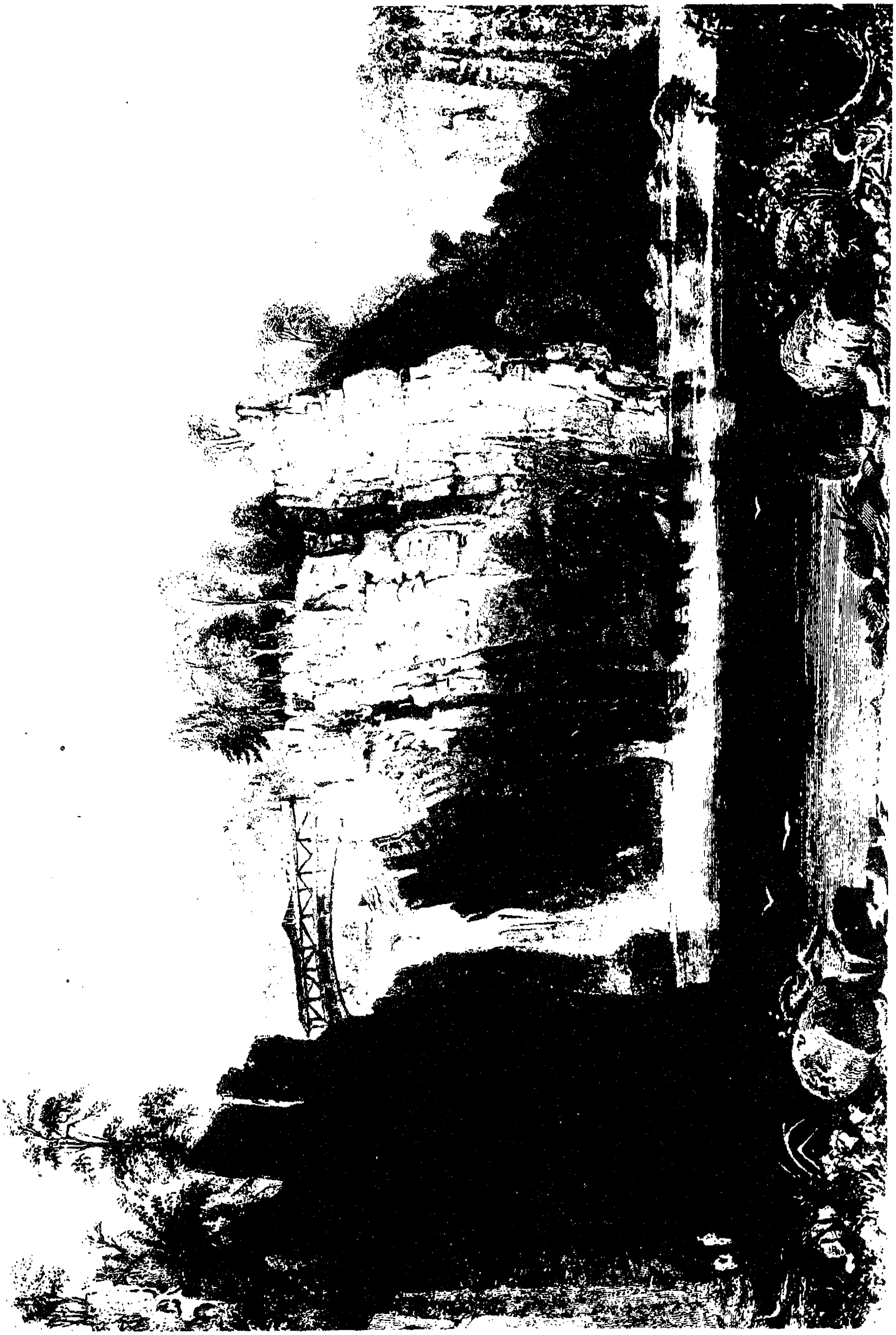

VIEW OF PASSAIC FALLS
by
W.H. Bartlett

FOSSIL GREAT LAKE3 OF THE NEWARK SUPERGROUP IN NEW JERSEY

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Introduction

Because Newark Basin lacustrine rocks are (1) often composed of sedimentary cycles, (2) traceable over very large areas, and (3) unusually rich in fossil remains, they are among the most interesting and challenging of Newark Supergroup deposits. While lacustrine sequences are found in all sedimentary divisions of the Newark Basin, those of the Lockatong, Feltville, and Towaco formations are known in greatest detail and are therefore the focus of this field trip. I concentrate on the interpretation of the lake sediments, paying special attention to some fundamental problems in their interpretation. In addition, I touch on some relevant paleozoology.

Lockatong Formation, Detrital cycles - General Comments

The Lockatong Formation (see Olsen, this fieldbook) is composed almost entirely of well-defined sedimentary cycles (Van Houten, 1969; and this fieldbook). Of the two short cycles described by Van Houten, chemical and detrital, only the latter will be discussed here; they resemble not only cycles found higher in the Newark Basin section, but also lacustrine sequences of other Newark Supergroup basins.

As originally noted by Van Houten, Lockatong detrital cycles clearly reflect the expansion and contraction of lakes. Recent study of these cycles (Figure 1) shows that each can be split into three lithologically identified divisions (from the bottom up): 1, a thin (ca 0.5 m) platy to massive gray siltstone representing a fluvial and mudflat to lacustrine (transgressive) facies; 2, a microlaminated to coarsely laminated black to green-gray fine, often calcareous siltstone (0.1-1.0 m) formed during maximum lake transgression; and 3, a generally thickly bedded or massive gray or gray-red siltstone or sandstone (0.5-4.0 m) usually showing a disrupted fabric and current bedding and sometimes bearing reptile footprints and root horizons (regressive facies).

If individual detrital cycles can be traced over the extent of the Lockatong Formation, the area of division 2 of each cycle is a measure of the average minimum size of the lake during maximum transgression; this is about 7000 km^2. Of course the actual size of the lakes were significantly larger than this. If, as may have been the case, the Newark, Gettysburg, and Culpeper basins were connected by open water at times, the lake would have been about the same dimensions as Lake Tanganyika or Lake Baikal; that is, about 32,500 km. While the lake may have been this large, actual tracing of individual cycles is reasonably complete only for the northern Newark Basin (see stops 2 - 4).

Vertical sections through Lockatong cycles show consistent lateral trends in lithology and paleontology (Table 1). If the assumption of basin-wide extension of individual cycles is correct, these trends reflect lateral changes through large lakes, rather than changes from one small lake to the next. Detrital cycles traced away from the geographic and depositional center of the Newark Basin show changes in faunal and floral assemblages due to deposition in progressively shallower water. These changes influence the entire cycle, although they are most obvious in division 2 (see Table 1). In addition to lateral change in facies, there is a correlated change in cycle thickness (see Fig. 2). For instance, along the Delaware River (at the geographic and depositional center of the basin), the mean thickness of detrital cycles is 5.2 m (Van Houten, 1969) while in the northern Newark Basin this thins to 1.5 m.

The microlaminated sediments of division 2 are made up of couplets of laminae, one of which is more calcareous than the other (in their unmetamorphosed state) (Fig. 3). Similar sediments are produced in a variety of modern lakes; in most of the studied cases the couplets are the result of seasonal variation in sedimentation and are thus varves (Nipkow, 1920, 1927; Kelts and Hsu, 1978; Tolonen, 1980; Edmonson, 1975; Sturm and Matter, 1978; Ludlam, 1969, 1973; but see Neev

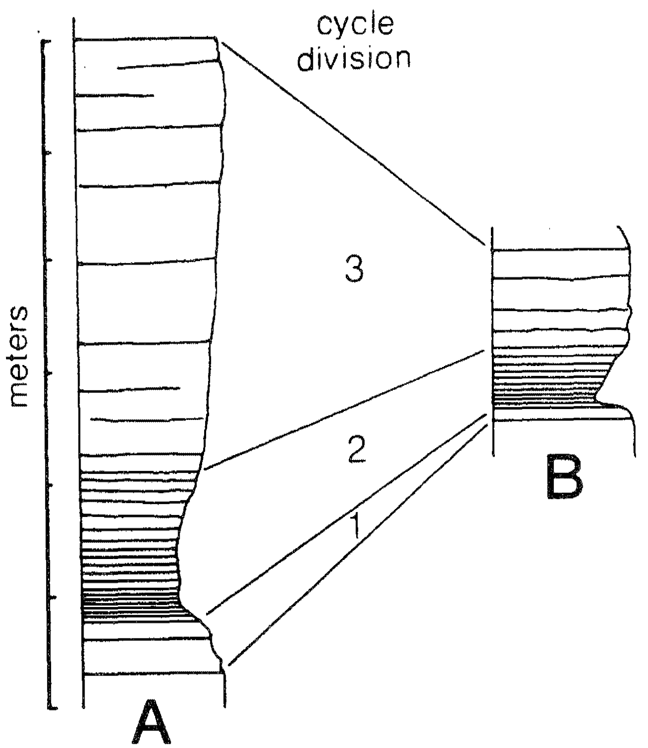


Fig. 1 Diagram of generalized Lockatong detrital cycles: A, cycle from the center of the Newark Basin; B, cycle from the northeastern edge of the Newark Basin. Based on sections exposed near Gwynedd, Pennsylvania (A) and Weehawken (B). For description see text.

and Emery, 1967). By analogy with these modern sediments, I regard the Lockatong sediment couplets as varves. Assuming that the rate of deposition is approximately the same for each division, we can estimate the duration of each cycle by extrapolating the average varve count per unit thickness to the non-varved portion of the cycle. While varve counts are still preliminary, my own work agrees with that of Van Houten (1969) in suggesting approximately 20,000 years per cycle for the central Newark Basin. In marginal areas, such as Weehawken (see stops 1 - 4), varve counts indicate much shorter durations for each cycle, on the order of 5000 to 10,000 years, which presumably indicates significant bypassing or erosion.

The Stratified Lake Model

The shallow water facies of division 2 are arranged around the deeper water facies (Figure 2, Table 1). The latter, which shows no bioturbation, is strongly suggestive of deposits formed today in lakes where the oxidation of accumulating organic matter produces an anoxic bottom layer of water (less than 2% saturation). This type of lake is termed "stratified"; the upper oxygen-rich water layer is called the "epilimnion" while the bottom, oxygen deficient, layer is referred to as the "hypolimnion" (Hutchinson, 1957). Those lakes which never experience the mixing of the epilimnion and hypolimnion (ie. destratification or turnover) are termed "meromictic" and those which mix rarely or at irregular intervals are called "oligomictic" (Hutchinson, 1957). Most temperate lakes mix once ("monomictic") or twice ("dimictic") each year.

Seasonal variations in sedimentation are preserved as varves in modern meromictic and oligomictic lakes because the hypolimnion has no little oxygen and so much toxic matter (such as H_2S) that burrowing organisms cannot survive (Moore and Scrutton, 1965; Davies and Ludlam, 1973; Kelts and Hsu, 1978). These same limiting conditions allow whole organisms which drift into the hypolimnion to be preserved without disturbance by scavenging animals (Schäfer, 1972).

In contrast to meromictic and oligomictic lakes, modern lakes with even very limited seasonal mixing or relatively slight amounts of hypolimnetic oxygen (2% of saturation or more) usually support dense colonies of burrowing animals which churn the sediments (Brinkhurst, 1974; Hiltunen, 1969; Cair, and Hiltunen,1965; Inlands Fisheries Branch, 1970; Davis, 1974; Kleckner, 1967). Thus among modern lakes, microlaminated sediments are produced almost exclusively by those which are oligomictic or meromictic.

Exceptions to this generality, however, are common enough to show that the presence of microlaminated sediments alone cannot be used to identify ancient deposits produced in stratified lakes. Lakes with extremely low levels of organic production, such as some alpine or glacial lakes, sometimes have microlaminated sediments (Sturm and Matter, 1978), presumably because there is too little organic matter in the sediments to support populations of sediment-burrowing organisms. On the other hand, there are lakes with very high organic production and are constantly mixed (holomictic), but which nonetheless produce microlaminated sediments (Tolonen, 1980). This may be because the rate of depletion of oxygen (by the oxidation of organic substances) on the lake bottom is greater than the rate of supply from the overlying waters, thus excluding a bottom fauna. In any case, in these lakes there are too few burrowing organisms to destroy the forming microlaminae. It is clear also that the conditions permitting the preservation of microlaminated sediments are varied; no single set of conditions is responsible for all modern examples.

The tolerances of the resident organisms to "adverse" conditions are also crucial in determining which lakes produce microlaminated sediments. We cannot assume that the sensitivity of sediment burrowing organisms has been the same since the Mesozoic; perhaps there has been a trend through the Phanerozoic towards the ability to survive in low oxygen and high hydrogen sulfide concentrations. If this were the case,

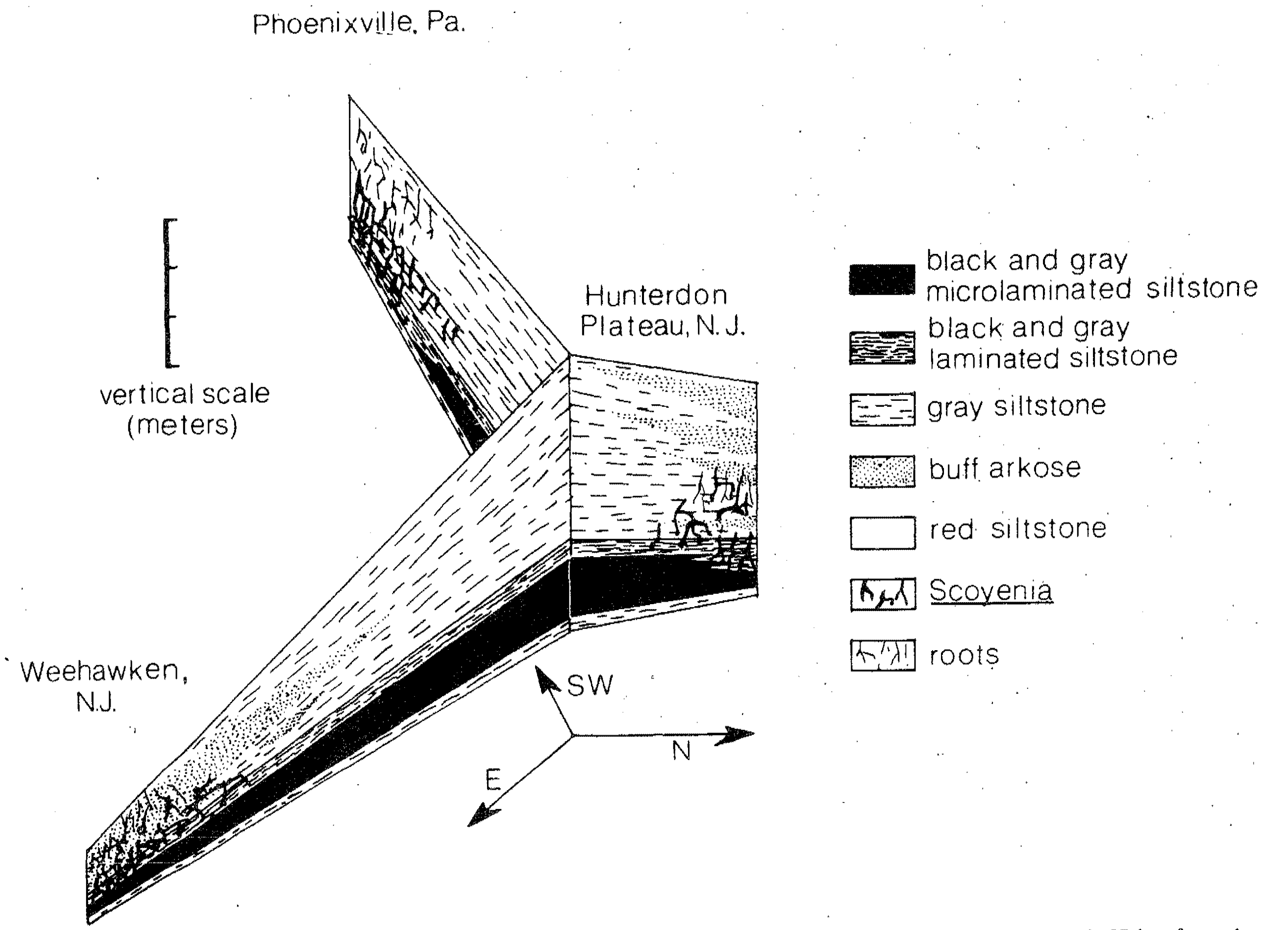


Fig. 2. Generalized facies relationships of Lockatong detrital cycles (horizontal distances not to scale); Phoenixville is 50 km from the southern portion of the Hunterdon Plateau (Stockton, New Jersey), which in turn, is 27 km from the northern corner of the plateau and 105 km from Weehawken, New Jersey.

and ancient organisms were less tolerant of anoxic conditions, a greater variety of ancient lakes could have produced microlaminated sediments.

Lockatong Invertebrates and Their Use as Depositional Indicators

The most abundant large (+2 mm) Lockatong invertebrates are bivalved crustaceans of the order Conchostraca (often called clam shrimp) (Figure 4) (Pennak, 1953). Conchostracans occur throughout division 2 from the deepest water facies to the shallowest and are often present in microlaminated beds lacking any other invertebrates. Today, conchostracans are almost entirely restricted to small, temporary bodies of water from which fish are absent (Hutchinson, 1967; Tasch, 1969; Tasch and Zimmerman, 1961; Packard, 1883); thus, the presence of conchostracans in ancient deposits has been interpreted as indicating similar temporary waters (Tasch and Zimmerman, 1961, 1961a; Tasch, 1961; 1964, 1969; Kobayashi, 1954). However, the Lockatong distribution of conchostracans is entirely at odds with their current distribution; conchostracans found in division 2 of Lockatong detrital cycles lived in very large lakes supporting large populations of fish and small aquatic reptiles. Similar situations occur in Palaeozoic and Mesozoic rocks throughout the world and include the Upper Pennsylvanian Linton Shale (D. Baird, pers. comm.), the Permian *Mesosaurus*-bearing beds of South America and southern Africa (D. Baird, pers. comm.), the Jurassic Jehol beds of China (Kobayashi, 1954), and the Cretaceous Sungari Series of Manchuria (Kobayashi and Huzita, 1942; Takai, 1942). In marked contrast, there are no conchostracans from the entire Cenozoic record (Tasch, 1969; Kobayashi, 1954). Clearly, either the habits of conchostracans or the factors which limit their distribution have changed since the Cretaceous. This points up the dangers of constant extrapolation from the recent; it makes the past look like a repeat of the present, hiding real changes which may have occurred. In this case the sedimentological context of Lockatong conchostracans demonstrates that their present environment is not the key to their past.

The lateral transition from microlaminated to coarsely laminated sediments in division 2 is correlated with the appearence of numerous podocopid ostracods similar to *Darwinula* (Figure 4). Today these crustaceans burrow in the sediments of a wide variety of fresh water environments from puddles to great lakes (Ed-

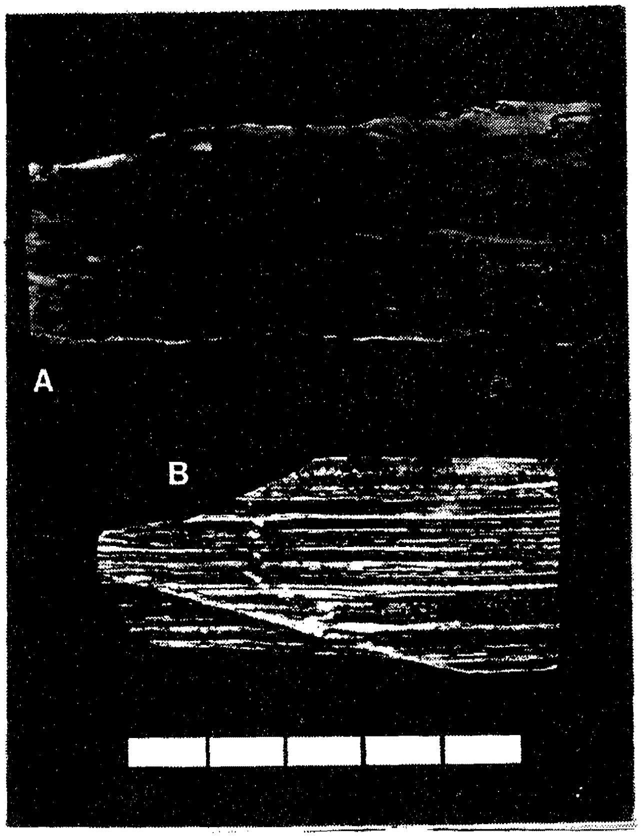


Fig. 3. Contrasting samples of division 2 of detrital cycles: A, microlaminated siltstone (hornfels) from the *Diplurus* -bearing portion of cycle 5 at Weehawken, New Jersey; B, intensively bioturbated siltstone from unidentified cycle at Phoenixville, New Jersey — this specimen contains many unionid clams (See C of Figure 4)

monson, 1959), but always in water with some oxygen. Thus, I infer that the appearance of abundant ostracods in division 2 indicates the presence of at least seasonally oxygenated water.

Farther from the depositional center of the cycles, distinctive large burrows (Figure 4) appear in the sediments of division 2. These burrows, called *Scoyenia* (White, 1929; Bain and Harvey, 1977) are from 0.3-1.3 cm in diameter, are marked by small 1-3 mm) longitudinally oriented ridges on the outside, and have a meniscus-type of infilling. In the Durham sub-basin of the Deep River Basin, they have been found in association with numerous crayfish (Bain and Harvey, 1977) and it is plausible that *Scoyenia* burrows are, in fact, crayfish burrows. Unlike the superficially similar marine *Ophiomorpha*, however, the maker of *Scoyenia* has never been found in its burrow and thus other kinds of arthropods cannot be ruled out.

Finally, restricted to the margin of the Lockatong in division 2 of detrital cycles and in the conterminous Stockton Formation (see Olsen, this fieldbook), clams appear (Figure 4). Today, clams are most commonly found in sediments below well-oxygenated waters (Edmonson, 1959).

Lockatong Fish

The preservation of Lockatong vertebrates varies vertically as well as horizontally in single cycles (Table 1). Generally, the presence of articulated fish is correlated with a distinct microlamination of the sediments. The beds transitional between divisions 1 and 2 are laminated but not distinctly varved and tend to contain isolated bones of fish and small reptiles. The lowest portions of division 2 are usually the best laminated and have the highest proportion of complete fish and reptiles (see Stop 2). The upper portion of division 2 becomes less distinctly laminated, up and as the laminated structure is lost, so are the articulated fish. The upper portions of division 2 often contain only fragmentary fishes or isolated bones; the sediments are poorly laminated and often contain abundant ostracods.

The lateral transitions from the deep to the shallow water facies of division 2 are similar to the vertical changes, in terms of fish preservation, again tracking the degree of lamination of the sediments (Table 1). The microlaminations of the low portions of division 2 persist the greatest distance laterally, perhaps reflecting the downward working of bioturbation agents after the lake bottom again became inhabitable.

Six genera of fish are known from the whole of the Lockatong Formation (Figure 5). Most abundant, both as fragmentary remains and whole fish, is the palaeoniscoid *Turseodus*. Next most common are small individuals of the coelacanth *Diplurus*. The holostean *Semionotus* and the subholostean *Synorichthys* are less common, on the whole, but are the dominant forms locally (Stops 2-4). The subholostean *Cionichthys* appears very rarely and the hybodont shark *Carinacanthus jepseni* is known from only one specimen (Olsen, McCune, and Thomson, In Press).

Along the marginal edge of the deep water facies of division 2 (such as at Weehawken) individual cycles are dominated by very large numbers of a few kinds of fish. In most cases only one genus is common in a particular unit (Stop 2), the others either being absent or very rare. Replacement of the dominant genus can occur between cycles in a vertical sequence or within division 2 of a single cycle. Along the Hudson River, in the northern Newark Basin, the number of different genera present in a single bed is usually not greater than three and so far has not exceeded four for an entire cycle. In contrast, the few well collected sections in the central Newark Basin show a much more even distribution of genera; for example, all six Lockatong genera have been found in the same 10 cm portion of one cycle even

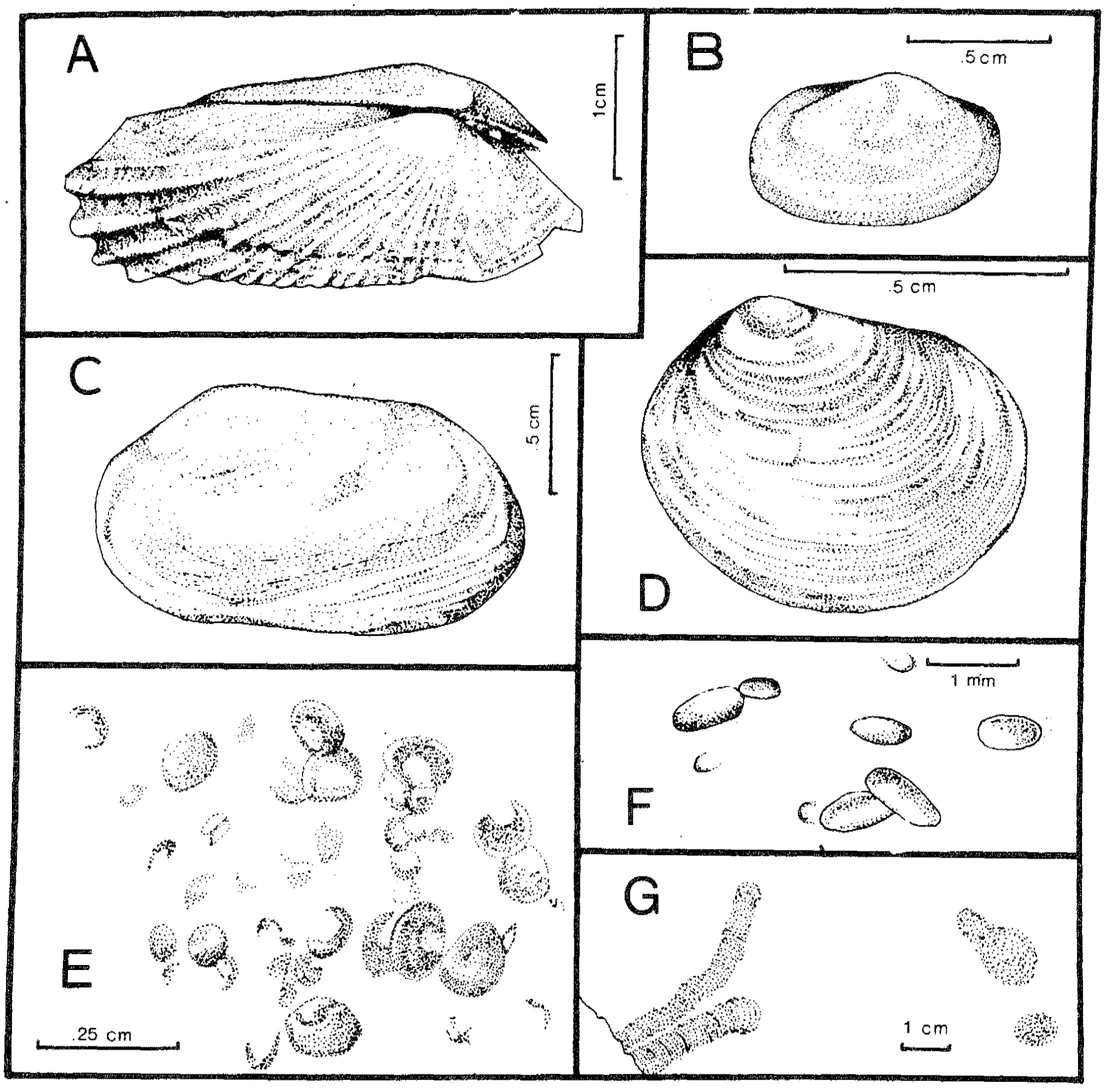


Fig. 4. Lockatong Formation invertebrates: A, B, and C, unidentified probable unionid clams from Phoenixville, Pennsylvania (AMNH Cope Collection); D, large individual clam shrimp valve *(Cyzicus* sp.) from Phoenixville, Pennsylvania (uncatalogued YPM (IP) Wherry collection); E, small clam shrimp from cycle 6, Gratacap's locality, Weehawken, New Jersey (YPM (IP) 28802; F, *Darwinula* - type ostracods, from upper part of division 2 of cycle 5, at the "Yale quarry", Weehawken, New Jersey (Field Number W5-1036); G, *Scoyenia* from cycle a at Palisades Interstate Park above Ross Dock, Fort Lee, New Jersey (YPM (IP) 28810).

though a total of less than 200 fish have been collected from the unit.

How does this rather incomplete picture of Lockatong generic diversity compare with that of modern lakes? At this point it becomes clear that very little is actually known about fish diversity in modern lakes - most of what is published is based on commercial fishery data which must be viewed with caution. The best data are available for Lake Victoria in Africa and this is presented in Figure 6.

By analogy with Lake Victoria (Figure 6) we would expect the largest number of fish genera in the Lockatong lake shallows and the lowest number in the lake center. In terms of fossilization, we might expect the central lake sediments to be numerically dominated by central lake fish, supplemented with drifters from the shallows. If Lockatong genera were similarly distributed, we would expect the fish living in the shallows to be represented in the sediments as isolated scraps, perhaps not even identifiable to genus, while the central lake fish would be much better preserved. The largest number of well preserved fish should come from the portion of the lake with the lowest number of genera. Thus, on the basis of the numbers of individuals per genus in Lake Victoria, we should expect the number of genera represented in the deep water facies of division 2 to be small.

The number of genera present and the relative abundances of the different genera determine the composition of a particular sample. In Lake Victoria, while 15 genera are present in water 0-9 m in depth, a sample of

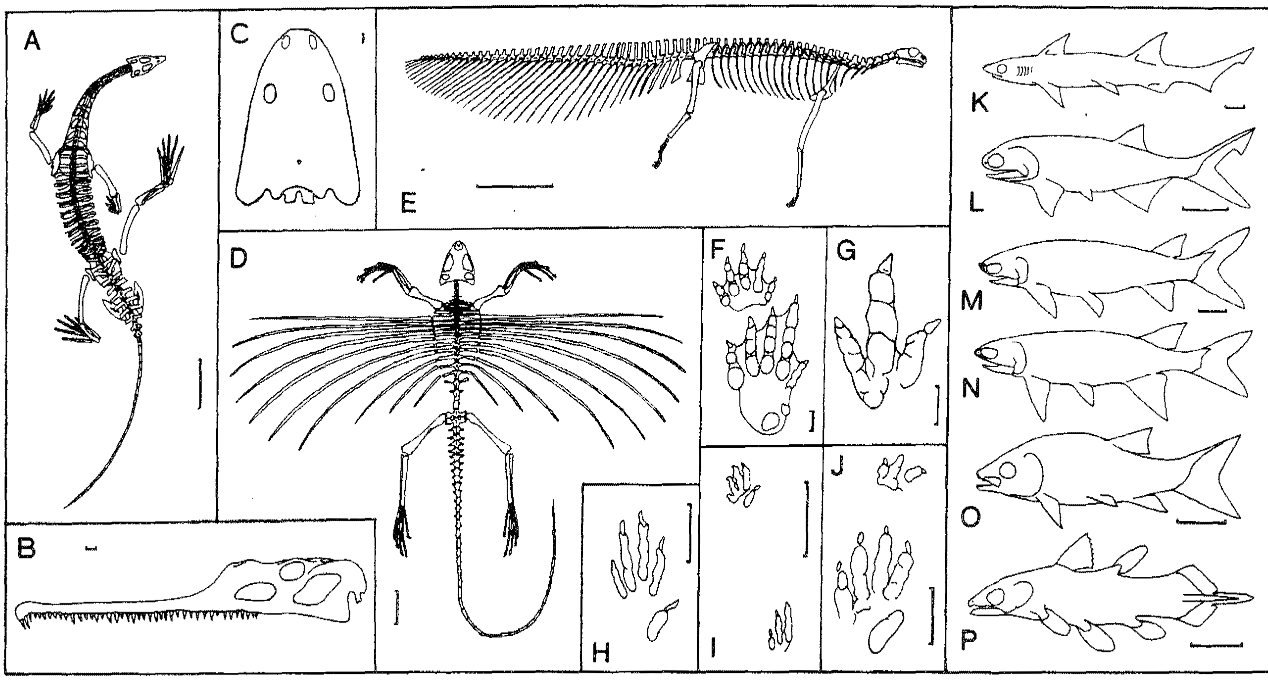


Fig. 5. Lockatong Formation vertebrates and reptile footprints from the upper Stockton, Formation (for repository abbreviations see Olsen, this Fieldbook) (From Olsen, In prep.); A, *Tanytrachelos* cf. *ahynis,* reconstruction; B, Rutiodon carolinensis, reconstruction; C, *Eupelor durus,* reconstruction; D, *Icarosaurus siefkeri,* reconstruction; E, "deep tailed swimmer", tentative reconstruction; F, *Apatopus lineatus,* composite right manus and pes; G, *Grallator* sp., left pes; H, *Gwyneddichnium minore,* right pes; I, *Rhynchosauroides brunswicki,* right manus and pes; J, *Chirotherium* cf. *eyermani,* right manus and pes; K, *Carinacanthus jepseni,* reconstruction; L, *Turseodus* sp., reconstruction; M, *Synorichthys* sp. reconstruction; N *Cionichthys* sp., reconstruction; O, semionotid of the "*Semionotus brauni* group", reconstruction; P, *Diplurus newarki,* reconstruction. Scale 2 cm.

1000 indentifiable fish from that area could be expected to yield only about 6 genera (using Hurlbert's 1971 refinement of Sanders' 1968 rarefaction technique -Peet, 1974 and Tipper, 1979),because some genera are much more abundant than others. In the middle of Lake Victoria, while the relative abundances of the genera are more equally distributed, the total number of genera is much reduced, so that the number of genera in a given sample would still be small. For a sample of 1000 fish from the deepest waters of Lake Victoria it is expected that about 4 genera would be recovered. Considering the limited sample size of well-preserved fish from the Lockatong and the lack of a well-preserved shallow water fish assemblage, the presence of only six genera is not very different from what might be expected of a modern lake.

This discussion is intended to indicate the problems inherent in comparing generic diversity of recent and fossil lakes, not to imply that the generic diversity of the Lockatong was similar to that of Lake Victoria. A sample of six genera appears reasonable for at least one great lake considering sampling bias, but it is also reasonable for a pond. This analysis of generic diversity is also clouded by the difficulty of applying comparative techniques developed for organisms living at one time to fossil organisms which lived over thousands of years in a changing environment. At this point, what little is known about modern lake diversity can serve as a null hypothesis, indicating in this case that simple comparisons of generic diversity between ancient and modern lakes is not, as yet, very informative.

Specific diversity is even more difficult to deal with than generic. Work on the number of species present in the existing sample of Lockatong fishes is just beginning (A. R. McCune, pers. comm.). While at this point we cannot pretend to know how many species of each genus are present, it is clear that some genera show more variability in morphology than others. The Lockatong fish genera may be ranked in terms of decreasing morphological diversity which may, in turn, reflect specific diversity as follows: ***Turseodus, Diplurus, Semionotus, Synorichthys, Cionichthys,*** and ***Carinacanthus.*** This morphological diversity is presently under investigation by A. R. McCune (Yale Biology) using a variety of computer assisted numerical techniques. Pending the results of the analysis, we suggest qualitatively that a sample of one genus contains more than one species if the range of variability in that sample exceeds the range of a single population of a congener preserved in a mass kill (known from other Newark deposits or other parts of the world). Thus, we expect the genus ***Turseodus*** to contain more species than the other Lockatong genera. As

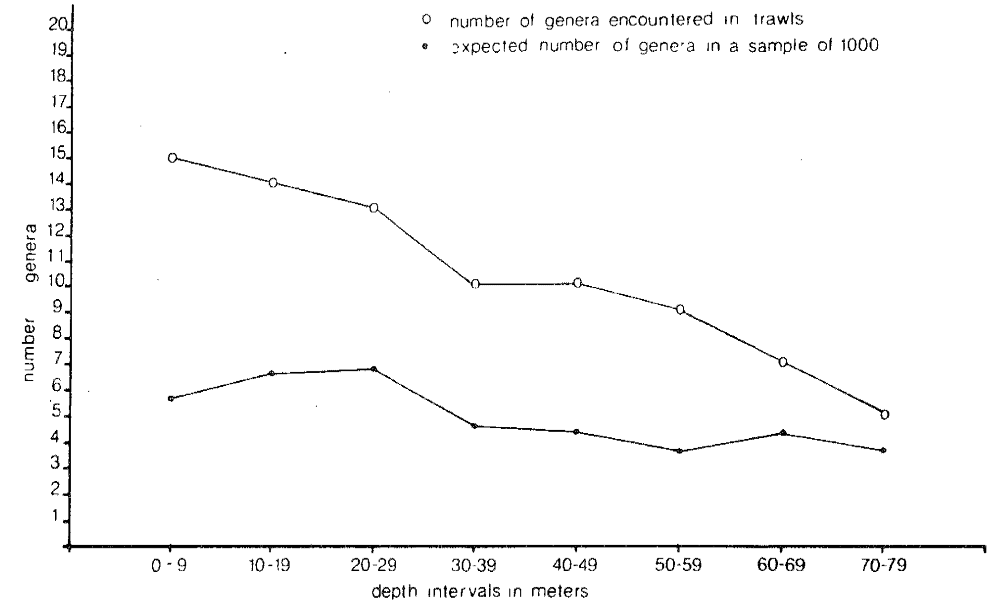


Fig. 6. Relative abundances of fish genera in Lake Victoria, East Africa.

For the purposes of this analysis I have followed the practice of Kudhongania et al. and group all non-*Tilapia* ciclid genera in *Haplochromis* since this is similar to what is easily recognized in paleontological context. While there are at least 22 genera in Lake Victoria only 15 occur outside of rivers and streams which enter the lake or occur in abundances great enough to be encountered in the experimental trawling operations.

Data are from Kudhongania (1972) and Kudhongania, et al. (1971) and were originally in the form of desmersal fish biomass estimates (which are essentially area weighted extrapolations of the trawling results). I divided the biomass estimate for each genus at a depth interval by the mean weight of an individual of that genus (derived from Beauchamp, R.S.A. and others, 1950) to obtain the approximate number of individuals.

Hurlbert's (1971) refinement of Sander's (1968) rarefaction technique was used to obtain the expected results for a sample of 1000 individuals.

will be discussed in succeeding pages, the morphological variability of Lockatong genera is small compared to certain younger Newark Basin forms.

Little Aquatic Reptiles

Two genera of aquatic reptiles are surprisingly abundant in cycles of the lower Lockatong. One, *Tanytrachelos* (Olsen, 1979) is a little (20-40 cm), long-necked, slender, lizard-like animal (Figure 5) whose nearest relative appears to be the much larger (1-6 m), monstrously long-necked *Tanystropheus* from the Old World Middle Triassic. Among reptiles *Tanytrachelos* is unusual because of the ease with which the skeletons may be sexed. One sex (male) has a pair of sickle-shaped bones which appear to be the reptilian analog of a mammalian baculum; the other sex lacks them. The "sex ratio" is about 50/50 in a large collection (ca. 150 specimens) of *Tanytrachelos* from its type locality in the Cow Branch Formation of the Dan River Group in North Carolina (Olsen, 1979).

The other genus (Figure 5), which has come to be known as the "deep tailed swimmer", has as yet no formal name (Colbert and Olsen, In Prep.). This small (ca. 20 cm) animal is characterized by a deep, ventrally directed tail fin supported by extraordinarily long hemal spines. In addition, its front legs are longer than its hind legs and its lower jaw is beak-like and toothless anteriorly. At this point, the relationships of this strange animal remain an enigma.

These little reptiles are not distributed through Lockatong detrital cycles at random. They are almost exclusively found, both as articulated skeletons and isolated bones in the lower parts of division 2, often in the lowest beds containing whole fish (see Stops 1 and 2).

Feltville Formation, Washington Valley Member - General Comments

About 3150 m above the early Late Triassic Lockatong Formation, is the first laterally extensive perennial lake sequence in the Early Jurassic (Hettangian) of the Newark Basin. This part of the lower Feltville Formation contains a limestone-bearing sequence which bears a gross resemblance in vertical sequence to a single Lockatong detrital cycle (Figure 7). I have been informally calling this portion of the Feltville the "Washington Valley member" and it can be split into three basic divisions at most exposures as follows (from the bottom up): 1, a 0 to 3 m gray to red siltstone and fine sandstone showing current bedding, root zones, abundant reptile footprints, and carbonized

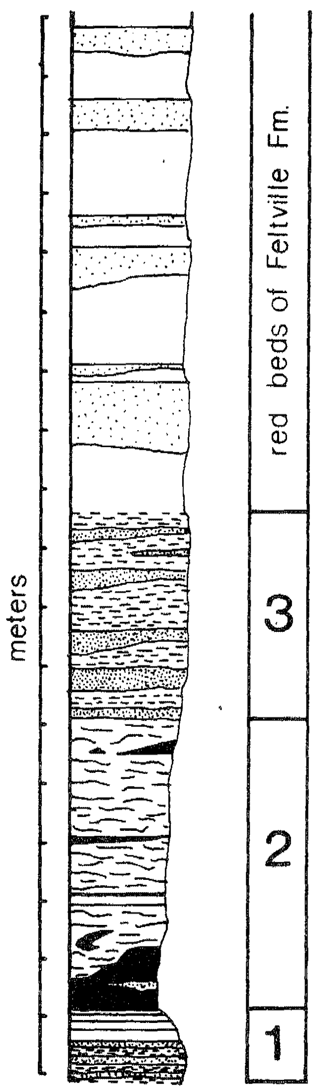


Fig. 7. Generalized section of "Washington Valley member" of Feltville Formation. Note resemblance to Towaco cycles (Figure 13) and Lockatong detrital cycles (Figure 3).

megafossil plants (transgressive facies); 2, a 0.5 to 5 m black, gray, or red and green-gray microlaminated to massive limestone and calcareous siltstone with abundant fossil fish and graded to massive siltstone (deep water facies); and a 1 to 3 m gray or red siltstone similar to division 1 but with fewer footprints (regressive facies). Division 1 grades down into and division 3 grades up into red and buff clastics. As there is only one unit like the Washington Valley member in the Feltville Formation, the sequence cannot be called cyclic. Nonetheless, the vertical sequence of beds and their fossil content show that, like Lockatong cycles, the Washington Valley member was deposited by the expansion and contraction of a large lake.

It is more difficult to assess the original area covered by the lake which deposited division 2 of the Washington Valley member than it is to assess the Lockatong lake area. Like all Newark Basin Jurassic beds, the Feltville Formation is preserved only in a few synclines along the major faults which cut the Newark Basin and form its western boundary (see Olsen, this fieldbook). So far the Washington Valley member has been positively identified in only the southern half of the Watchung Syncline and in the New Germantown Syncline. Exposures are too poorly known in the Sand Brook and Jacksonwald Synclines and in the northern half of the Watchung Syncline to determine the presence or absence of the Washington Valley member in these areas. Given the present state of knowledge, the minimum area covered by the lake which deposited division 2 is --- km^2 although the lake was probably much larger.

Lateral facies relationships in the Washington Valley member are very different from Lockatong detrital cycles despite the similarity in vertical section. On a small scale, the Washington Valley member shows lateral variation in thickness and lithology (Figure 8) far outside the range of Lockatong cycles. Thickness changes markedly along strike as does color. Within 300 m in the Watchung Reservation (type area for the Feltville Formation) the color of the limestone of division 3 changes from gray and black to white and green-gray and the color of fish bone changes from black to amber. Siltstones associated with all three divisions change from gray to red in the same area, but all the beds still retain palynomorphs and black coalified plant remains. The thickness of the red siltstone between the Washington Valley member and the underlying Orange Mountain Basalt varies markedly along strike as well; at some localities division 2 rests directly on the basalt (Figure 8). I believe these lateral changes reflect an irregular depositional surface.

On a larger scale, the Washington Valley member thickens towards the New Germantown Syncline, as does the whole of the Feltville (Figure 9). This thickening is in the same direction as the mean paleocurrent vector for the formation which is southwest (pers. obs. and Manspeizer, pers. comm.). Presumably, this indicates that the depositional center of the Feltville, unlike that of the Lockatong, was located near the present western edge of the Newark Basin.

The relationship between the calcareous and non-calcareous portions of division 2 is complex, especially in the Watchung Syncline exposures. While there is almost always a basal laminated limestone bed (Figure 10) the higher limestone units are very discontinuous, interrupted by massive to crudely bedded gray siltstone. These limestone units usually have scoured non-gradational tops. It appears that some episodes of limestone deposition were separated by intervals of submarine scour which removed much of the originally

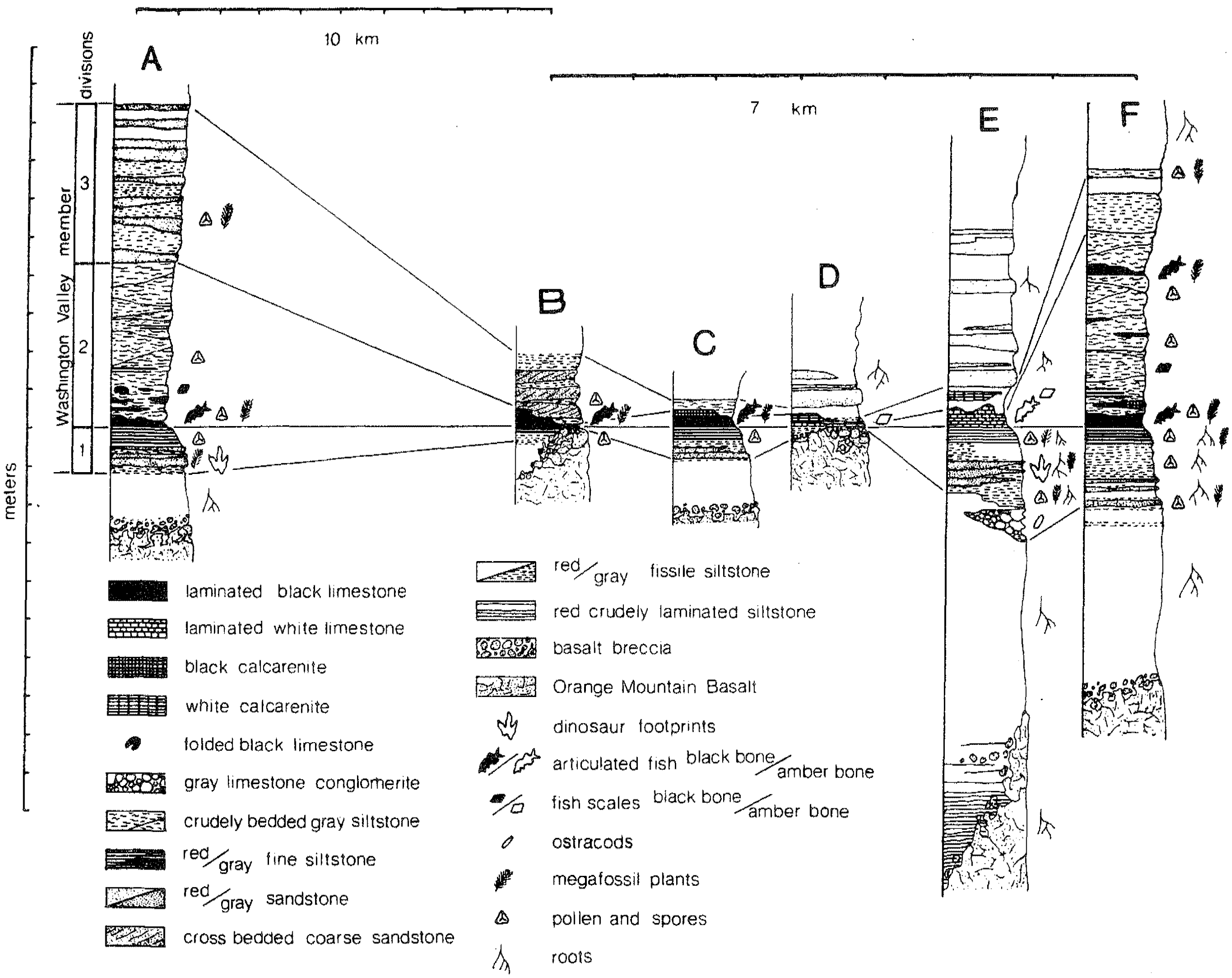


Fig. 8. Small scale lateral change in Washington Valley member: A, outcrop along East Branch about 145 m northwest of Vosseller Road near intersection with Roberts Road, Somerset County, New Jersey; B, banks of small stream running parallel to and on the southeast side of Valley Road, 1.6 km north of Watchung, New Jersey rotary (Somerset County). Elsinore Drive crosses this stream 80-100 m down stream from locality; C, bluffs and pool exposures along Green Brook about 400m northeast of intersection of Plainfield Avenue, Valley Road, and Bonnie Burn Road and about 618m down brook from overpass of Plainfield Avenue over brook (outcrops at boundary of Union and Somerset Counties); D, outcrops along Green Brook north of (c) above and about 200m, south of the Plainfield Avenue bridge over Green Brook; E, two combined sections, 400m apart, one on the south, one on the north side of Blue Brook about 1.9km and 2.3 km respectively, upstream from the crossing of Sky Top Drive over Blue Brook, Watchung Reservation, Union County, New Jersey — type section of the Feltville Formation; F, outcrops in bluff of small tributary of Blue Brook, 260m south of Lake Surprise, Watchung Reservation, Union County, New Jersey.

deposited limestone. Support for this hypothesis comes from the presence of beds of calcarenite made up of redeposited limestone (Figure 10) and the presence of occasional rolled beds of limestone isolated in gray siltstone (Figure 10).

Thus, a relatively deep water (plus several tens of meters) environment is suggested by most features of division 2 throughout most of its exposed area. On the other hand, at least the upper part of division 2 in the white limestone and red siltstone exposures in the Watchung Reservation (E of Figure 8) shows some features suggestive of shallow water deposition and shallow water reworking of carbonates (Manspeizer, this Fieldbook).

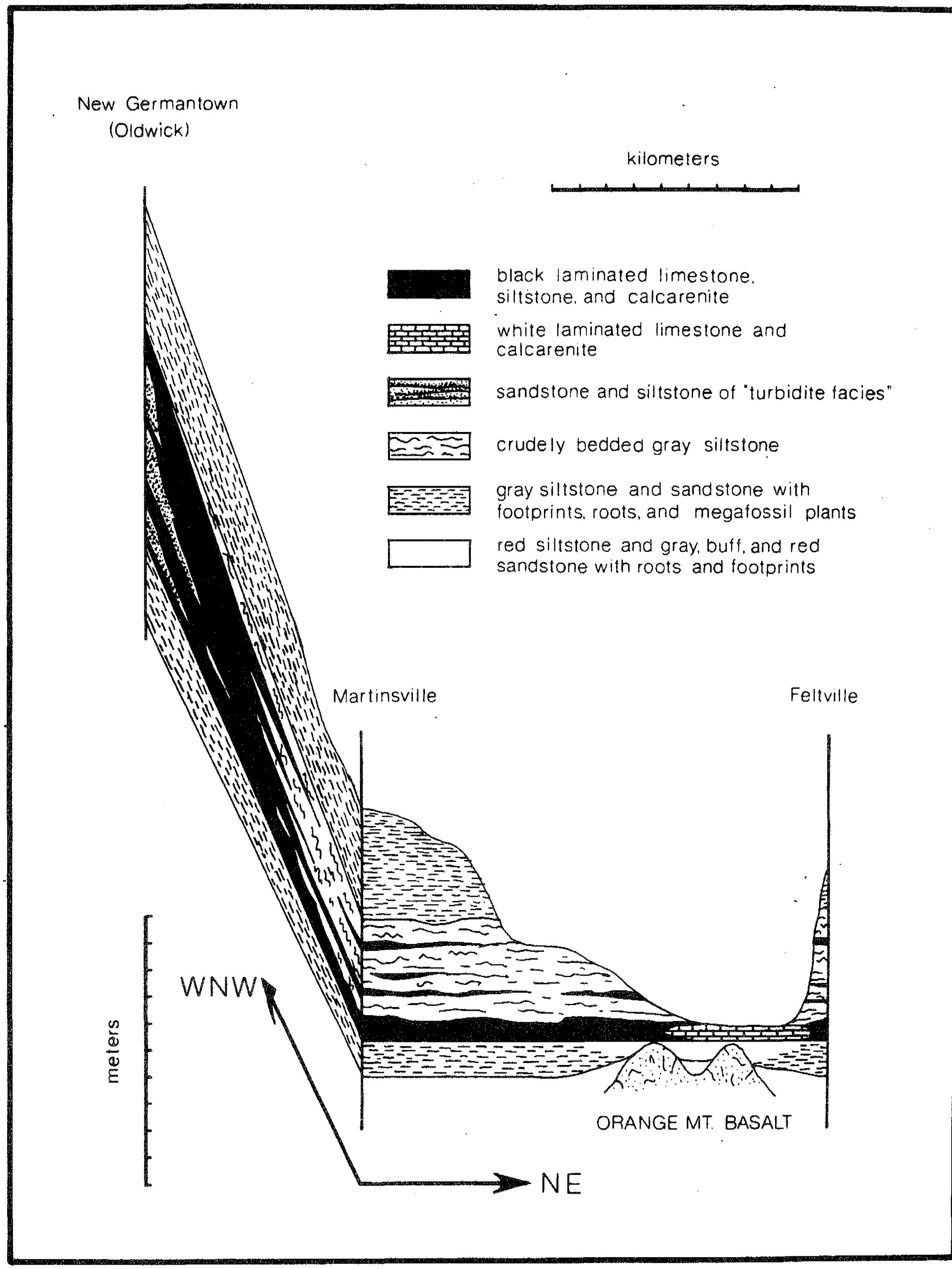


Fig. 9. Lateral facies relationship in Washington Valley member.

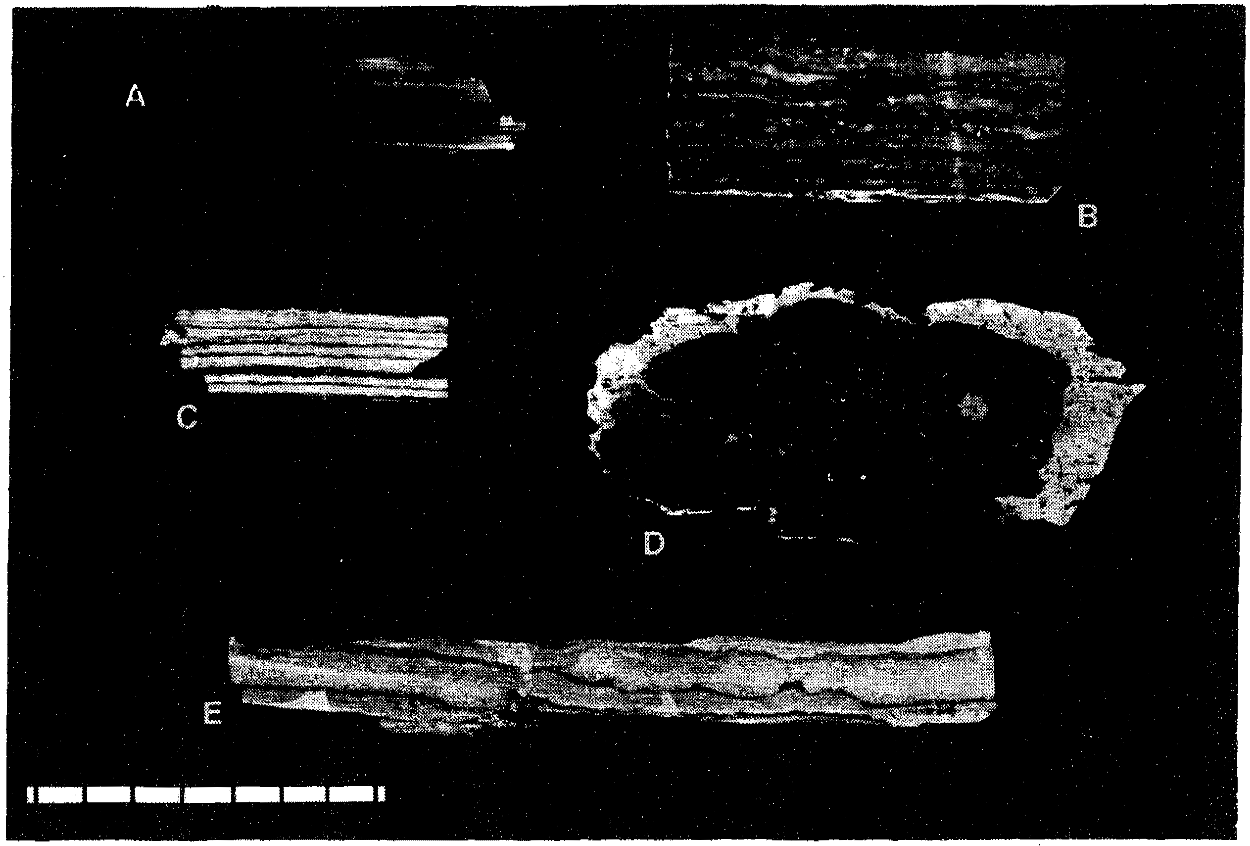


Fig. 10 Hand samples of portions of division 2 of the Washington Valley member: A, laminated gray siltstone from upper part of division 2 from a small tributary of Rockaway Brook in the New Germantown Syncline—dark laminae differ from light by increased content of Kerogen, primarily pollen and spores; B, light gray laminated calcarenite from upper part of division 2 from southern exposures in the Watchung reservation; C, laminated (and in part microlaminated black limestone, from bluff along the East Branch of Middle Brook, Martinsville, New Jersey — couplets consist of kerogen rich claystone siltstone lamina and a kerogen containing limestone lamina; D, coarse gray silty calcarenite, from bluff along the East Branch of Middle Brook, Martinsville, New Jersey; E, thin sandy turbidites, from a small tributary of Brook in the New Germantown Sycline — graded beds consist of fine sand grading up into gray silt and then fine dark gray kerogen - rich siltstone.

All samples are polished and wetted with glycerol. Scale in cms.

In contrast to the Watchung Syncline exposures, those of the Oldwick Syncline contain little massive siltstone. Instead, the siltstones are well bedded, often sandy, sometimes conglomeritic, and are usually made up of beds 1 to 5 cm thick showing a distinct graded pattern (Figure 10) characteristic of turbidites. (A turbidite is a sedimentary unit showing a characterisitic upwards fining in grain size associated with a series of structures indicating deposition by intrusions of dense sediment-laden water which flow beneath less dense water along the basin floor — turbidity currents.) While turbidites are usually considered characteristic of marine environments (Bouma, 1962, 1964), there are no *a priori* reasons why they should not occur in all bodies of water. In fact, turbidity currents do play major roles in lacustrine sedimentation; for instance, they account for as much as half of the accumulated sediments in meromictic Green Lake, Fayetteville, New York (Ludlam, 1974). Houbolt and Jonker (1968) show that Lake Geneva (Switzerland) also has thick accumulations of turbidites and these are very similar to the New Germantown Syncline examples.

Those features of the deep water facies of division 2 of Lockatong detrital cycles which are consistent with the stratified lake model of deposition are also present in the laminated portions division 2 of the Washington Valley Member. There are, however, major differences in facies patterns between the Lockatong cycles and the Washington Valley member which are at least partially due to the different cross-sectional shape of the lake. For instance, division 2 of the Washington Valley member lacks macroscopic benthic organisms throughout its preserved area. Also, the microlaminated, whole-fish-bearing portions of division 2 extend to the western edge of the Newark Basin, whereas in Lockatong lakes, microlaminated beds get no closer to the basin's western edge than a few kilometers. This and the presence of interbedded conglomerates in division 2 show that the western edge of

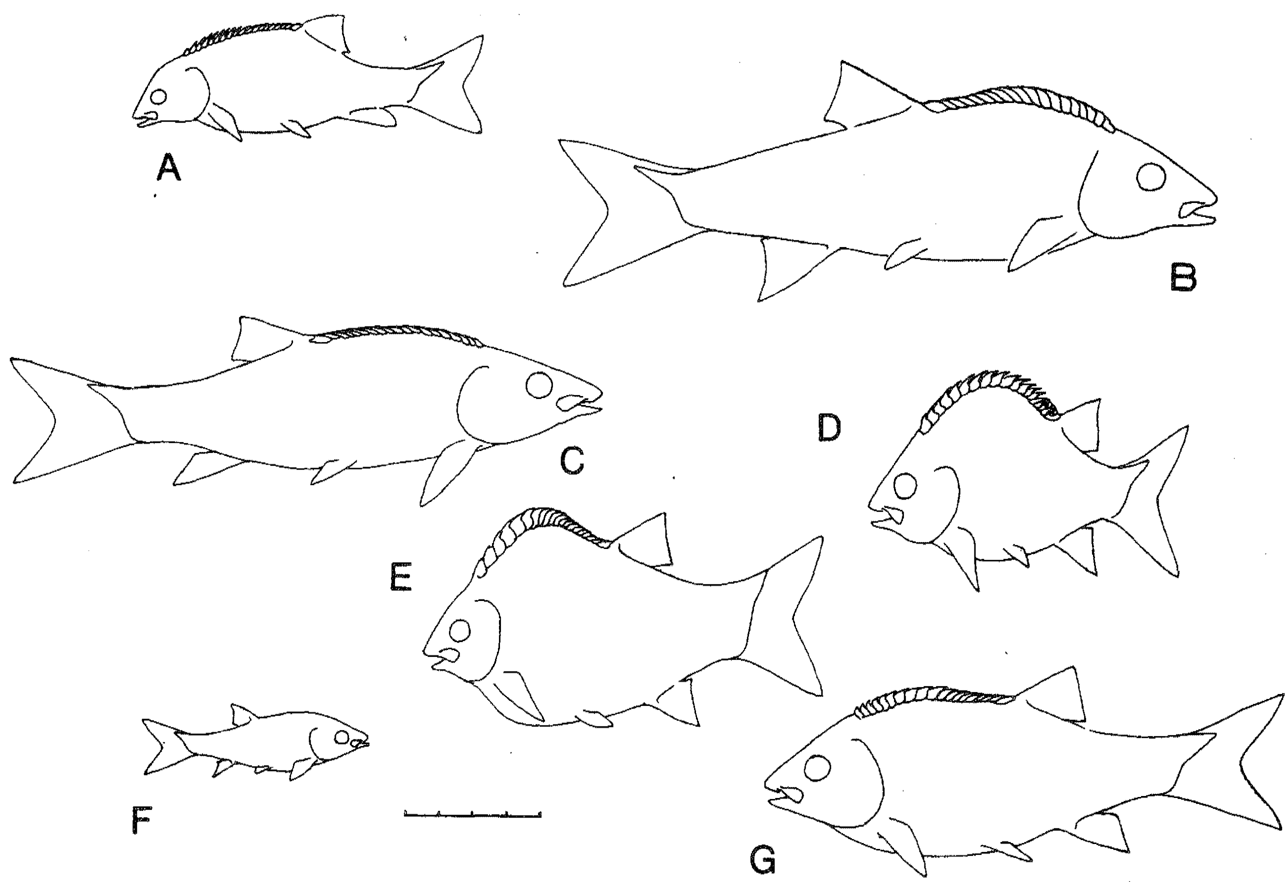


Fig. 11 Outline shapes of semionotid fish from the Washington Valley member of the Feltville Formation; A, AMNH 672 from Old Field's Copper Mine, Watchung, New Jersey (Figured in Newberry, 1888); B, YPM 6452 from bluff along East Branch of Middle Brook, Martinsville, New Jersey; C, YPM 6455, from same locality as B; D, YPM (uncatalogued specimen) from small tributary of Rockaway Brook, in the New Germantown Syncline, Oldwick, New Jersey; E, YPM 6809, from same locality as B; F, YPM 6450, from same locality as B; G, YPM 7763, from same locality as B.

These are attempted reconstructions of the individuals listed above: They are designed to give a general feeling for morphological variability among Feltville Semionotids rather than details of any one specimen. Scale in cms.

the Washington Valley lake basin was steep.

Feltville Formation Fish

While invertebrates are very rare in the Washington Valley member, fossil fish are abundant in the laminated limestone and thin turbidites. The kinds of fish and their patterns of diversity are very different from the Lockatong; *Semionotus* is everywhere overwhelmingly abundant. The only other genus present is the subholostean *Ptycholepis* and this is represented by only a few characteristic skull bones and scales. This apparent low generic diversity is offset by very high levels of morphological diversity among semionotids (Figure 11). This variability far exceeds that of the entire Lockatong sample of semionotids (+ 1500 specimens) despite the much smaller size of the Washington Valley sample. Using the rule of thumb outlined for Lockatong fish, it appears that this amount of morphological diversity reflects the presence of an unusually high number of semionotid species. The relatively small number of whole Washington Valley member fish precludes, at this point, a minimal species count, although such an effort is planned (A. R. McCune, pers. comm.).

Interbasin Correlation by Semionotids

The most distinctive semionotids present in the Washington Valley member of the Feltville Formation belong to what I have called the "*Semionotus tenuiceps*-group" (Figure 12). They are characterized by large and often elaborate scales in front of the dorsal fin. Similar fish are known from only two other formations in the Newark Supergroup: the Towaco Formation of the Newark Basin (see Olsen this fieldbook) and the Turners Falls Sandstone of the Deerfield Basin. Despite the proximity of the Deerfield and Hartford basins, no fish of the "*S. tenuiceps* group" have been found in the latter. Likewise, the subholostean *Redfieldius,* semionotids of the "*S. micropterus* group", and *Diplurus* cf. *longicaudatus* which are present in both the Shuttle Meadow and East Berlin formations of the Hartford Basin are absent from the Feltville Formation and

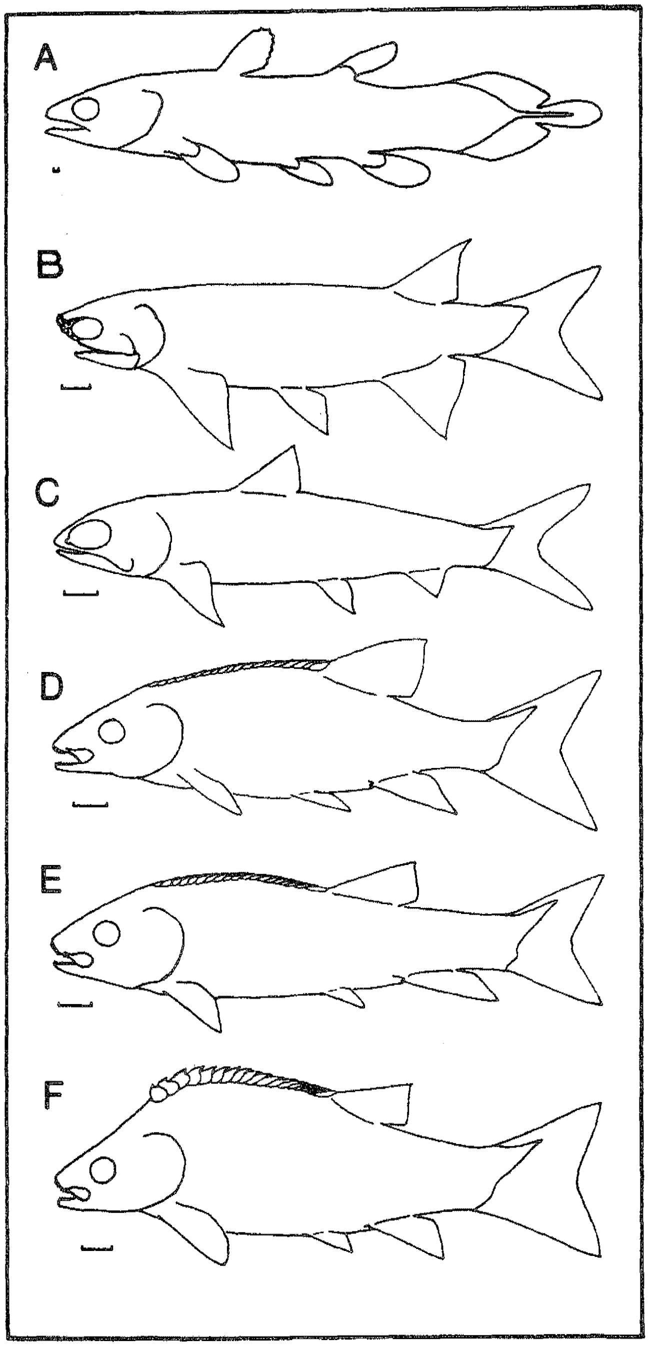


Fig. 12 Reconstructions of fishes of the Newark Jurassic: A, *Diplurus longicaudatus;* B, *Redfieldius* sp.; C, *Ptycholepis marshi;* D, member of the "*Semionotus elegans* group"; E, member of the "*Semionotus micropterus* group"; F, member of the "*Semionotus tenuiceps* group".
Adapted from Olsen (In Prep). Scale 1 cm.

Turner Falls Sandstone. Therefore, the fish evidence does not support correlation of the three lava flow formations and interbedded sediments of the Newark and Hartford Basins as has been suggested. The presence of *Redfieldius* higher in the Newark Basin section (Boonton Formation) suggests that the Feltville Formation (and the Towaco Formation and Turners Falls Sandstone as well) are older than the Shuttle Meadow Formation (Olsen, McCune and Thomson, In Press).

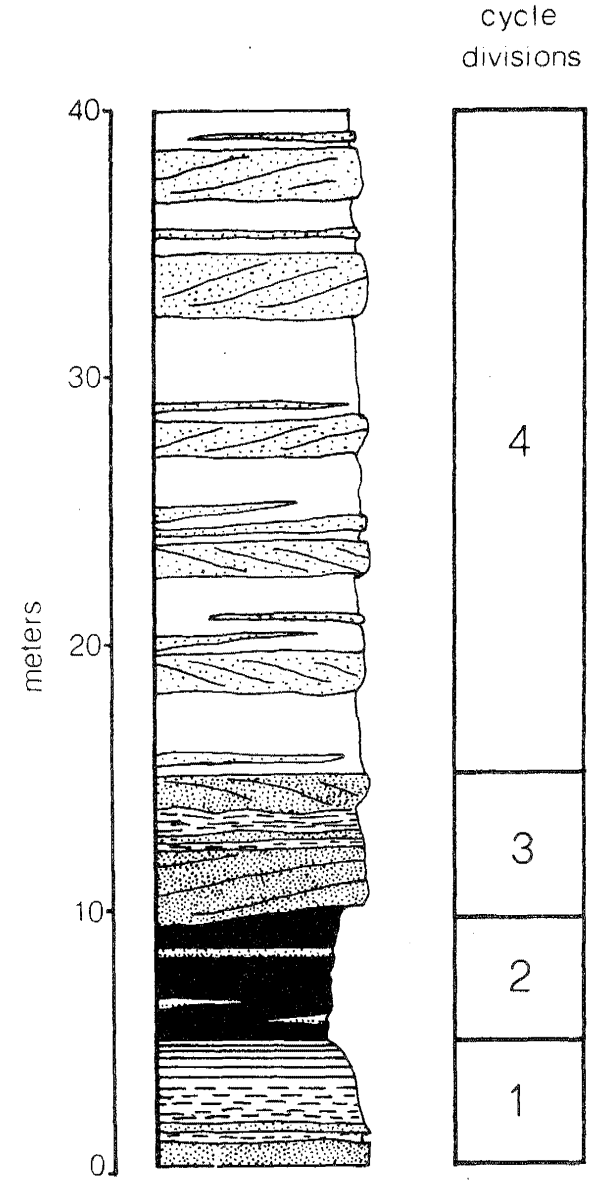


Fig. 13 Generalized Towaco Formation cycles. Description in text.

Towaco Formation Cycles - General Remarks

The Towaco Formation, like the Lockatong, consists predominantly of sedimentary cycles (Figure 13) produced by the expansion and contraction of large lakes. In contrast to the Lockatong, Towaco cycles have a mean thickness of 30 m and contain thick sequences of red clastics. In gross form, Towaco cycles look like stretched out Lockatong detrital cycles with a concommitant reduction in the density of various features of bioturbation and diagenesis and an increase in the preservation of primary sedimentary structures. Towaco cycles also resemble the Washington Valley member if the overlying red beds of the Feltville Formation are added. The cycles of the Towaco Formation can be broken, for convenience, into four basic divisions as follows (from the bottom up): 1, a 1 to 5 m gray siltstone and sandstone (or conglomerate) often with root horizons, reptile footprints, and large to small scale

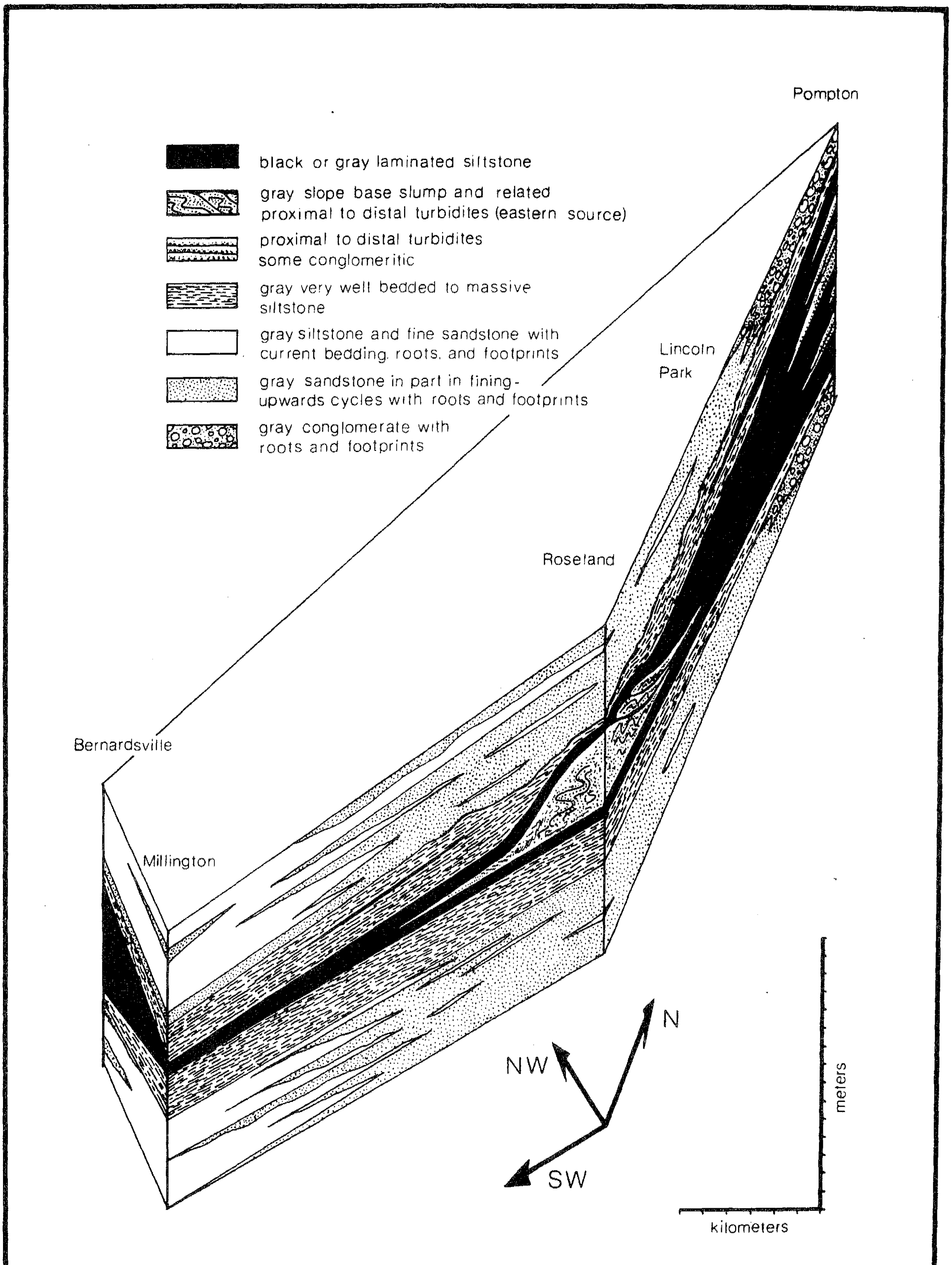


Fig. 14 Lateral facies relationship within divisions 1—3 of Towaco cycles.

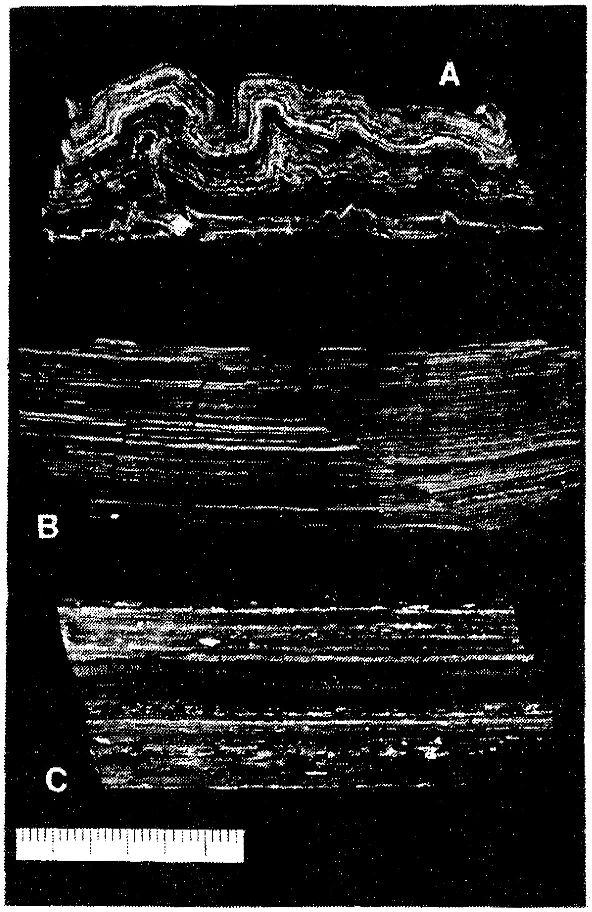


Fig. 15 Hand samples of the microlaminated portion of division 2 of Towaco cycles showing the northward increase in microlamina thickness: A, microlaminated silststone in disharmonic folds from upper cycle, Walter Kidde Dinosaur Park; B, microlaminated siltstone with small syndepositional fault from uppermost Towaco cycle, Toms Point, Lincoln Park, New Jersey; C, microlaminated siltstone from the third cycle from the top of the Towaco Formation, Wayne, New Jersey.

Samples arranged with the most northern sample, uppermost. Scale in cms.

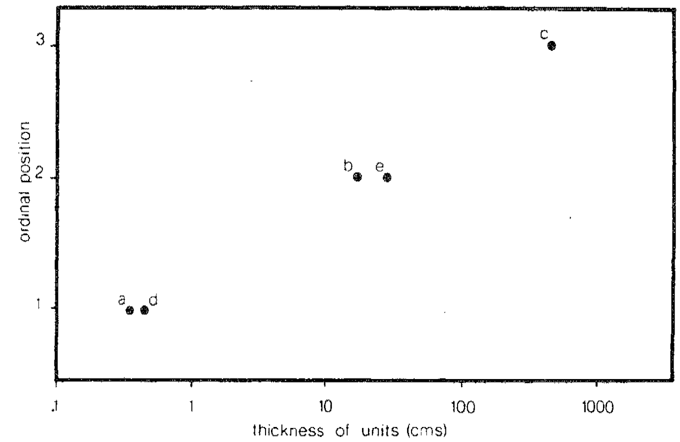


Fig. 16 Graph of the relationship between thickness and relative position of Towaco Formation turbidites at the Walter Kidde Dinosaur Park, "Ordinal" position refers to the position of each turbidite in the sequences of units a, b, c and d, e as shown in Figure 45.

crossbedding (transgressive facies); 2, a 1 to 5 m thick gray to black siltstone with a 0.1 to 5.0 m thick gray to black microlaminated calcareous portion often with numerous fish (deep water facies); 3, a 3 to 6 m gray clastic unit similar to division 1 (regressive facies); and 4, a thick (20 - 30 m) red clastic sequence often composed of several fining-upwards cycles containing abundant reptile footprints, root horizons, mudcracked surfaces, and beds with numerous carbonate rich nodules (fluvial, flood pain, and flood basin facies).

Individual Towaco cycles resemble the Washington Valley member of the Feltville Formation in lateral facies relationships (Figure 14), again contrasting with the Lockatong. All divisions of the Towaco cycle coarsen towards the north, and the microlaminated portion of division 2 thickens by more than an order of magnitude towards the Ramapo Fault. This microlaminated portion appears varved, similar to the microlaminated portions of Lockatong cycles and the Washington Valley member. Varve thickness increases in the same general direction as the entire microlaminated sequence (Figure 15), although only by a factor of five. The structures and fossils in these varved beds are consistent with the stratified lake model of deposition. However, the more massive fine siltstone portions of division 2 are more consistent with a model in which the lake experienced at least seasonal overturn; fossil fish are present in these beds but only as isolated bones and scales.

Lacustrine Turbidites of Towaco Cycles

At a number of exposures, division 2 of Towaco cycles contain beds which I interpret as lacustrine turbidites of two types. One series of turbidites, formerly exposed in the Roseland (Riker Hill) Quarry, conform to a proximal-to-distal turbidite model developed originally for marine flysche sequences by Allen (1969). This sequence, described in more detail for field trip Stop 5, appears to have been produced by the lateral migration of a submarine channel fan. Houbolt and Jonker (1968) described a similar sequence in Lake Geneva where turbidity currents are produced when the cool sediment-rich waters of the Rhone River underflow the relatively warm waters of the lake. The stream of the Rhone retains its integrity and flows towards the deepest part of the lake along a submarine channel to a depth of about 300 m where it dissipates into a channel fan. Houbolt and Jonker recognize channel deposits, levee deposits, channel fan sediments, fan margin beds, and central plain deposits, all deposited in deep water as a direct result of turbidity currents. I interpret the coarse-grained and crudely bedded units in the middle of the lower cycle at the Roseland (Riker Hill) Quarry (Stop 5)

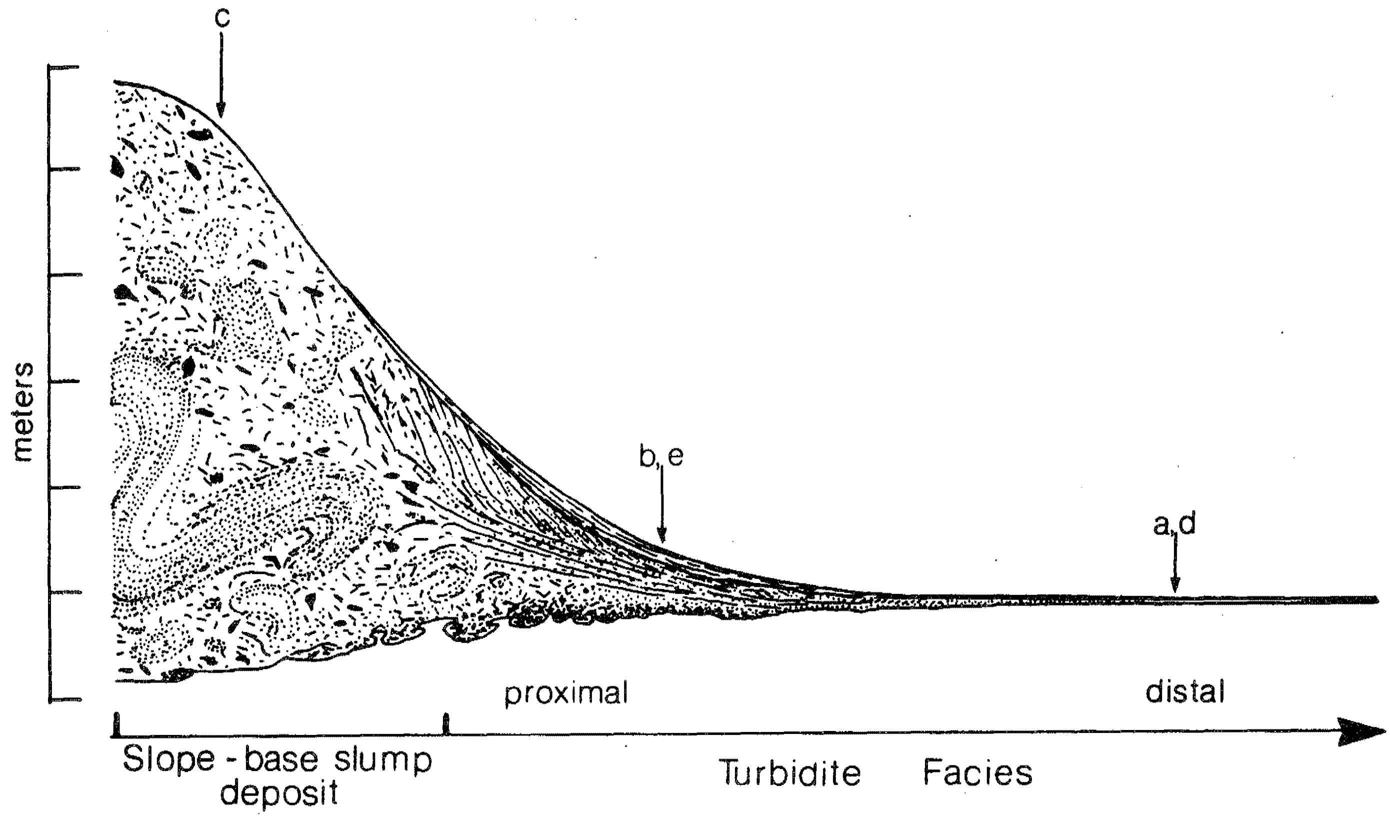


Fig. 17 Model of proximal to distal facies relationships in a single hypothetical Towaco Formation turbidite. Letters a, b, c, d, and e refer to actual turbidites described in Figure 45 and graphed in Figure 16. I do not mean to imply that all Towaco Turbidites originated from a slump.

as the result of lateral migration of a similar set of facies. The maximum thickness of these Towaco turbidites increases exponentially above the microlaminated siltstones in division 2 of the lower cycle (Figure 16) as might be expected of such a channel approaching a site at a nearly constant rate (Allen, 1969). The slope of the approaching fan would be the source of the slumped beds as depicted in Figure 17. In this model, water depth remains constant, but an alternative could involve a decrease in water depth resulting in the encroachment of the shore on the center of the lake. The sense of rotation of the folds in the slumped beds indicate transport from the east; presumably this was the direction from which the channel fan approached.

A second series of turbidites is exposed in Towaco cycles near the Ramapo Fault at Bernardsville and Wayne, New Jersey. These are graded beds, 0.5 to 20 cm thick, which occur throughout the otherwise microlaminated portions of division 2 and which resemble the turbidites of the Washington Valley member in the New Germantown Syncline. Some of the thicker turbidites are conglomeritic at their base and clearly scour the underlying microlaminated units. The pebbles found in these beds are up to 3 cm in diameter and suggest a source from the west. Thinner sandy turbidites often have casts of tool marks on their lower suface. These turbidites, apart from their clastic composition, resemble units deposited by turbidity currents in meromictic Green Lake, Fayetteville, New York (Ludlam, 1973). These turbidity currents begin along the lake basin margin as slumps, which slide down the basin slope, liquify as they mix with water.

The picture derived from facies analysis is one compatible with a model of a large perennial stratified lake which was wedge-shaped in cross-section, deepest near the Ramapo Fault, and receiving detritus primarily from the east but with a significant western input at the western lake edge.

Fluvial and Flood Plain Facies of Towaco Cycles

The broad area of Towaco Formation exposed between the northern and southern corners of the Watchung Syncline is characterized by cycles in which divisions 1, 3, and especially 4 consist primarily of fining-upwards cycles each much smaller than Towaco cycles (Figure 18). The lower portions of these cycles consist of fine to coarse sandstone or fine conglomerate which cuts down into the underlying siltstone of the previous fining-upwards cycle, often producing beds of rip-up-clasts. This portion of the cycle usually shows low angle inclined beds, each of which presents a variety of small scale current structures indicating flow about perpendicular to the original slope of the inclined beds (paleocurrent vector mean is N 39° W, while the mean for the dip direction of the inclined beds is S 24° W).

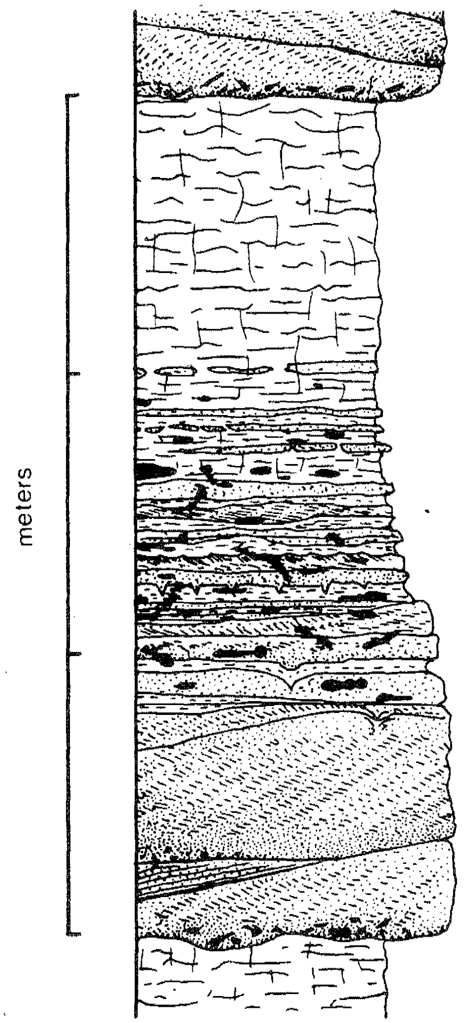


Fig. 18 Generalized fining - upwards cycle of Towaco Formation interpreted as due to laterally migrating streams.

This is followed in vertical sequence by beds of fining-upwards sandstones with climbing ripples, sole casts of reptile footprints and tool marks, alternating with beds of fine, often ripple bedded siltstone. The upper beds are fine, sometimes massive siltstone with much less prominent current bedding, frequent mudcracks, and dolomitic nodules. All portions of these fining-upwards cycles contain abundant roots; in gray beds these roots are preserved as coalified compressions, while in the red beds they are preserved as red siltstone casts.

Shallow laterally migrating rivers and streams could have produced these fining-upwards cycles. The lower portions of each cycle appear to be channel (lateral accretion) deposits, predominately point bar. The middle portion of the cycle probably represents a bank deposit and includes numerous levee and crevasse splay beds. The upper fine grained portion of each cycle appears to be a flood basin (ephemeral lake) and flood plain deposit. Following Allen's (1964, 1965, 1970) interpretation, deposition of these fining-upwards cycles occurred as follows: 1, the migrating channel cuts down into older beds in the direction of migration, redepositing the older sediments as channel deposits; 2, bank and then flood basin sediments follow in vertical sequence as the channel migrates away from a given section. The result at any section is a strongly asymetrical, fining-upwards cycle.

While the interpretation of these cycles as the result of laterally migrating channels is the first to come to mind, alternative models are possible. One, which I feel requires additional attention, regards the base of each fining-upwards cycle as a regressive shore facies of an ephemeral lake and the upper parts as a trangressive facies. These lakes would, of course, be much smaller than the lakes producing the full Towaco cycle. Critical tests of these hypotheses must be sought out.

Reptile Footprints

Reptile footprints occur abundantly in Towaco cycles,especially in fining-upwards cycles of division 4 adjacent to divisions 3 or 1. They can be a beautifully detailed record of living, moving animals. Ichnology, the study of footprints, should offer considerable insight into aspects of paleobiology unapproachable by conventional methods of analysis, for instance, how the

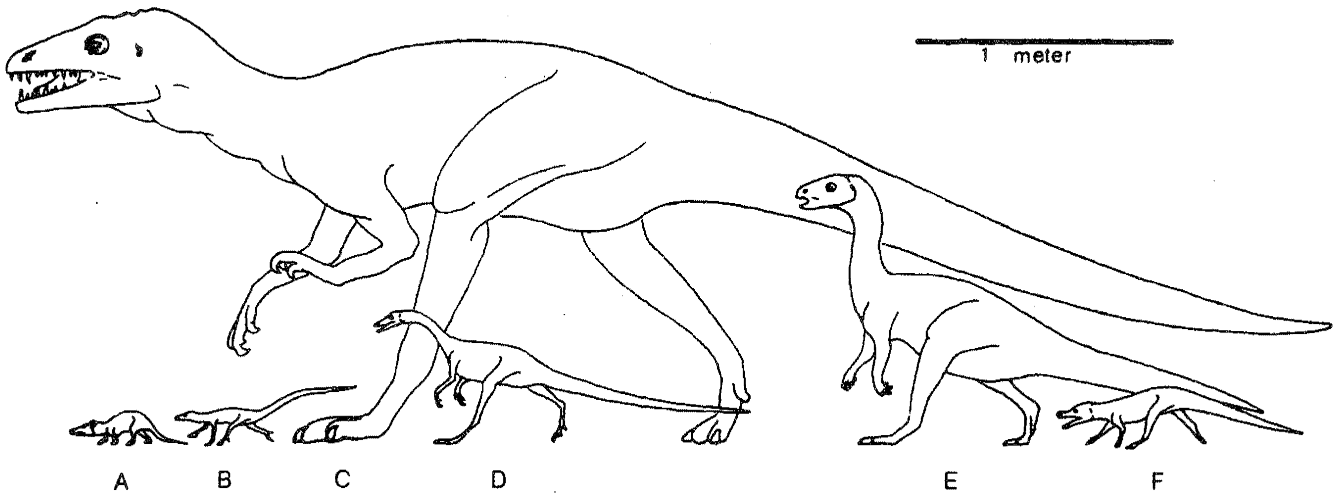


Fig. 19 Possible appearance of some representative Towaco Formation trackmakers: A, advanced mammal-like reptile or early mammal; B, lizard or lizard-like sphenodotid rhynchocephalian which produced *Rhynchosauroides*-type tracks; C, large carnivorous theropod dinosaur which produced the large grallatorid tracks usually called *Eubrontes* or *Anchisauripus minusculus;* D, small carnivorous theropod dinosaur responsible for the small grallatorid tracks of the *Grallator*- and *Anchisauripus hitchcocki*- types; E, small ornithischian dinosaur which produced *Anomoepus* tracks; F, small sphenosuchid thecodont (crocodilomorph) which probably made *Batrachopus* footprints.

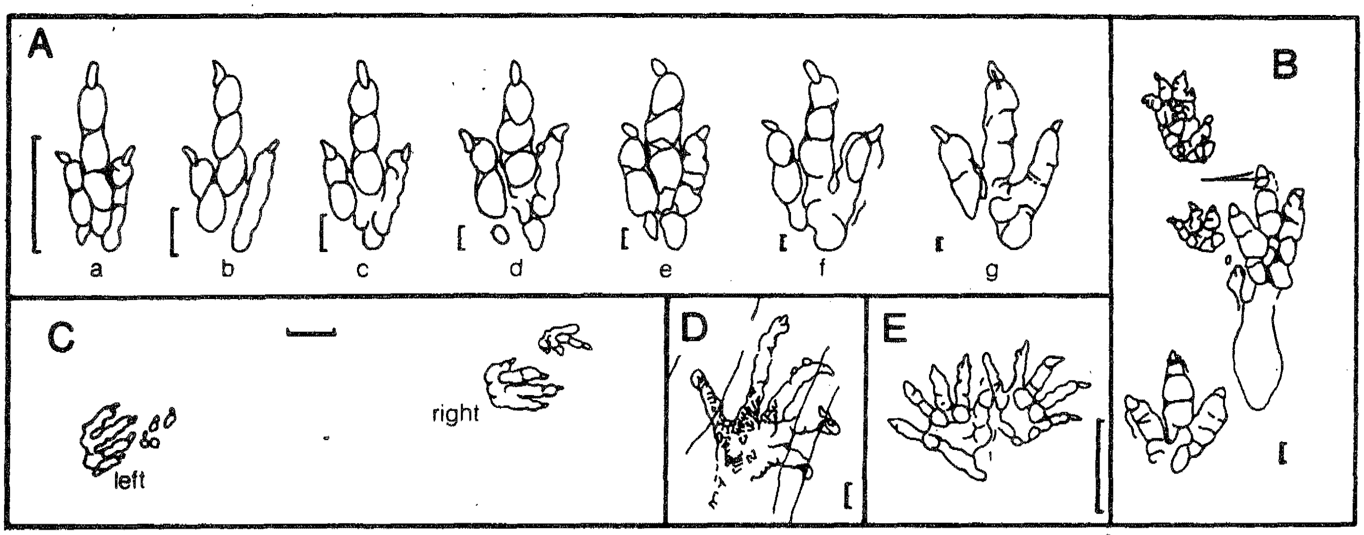


Fig. 20 Footprints from the Towaco Formation: A, Footprints of the *Grallator* type (footprints a-g arranged from left to right in order of increasing size, all right pedes, scale 2 cm); B, *Anomoepus,* two right pes impressions (one showing metatarsus impression), and three right manus impressions, scale 2 cm; C, left and right manus - pes sets of *Batrachopus,* scale 2 cm; D, *Rhynchosauroides,* left manus scale 2 mm; E, possible advanced therapsid (mammal-like reptile) or early mammal left manus and pes set, scale 2 cm.

A, (a) personal collection of John Colegrande, (b, c, d, g) RU main display slab, (e, F) lost specimens, Essex County Park Commission collection; B, RU main display slab; C, PU uncatalogued specimen; D, PU 18563; E, personal collection of Larry Felder.

animals moved and which ones inhabited the same small area. Ichnology can also provide biostratigraphic evidence where skeletal remains are lacking.

Unfortunately, no comprehensive work on Newark Supergroup footprints exists; the closest thing published is Lull's (1904, 1915, 1953) treatise on the "Triassic Life of the Connecticut Valley", and this work is very out of date. What follows is an outline of the footprints found in the Towaco Formation with some preliminary observations on their makers (Figure 19).

Rhynchosauroides sp.

A single natural cast of the imprint of a manus (fore foot) from an otherwise poor trackway is the only definite record of lepidosaurs (lizard-like reptiles) from the Towaco Formation. In Triassic deposits, this type of track is termed *Rhynchosauroides,* although the kind of manus it represents occurs in a large range of lepidosaurs including (essentially modern) lizards and sphenodontid rhynchocephalians. Both of these groups were present by the end of the Triassic and it is somewhat puzzling that this sort of track is not more common in post-Triassic deposits. This particular foot-

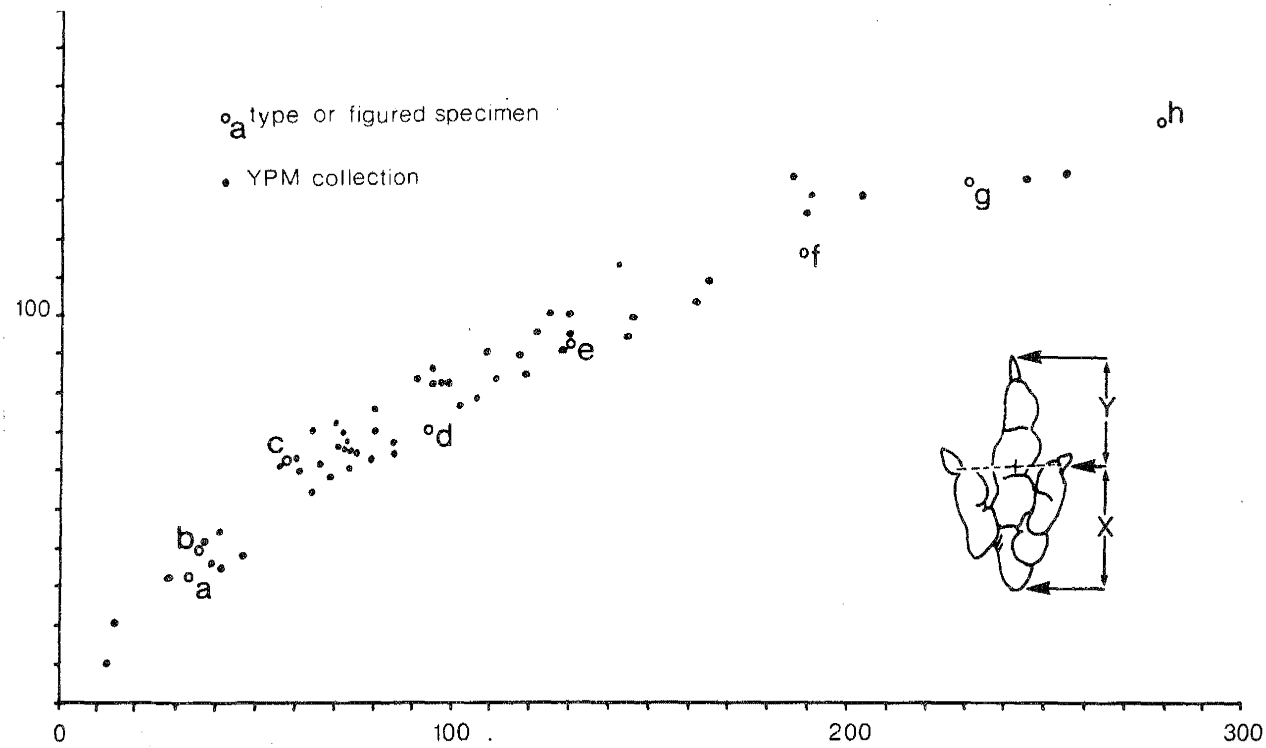


Fig. 21 The relationship between the projection of digit III past digits II and IV and the rest of the pes impression. Note the relative decrease in the projection of digit III with the absolute increase in the pes length.

print (Figure 20) is not quite like either of the two named Newark taxa, *Rhynchosauroides brunswickii* and *R. hyperbates* (Baird, 1957), but with only one well preserved footprint, formal description of this form is unwarranted.

Batrachopus sp.

Tracks assigned to the footprint genus *Batrachopus* (Figure 20) are the most abundant small non-dinosaur footprints in the Towaco Formation. The lack of a well-defined digit V on the pes (hind foot), and the small size of the manus with five subequal toes suggests a crocodilomorph as the maker of this track. Crocodilomorphs, including both true crocodiles and the more gracile sphenosuchids, are known from Early Jurassic rocks from various parts of the world.

Grallator Spp.

The most abundant footprints in the Towaco Formation are small to large, functionally three toed tracks which using Lull's (1915, 1953) terminology, would be called *Grallator, Anchisauripus,* and *Eubrontes* (Figure 20 and 21). There is never a manus impression, and the pes imprint is usually narrow - especially so in small individuals - with the angle between digit II and IV being from 15° to 45°. The shape of the pes and the nature of the skeleton reconstructed from it, clearly indicates the carnivorous theropod dinosaurs (Peabody, 1948; Baird, 1957, In Press; Galton, 1976).

The specimens illustrated by Lull (1915, 1953) as typical of *Grallator, Anchisauripus,* and *Eubrontes* show differences in proportions which probably reflect real differences in foot structure (Baird, 1957); the main factor responsible for this, however, is principally the relative length of digit III. A reasonable measure of this factor is the projection of digit III past II and IV. If this measure is graphed against the remaining length of the foot (Figure 21), it becomes apparent that the shape of the pes impression changes continuously with size. It is my opinion that the footprint genera *Grallator, Anchisauripus,* and *Eubrontes* form a continuum similar to what would be expected of tracks of individuals of different ages perhaps representing a single dinosaur species. It is therefore reasonable to synonymize the junior names *Eubrontes* and *Anchisauripus* with the senior name *Grallator.* This is not to say that all Towaco *Grallator* foot-prints were necessarily made by a single dinosaur species. Although I believe there were several species of theropod dinosaur trackmarkers, I also believe that without further detailed analysis, different species of *Grallator* should not be recognized in the Towaco assemblage.

Anomoepus Spp.

Anomoepus tracks (Figure 20) are generally small (pes 1.5 - 20 cm) and are characterized by a broad, often four toed pes and a manus with five (rarely four) subequal digits. The structure of *Anomoepus* tracks fits what is known about several small herbivorous early Mesozoic ornithischian dinosaurs such as fabrosaurs. As is the case for *Grallator,* there were probably a number of species (if not genera) of small ornithischians

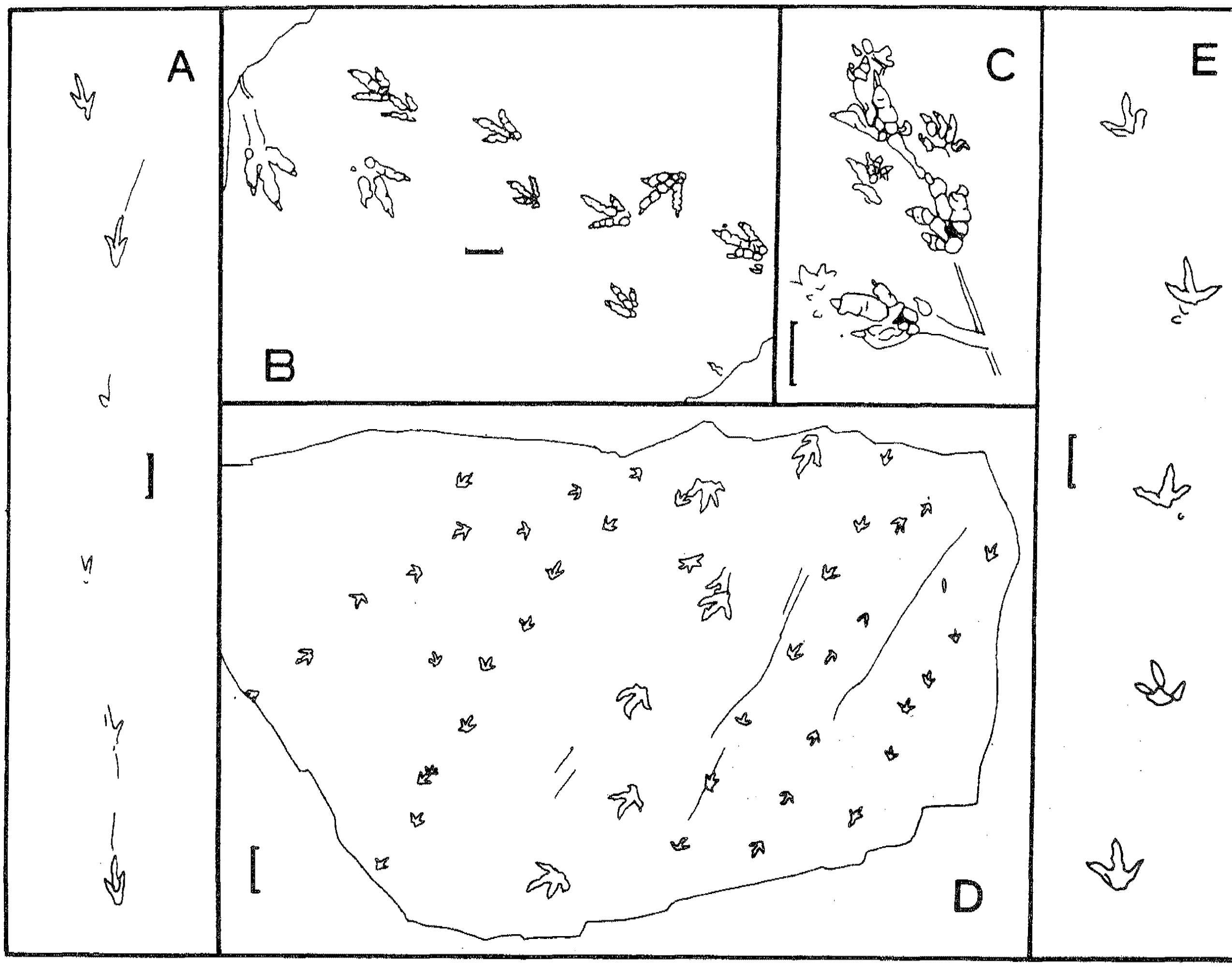


Fig. 22 Footprints plausibly produced by juveniles of the animals, which made *Grallator* and *Anomoepus:* A, grallatorid footprints (cast is YPM 5900, original in personal collection of Robert Salkin); B, *Anomoepus* - type footprint (PU uncatalogued); C, *Anomoepus* - type footprints with manus impressions (personal collection of John Colegrande); D, *Anomoepus* - type trackways -two different sizes of individuals (personal collection of Anthony M. Lessa); E, possible *Anomoepus* - type trackway (cast is YPM 5901, original in personal collection of Robert Salkin).
Scale: S, B, C, E, 2 cm; D, 5 cm.

capable of making *Anomoepus* tracks present during Towaco deposition.

Baby Dinosaurs

Tracks of reptiles like those in Figure 20 are common throughout early Jurassic beds of the Newark Supergroup (Olsen and Galton, 1977) and are also known from the early Jurassic rocks of southern Africa and the southwestern United States. What makes the assemblage of tracks in the Towaco Formation unusual is the abundance of very small (less than 3 cm) dinosaur footprints. Some of these probably represent small adult forms but most make sense as baby dinosaurs (Figure 22). Two basic kinds of these small tracks have been found - one clearly of the *Grallator* type, the other of the *Anomeopus* type. Judging from the extremely large numbers of small *Anomoepus* tracks on single bedding plains (Figure 22), the juvenile trackmakers may have been gregarious, as has been suggested for a number of other dinosaurs (Ostrom, 1972; Horner and Makela, 1979).

Among the many small vertebrate footprints so common at the Dinosaur Park are several quadrupedal trackways of a type new to the Newark Supergroup (Figure 20, E). The manus and pes impressions are five-toed and almost equal in size; the pes has a large "heel pad" on its lateral side. The only latest Triassic and Early Jurassic vertebrates with skeletal structure comparable to these tracks are advanced mammal-like reptiles or early mammals. If the latter is correct, these footprints represent the oldest New World record of mammals.

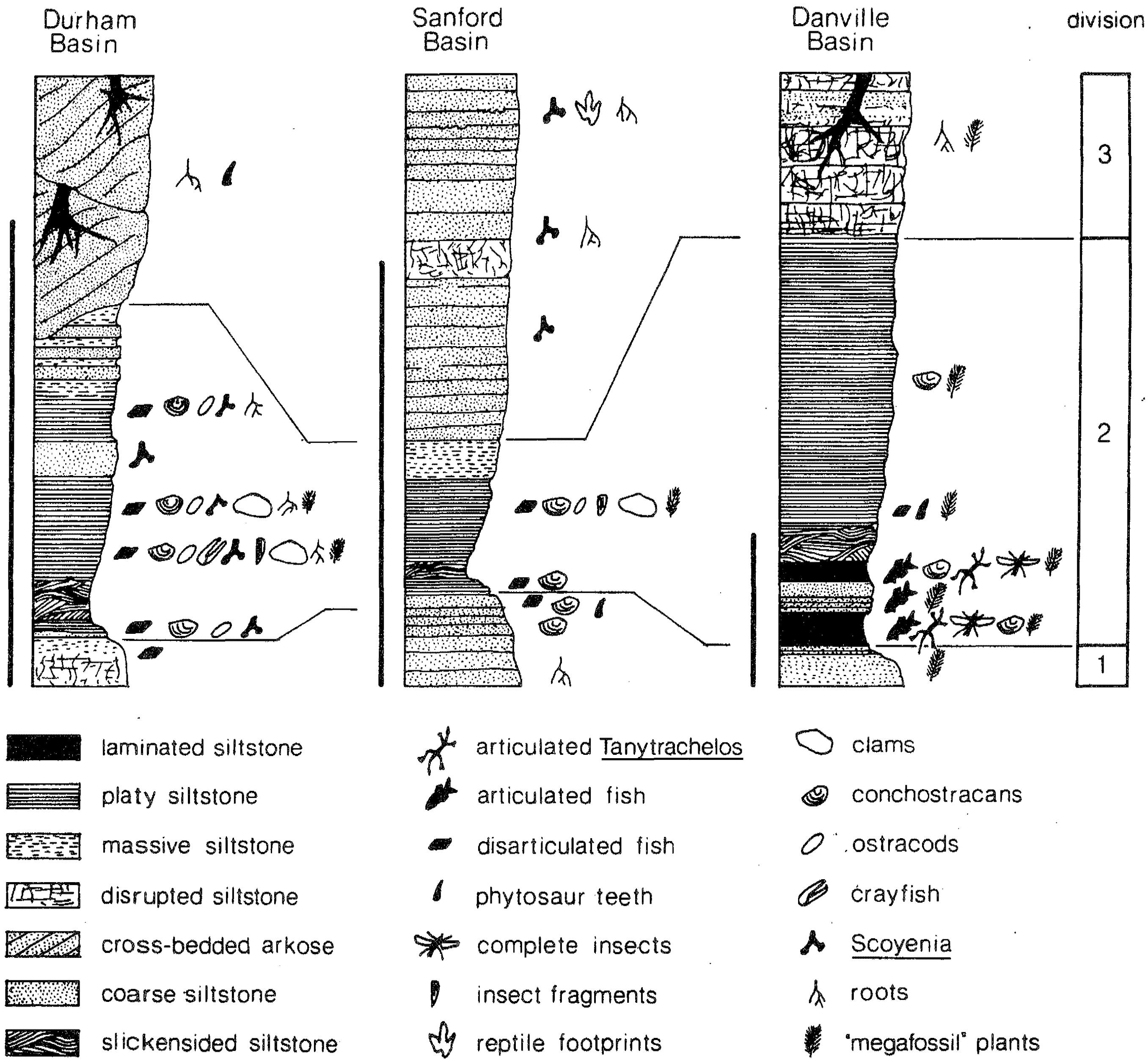


Fig. 23 Lockatong-like sequences from other portions of the Newark Supergroup. Durham Basin section consists of red and green-gray clastics while Sanford and Danville Basin section are gray and black. Durham Basin section from Bain and Harvey, 1977; Sanford Basin section from exposures along State Road 1621 in Carbonton, North Carolina; Danville Basin section from Olsen, et al., 1978.

Comparative Paleolimnology

Cyclic lacustrine sequences similar to detrital cycles and Towaco cycles occur in other basins of the Newark Supergroup. Lockatong-like sequences are present in the New Oxford Formation of the Gettysburg Basin, the Cow Branch Formation of the Dan River Basin (Olsen, et al., 1978), the Cumnock Formation of the Sanford Basin (Deep River Basin), and the unnamed lacustrine unit of the Durham Basin (Deep River Basin) (Bain and Harvey, 1977) (see Figure 23). The age of all these units is Middle to Late Carnian of the Late Triassic (Cornet, 1977; Olsen, McCune, and Thomson, In Press). Each of these lacustrine sequences was produced by an individual lake, although each closely resembles a portion of the range of facies present in Lockatong detrital cycles. While the Cow Branch Formation, like the Lockatong, shows the "full" lateral sequence of deep to shallow facies of division 2 of the cycles, the Cumnock and New Oxford formations show only the middle-to shallow-water facies, and the unnamed Durham Basin unit shows only the shallow-water facies. The features which make the Lockatong-like sequences resemble each other include the details of sediment-organism relationships and the nature of the lateral changes in facies. The same features are very different in Newark Supergroup lacustrine sequences of other ages.

Towaco-like sequences (Figure 24) include the Washington Valley member of the Feltville Formation, the "Durham Fish Bed" of the Shuttle Meadow Formation, the East Berlin Formation (both in the Hartford

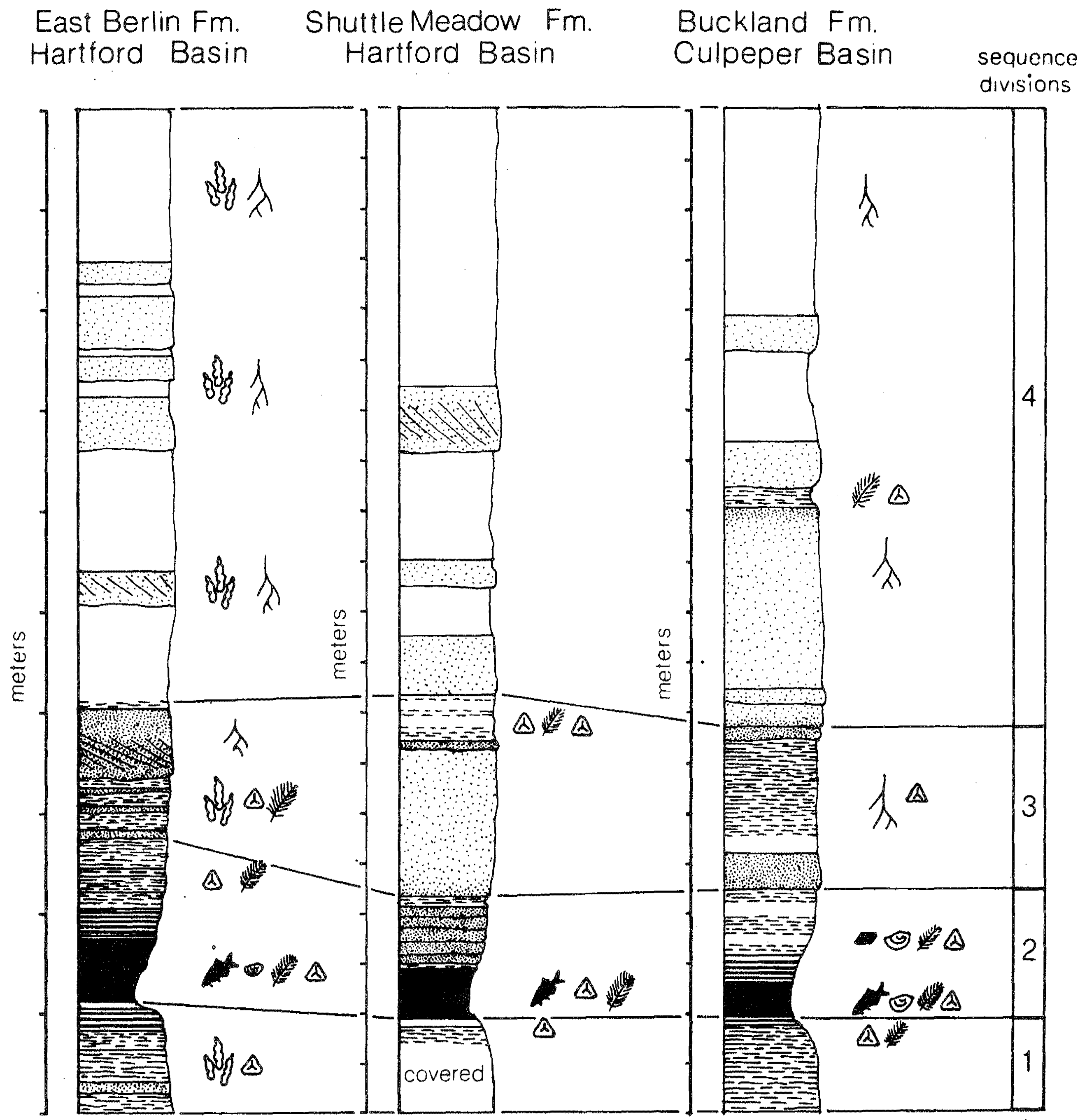


Fig. 24 Towaco-like sequences from other portions of the Newark Supergroup. Lithologic and fossil symbols from Figure 44 except for the conchostracans which are from Figure 23.

East Berlin Formation section adapted from Hubert, Reed, and Carey, 1976; Shuttle Meadow Formation section adapted from Cornet, Traverse, and McDonald, 1973; Buckland Formation section adapted fom Cornet, 1977.

Basin) (McDonald, 1975; Cornet, Traverse and McDonald, 1973; Hubert, Reed, and Carey, 1976), and sedimentary member I-II of the Buckland Formation of Lindholm (1980). For all these cases (except the last, for which the data are not compiled), division 2 of the units thicken towards the down dip edge of their respective basins. The age of all these beds is Hettangian or Sinemurian (Early Jurassic) (Cornet, 1977; Olsen, McCune, and Thomson, In Press).

There are a great many lacustrine sediment types in the Newark Supergroup which I have not mentioned or discussed but which show repetitive patterns in lithology and paleontology very different from Lockatong or Towaco-type sequences. Study of these sequences is crucial to understanding the larger picture into which fit the sediments discussed above.

The differences between Lockatong, Feltville, Towaco, and other Newark lacustrine sequences are partly due to such physical factors as climate, lake basin morphology, and chemical input from source rocks. Analogy with modern lakes is an effective tool for interpreting these differences for physical processes. The other crucial, non-repeating aspect of the differences between Lockatong and Towaco-like sequences are biotic namely the evolution, origination, and extinction of groups of organisms which influence lacustrine sedimentation. Of course, these factors are intimately intertwined, so much so that many aspects of ancient lake ecology and history may be impossible to untangle, especially given the limitations of the fossil record. However, comparative limnology has been a major tool of limnologists working on interdependent processes in modern lakes, and I believe a similar approach can be used to identify some of the features of Mesozoic lakes which are common to them, but which may be missed if they are interpreted strictly according to modern conditions. Clearly this goal cannot be obtained without first identifying the factors that are shared with modern lakes. If a wide range of lake systems deposited over a "short" interval of time, (say the Late Carnian), are examined at least the effects of biological evolution (on the scale effecting lake sediments) could be held constant. Likewise, looking at lake systems in similar physical environments through time should point up the roles of biological change. By deducing from biologically mediated processes in modern lakes we can see if the ancient lakes conform to "predictions" based on these processes. As yet, this approach is essentially untried in paleolimnology, although I hope that a study of the differences between various Newark lacustrine sequences is a step in that direction.

Climatic Change and Lake Ontogeny

The regularity of Lockatong and Towaco cycles and their periodicity in thickness suggest a cyclic and periodic cause of the rise and fall of the lakes which produced them. The analysis of this cause is one of the most difficult and challenging of paleoecological and paleolimnological problems. Limnologists working on modern lakes tend to concentrate on the origin of the lake basin as the proximal cause of the lake - the beginning of what is usually seen as an inexorable succession of stages leading to the filling in of the lake by vegetation and sediments (Wetzel, 1975). Intrinsic, biologically mediated changes have been stressed as the major factors in lake ontogeny (Odum, 1959, 1969) rather than external forcing processes such as climatic change. While this largely successional approach to lake ontogeny (see Drury and Nisbet, 1973) may be valid for ponds and some lakes, for large lake systems such as the African Great Lakes or Newark Supergroup lacustrine sediments it may have little to offer. For example, the thickness of a Lockatong detrital cycle (mean of 5.2 m in the central Newark Basin) is simply too small to represent the infilling of a lake, which during its deeper stages covered more than 6000 km^2 and deposited microlaminated sediments. Here, paleolimnology offers evidence which shows much of the existing work on lake ontogeny to be on a scale inappropriate to large lakes. Lake Michigan is unlikely to meet its end by the action of watercress.

The gross expansion of Lockatong and Towaco lakes most likely was the result of large external forces,specifically climate and tectonics. It is difficult, however, to find evidence which is exclusively explained by only *one* of these causes. It may be futile too; there is no need for there to be only *one* sufficient cause for the phenomenon. At the present, I favor the hypothesis that cyclic changes in precipitation caused the rise and fall of these lakes, a hypothesis first put forth by Van Houten (1962, 1969). Climatic changes act within the context of tectonic changes, which in themselves seem inadequate to explain the periodicity in thickness of the cycles. Periodically fluctuating climate is, at this point, much easier to envision and explain (Croll, 1890; Milankovitch, 1920, 1941; Imbrie, 1979). Indeed, the modern African Great Lakes appear to fluctuate in response to changing climate in ways similar to those hypothesized for Newark lakes. Livingston (1975) provides evidence that 14,000 years ago Lake Victoria was 75 m shallower than now (present maximum depth 88 m) and Hecky and Degens (1973) suggest that Lake Tanganyika was 600 m shallower than now (present maximum depth 1470 m). Increased precipitation appears to be the cause of the great rise in lake level since that time (Livingston 1975) and this increase in precipitation is tied into the periodic climatic cycles of the Holocene (Kukla, 1977; Hays, Imbrie, and Shackelton, 1976; Williams, 1975). As in these modern lakes, I believe that Newark lake basins themselves were created and controlled in depth by tectonism, but that the rise and fall of lake level within that basin was largely controlled by climate.

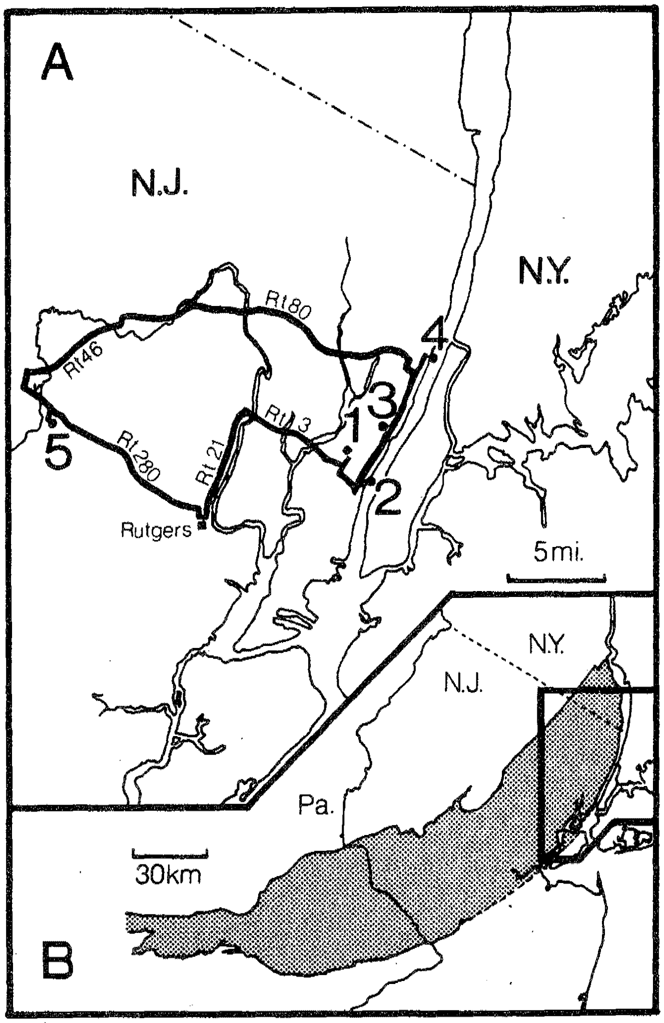


Fig. 25 A, Field Trip Route showing stop locations; B, Newark Basin (shaded) and position of map in A (outlined box at northern end of Newark Basin.)

ROAD LOG

Mileage

0.0 Leave Rutgers University parking lot; turn left onto Warren Street. Rutgers University, Newark Campus sits on late Norian or earliest Rhaetic sandstones and siltstones of the Passaic Formation.

0.1 Turn left (north) onto Washington Street, pass Newark Museum on left.

0.4 Cross Broad Street onto Harrison Avenue heading east.

0.6 Turn left on to McCarter Highway (Route 21) and head north. Route 21 follows the west bank of the Passaic River along the strike of the Passaic Formation.

3.2 Pass Belleville Avenue. Just north of Belleville Avenue and 1.1 miles east of Route 21 is the old Schuyler Copper Mine worked from about 1720 to about 1900 (Lewis, 1906). The ore occurs in gray arkosic sandstone and gray siltstone invaded by small dikes and sills of diabase. Lewis (1906) lists chalcocite, chrysocolla, and malachite as the major copper minerals with minor amounts of azurite, cuprite, and native copper.

4.8 Fragments of phytosaur skull and reptile footprints found in Passaic Formation "brownstone" quarry near here (Edwards, 1895; Lull, 1953).

6.6 Turn right onto exit road for Route 3. Take ramp for Route 3 east.

7.0 Enter Route 3 east heading towards Lincoln Tunnel. Route 3 cuts across strike through Norian and Late Carnian Passaic Formation. This portion of the Passaic Formation is the lateral equivalent of the entire Delaware River section of the Passaic and upper Lockatong (see Van Houten, this Fieldbook)

8.4 Entering Hackensack Meadows. About 0.2 mi. southwest of this point are excellent exposures of Passaic Formation including a series of gray sandstone beds (ca. 2 m) stained with chalcocite, malachite and azurite. Old (?exploratory) shafts are evident in the outcrops. Lithology of copper-bearing units very similar to beds at Schuyler Mines. I have found reptile footprints assignable to *Rhynchosauroides brunswickii* and *Grallator* sp. and in addition, horseshoe crab tracks called *Kouphichnium* and *Scoyenia* burrows in the fine red siltstones surrounding the gray sandstone. Lower red beds of exposure contain well developed caliche horizons similar to those described by Hubert (1977) from more or less contemporary beds of the New Haven Arkose (Hartford Basin). Further southwest, (0.3) mi are additional exposures along former Erie Lackawanna Railroad tracks showing an unusual reverse fault dipping to the west and downthrown on the east. Slickensides confirm the dipslip nature of the fault. Hackensack Meadows, over which Route 3 crosses, are underlain by relatively fine-grained red and minor gray beds of Passaic Formation.

11.7 Ridge just south of here (Secaucus) has exposures of gray sandstones and siltstones which could be lateral equivalent of McLaughlin's (1948) Graters Member.

12.2 Exit right for North Bergen (Plank Road).

12.3 Cross over Route 3 heading east on Plank Road.

12.8 Veer left at fork in road.

12.9 Turn left (north) on Route 1 and 9 (Tonnelle Avenue).

13.6 On right is open cut in Stockton Formation and west portal of tunnel for Penn Central Railroad. Cut exposes upper Stockton beds described by Darton (1883). At east end of cut at tunnel is excellent exposure of the contact between the Stockton Formation and the Palisade Diabase. Stockton beds dip at 15° NW while the irregular contact dips at 60° NW. This contact is locally welded according to Darton (1890) and Lewis (1908). This is one exposure where the Palisade Sill is described as having a dike-like appearance. Actually, these exposures and similar ones nearby are perhaps better explained by a local stepping up of the Palisade Sill as shown in Figure 26.

14.3 Contact of uppermost Stockton with Palisade Sill directly on right (east). Stockton dips 15° NW and the contact dips 45° to 80° NW. This appears to be a continuation of the contact surface exposed at the Penn Central tunnel previously described. Recrystallized arkose of Stockton

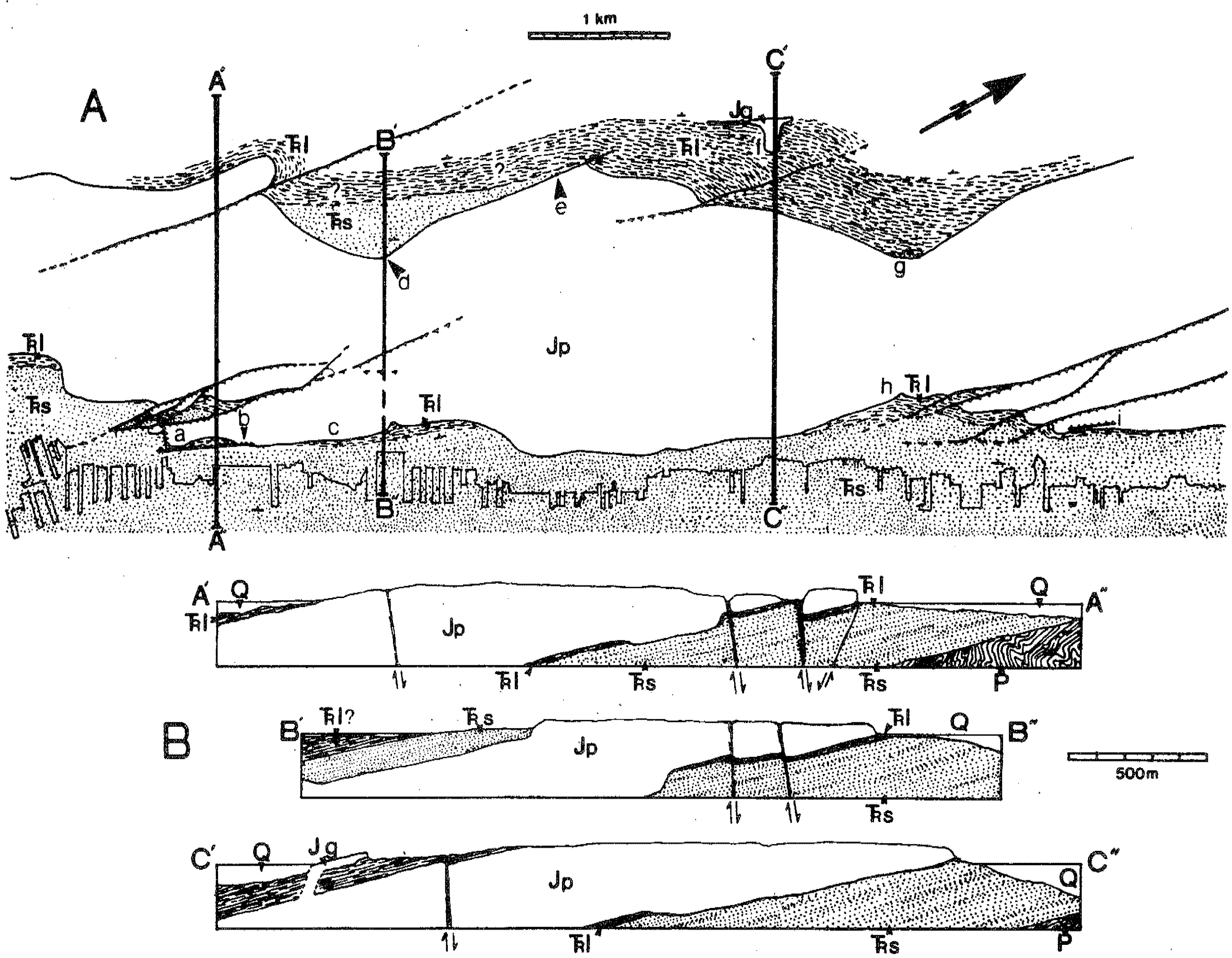


Fig. 26 Map of the Weehawken area (A) and interpretive sections (B): Trs. Triassic Stockton Formation; Trl, Triassic Lockatong Formation Jp, Jurassic Palisade Diabase; Jg, Jurassic Granton Sill; P, metamorphic Palaeozoic rocks; Q, Quaternary sediments of the Hudson River and Hackensack Meadows; a, King's Bluff (stop 2); b, "two runs" exposures below the "duelling grounds"; c, Gratacap's (1886) locality; d, west portal southern tunnel of old New York, Susquehanna and Western Railroad Tunnel; e, exposure at mileage 14.3 of Field Trip; f, Granton Quarry (stop 1); g, west portal old northern tunnel of New York, Susquehanna Railroad; h, Gorge and River Roads exposures (stop 3); i, west dipping normal fault in small quarry, Edgewater.

Formation is sheared and dragged upwards close to contact with fine slickensides indicating down-dropping to the west. There are no indications of movement in the diabase, however. Basal Lockatong hornfels 100 m to the north, dip 15° NW and lie concordantly on the Palisade Sill. A possible interpretation of these exposures might be that the apparent movement in the Stockton occurred during intrusion of the sill.

14.5 Dip slope of Palisade Sill mantled by northwesterly dipping Lockatong Formation. Contact appears concordant from here to Granton Quarry.

15.1 **STOP 1** Abandoned Granton Quarry in lower Lockatong Formation hornfels and overlying Granton Sill. Turn left off Route 1 and 9 into parking lot for Shop-Rite employees at Diana Stores Corporation.

Eleven Lockatong cycles are exposed on the sill-capped hill: seven are exposed on the south facing exposure (Figure 27); three additional cycles are exposed on the east facing exposure; and all 11 cycles are exposed on the north facing exposure but are not accessible without special permission. The base of the section appears to be 38 - 46 m above the contact with the Palisade Sill (Van Houten, 1969). This contact may be following what was, prior to intrusion, the Stockton-Lockatong contact.

According to Van Houten (1969) these Lockatong hornfels include calc-silicate varieties in the middle carbonate-rich part, and extensively feldspathized and recrystallized diopside-rich arkose in the upper part. Some beds of arkose show well developed crossbedding (Figure 28). Because of the buff arkose at the top of nearly every cycle, these are the most visually graphic of the detrital cycles seen on this field trip; here the many correlated changes occurring though individual cycles can be easily seen (Figure 29).

Cycles 3 and 7 (Figure 29) have produced representatives of all the known (skeletal remains of) Lockatong

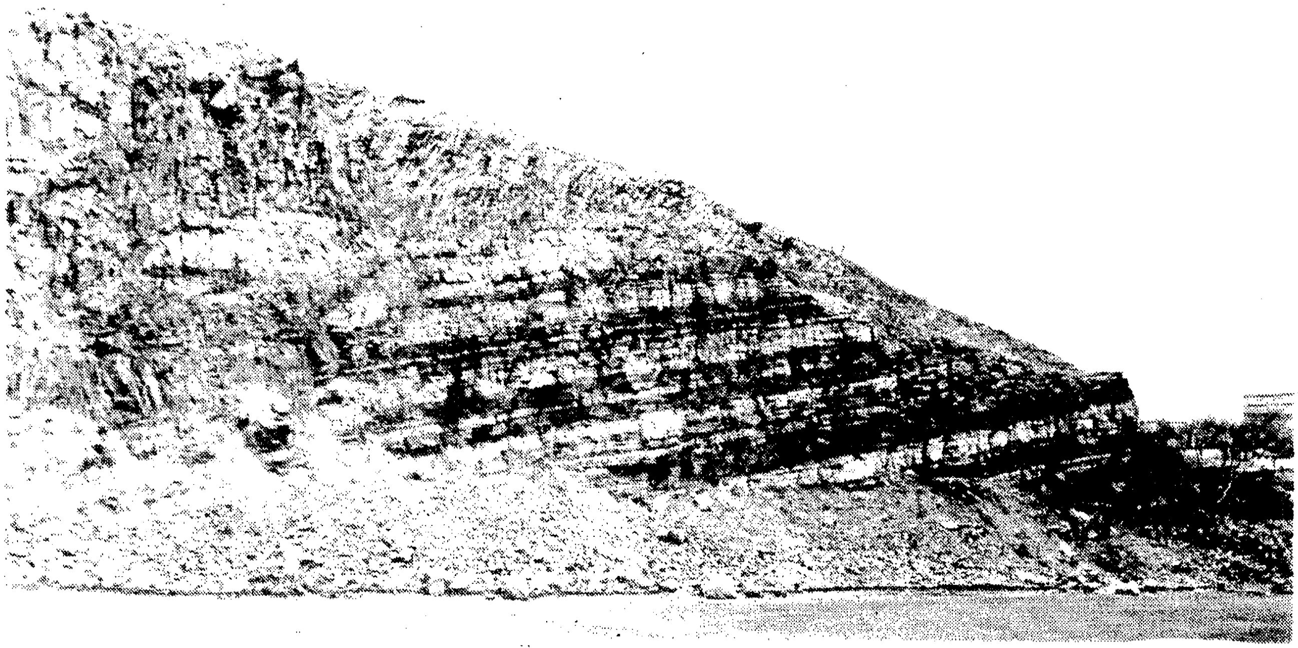


Fig. 27 South facing wall of remnant of Granton Quarry showing detrital clycles G1-G7 and Granton Sill. View is to the northeast and dip-slope of Palisade Sill is visible in the background.

Fig. 28 Cross bedding in buff arkose of cycle G9 (see Figure 29). Exposure on north face of quarry remnant.

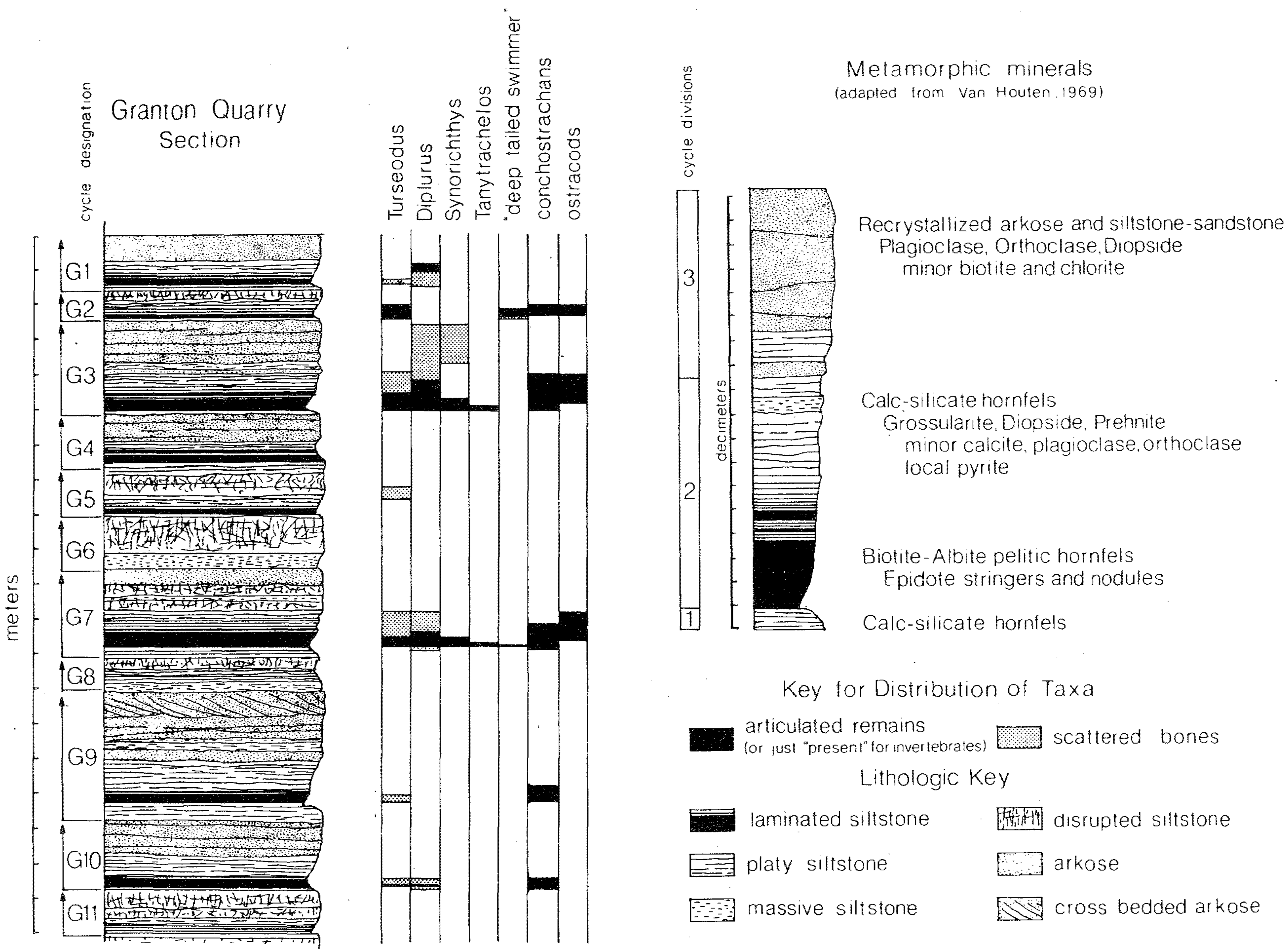


Fig. 29 Granton Quarry section showing fossils and distribution of metamorphic minerals in generalized cycle.

Fig. 30 Newly discovered virtually complete *Tanytrachelos* skeleton from the basal portion of division 2 of cycle G7. Neck is partly disarticulated and twisted back over body so skull rests just right of the middle of the back.

This specimen was discovered by James Leonard and Steve Steltz this year.

... and the amphibian *Eupelor*. The ... portions of division 2 of both of these cycles have extremely high densities of fossil fish, especially the coelacanth *Diplurus newarki* Schaeffer (1952). Small reptiles are also surprisingly abundant (Figure 30). Many important fish and unique reptile skeletons have been discovered here by dedicated amateurs, and donated to various museums through the years (Colbert, 1965, 1966; Schaeffer, 1952; Schaeffer and Mangus, 1971; Colbert and Olsen, In Prep.; Olsen and Colbert, In Prep.).

At the south-facing exposures, cycles 1 and 2 are broken and injected by diabase of Granton Sill (Van Houten, 1969). Notice the absence of prominent folding at the diabase-sediment contact. The total thickness of the sill is 20 m.

One or two bedding plane thrust faults, always thrusting to the east, are present in division 2 of nearly every cycle at Granton Quarry. Slickensides are usually present and indicate that movement occured parallel to dip. All joint sets ... cut by these thrusts, their displacement indicates each fault has a net slip of .5 to 1.5 cm. This type of minor thrust fault is evident in virtually all Newark Supergroup lacustrine cycles and can be seen at every stop of this trip.

15.2 Return to Route 1 and 9, turn right and head south.

17.7 Exit for Lincoln Tunnel and Route 495. Turn right off Route 1 and 9 (Tonnelle Avenue) onto entrance ramps and follow signs around for Lincoln Tunnel onto Route 495. Cloverfleaf at this intersection rests on Lockatong hornfels and Palisade Sill (Fluur, 1941).

18.2 Open cut for Route 495 in Palisade Diabase. Construction of cut exposed a number of easterly down-dropping dip slip faults which were described by Fluur (1941).

19.2 Take right hand exit "Last exit in New Jersey" (Pleasant Avenue, Weehawken); get immediately in right lane after exit. Reentrant in Palisade Escarpment at this point created by differential weathering along a series of dip slip faults, the cumulative dip slip amounting to about 70 - 80 m.

19.4 Turn right onto Boulevard East (heading south). This street parallels one of the larger faults, in this case one responsible for the abrupt truncation of the western portions of Kings Bluff directly to the left (east) (Flurr, 1941).

19.6 Turn left at light onto Baldwin Avenue. According to Fluur (1941), construction along this road revealed a small fault striking nearly E-W.

19.7 Cross Conrail tracks and follow road around to left. Watch out for trucks and trains!

19.9 **STOP 2** Kings Bluff, Weehawken. East face of Palisade ridge with exposures of long series of Lockatong cycles, tongues of Stockton-like beds, and alternating concordant-discordant contacts with the Palisade Sill. Park in lot on west side of road near the railroad tracks.

This is the first of three stops designed to show the lateral continuation of individual detrital cycles and the lateral change in sedimentary and metamorphic facies.

Lockatong and Stockton sediments and their contacts with the Palisade Sill are exposed at numerous places along the Palisade escarpment from Hoboken, New Jersey to Haverstraw, New York. Study of these exposures is permitting a cycle-by-cycle correlation of the Lockatong for at least 15 km of this distance, the cycles mapped so far are designated informally in Figures 31, 32, and 33. To the south at Hoboken the Palisade Sill rests near the base of cycles 5 and 6 (Figure 31). To the north towards the Lincoln Tunnel Toll Plaza, the contact drops more than 250 m into the Stockton Formation. At Kings Bluff, this contact abruptly rises again to cycle 0, staying within division 2 of this cycle for at least 300 m north. The olivine zone of the Palisade Sill produces an obvious bench along the escarpment, essentially paralleling the lower contact of the sill as observed by Walker, 1969 (Figure 31).

Note the thin sill which branches off from the main sill intruding between cycles a and b. This sill definitely runs north for at least 400 m and was encountered during the excavations for the ventilation buildings for the Lincoln Tunnel (Figure 31) (Fluur, 1941). It may go at least another 200 m (Figure 36).

About 30 m south of the ventilation buildings, my colleagues and I opened a quarry (Figure 34) in cycles 5 and 6 for Lockatong fossils as part of a larger project studying fish evolution headed by Dr. Keith S. Thomson of Yale. So far, more than 3000 fish and reptiles have been recovered

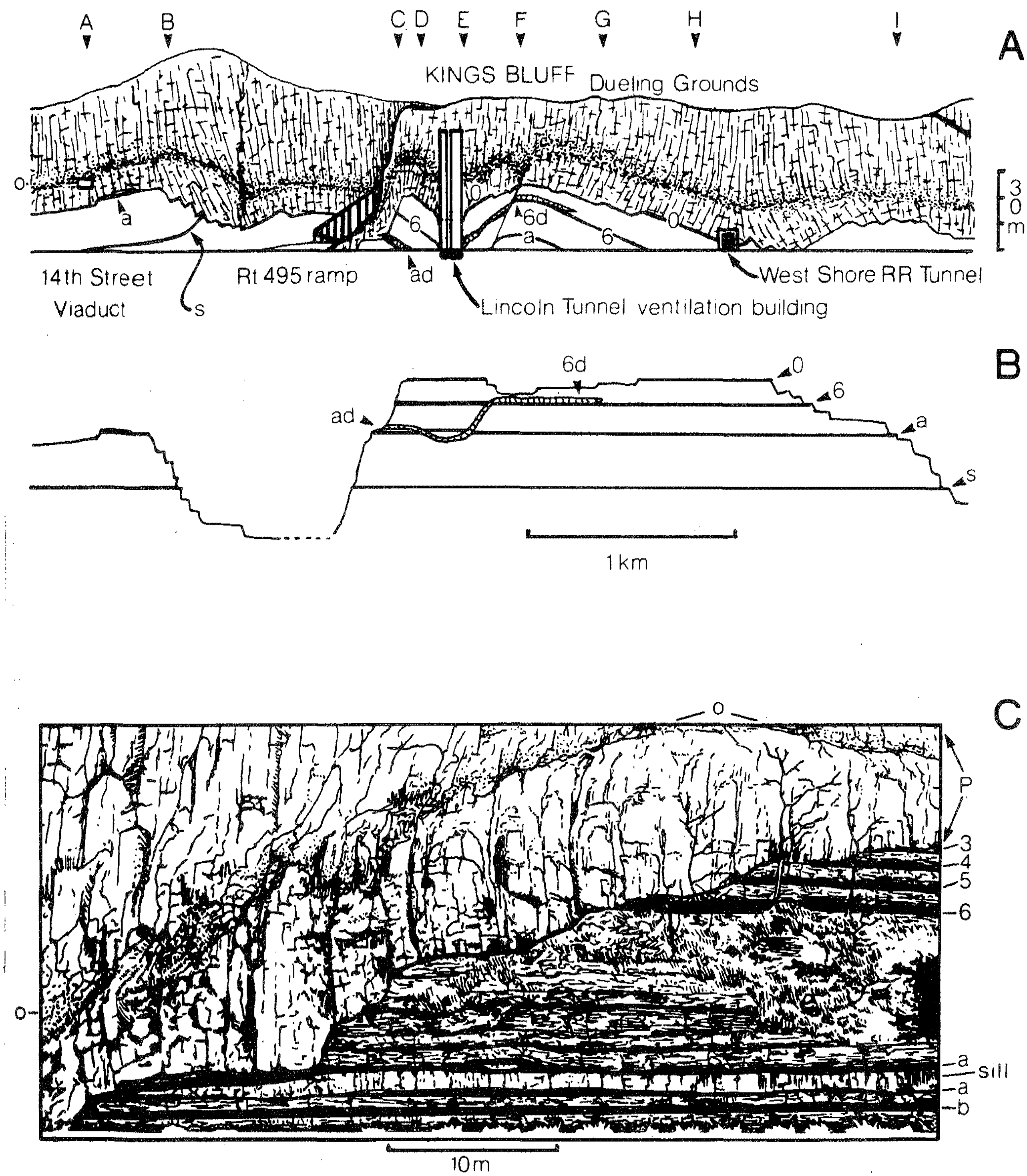


Fig. 31. A, view of Palisades Escarpment looking northwest -note vertical exaggeration: (A, exposure below west portal 14th street viaduct, Hoboken; B, exposures west of west end of Chestnut Street, Hoboken; C, Kings Bluff, Weehawken; D, position of "Yale quarry" in cycles 5 and 6, Weehawken, E, exposures of cycles 0-6 at north side of ventilation building, Weehawken, F, "two runs" exposures of cycles 4-f and position of folded beds in Figure 36, G, position of Gratacap's (1886) Weehawken fossil fish locality in cycle 6, H exposure of cycle 0 at south side of west portal southern tunnel of New York, Susquehanna and Western Railroad; I, area where diabase cuts down into Stockton Formation; O, a-6, cycles thus designated; 5, Stockton-Lockatong contact; ad, thin diabase sill intruding cycle a; 6d, thin diabase sill intruding cycle 6; 0, olivine zone of Palisade Sill

B, section from Hoboken to West New York reconstructed with fault displacement removed showing large irregularities of hornfels-diabase contact. Abbreviations as in A.

C, section exposed on east face Kings Bluff show Palisade Diabase cutting obliquely accross cycles 3-b and thin sill intruding cycle a: P, Palisade Diabase; other abbreviations as in A.

Drawing is adapted from Darton 1880.

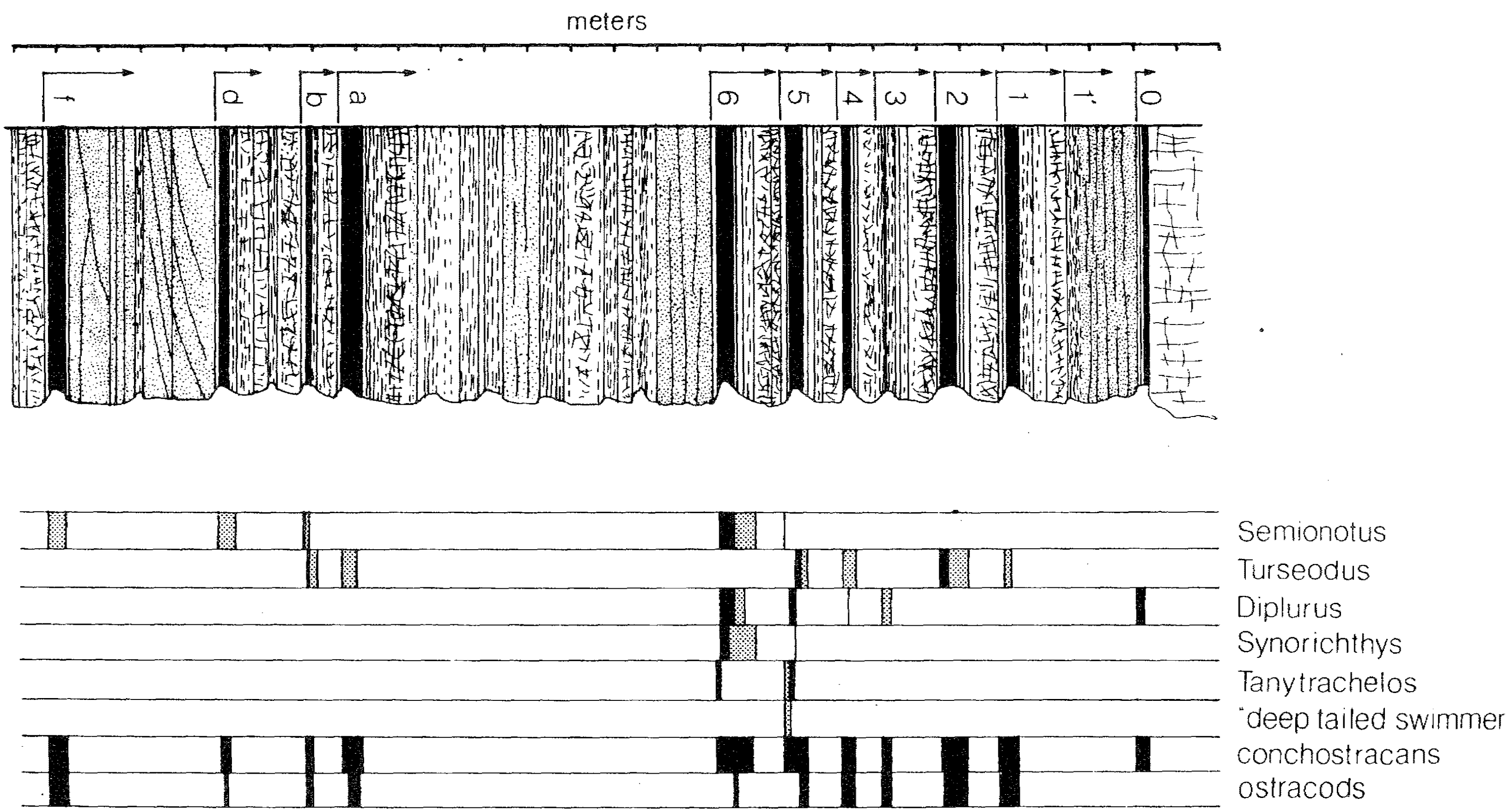


Fig. 32 Section showing position and nature of fossils, Kings Bluff, Weehawken. Symbols as in Figure 29.

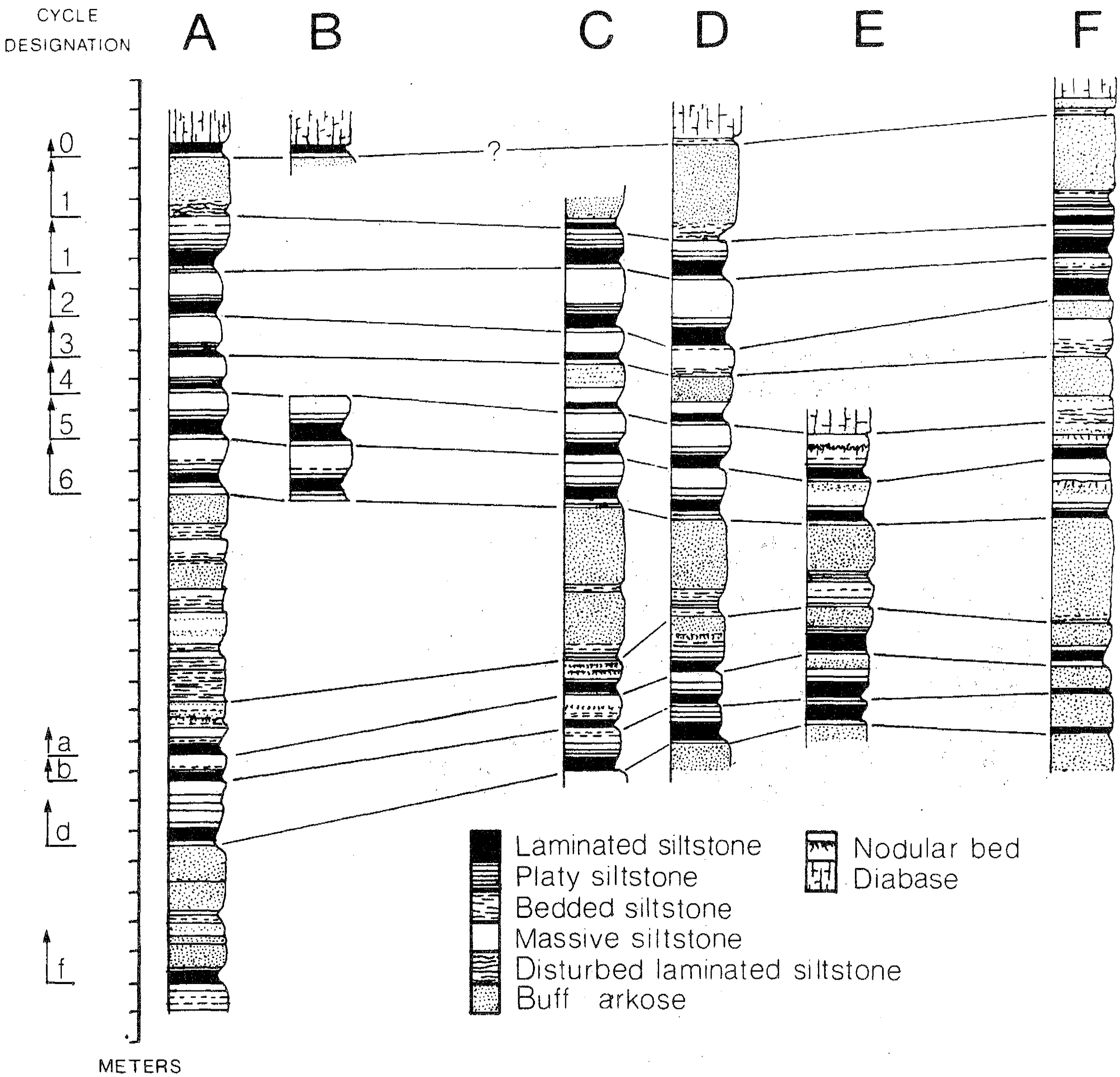


Fig. 33 Correlation of cycles from Kings Bluff, Weehawken to Ross Dock, Fort Lee; A, Kings Bluff exposure; B, Gratacap's (1886) Weehawken locality and exposure of cycle 0 to the north; C, Gorge and River Roads exposure, Edgewater; D, exposure at east portal northern tunnel for old New York, Susquehanna Southwestern Railroad; E, "old trolley route" below old Palisades Amusement Park, Fort Lee; F, exposures west of Ross Dock, Palisades Interstate Park, Fort Lee. Exposures A and F are 12 km apart; the other sections are positioned to scale.

24.4 Turn right back onto River Road and head north.

24.6 Large xenoliths exposed on left (west) in excavation behind Virginia Lee Lace Co. (Van Houten, 1969).

24.8 Passing over eastern portal of tunnel for former New York Susquehanna and Western Railroad. Directly under bridge for River Road is complete section of Lockatong cycles 1'-6 and a. This same section is then repeated by a fault striking north. Cycle 2 is unusually fossiliferous, producing large numbers of well preserved *Turseodus* and fragmentary large *Diplurus*. At west portal of tunnel is a large open cut in upper Stockton and lower Lockatong. Contact with sill dips 65° NW while Stockton and Lockatong dip 15° NW. These exposures appear to be a repeat of the pattern seen at mileages 13.6 and 14.3 as shown in Figure 26.

25.2 Old quarry on left with excellent exposures of cycles 4 - f and underlying Stockton Formation. Small fault exposed at back of quarry which drops down the western block.

26.3 Up hill on left on west side of Undercliff Avenue is long series of outcrops along abandoned trolley route (Van Houten, 1969). Exposures include upper Stockton Formation and lower Lockatong including cycles 5 and 6 and a, b, and c. The base of Palisade Sill is well exposed with large xenolith of cycle 5 suspended about 5 m above Lockatong-sill contact. Cycle 5 below contact contains scapolite-

Fig. 34 "Yale quarry" during summer of 1979. From left to right Amy R. McCune, Donald Baird, and Keith S. Thomson. Wooden frame is device for recording horizontal position of specimens in excavation. Rear portions of frame rest on division 2 of cycle 5. Donald Baird is sitting on upper parts of division 2 of cycle 6.

aegirine and Na-feldspar hornfels, while xenolith of same unit consists of very course grained biotite, Na-feldspar hornfels with minor pyroxenes, and beds of cordierite, biotite Na-feldspar hornfels (Van Houten, 1969).

27.5 Turn right off Right Road into entrance for Palisade Interstate Park. Follow park road around to north. A significant portion of a large phytosaur skeleton was found in upper Stockton beds near here in 1911. The skeleton, named *Rutiodon manhattanensis* by Friedrich von Huene (1913), is not generically determinate because it lacks a skull.

Reentrant in Palisade escarpment at this point is due to a few east dipping normal faults.

27.6 Olivine zone of Palisade Sill on left. Diabase below olivine zone has distinct laminated appearance.

28.0 Irregular contact of Palisade Sill with Lockatong Formation -stratum uncertain (Figure 39).

28.1 Pass under George Washington Bridge.

28.2 Additional exposures of Lockatong-sill contact on left -largely conformable. On the right, at the base of the hill, is a foot path along which are exposures of buff arkose and red and purple siltstone of the upper Stockton Formation. These are the most southerly exposures of a facies of the Stockton Formation visible along the Hudson from here to Haverstraw, New York (Olsen, Baird, Selden, and Salvia, In Prep.).

28.4 Circle in park road at base of shear face of Palisade Sill. Take road which veers off on right towards Ross Dock.

28.7 **STOP 4** Ross Dock, Palisade Interstate Park. Lunch and extensive exposures of cycles 1' - 6 and a - c and irregular lower contact of Palisade Sill. Park in lot, have lunch, then take stone steps up hill (west) to road at level of circle (River Road of park) and walk north along road to exposures of Lockatong (Figure 40).

Proceed north along road, slowly walking down section (Figures 40 and 41). Cycle 1' and overlying 4 m of arkose with no sign of cycle 0 which presumably pinched out or was cut out south of here. Cycle 1 is present but poorly exposed. Cycle 2 is very well exposed and contains the same fossils as at mileage 24.8, although there are fewer whole *Turseodus*. Cycles 3 and 4 are evidently replaced by buff, crossbedded arkose. Cycles 5 and 6 very well exposed. Middle part of division 3 of cycle 6 contains distinctive nodular calcareous bed resembling caliche. Cycle 5 still shows the same basic sequence of beds and vertebrates as previous stops, but cycle 6 is noticeably coarser with fewer less well laminations and there are less fish. Upper division 1 of cycle 6 has produced a partial arthropod of uncertain relationships about 20 cm long.

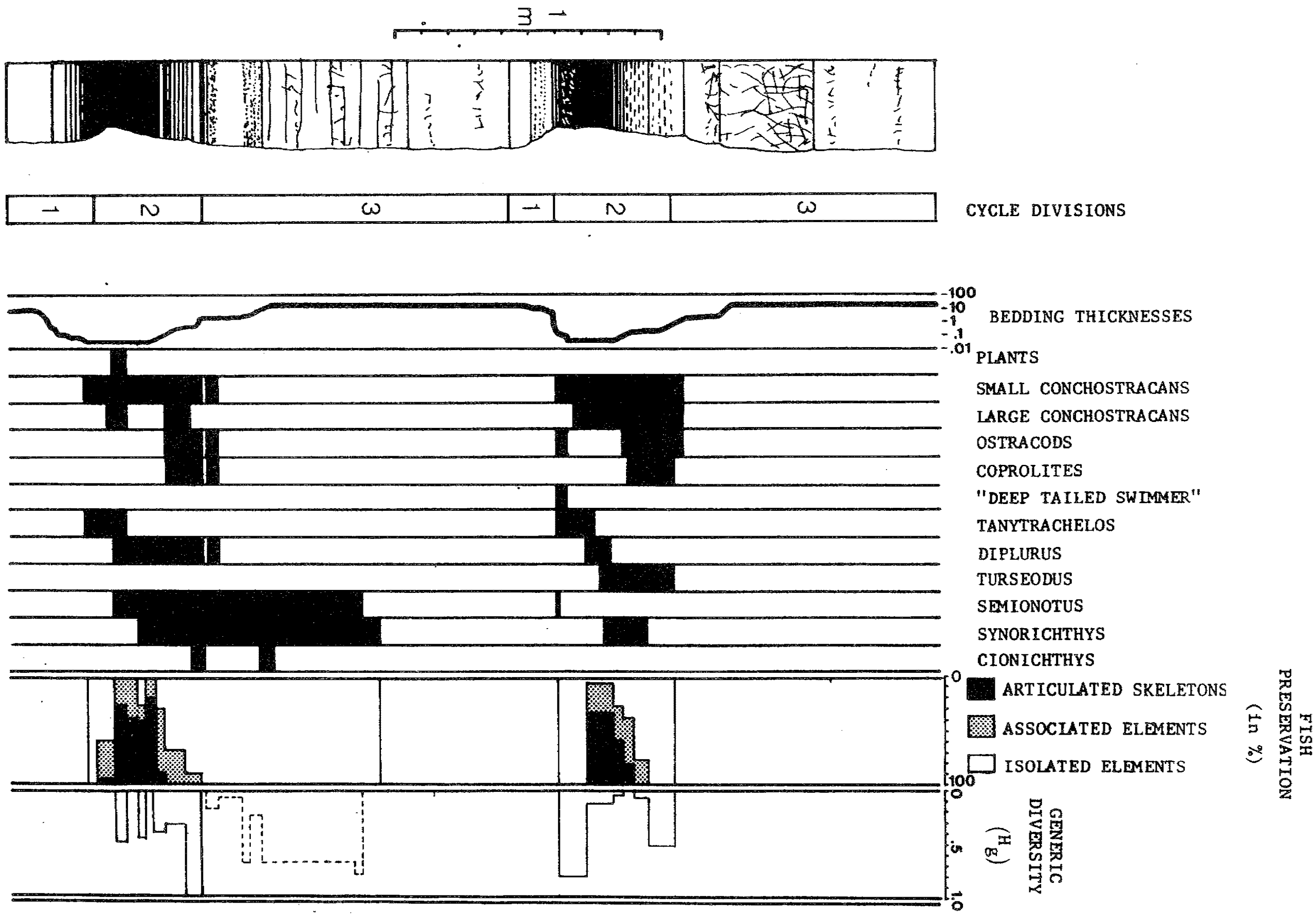


Fig. 35 Preliminary results of excavations in cycles 5 and 6, Kings Bluff, Weehawken. Symbols as in Figures 29 and 38. Generic diversity (Hg) is the Shannon—Weaver (1949) information index.

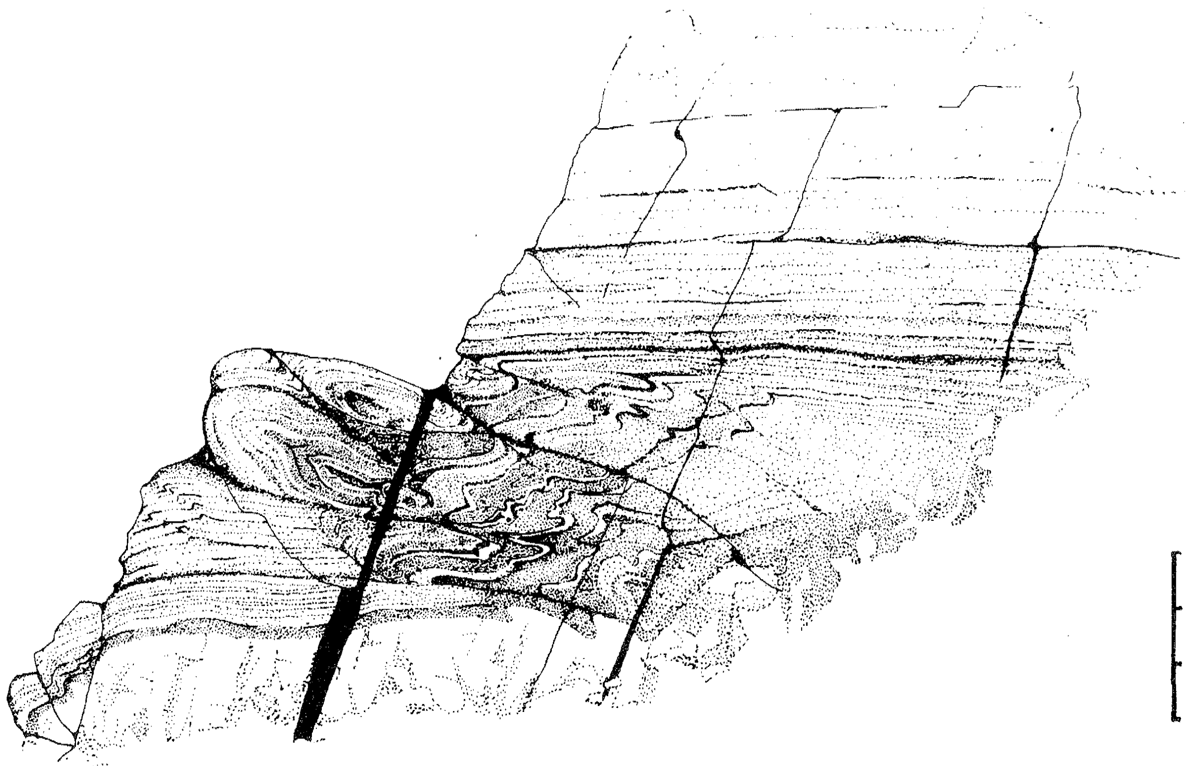


Fig. 36 Folding associated (but not necessarily causally connected) with westward dipping normal faults at "two runs" outcrops (see Figure 31). Plane of outcrop is parallel to regional strike of beds.

The tongue of buff arkose between cycles 6 and a is thinner than at Stop 3 and coarsely crossbedded. Lower arkose cuts down into cycle a at this exposure, eliminating its division 2 (Figure 42). Mean paleocurrent vector for these crossbeds is N 59° W (based on 8 readings).

Cycle a is penetrated by numerous *Scoyenia* burrows (which were definitely not present at mileage 26.3) as are what appear to be cycles b and c. We are clearly in the shallow water facies of division 2 of cycles a - c at this point but only just leaving the deep water facies of division in cycles 2, 5, and 6.

Cycle a shows well developed fracture cleavage in division 1. Cleavage dips 25° to 30° and strikes S 78° W. Cleavage is strata-bound but discontinuous, passing laterally into breccia or non-cleaved beds. What is the significance of these structures?

The facies trend in the Lockatong from Stops 2, 3, and 4 is from a more central basin facies to a marginal facies. The monotony in horizontal continuity gives way laterally to heterogeneity (Figures 33 and 38). Those cycles with the best developed microlaminae and the best preserved fish at Stop 2 are also those which persist the longest with the least change.

29.9 Return to park entrance. Leave park and turn right.

30.0 Turn left onto Main Street (Bergen County Route 11), proceed west.

30.5 Turn right onto Lemoine Avenue, continue north crossing over west portal George Washington Bridge.

30.8 Turn left (west) onto Cross Street. Keep left.

31.4 Veer left onto entrance ramp for Route 95 - 80. Proceed on Route 95 S.

32.4 Open cut in Palisade Sill and Lockatong hornfels. According to Van Houten (1969), hornfels include grosularite-andradite, prehnite, and diopside varieties. Lockatong cycles fossiliferous, as usual, and these cycles may tie in with Granton Quarry cycles (Stop 1).

34.0 Veer right onto exit for Route 80.

34.5 Beginning of type section of Passaic Formation (section A Olsen, this Fieldbook) in open cuts for Route 80.

37.6 Section B of type section of Passaic Formation.

38.7 Section C of type section of Passaic Formation.

42.5 Section D of type section of Passaic Formation.

44.2 Garrett Mountain visible on left (south), Passaic Falls is on the right (north). The upper Passaic Formation of Rhaetic age (latest Triassic) has produced near here a series of well preserved skeletons of the highly specialized procolophonid reptile *Hypsognathus* (Colbert, 1946). About one skeleton or skull is found per decade.

44.7 Contact of Passaic Formation with overlying Orange Mountain Basalt on left (south). This is section E of the type section of the Passaic Formation. A series of faults cut the Orange Mountain Basalt here, some of which are visible in the cut on the left, just west of the Passaic-Orange

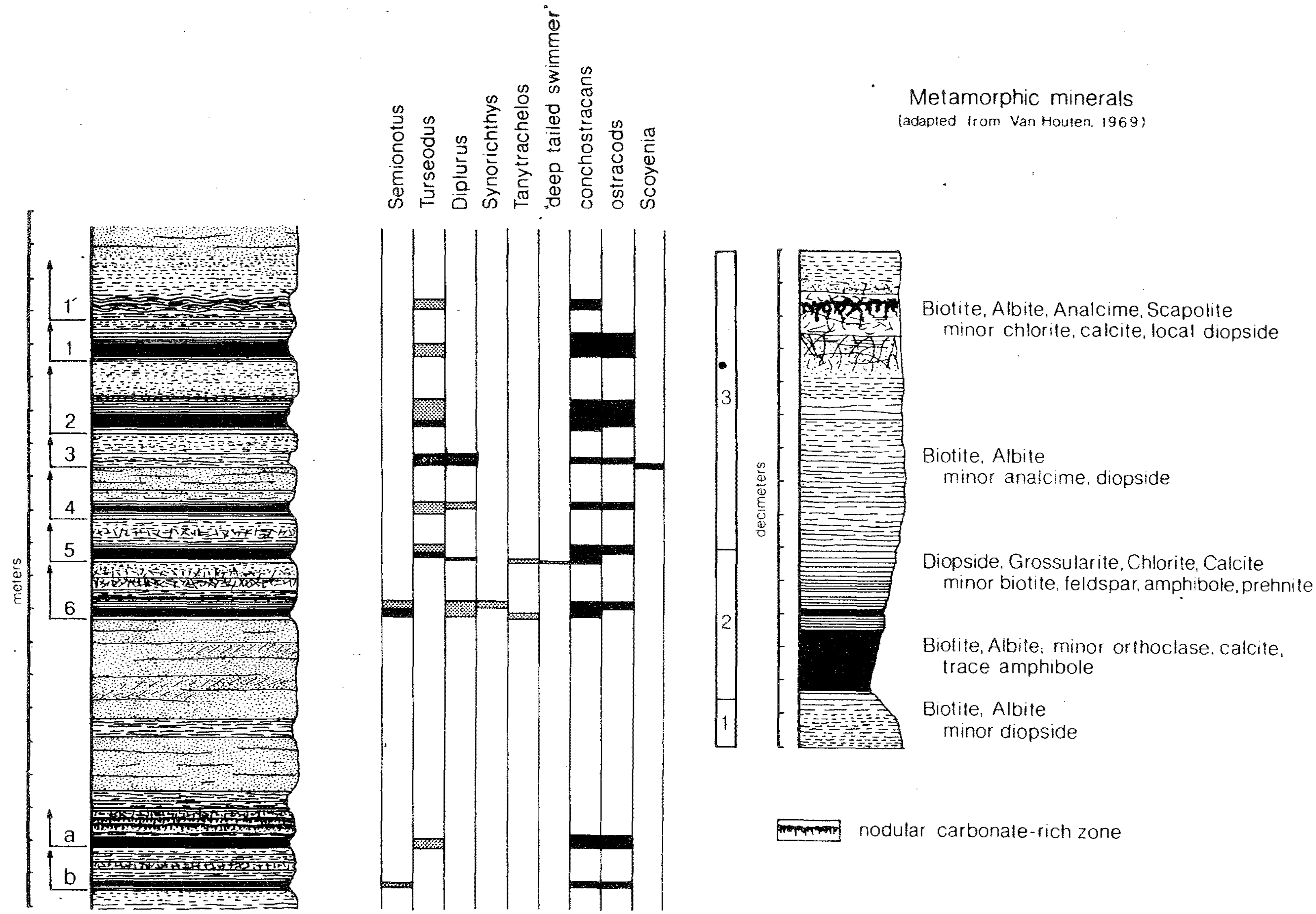


Fig. 37 Section at Gorge and River Roads, Edgewater showing position and nature of fossils and metamorphic minerals in generalized cycle. Lithologic symbols as in Figures 24 and 39.

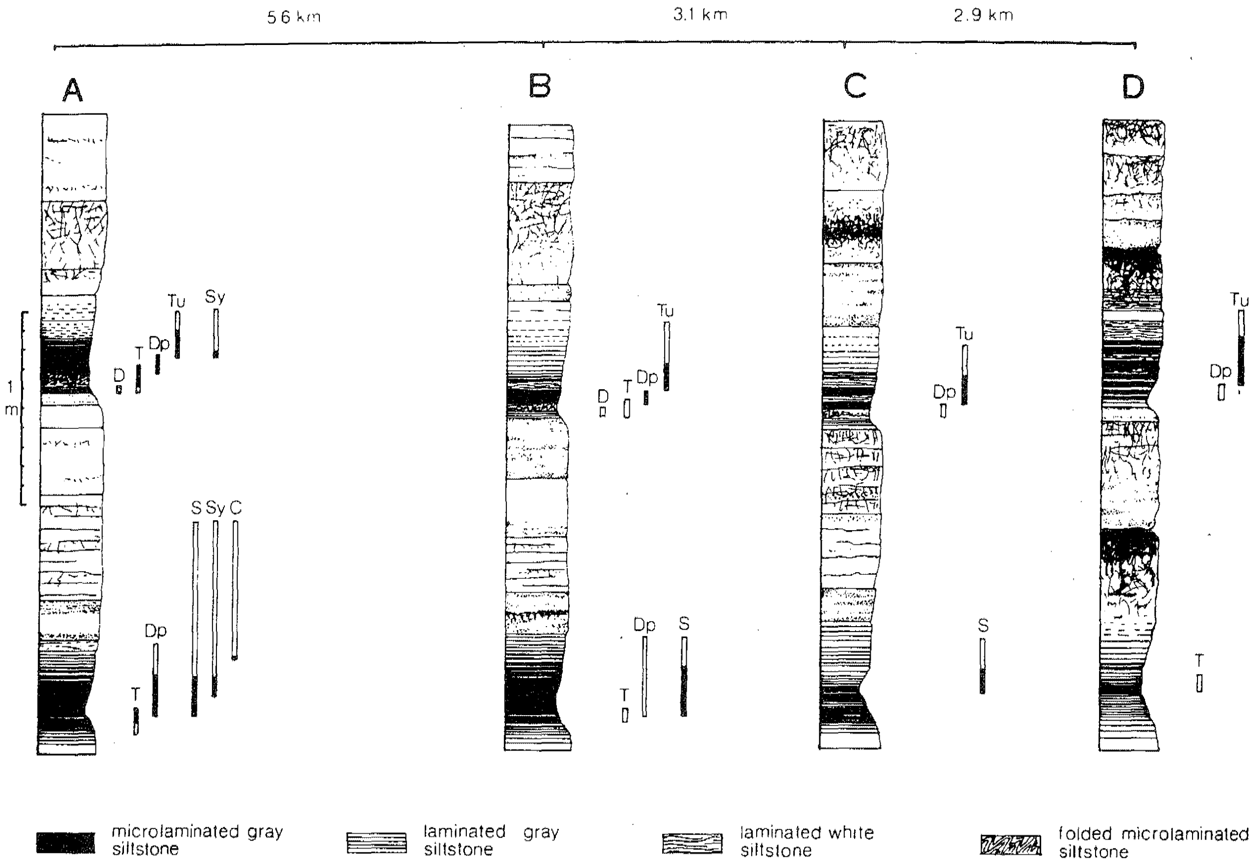


Fig. 38 Comparison of section of cycles 5 and 6 showing distribution and preservation style of fish: A, Kings Bluff, Weehawken; B, Gorge and River Roads, Edgewater; C, "old trolley route", Fort Lee, D, west of Ross Dock, Palisades Interstate Park, Fort Lee.

Abbreviations for fossils as follows: D, "deep tailed swimmer"; Dp, *Diplurus;* C, *Cionichthys:* T, Tanytrachelos; TU, *Turseodus;* Sy, Synorichthys; S, *Semionotus.* Open column under abbreviation of taxon stands for presence of dissarticulated fish while solid column indicates the presence of complete specimens.

Lithogic symbols as in Figures 29 and 30 except as shown.

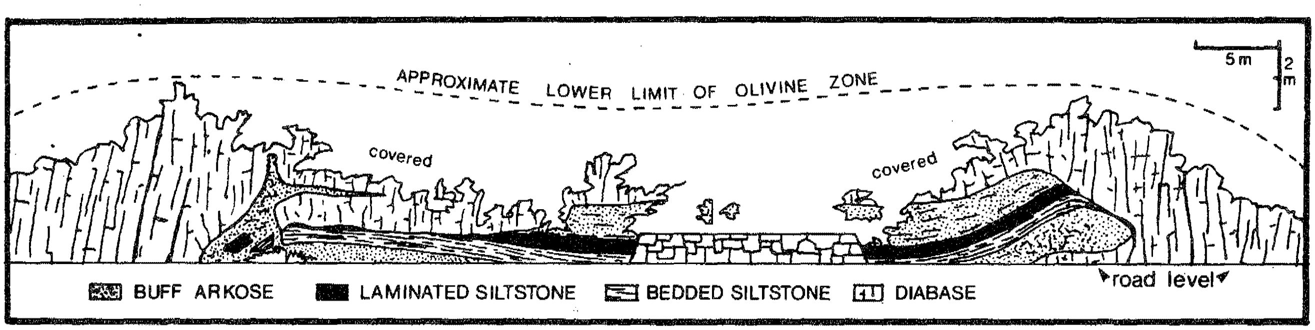


Fig. 39 Exposures of discordant contact of Palisade Diabase and Lockatong Formation, south of George Washington Bridge on road from River Road to Ross Dock in Palisades Interstate Park, Fort Lee.

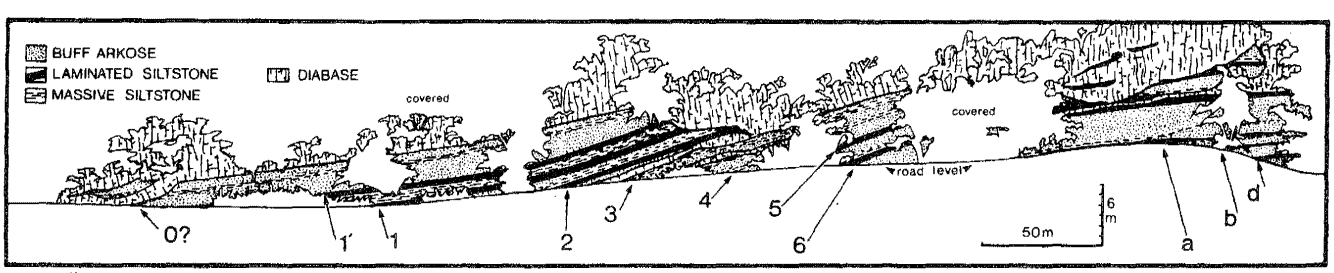


Fig. 40 Exposures of Palisade Diabase and cycles 0-d west of Ross Dock, Palisades Interstate Park, Fort Lee.

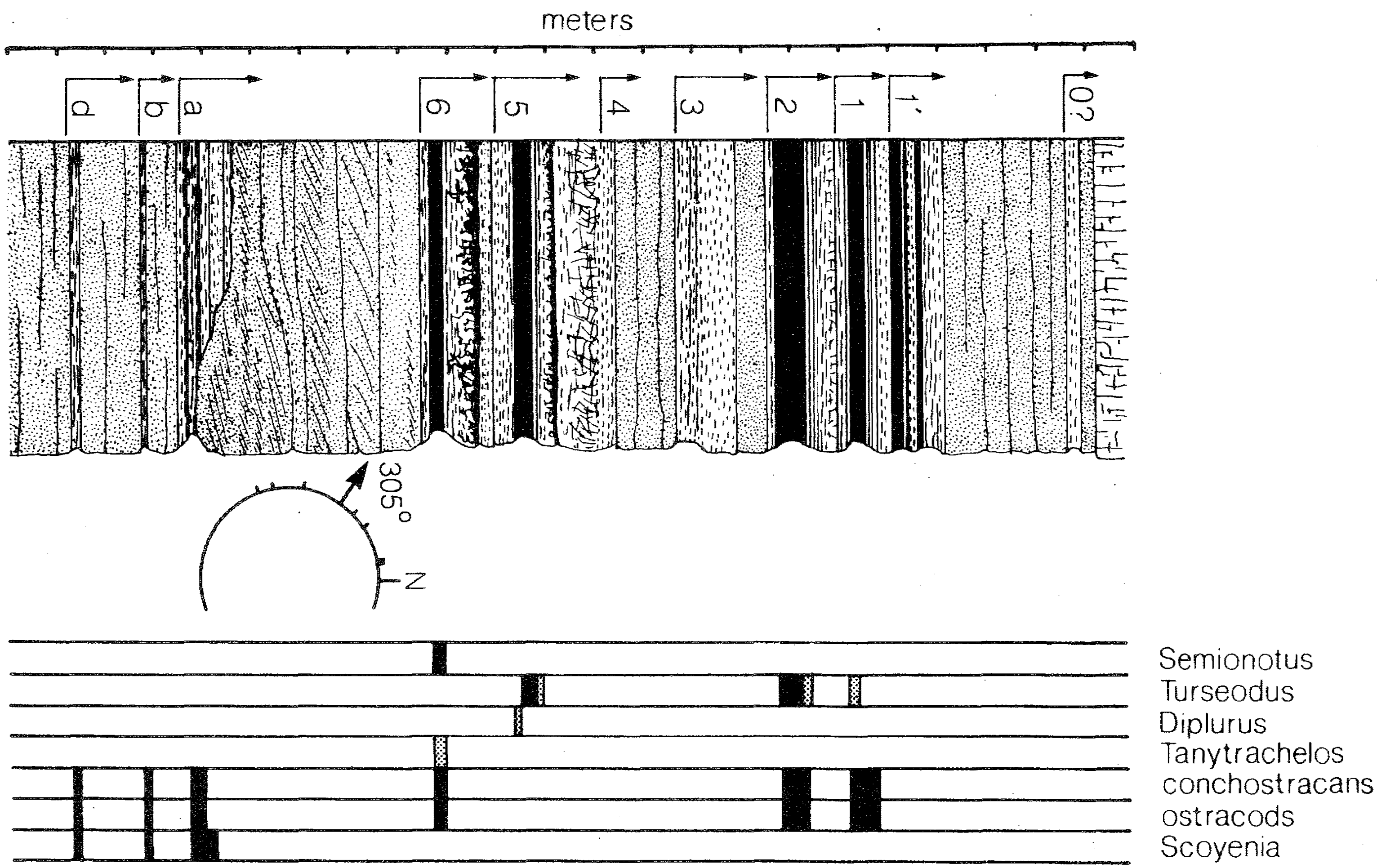


Fig. 41 Section west of Ross Dock, Palisades Interstate Park, Fort Lee showing distribution of major fossils and paleo-current data (n-7) for crossbedded buff arkose between cycles 6 and a.

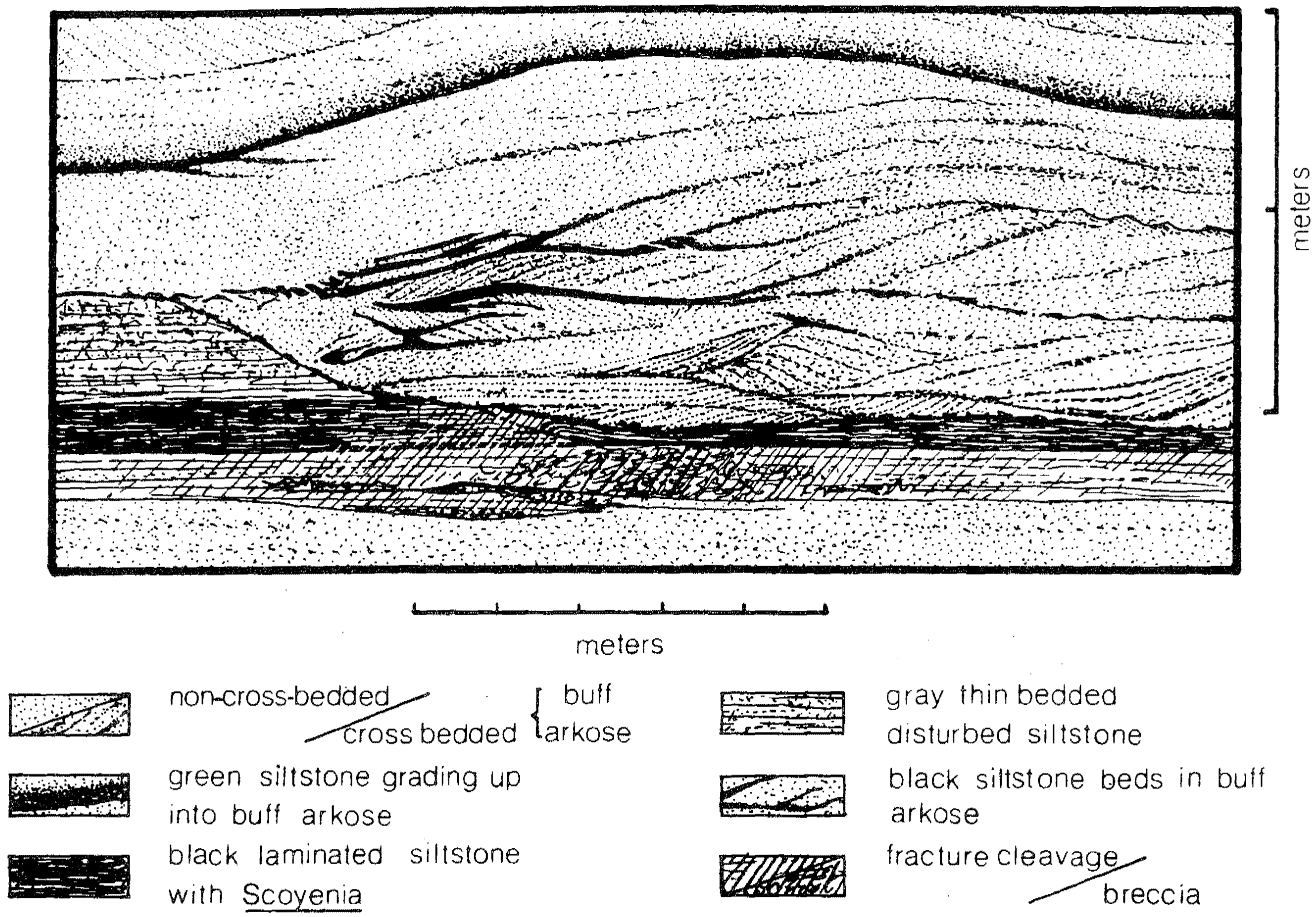


Fig.42 Down-cutting crossbedded arkose which eliminates most of cycle a (black laminated siltstone with *Scoyenia)*. Exposure is most northern of those shown in Figure 40.

Mountain Basalt contact. Triassic - Jurassic boundary is somewhere within a few meters below contact.

46.2 Crossing Passaic River, which here follows the Feltville-Orange Mountain Basalt contact.

48.7 Intersection with Route 46 W. Take exit on right for Routes 23 and 46.

48.9 Veer right onto exit for 23 South and 46 West.

49.4 Veer right onto exit for Route 46 West. Proceed on Route 46 west over broad flat expanse of Towaco Formation mantled by Pleistocene and Recent deposits.

54.7 Type section of Hook Mountain Basalt is on right (north) in cuts for Hook Mountain Road and Route 80. Pass into Boonton Formation.

55.1 Take right hand exit for New Road. Follow around to left (south) and head south along New Road towards Route 280.

56.0 Intersection for Route 280 east. Leave New Road, turn right onto entrance ramp for Route 280 east.

58.3 Exit on right for Eisenhower Parkway soutn (Exit 4A). In this area we cross back over buried portion of Hook Mountain Basalt which links up Riker Hill and Hook Mountain (see Olsen, this Fieldbook).

59.0 Excellent exposures on left (east) of contact between Towaco Formation and Hook Mountain Basalt in Nob Hill Apartment complex (former east half of Roseland (Riker Hill Quarry). Two flows of Hook Mountain Basalt visible here (cumulative thickness 110m).

59.3 Turn left onto Beaufort Avenue. Take Beaufort Avenue south following along the back slope of Riker Hill.

59.7 Turn left into entrance road for Riker Hill Park of Essex County Department of Parks, Recreation, and Cultural Affairs (former Essex County Park Commission). Follow road up dip slope of Hook Mountain Basalt. Follow signs to Geology Museum.

60.1 **STOP 5** Geology Museum and Walter Kidde Dinosaur Park (former west side Roseland (Riker Hill) Quarry). Park in lot and look over exhibits at Geology Museum. Then take access path from Geology Museum over the crest of Riker Hill and down, through wooded area into Dinosaur Park. *Always get permission before entering park.*

As it stood in 1975, the Roseland Quarry occupied 55 acres, exposed 95 m of upper Towaco Formation - including two complete Towaco cycles, and exposed about 50 m of the overlying Hook Mountain Basalt (Figures 43 and 44). The quarry became very well known in the late 1960's

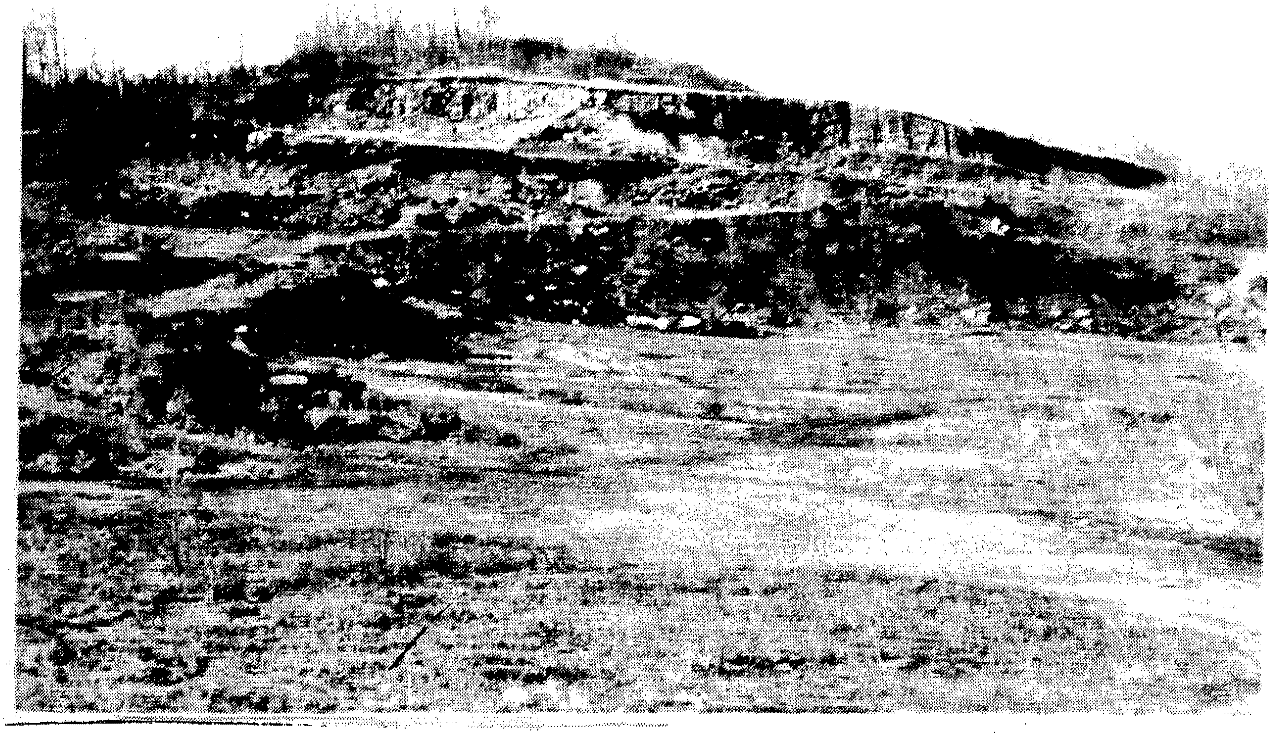
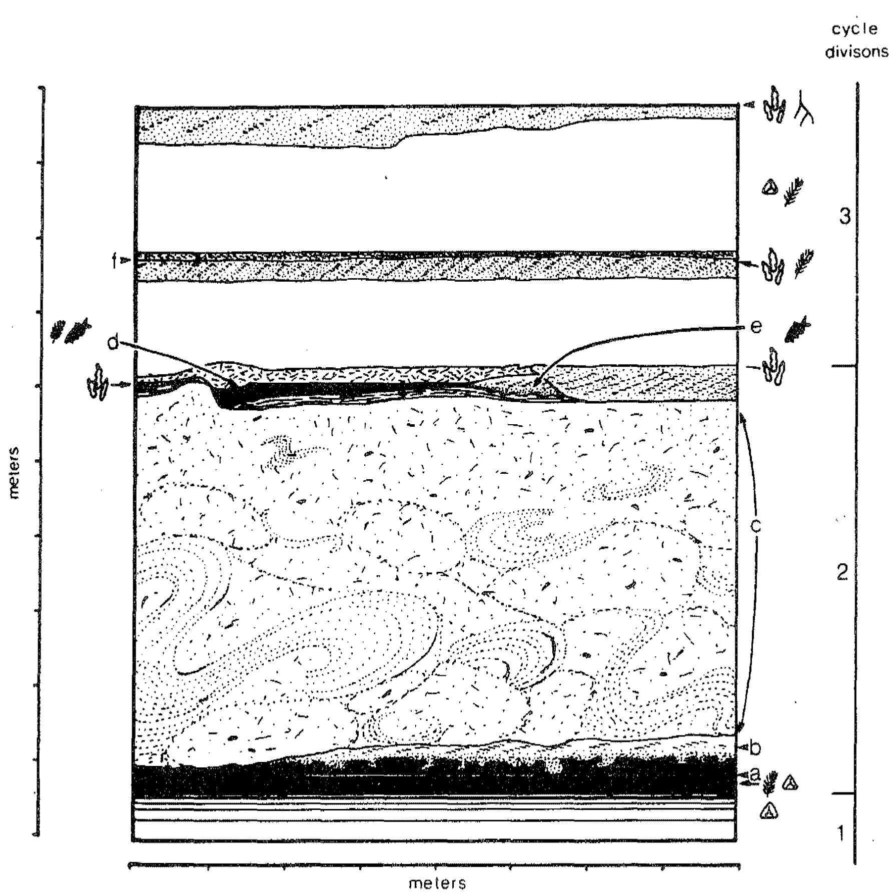
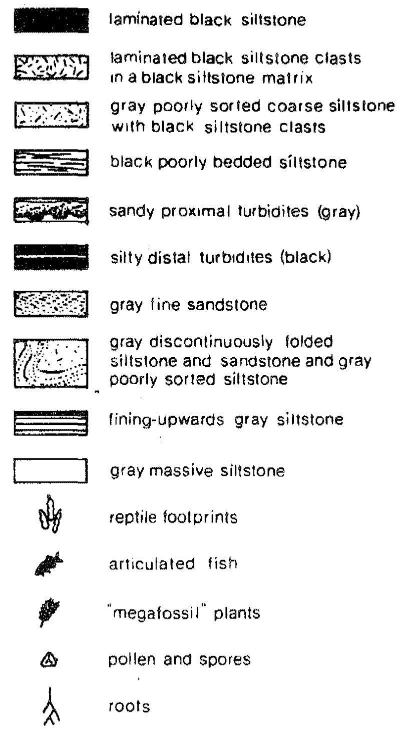


Fig. 43 Roseland Quarry in 1975 prior to development of "Nob Hill". View is to the west.





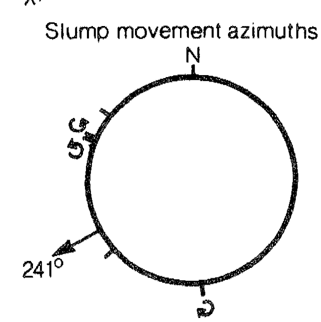


Fig. 44 Section at Roseland Quarry. Only cycle A and Hook Mountain Basalt are presently exposed.

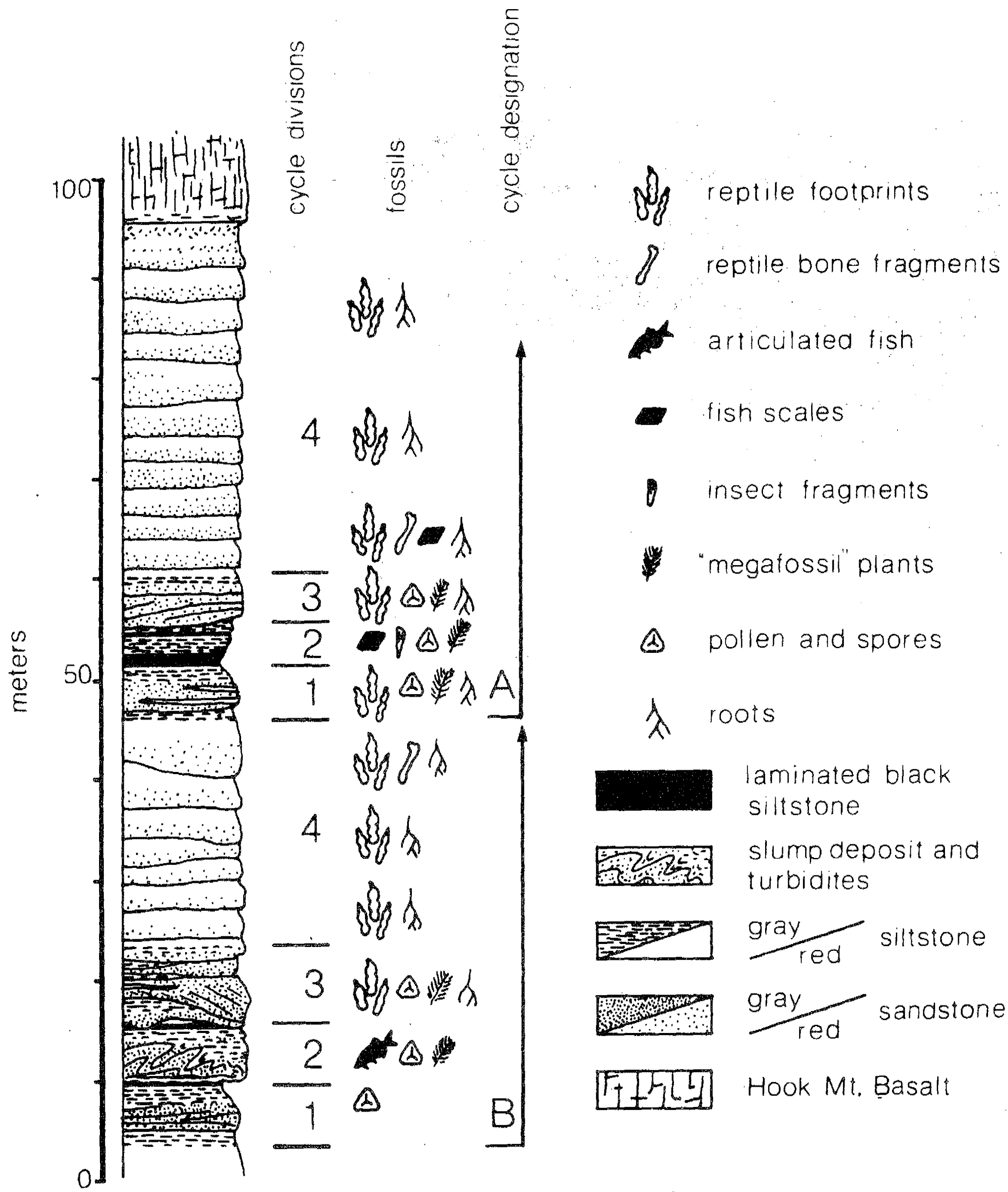


Fig. 45 Section along strike of upper part of division 1, all division 2, and lower division 3 of cycle B Roseland Quarry, now no longer exposed.

and early 1970's for its prolific dinosaur footprints. Because of the scientific and educational potential of the site the then owners, Walter Kidde and Co. Inc., donated the most productive 15 acres to the Essex County Park Commission. The site now awaits development.

Before the other 40 acres were developed as the Nob Hill development, the following features could be seen:

1 , lateral changes in facies within divisions 1 - 3 of the lower cycle (Figure 45). The microlaminated beds of division 2 produced many fossil fish, all *Semionotus* (Figure 46) as did a number of the thinner (30 cm) turbidites.

2 , two upwards coarsening turbidite sequences, the lower being by far the larger (Figure 45). The lower sequence shows large scale slumped beds resembling "wild flysche" associations. Some of the "roll over" structures are 2 to 3 m in diameter. Transport was from the east.

3 , abundant dinosaur footprints in possible crevasse splay (in division 3) of channels about 70 m to north of tracks (Figure 47). Orientation of trackways proved to be parallel to paleocurrent directions derived from ripple marks within the footprint-bearing bed and oriented plant debris in overlying beds.

4 , Series of 7 fining-upwards cycles of division 4 of the lower Towaco cycle in the Quarry. Middle 3 cycles had

Fig. 46 *Semionotus* from division 2 of cycle B at Roseland Quarry. Specimen Lost. Quarter for scale.

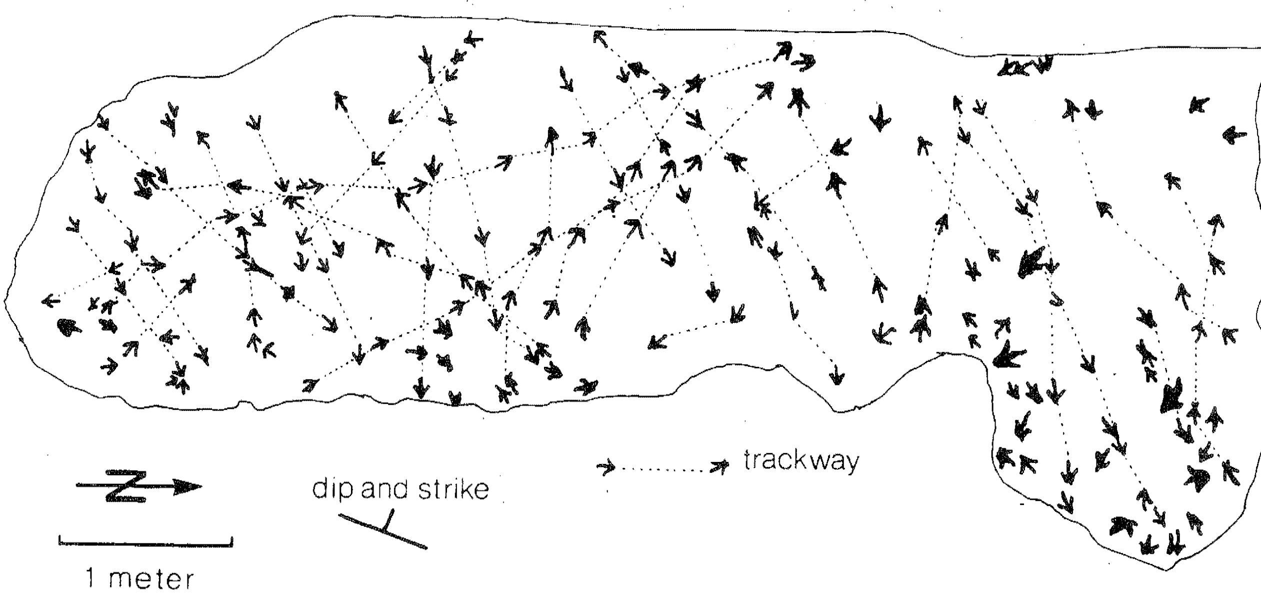


Fig. 47 Grallatorid footprints from the lower part of division 3 of cycle B, Roseland Quarry. These tracks occur in unit marked F on Figure 45. Specimens destroyed.

extensively developed dolomitic nodules and deeply mudcracked beds. Second fining-upwards cycle from the bottom with laminated silty beds (?flood basin) with abundant clay filled root casts, many of which are surrounded by dolomitic nodules (Figure 48).

In the presently exposed beds the following can be seen:

1, uppermost fining-upwards cycle of lower Towaco cycle still exposed along eastern boundary of park. The upper and middle parts of this cycle have the best reptile footprints in the quarry and hold the key to the park's development. Footprints are especially abundant in interbedded sequences of possible crevasse splay sandstone and flood basin siltstone. Basal sandstone portions of cycle are locally deeply down cut into underlying beds and contain beds of mud-chip conglomerate and casts of tree limbs and roots. Uppermost portions of the cycle consist of fine siltstone transitional into the lower parts of division 1 of the upper Towaco cycle. Transitional beds with numerous red siltstone roots surrounded by greenish halos.

2, exposure of complete Towaco cycle. Division 1 contains prominent fine sandstone beds with large calcareous concreations which weather out to form limonite filled cavities and extensive large (1-4 cm) coalified roots which probably belong to conifer trees? Crevasse splay beds in division 1 covered with little dinosaur footprints. Identical beds occur in division 2 of this cycle exposed in Chatham, New Jersey, 13 km south of here.

Fig. 48 Dolomitic nodules around root-casts in red coarse siltstone division 4 of cycle B Roseland Quarry.

3, microlaminated portion of division 2 has very well developed white-black microlaminae (Figure 15) - but no fish have been found yet, however. Upper parts of microlaminated beds contain distinctive nodules of black chert. Black, coally-looking siltstone surrounding chert bed has several bedding thrusts similar to those seen in the Lockatong at Stops 1 - 4. Microlaminated beds locally involved in disharmonic folds (Figure 15). Like the beds of division 1, these portions of division 2 look exactly the same in the Chatham exposures.

4, casts of a salt present in coarse siltstone beds above microlaminated portion of division 2.

5, massive fine gray siltstone in upper parts of division 2 have well-preserved conifer foliage, pollen and spores, individual fish scales *(Semionotus)*, and rare insect fragments.

6, complex series of sandstones and siltstones of division 3 showing features suggestive of both laterally migrating channels and prograding deltas.

7, lowest fining-upwards cycle in division 4 (Figure 49) shows slip-off faces of point bar and beds of intraformational conglomerate with coprolites, fish scales, reptile bone fragments, and abundant dinosaur footprints. The latter features could represent a dinosaur "wallow".

8, 10 successive fining-upwards cycles of division 4. Rill marks very well developed in bank portions of one of the middle cycles (Figure 50). These sorts of rill marks, typical of channels with rapidly dropping water levels, have long been confused with plant remains (it is easy to see why) and have received the name *Dendrophycus* (Newberry, 1888).

9, unique small reptile footprints with structure highly suggestive of advanced mammal-like reptiles or mammals (Figure 20) are present in upper fining-upwards cycles. If they do represent mammals, they will be the oldest North American record.

10, very badly weathered "tuff" between normal Towaco Formation and Hook Mountain Basalt. This unit is enigmatic but very widespread at this stratigraphic position. Fresh exposures were described by Lewis in 1908 (see Olsen, this Fieldbook).

60.5 Leave Walter Kidde Dinosaur Park and Riker Hill Park returning to Beaufort Avenue. Turn right (north) onto Beaufort.

60.9 Turn right off Beaufort onto Eisenhower Parkway heading north.

61.9 Take right hand exit for Route 280 east. Head east on 280 up dip slope of Preakness Mountain Basalt. Outcrop width of Preakness Basalt is very large in this area, suggesting a thickness of 500 m for the basalt. I believe this is due to a number of small strike faults and the true thickness is closer to 300 m. These faults in combination with the multiple flow character of the Preakness Basalt produced the many small ridges visible while driving up the dip slope.

64.8 Type section of the Preakness Basalt in deep open cut for Route 280. Section exposes about 100 m of the lower flow. Note distinctive "splintery" nature of the lower 50 m (see Olsen, this Fieldbook). This section is cut by a series of faults all apparently left lateral and all showing little or no apparent dip slip offset (Figure 51).

65.2 Contact between Preakness Basalt and Feltville Formation poorly exposed on south side of road.

65.6 Unexposed contact between Feltville Formation and underlying Orange Mountain Basalt below this point.

65.9 Exposures of ?second flow of Orange Mountain Basalt.

66.3 Type section of Orange Mountain Basalt in very long and deep open cut for Route 280 (see Olsen, this Fieldbook; Manspeizer, this Fieldbook). Section exposes about 55 m of lower flow as well as a number of left lateral faults similar to those seen at mileage 64.8. Left lateral faults are present here as they are at mileage 64.8. At one portion of the cut, on the north side is 20 m long horizontally slickensided fault plane. Note the very different appearance of basalt (in terms of jointing) from the Preakness Basalt.

66.7 Contact of Orange Mountain Basalt and Passaic Formation was well exposed during construction of this cut, at this point.

66.8 Cuts in uppermost Passaic Formation here have produced phytosaur footprints called *Apatopus* and the possible crocodillo-morph tracks called *Batrachopus*. The Triassic -Jurassic boundary lies somewhere within the upper few tens of meters of the Passaic Formation here.

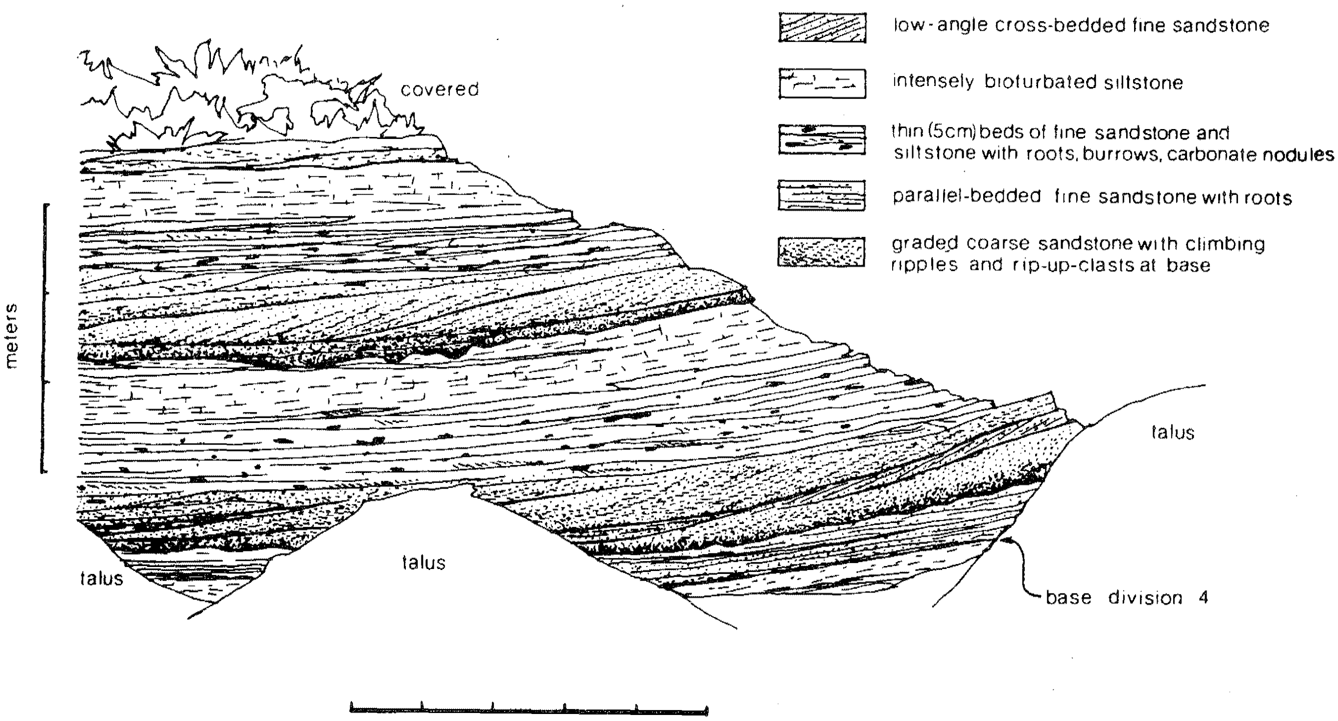


Fig. 49 Outcrop of fining - upwards cycles lower part of division 4, cycle A.

71.2 Sedimentary cycle in Passaic Formation formerly exposed here. A very well preserved palynomorph assemblage recovered from fine gray siltstones of this unit suggest a lower Rhaetic age (Cornet, 1977). This unit has also produced a series of reptile footprints including large and small *Grallator* and *Chirotherium* sp. *Scoyenia* is abundant as is the conchostracan *Cyzicus*. Equivalent beds are exposed at the same stratigraphic position in New Brunswick, New Jersey. The entire Passaic Formation section from this unit to the Orange Mountain Basalt is above the entire Delaware River section of the Passaic Formation, which extends upwards only into Norian beds (Cornet, 1977).

71.3 Take 1st Street exit, turn right.

71.6 Turn left onto Central Avenue.

72.6 Turn right onto Washington Street.

72.7 Turn right onto Warren Avenue.

72.8 Rutgers University parking lot - end field trip.

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Fig. 50 Natural cast of rill marks, middle portion division 4, cycle A. Specimen in private collection.

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Note: All of stop 2 and the acknowledgments were unintentionally omitted from the original printed version of this paper.

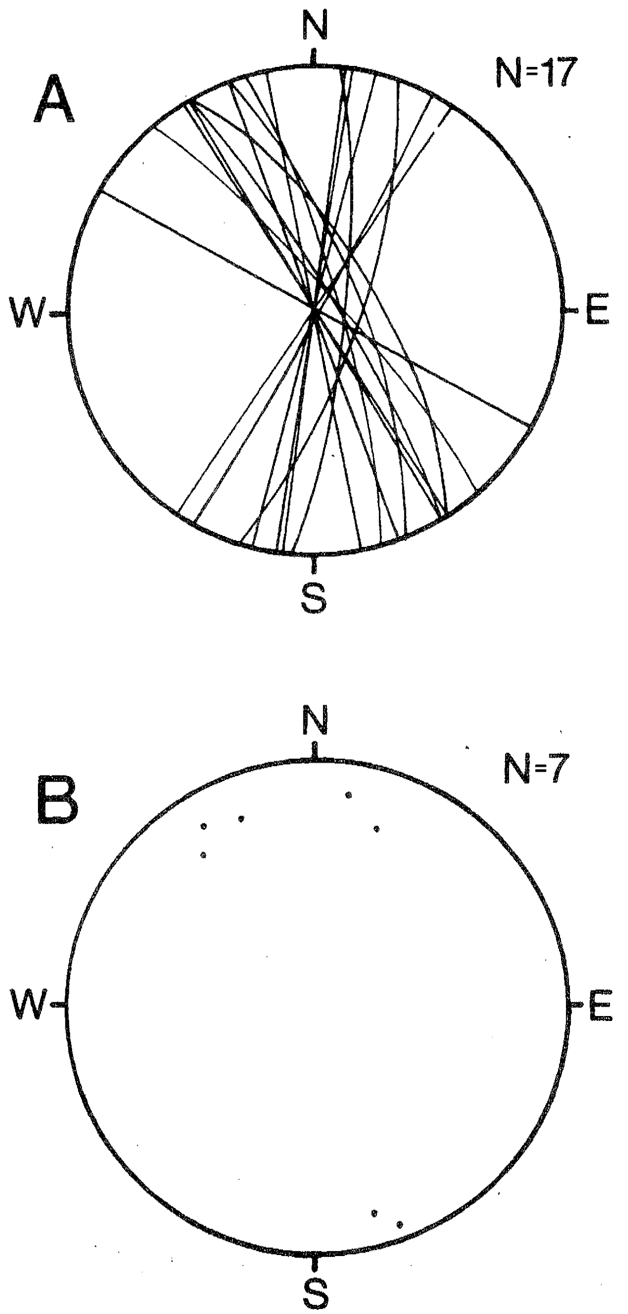

Fig. 51 Plots of faults exposed in type sections of Orange Mountain and Preakness basalts along Route 280: A, equal area net plot of seventeen fault planes; B, equal area net plot of lines parallel to slickensides present in seven of the faults in A. Lower hemisphere projections.

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