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-

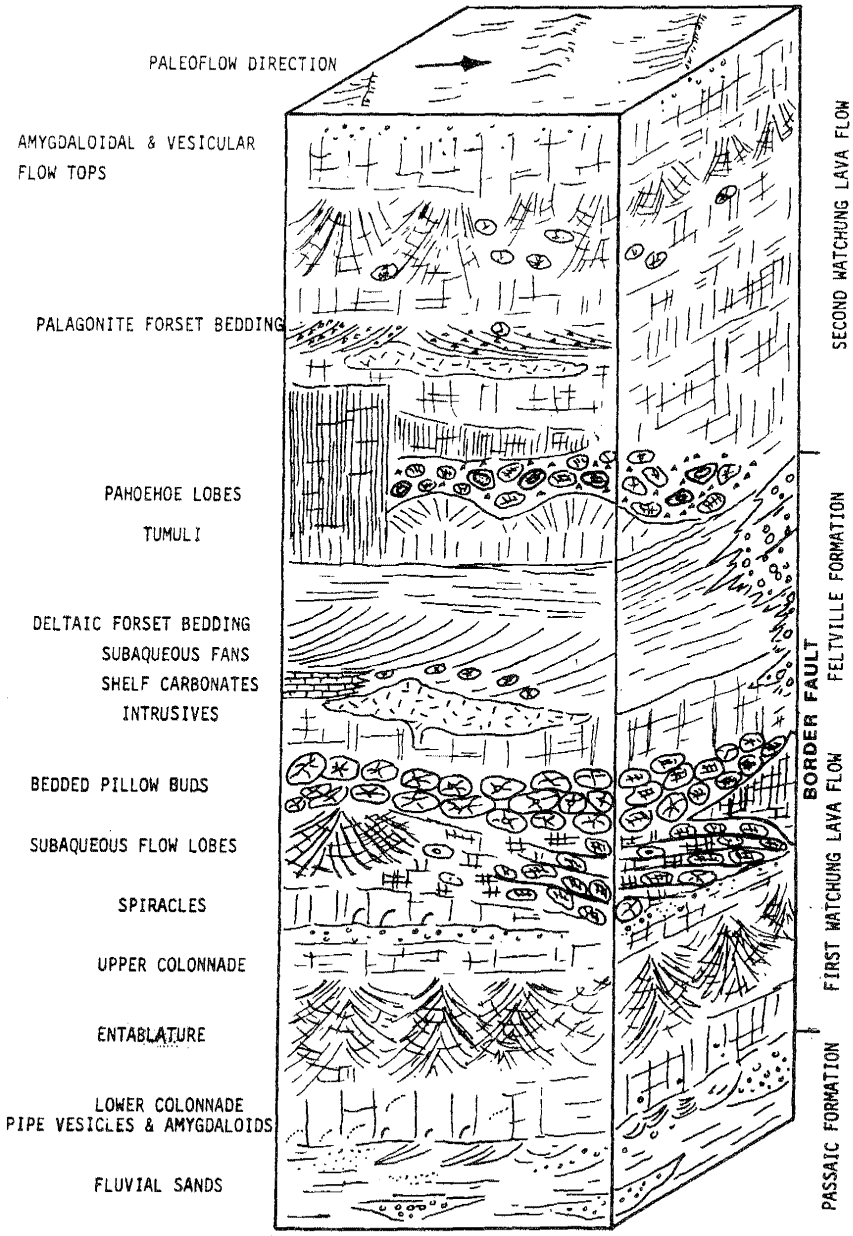


Fig. 1 Schematic diagram of the volcanic and sedimentary structures to be studied on the field trip.

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.

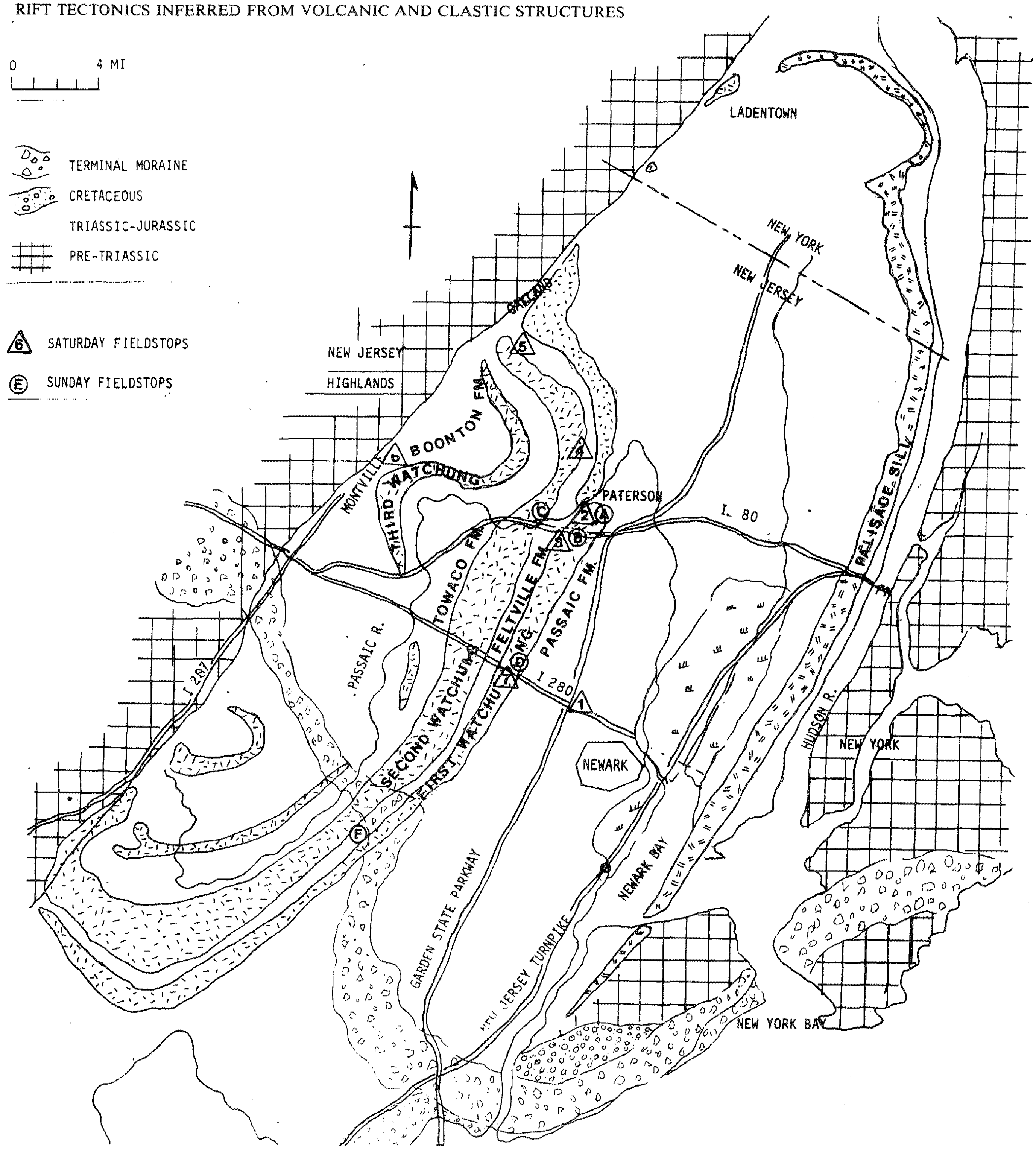


Fig. 2 Location map, showing generalized geology and field stops.

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,

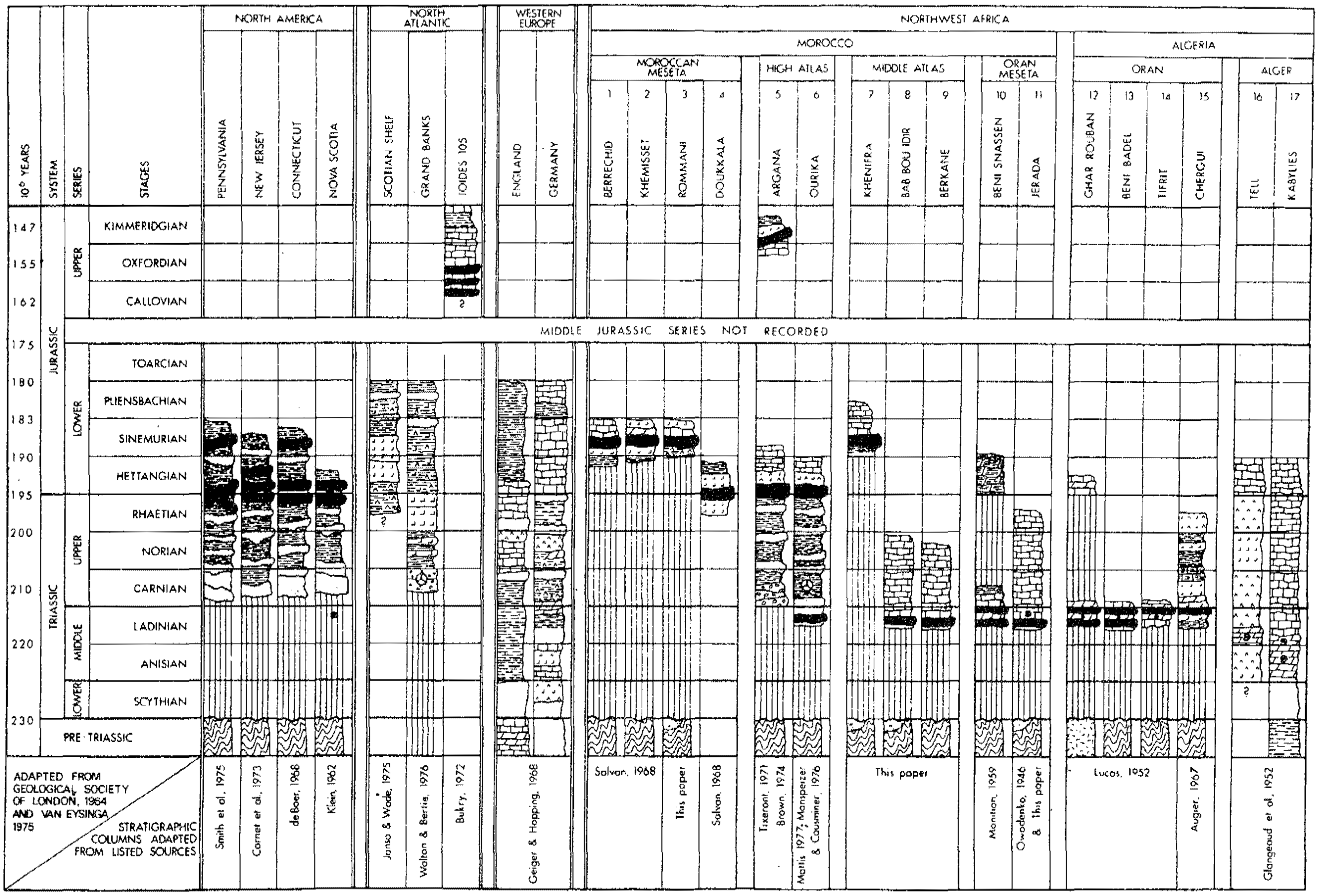


Fig. 3 Intercontinental correlation chart. Conventional symbols depict time - and rock - stratigraphic units (Manspeizer and others, 1978).

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

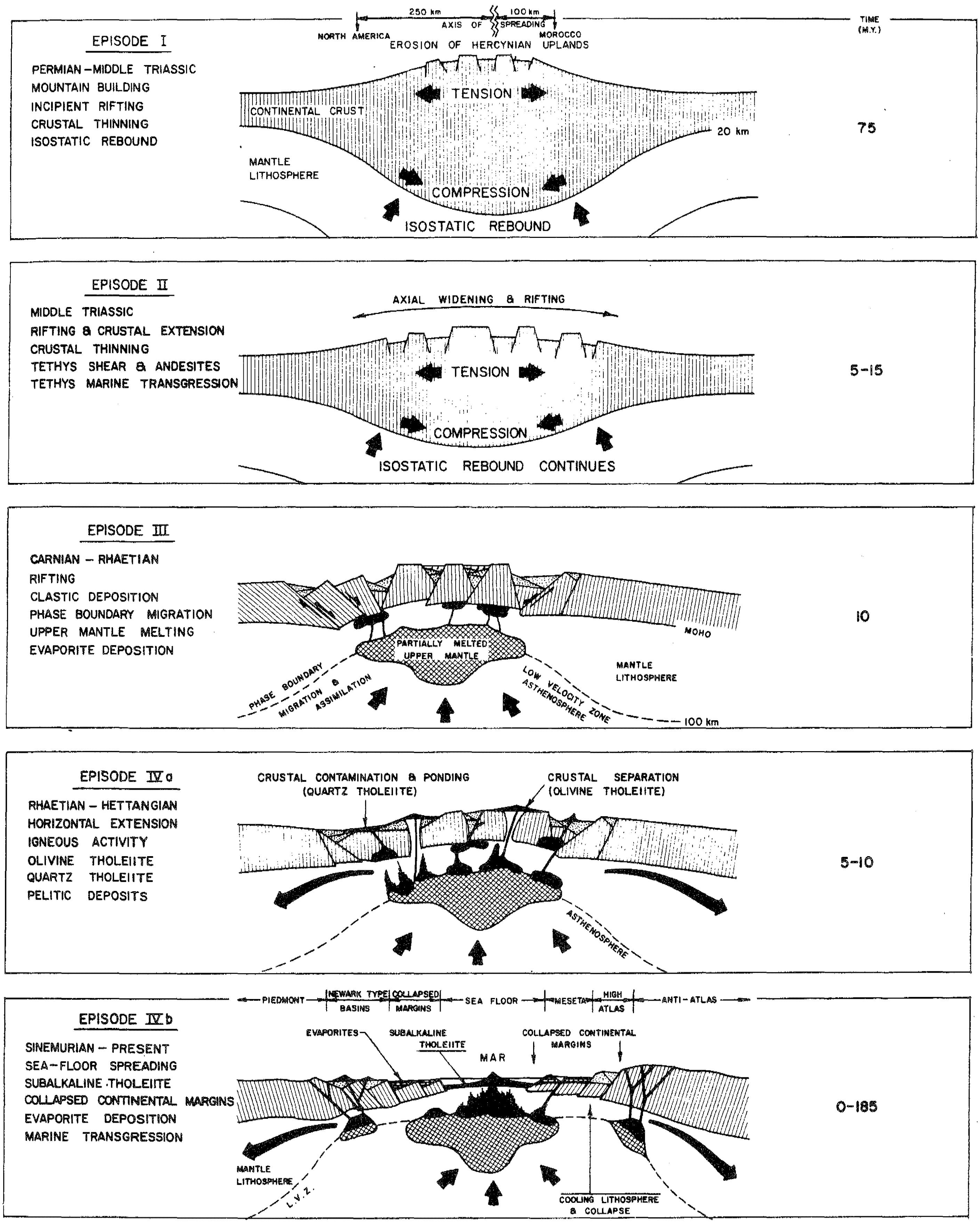


Fig. 4 Conceptional model showing tectonic episodes from initial crustal thinning and rifting to sea-floor spreading. (Manspeizer and others, 1978).

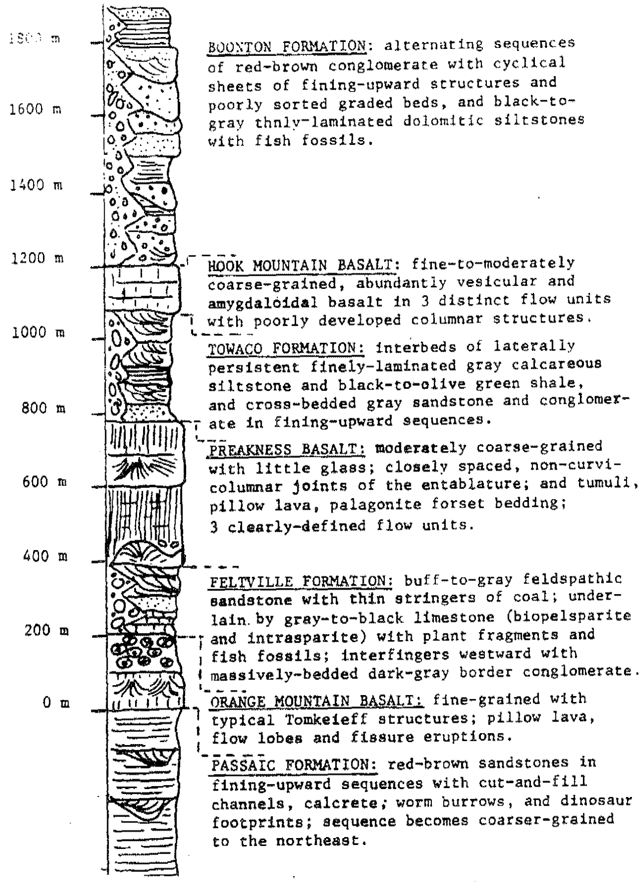


Fig. 5 Schematic composite column for the latest Triassic-Jurassic rocks, Newark Basin.

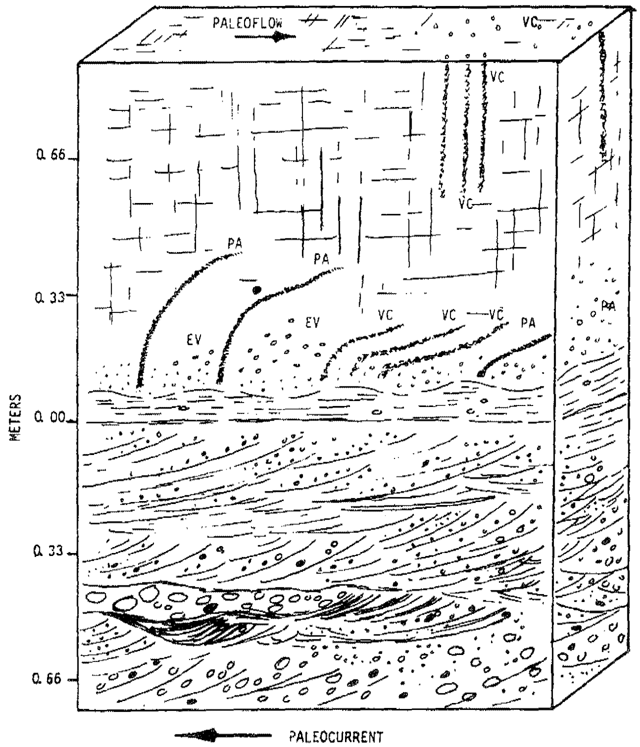


Fig. 6 Field sketch showing contact of the Orange Mountain Basalt with oriented pipe amygdaloids (pa), pipe vesicles (pv) and vesicle cylinders (vc), and underlying cross-bedded pebbly sandstone of the Passaic Formation, McBride Ave., Paterson. Structures indicate that the lava flowed towards the northeast, 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 tuffaceous 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).

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.

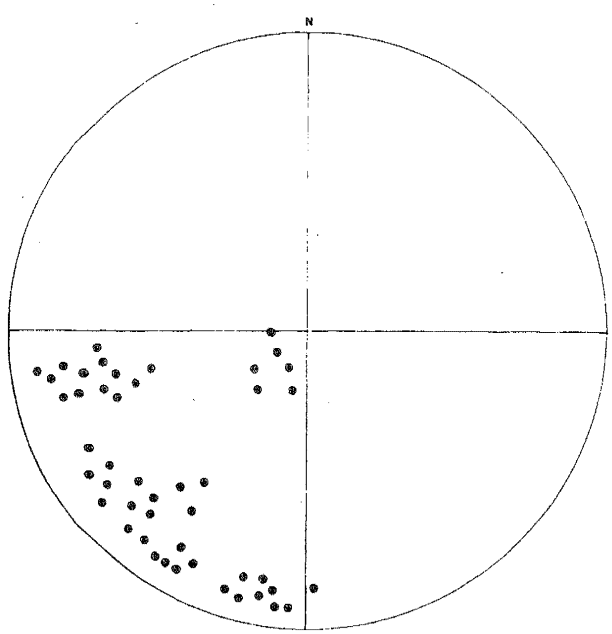


Fig. 7 Stereographic projection of pipe amygdaloids and pipe vesicles, Orange Mountain Basalt, McBride Ave., Paterson.

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

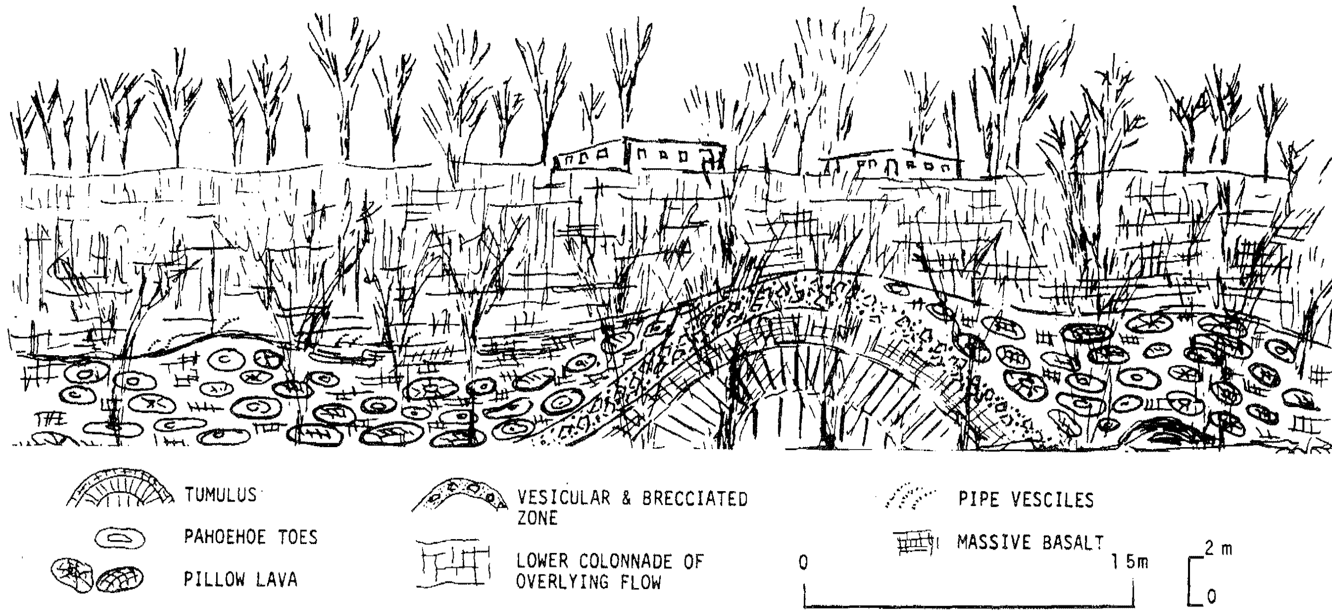


Fig.9 Field sketch of tumulus with overlying pillow-pahoehoe complex that thins along the crest of the tumulus and is overlain by columnar basalt of the second flow unit; Little Falls.

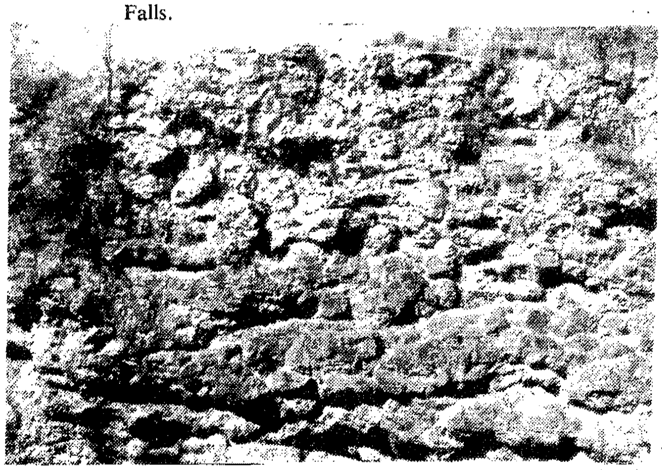


Fig.10 Pillow buds of the subaqueous flow lobe in longitudinal view, overlain by bedded pillow buds in cross-sectional view; Upper New Street Quarry, Paterson.

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-

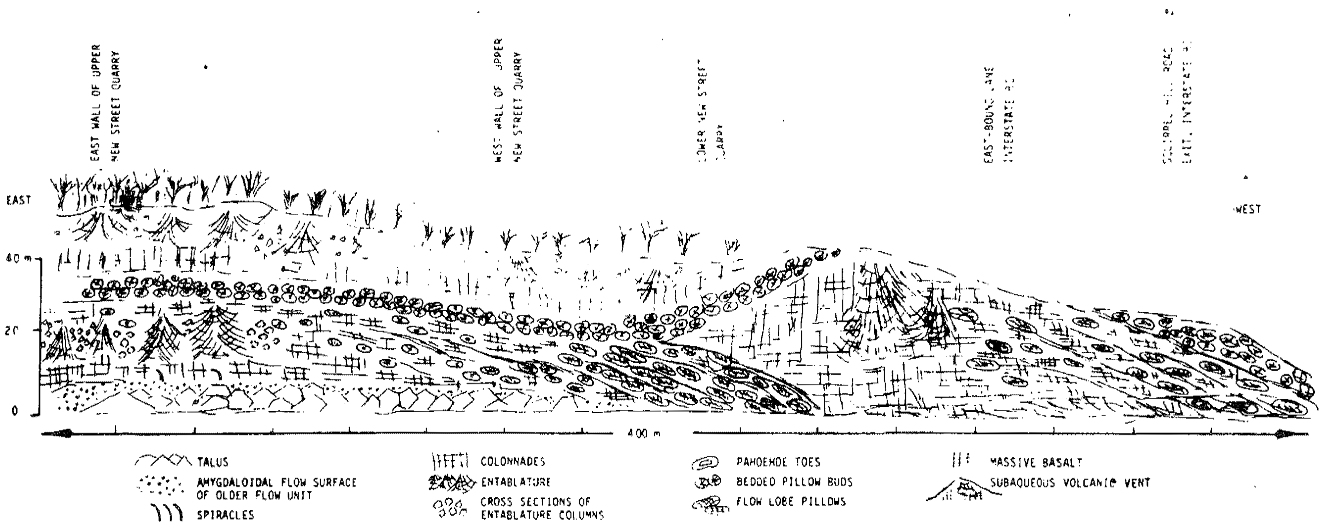


Fig. 11 Field sketch of volcanic structures studied in the second flow unit of the Orange Mountain Basalt in the Upper and Lower New Street Quarries and along I-80; note: longitudinal section of the subaqueous flow lobe, volcanic vent, bedded pillow lavas, an overlying Tomkeieff sequence and underlying amygdaloidal flow top.

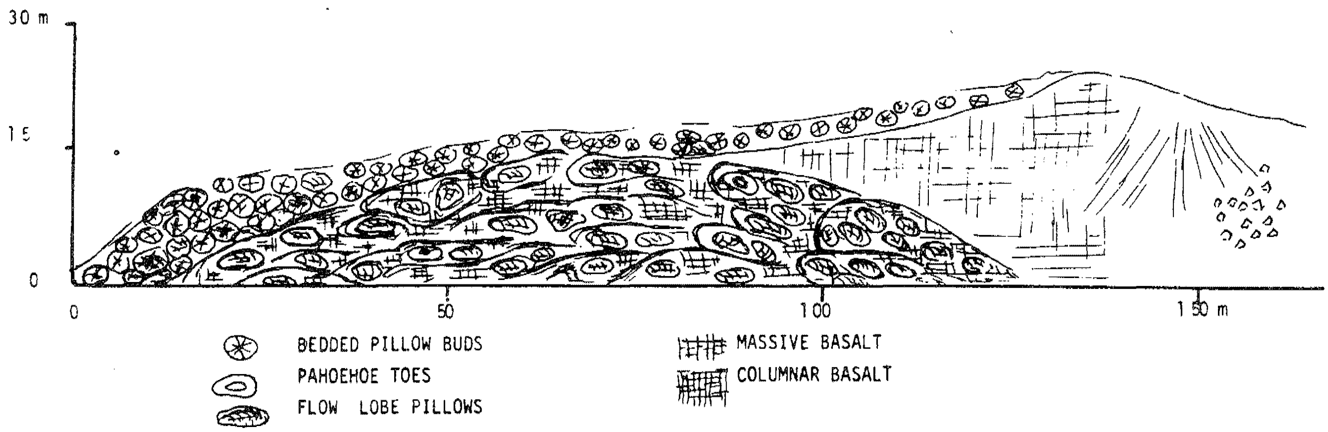


Fig. 12 Field sketch of the lower New Street Quarry, showing transverse section of the subaqueous flow lobe, volcanic vent, and overlying bedded pillow lava.

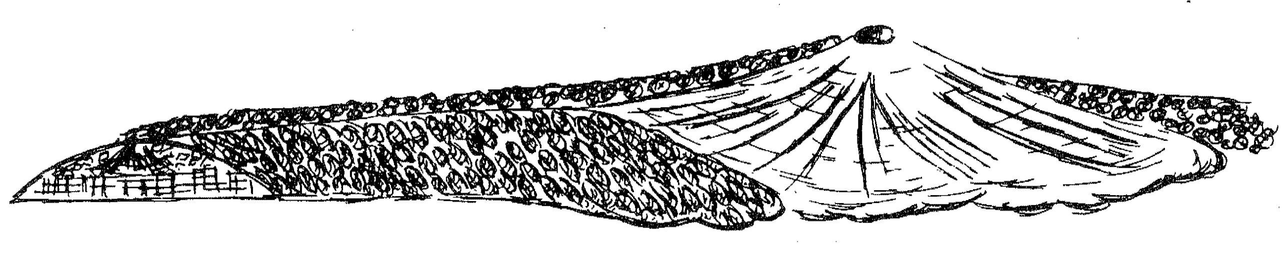


Fig. 13 Conceptual view of subaqueous flow lobe, volcanic vent and bedded pillow lavas; New Street Quarries, Paterson.

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.

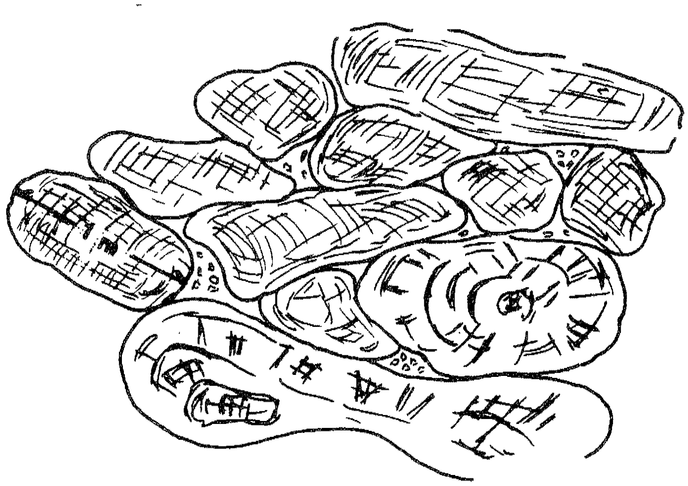


Fig. 14 Field sketch of pillow buds of the subaqueous flow lobe, Upper New Street Quarry. Pillows are elongate ellipsoidal masses that form a tight structural framework with open interstices and without volcanic breccia.

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.

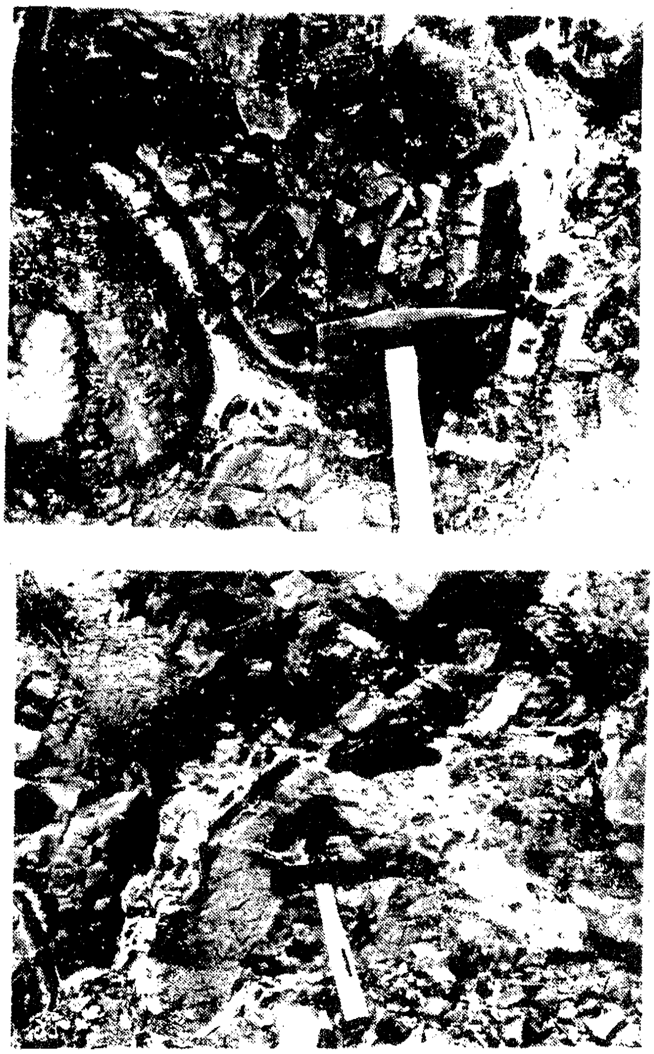


Fig. 15 Pillow buds with massive pillow cores, checkered exterior glassy rind, interstitial angualr clasts of basaltic glass surrounded by and cemented with calcite, quartz and zeolite. Note: that the clasts are displaced from the pillow rind by secondary mineralization.

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-

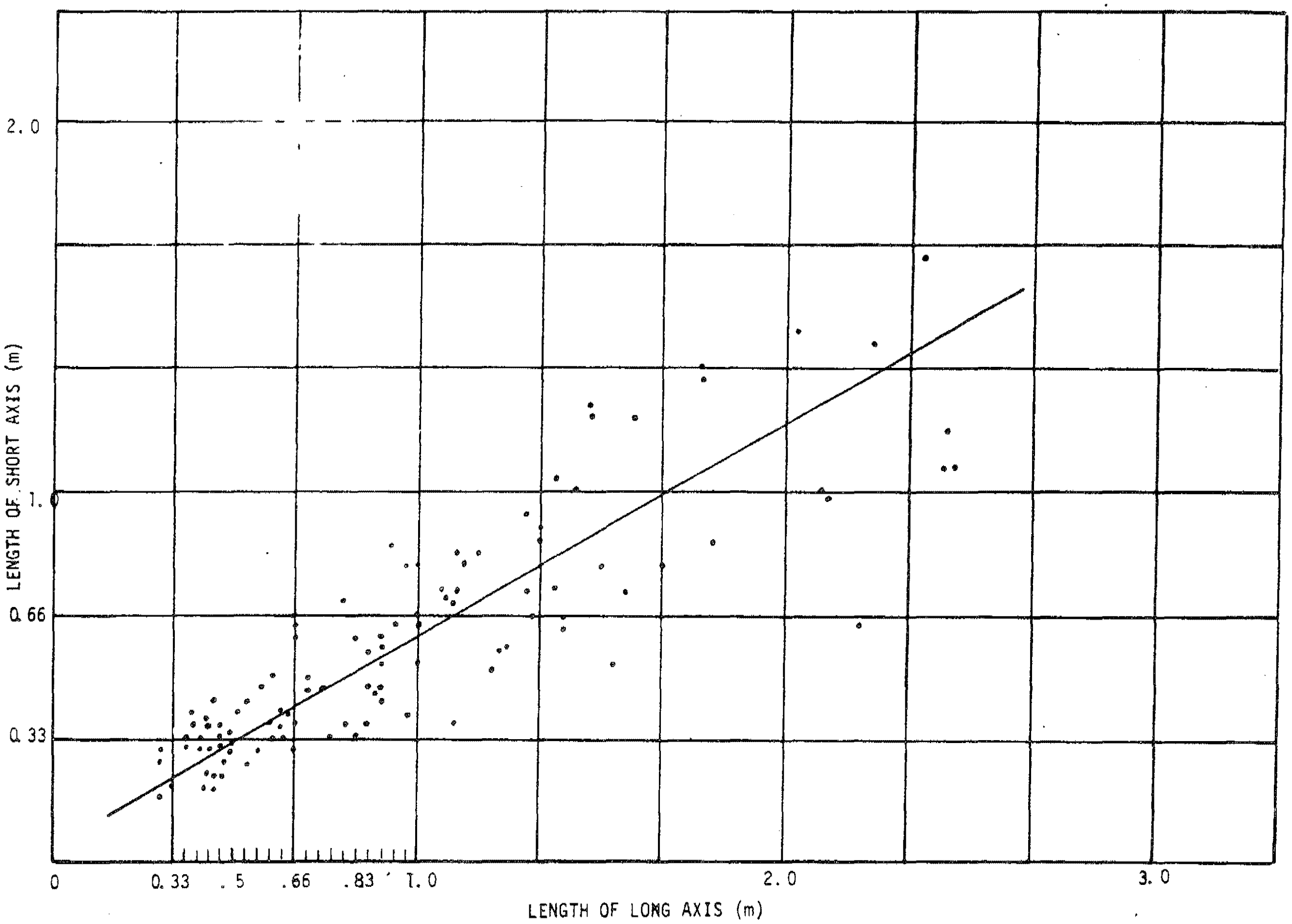


Fig. 16 Shape of pillow buds; plot of long axis vs. short axis of pillow buds; Upper New Street Quarry, Paterson (Data, D. Bello, pers. comm.).

columnar, in the Second Watchung it is characteristically composed of very long (about 25 m) and fairly continuous, slender (about 10 cm in diameter), nonradiating, 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-

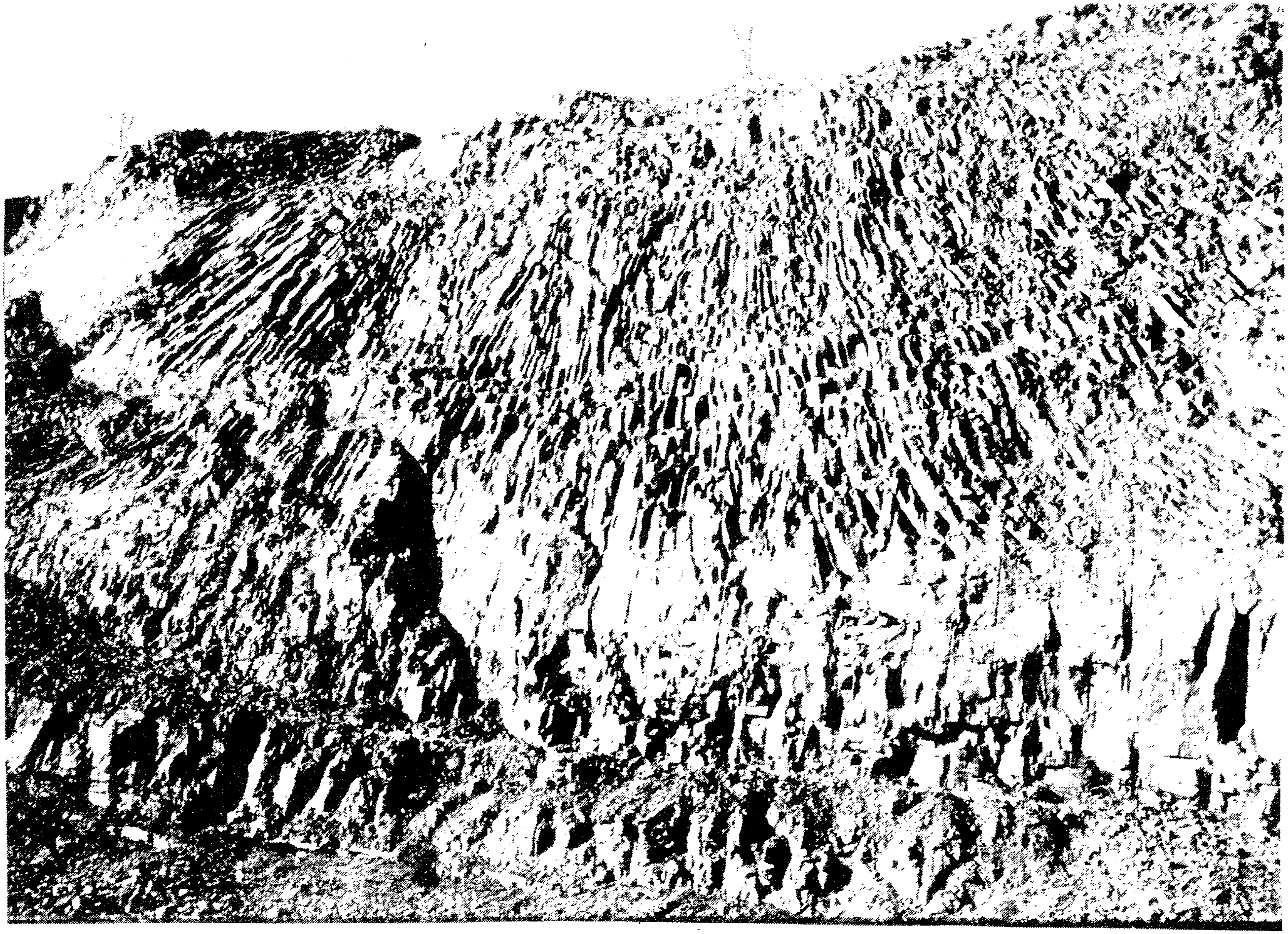


Fig. 17 Tomkeieff structural sequence of lower colonnade, entablature and partially exposed upper colonnade. Note radiating and bifurcating columnar joints and cross joints which are concentric about the apex of radiating; refraction of joints into the lower colonnade; and conformable sequence of sedimentary rocks below the igneous sequence. Orange Mountain Basalt, I-280, West Orange.

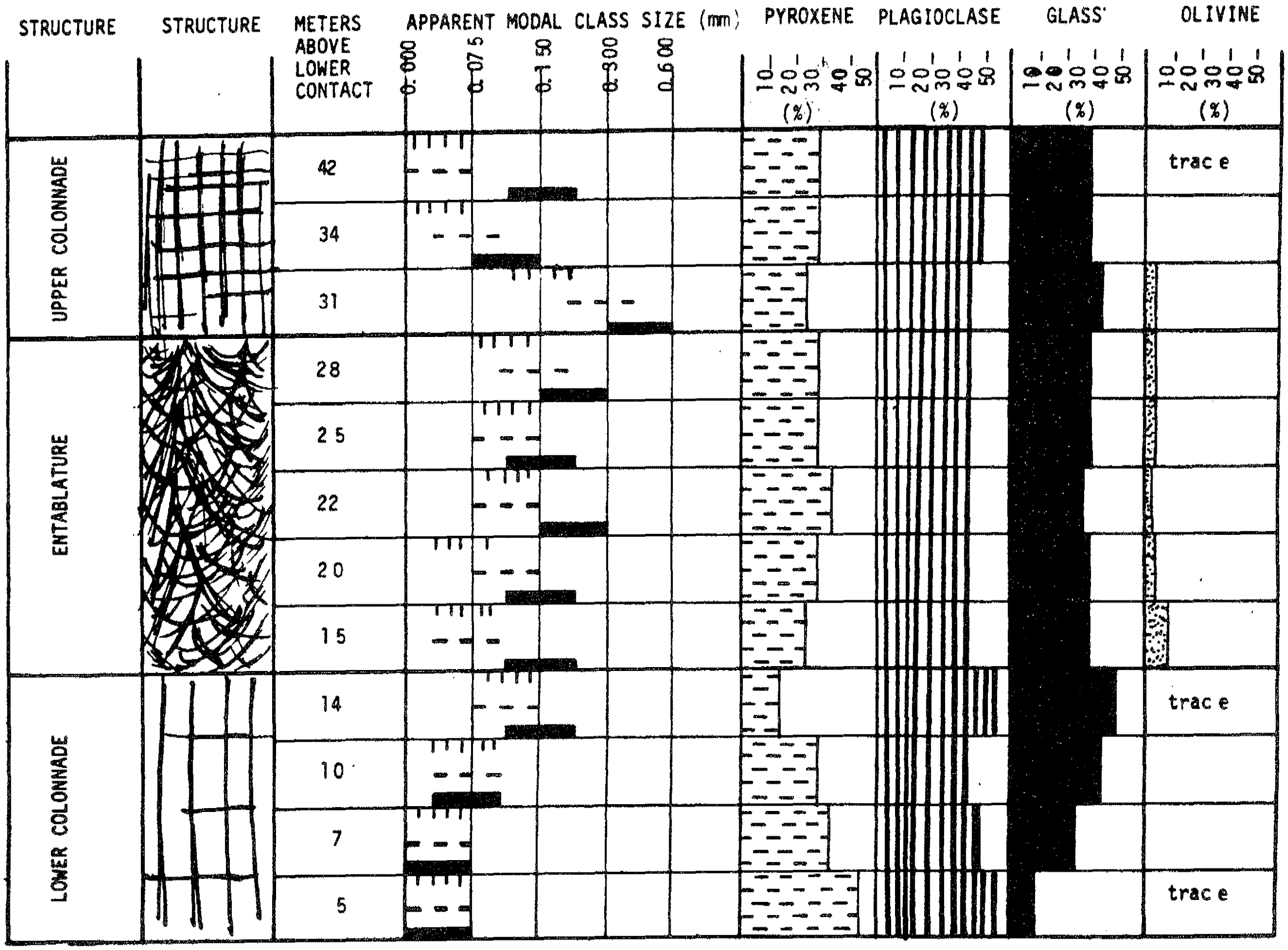


Fig. 18 Plot of mineral and glass content and texture against the Tomkeieff sequence of colonnades and entablature, Orange Mountain Basalt, I-280, West Orange.

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-

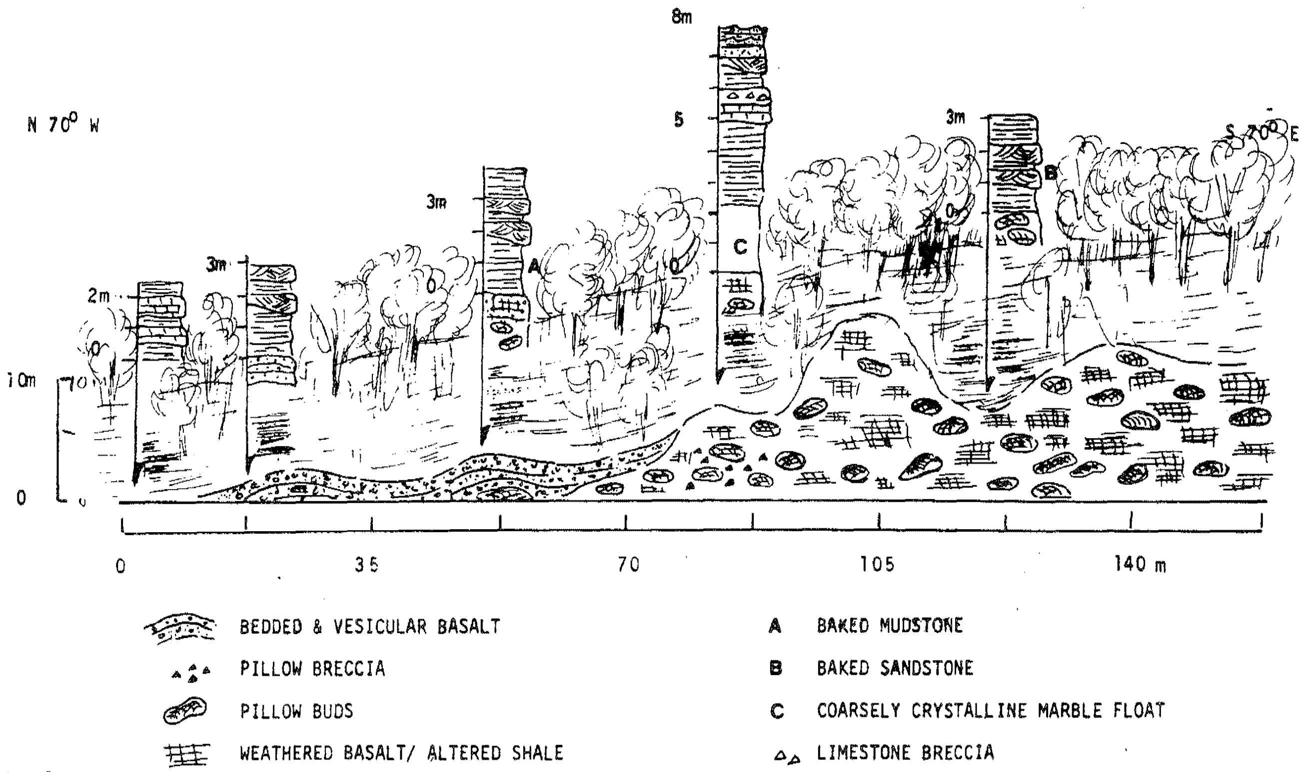


Fig. 20 Field sketch of the Orange Mountain Basalt in contact with the overlying Feltville Formation, ravine near the old copper mine, south side of Blue Brook, Watchung Reservation, Union County.

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

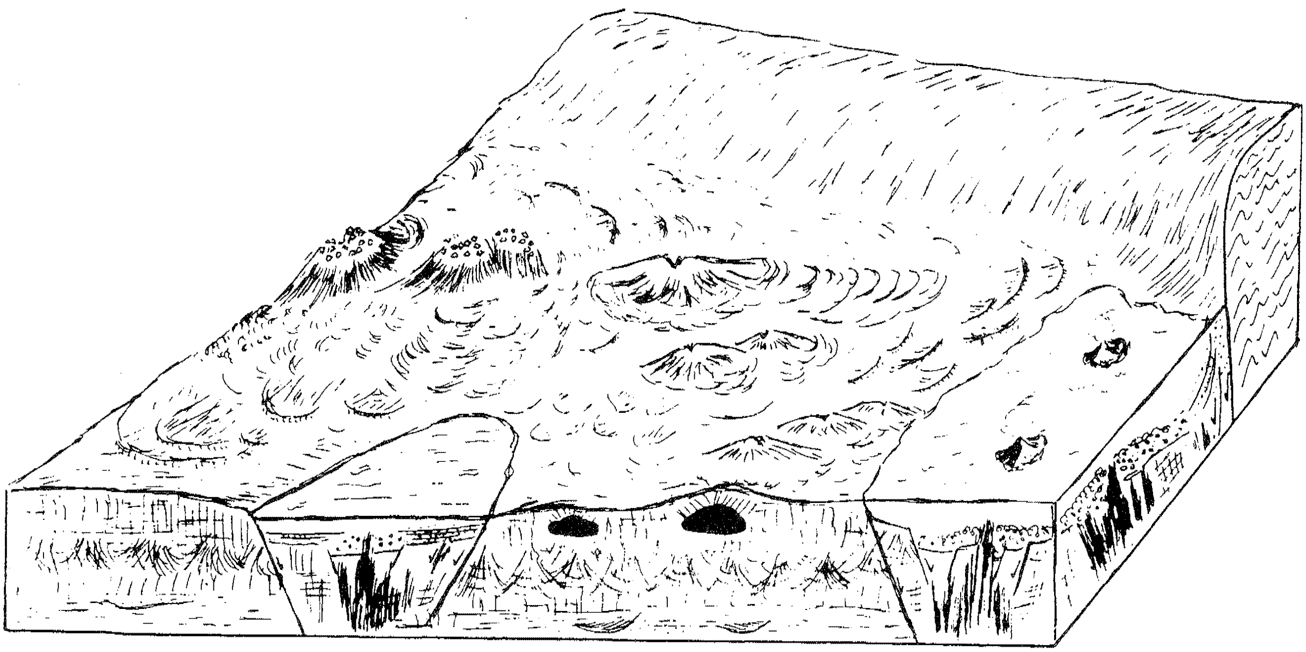


Fig. 21 Schematic block diagram illustrating volcanic structures and paleogeography of the Newark Basin during the extrusion of the First and Second Watchung lavas.

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

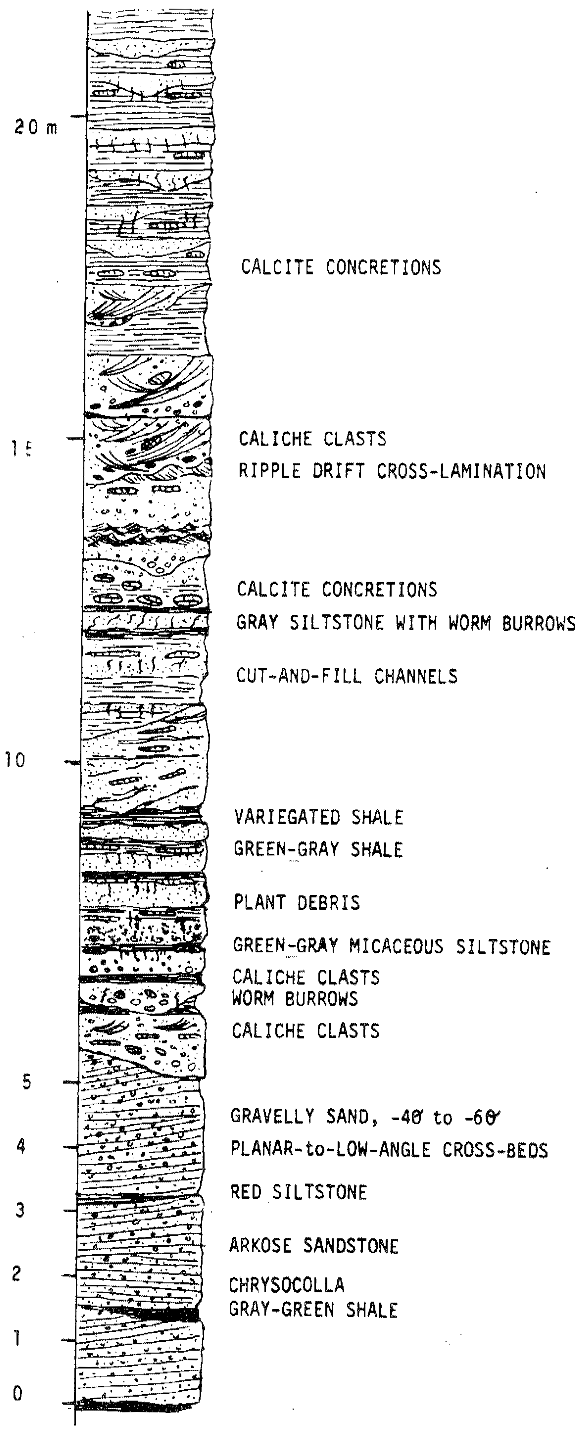


Fig. 22 Columnar section through part of the Passaic Formation, an inferred fluvial-playa sequence; I-280, East Orange.

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).

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 underly-

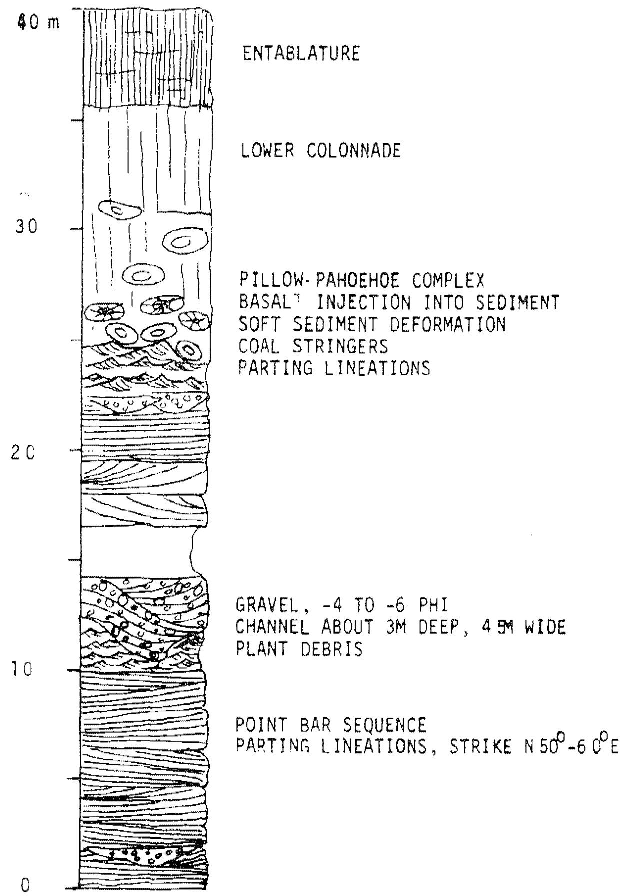
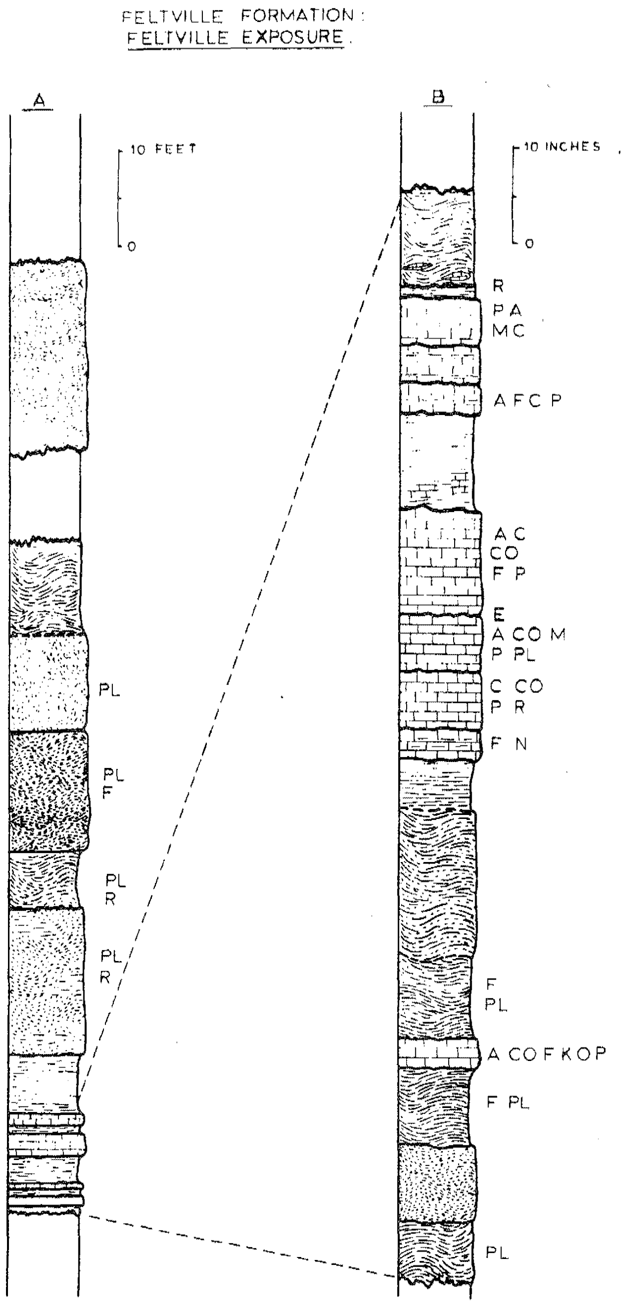


Fig. 23 Columnar section through part of the Feltville Formation, an inferred fluvial-deltaic sequence; small ravine near Belmont and Overlook Avenues, Haledon.

ing 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

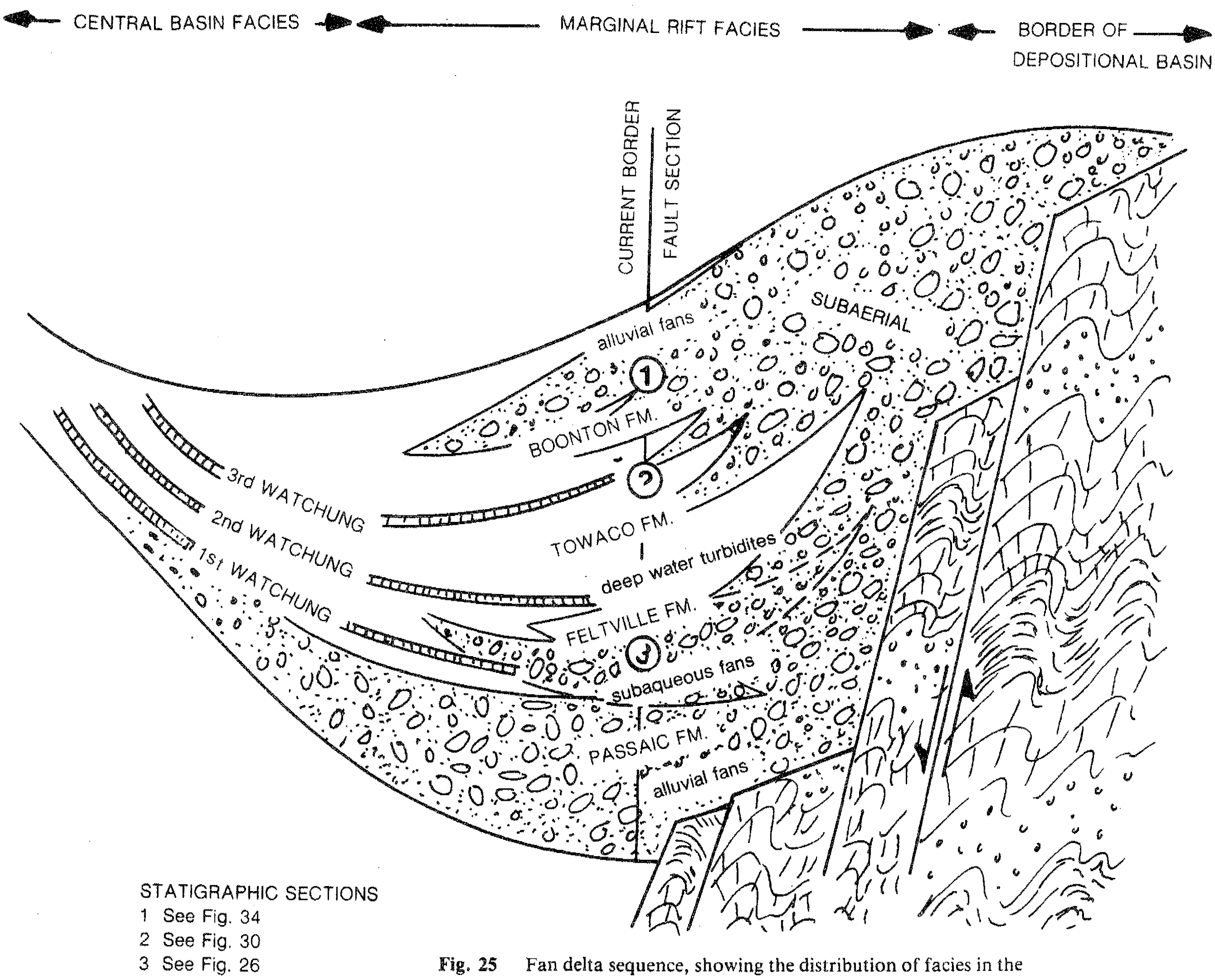


Fig. 25 Fan delta sequence, showing the distribution of facies in the basin.

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.

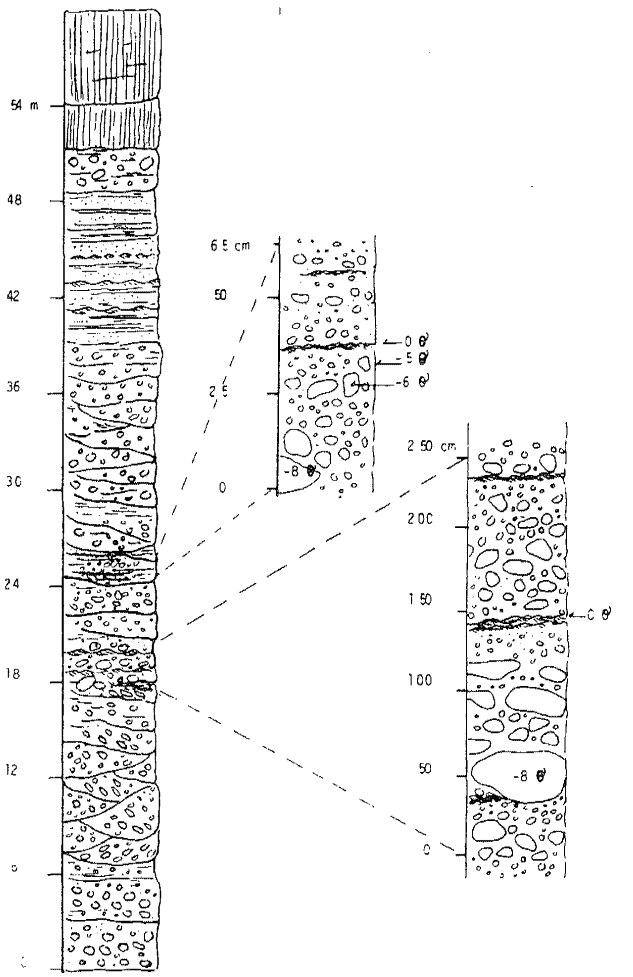


Fig. 26 Stratigraphic section through part of the Feltville Formation, inferred to represent a subaqueous fan deposit of the marginal border facies; beneath Preakness Basalt, behind shopping center off route 202, Oakland.

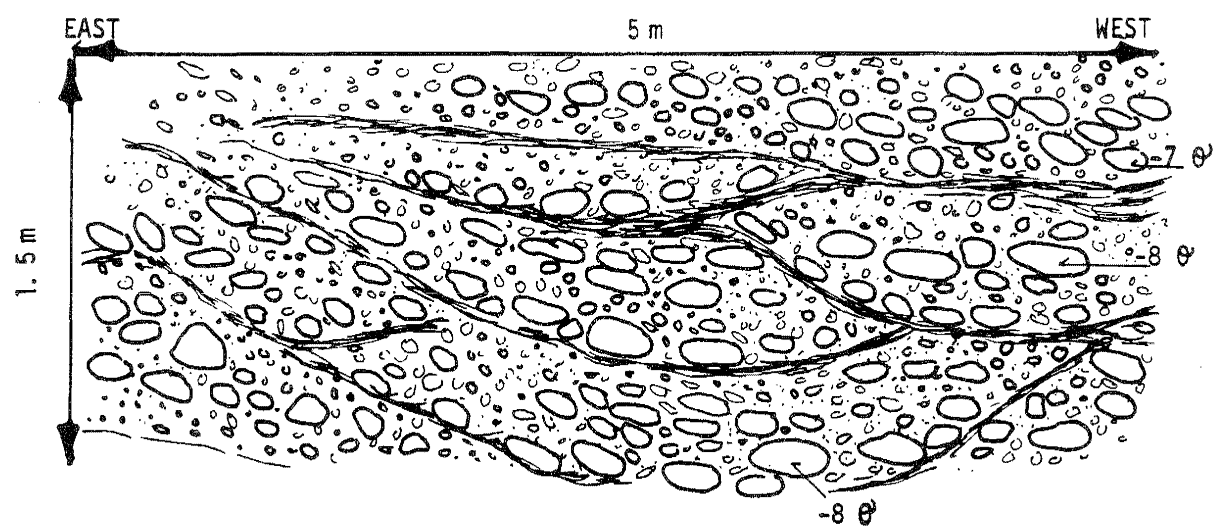


Fig. 27 Field sketch of cut-and-fill channel deposits, Feltville Formation, behind shopping center off route 202, Oakland.

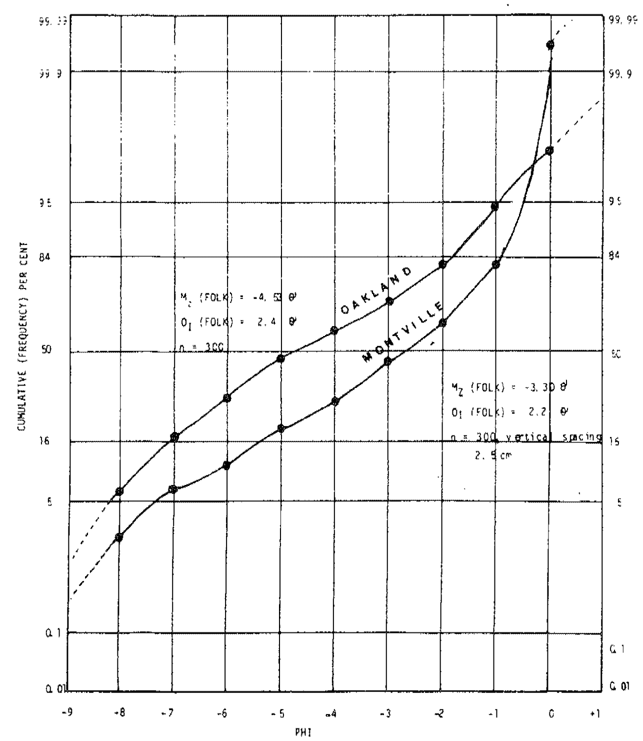


Fig. 28 Cumulative-frequency curve; grain size data in phi units and plotted on probability paper. Data for Oakland and Montville sections obtained from stratigraphy class exercise, Spring, 1980.

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-

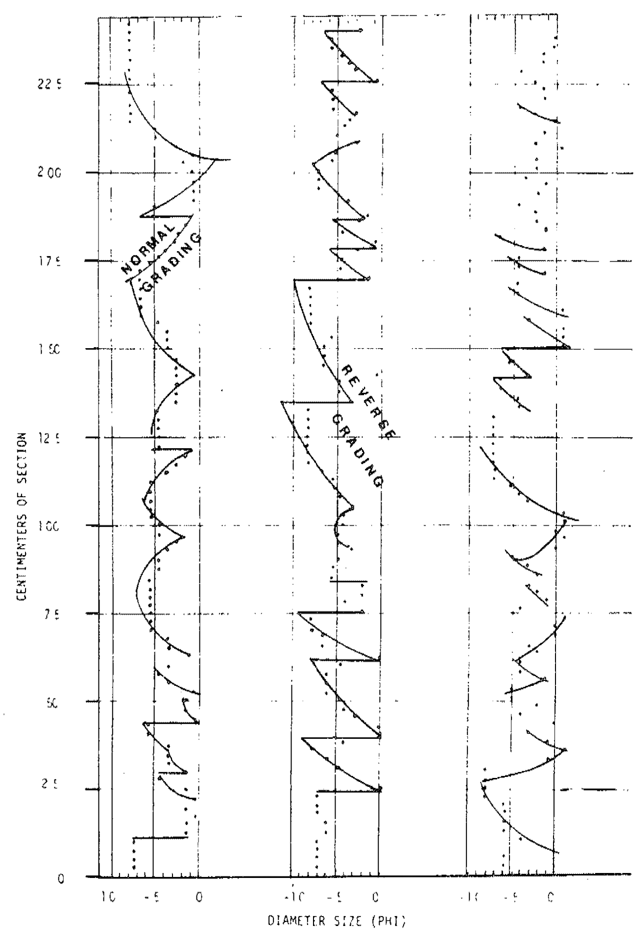


Fig. 29 Patterns of sedimentation reflected in grain-size variation through part of the Feltville Formation, inferred to represent a subaqueous fan deposit. Grain-size data (in phi units) was obtained in vertical section on 2.5 cm sampling grid. Section studied behind shopping center off route 202, about 40 m below Preakness Mountain Basalt, Oakland.

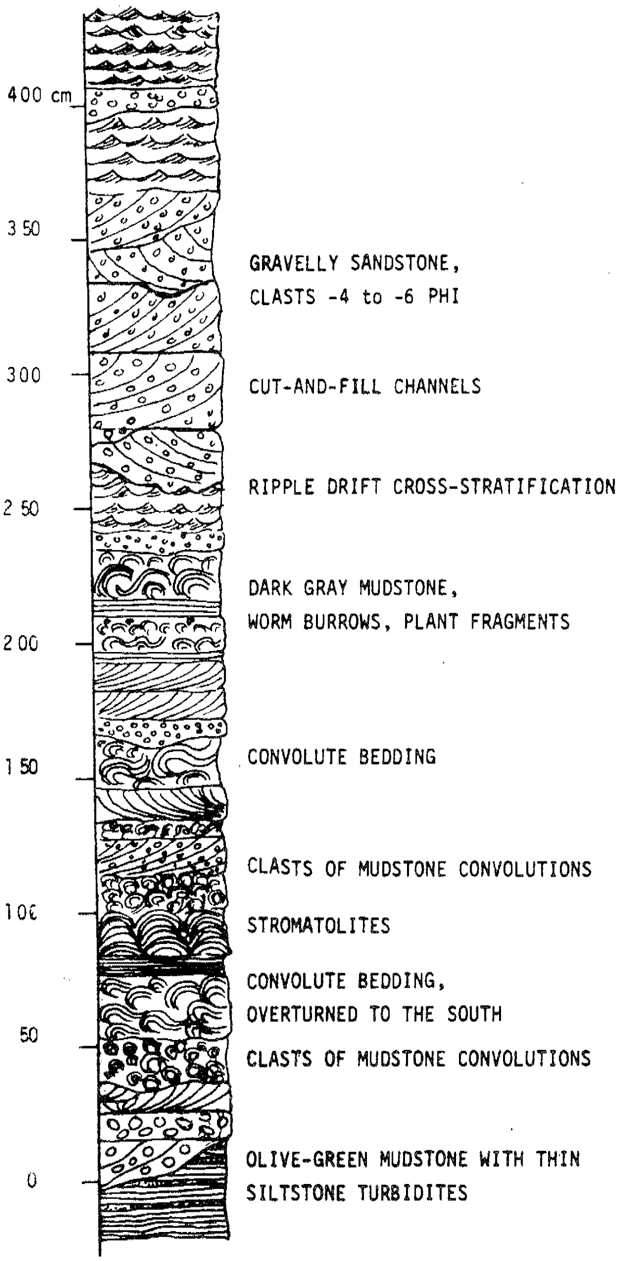


Fig. 30 Columnar section through part of the Towaco Formation deposited on a subaqueous slope over deep water turbidite deposits; Wayne.

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

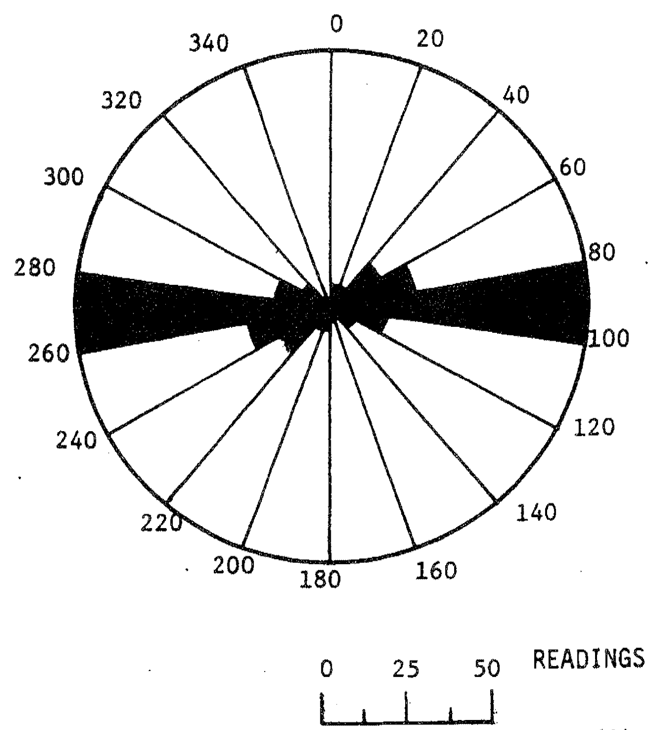


Fig. 31 Current rose diagram: azimuth of elongate pebbles, Boonton Formation, alluvial fan facies, Montville (Data, S. Hall, pers. comm).

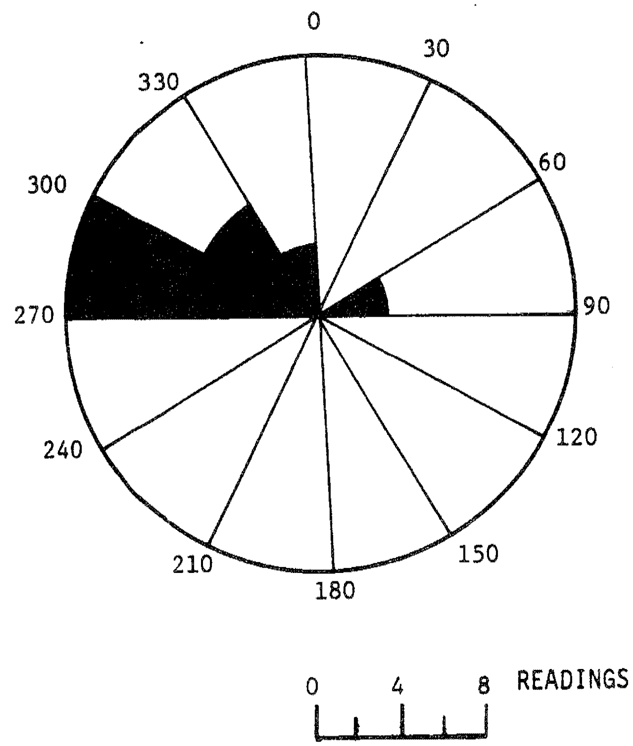


Fig. 32 Current rose diagram: azimuth of imbricated pebbles, Boonton Formation, alluvial fan facies, Montville (Data S. Hall pers. comm.) west-to-east paleocurrent.

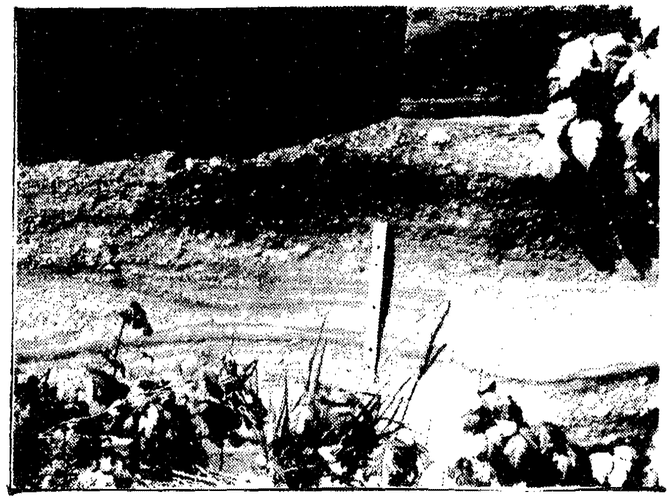
deposits, the poorly sorted and graded beds of the debris flow stand in marked contrast to the stratified, rippled, cross-bedded and scoured bedding of the water laid deposits (Fig. 33). The sheet-like dimensions of the beds are a function of sheet-flood and debris flow sedimentation. Beds in the lower 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 upthrown 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



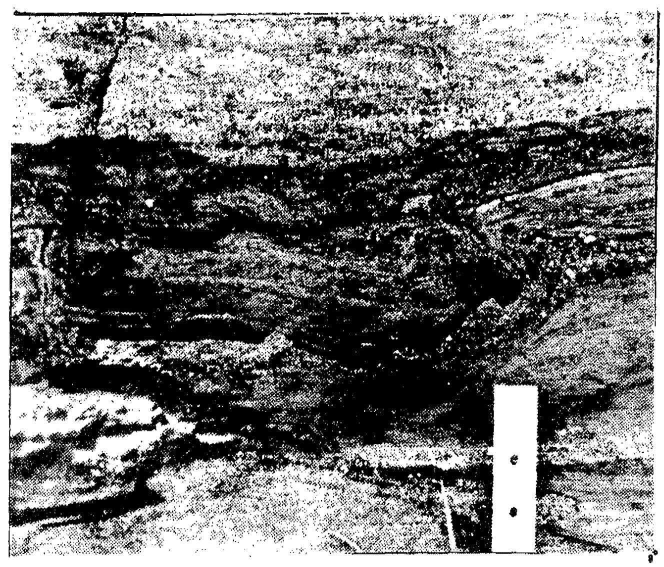


Fig. 33 Sedimentary structures of the Alluvial fan facies, Boonton Formation, near the intersection of River Road and Dahl Ave., Montville.

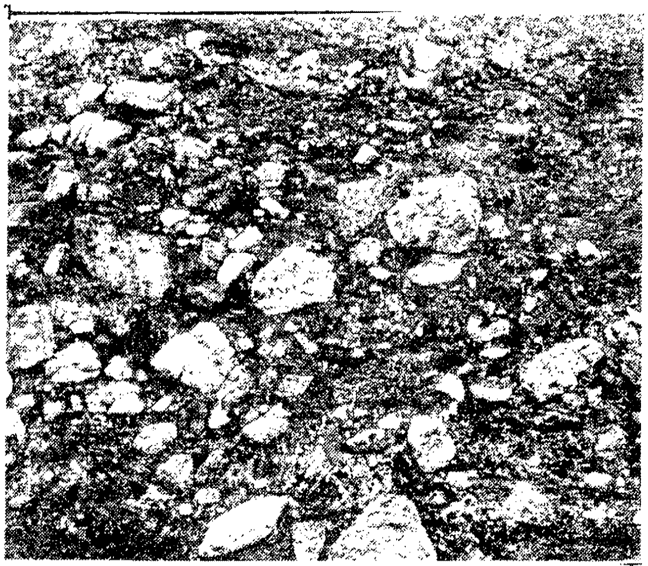
a) Aligned dreilkanters,sandblasted ventifacts; quarter for scale.

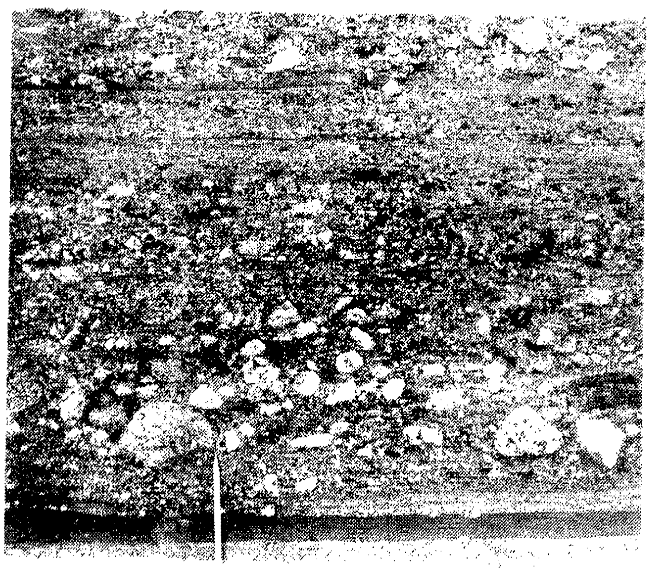
b) Sand wave (left side) and antidunes (lower right side); current left to right 25 cm rule for size.

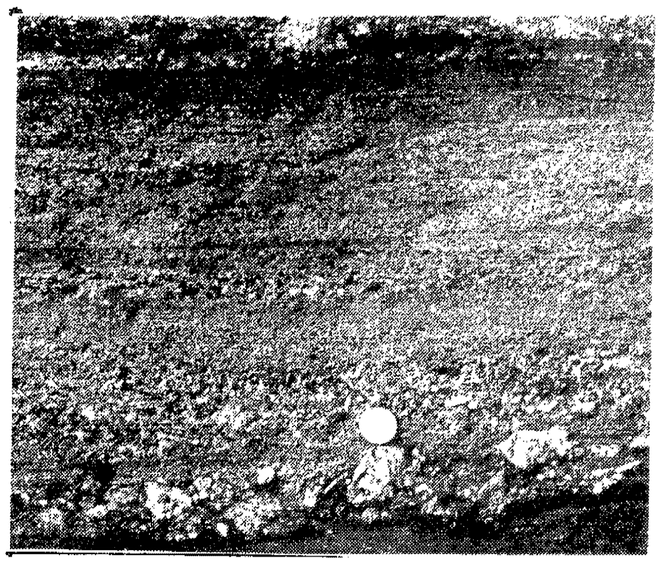
c) Clast orientation, note glacial striations.

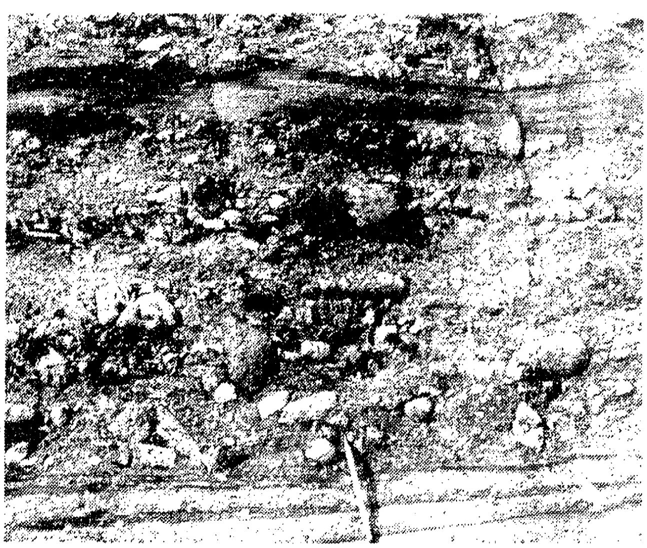
d) Convolute bedding; 10 cm of scale exposed.

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.

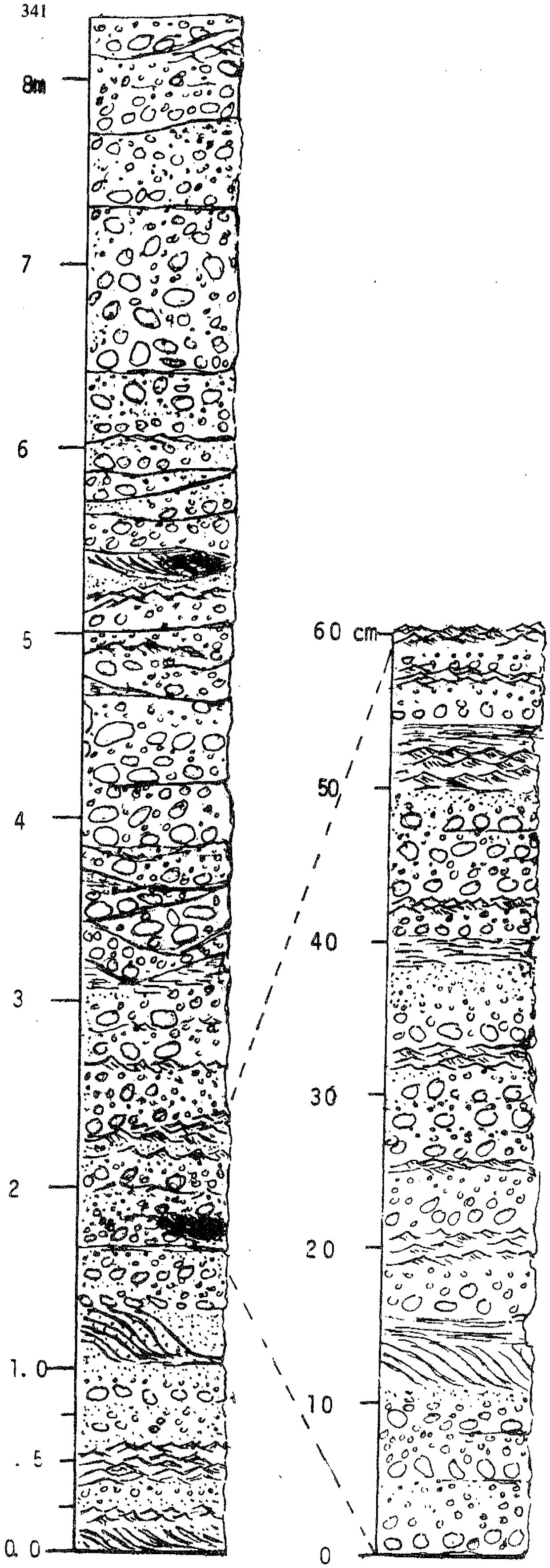


Fig. 34 Stratigraphic section through that part of the Boonton Formation inferred to represent an alluvial fan prograding eastward from the western border fault.

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.

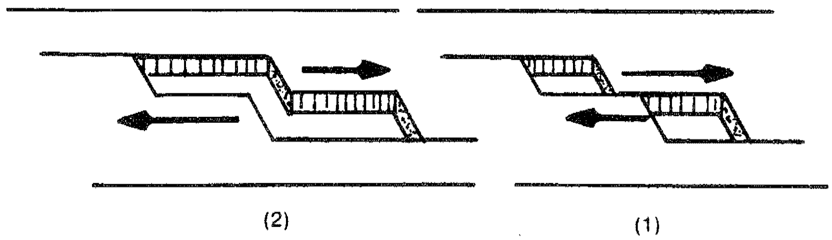


Fig. 35a Coalesces of 2 rhomb-shaped grabens to produce a composite graben

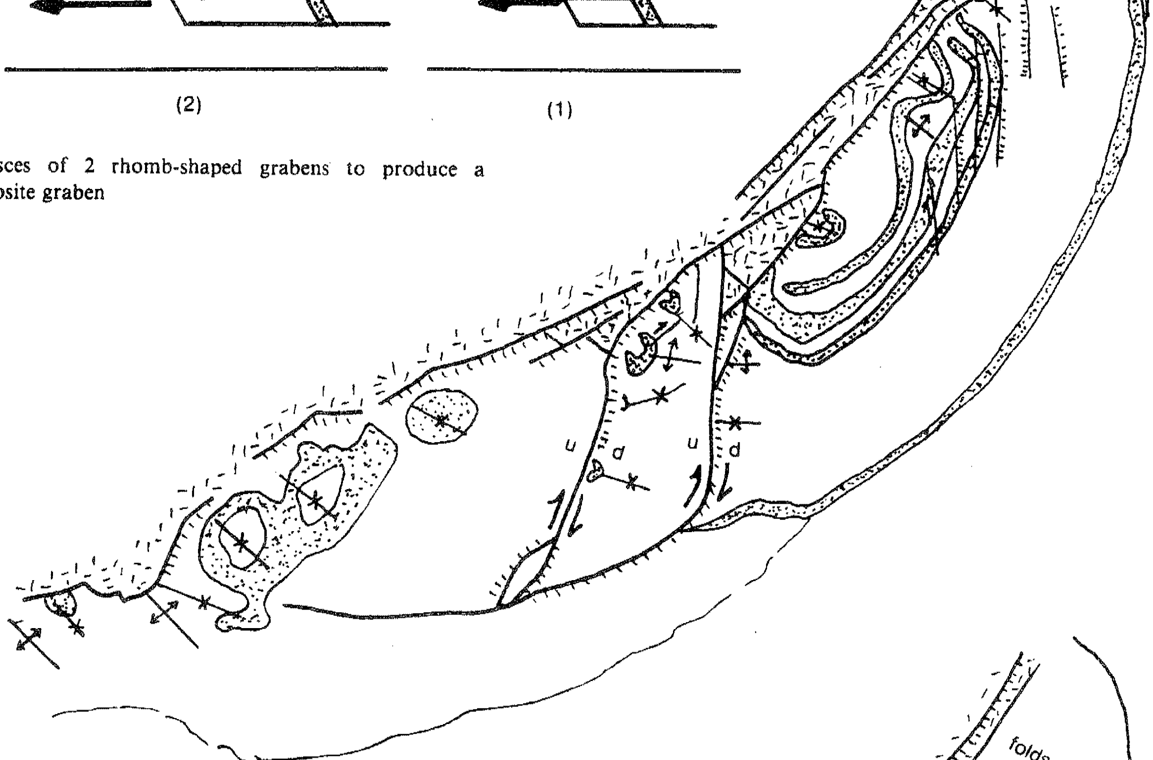


Fig. 35b Generalized stuctural geology map of the basin

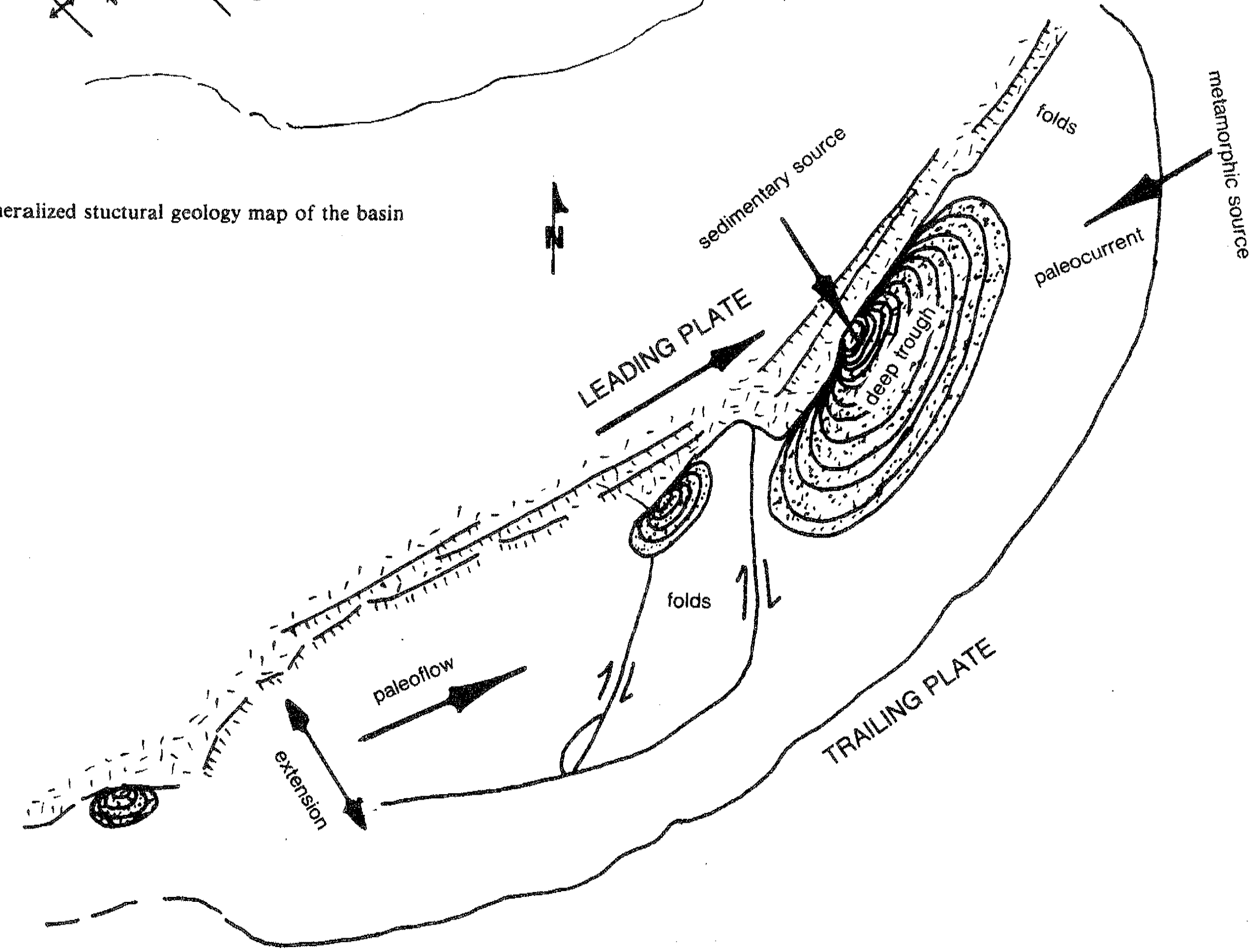


Fig. 35c Tectonic Model for the Early Jurassic

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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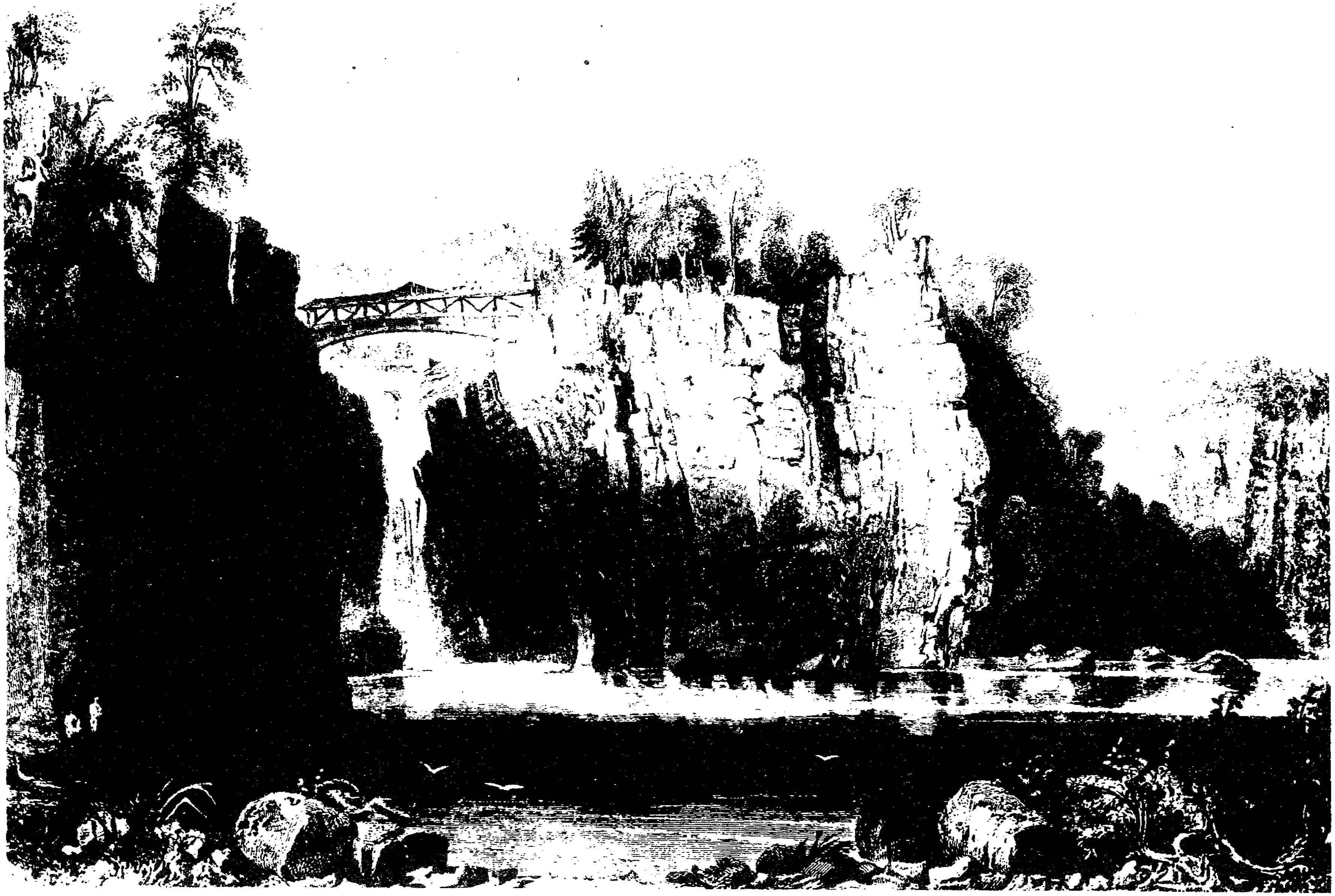

VIEW OF PASSAIC FALLS
by
W.H. Bartlett