

Field Trip Guide for the 68th Annual Meeting of the New York State Geological Association

edited by
Alan I. Benimoff
Anderson A. Ohan



**Hosted by:
Department of Applied Sciences
The College of Staten Island/CUNY
Staten Island, NY 10314**

October 18-20, 1996

Field Trip Guide for the 68th Annual Meeting of the New York State Geological Association

edited by

Alan I. Benimoff
Anderson A. Ohan

October 18-20, 1996

**Hosted by:
Department of Applied Sciences
The College of Staten Island/CUNY
Staten Island, NY 10314**

This guidebook was published by the New York State Geological Association. Additional copies may be obtained from the Executive Secretary of the NYSGA:

Dr. William Kelly
Executive Secretary
New York State Geologic Survey
Room 3140 Cultural Educational Center
Albany, NY 12230

ISSN 1061-8724

TABLE OF CONTENTS

A1	EARLY JURASSIC DIABASE SHEETS AND BASALT FLOWS, NEWARK BASIN, NEW JERSEY: AN UPDATED GEOLOGICAL SUMMARY AND FIELD GUIDE John H. Puffer and Jonathan M. Husch,	1
A2	STRATIGRAPHY, STRUCTURAL GEOLOGY, AND DUCTILE- AND BRITTLE FAULTS OF NEW YORK CITY Charles Merguerian	53
A3	A SURVEY OF THE NATURAL AND URBANIZED SHORELINE ON THE SOUTH SHORE OF LONG ISLAND AND STATEN ISLAND - A DILEMMA IN COASTAL MANAGEMENT Fred P. Wolff, Nicholas K. Coch, and Robert J. Johnson	79
A4	STRATIGRAPHY AND HYDROGEOLOGY OF THE UPPER CRETACEOUS RARITAN, MAGOTHY AND CHEESEQUAKE FORMATIONS, NEW JERSEY COASTAL PLAIN Peter J. Sugarman	99
A5	DEGLACIATION OF CENTRAL LONG ISLAND Les Sirkin	113
A6	HIGHLIGHTS OF STATEN ISLAND GEOLOGY Alan I. Benimoff and Anderson A. Olan	125
B1	SEDIMENTARY ENVIRONMENTS IN THE NEWARK BASIN IN NEW JERSEY AND CONTIGUOUS NEW YORK Gerald M. Friedman	143
B2	SERPENTINITES OF NEW YORK CITY AND VICINITY John H. Puffer	157
	ERRATA <i>in</i> 1995 Field Trips for the 57 th annual meeting of the New York State Geological Association, J.I. Garver, and J.A. Smith, Editors.FLYSCH AND MOLASSE OF THE CLASSICAL TACONIC AND ACADIAN OROGENIES: MODELS FOR SUBSURFACE RESERVOIR SETTINGS GERALD M. FRIEDMAN	177

EARLY JURASSIC DIABASE SHEETS AND BASALT FLOWS, NEWARK BASIN, NEW JERSEY: AN UPDATED GEOLOGICAL SUMMARY AND FIELD GUIDE

JOHN H. PUFFER

Geology Department
Rutgers University
Newark, NJ 07102

JONATHAN HUSCH

Department of Geological and Marine Sciences
Rider University
Lawrenceville, NJ 08648-3099

INTRODUCTION

Many important features of the early Jurassic igneous rocks exposed in the northern and central Newark Basin can be examined at the stops detailed below and located in Figures 1 and 2. The narrative preceding the road log and site descriptions is an update of one presented by Puffer and others (1992) and focuses on two aspects of the igneous activity that are the subject of considerable ongoing research. **Part One - The PRHL and Other Diabase Sheets** reviews the petrogenetic processes responsible for producing the rock compositions found within the sheets. In particular, evidence is presented that low density, late-stage granophyric magmas, produced by the olivine-absent crystal fractionation of an Eastern North America (ENA) quartz-normative high-titanium tholeiite (HTQ) magma, migrated laterally and vertically to the highest structural levels within any given sheet. In addition, each sheet apparently differentiated as a relatively closed system with little, if any, of the residual magmas reaching the surface flows of the Watchung Basalts. **Part Two - The Watchung Basalts** is a review and discussion of the geochemical data showing that the youngest of the three basalts formations, the Orange Mountain Basalt, is part of a huge chemically uniform HTQ igneous province and appears to be largely unchanged by fractionation from its mantle source, either an undepleted subcontinental lithosphere or a slightly enriched lithosphere produced by previous subduction events throughout the Paleozoic. The overlying basalt formations, the Preakness and Hook Mountain Basalts, are much more chemically diverse and contain high-iron (HFQ) and low-titanium (LTQ) quartz-normative ENA magma types derived from mantle sources chemically modified or distinct from the HTQ source.

NARRATIVE

The Newark Supergroup of the Newark Basin ranges in age from Carnian (Late Triassic) to Sinemurian-Pliensbachian (Early Jurassic) and is divided by Olsen (1980) into nine formations with a total thickness of over 7,700 m. From bottom to top these formations are: Stockton Formation (maximum 1800 m); Lockatong Formation (maximum 1150 m); Passaic Formation (maximum 6000 m); Orange Mountain Basalt (OMB; maximum 200 m); Feltville Formation (maximum 600 m); Preakness Basalt (PB; maximum 300 m); Towaco Formation (maximum 340 m); Hook Mountain Basalt (HMB; maximum 110 m); and Boonton Formation (maximum 500+ m).

The Newark Basin is a deeply eroded half graben containing the thickest preserved section of the Newark Supergroup and encompassing an area of approximately 129,500 km² (50,000 mi²) in southeastern New York, northern and central New Jersey, and eastern Pennsylvania (Fig. 1). The sedimentary rocks and volcanic flows of the basin dip 5°-25° to the northwest, typically dipping $\cong 15^\circ$ throughout most of central and northern New Jersey. Red siltstones, dark gray mudstones, and tholeiitic basalts are the dominant lithologies of the basin. Intrusive into the three lowermost formations of the Newark Supergroup are numerous sills, sheets, and dikes of diabasic and related igneous rocks.

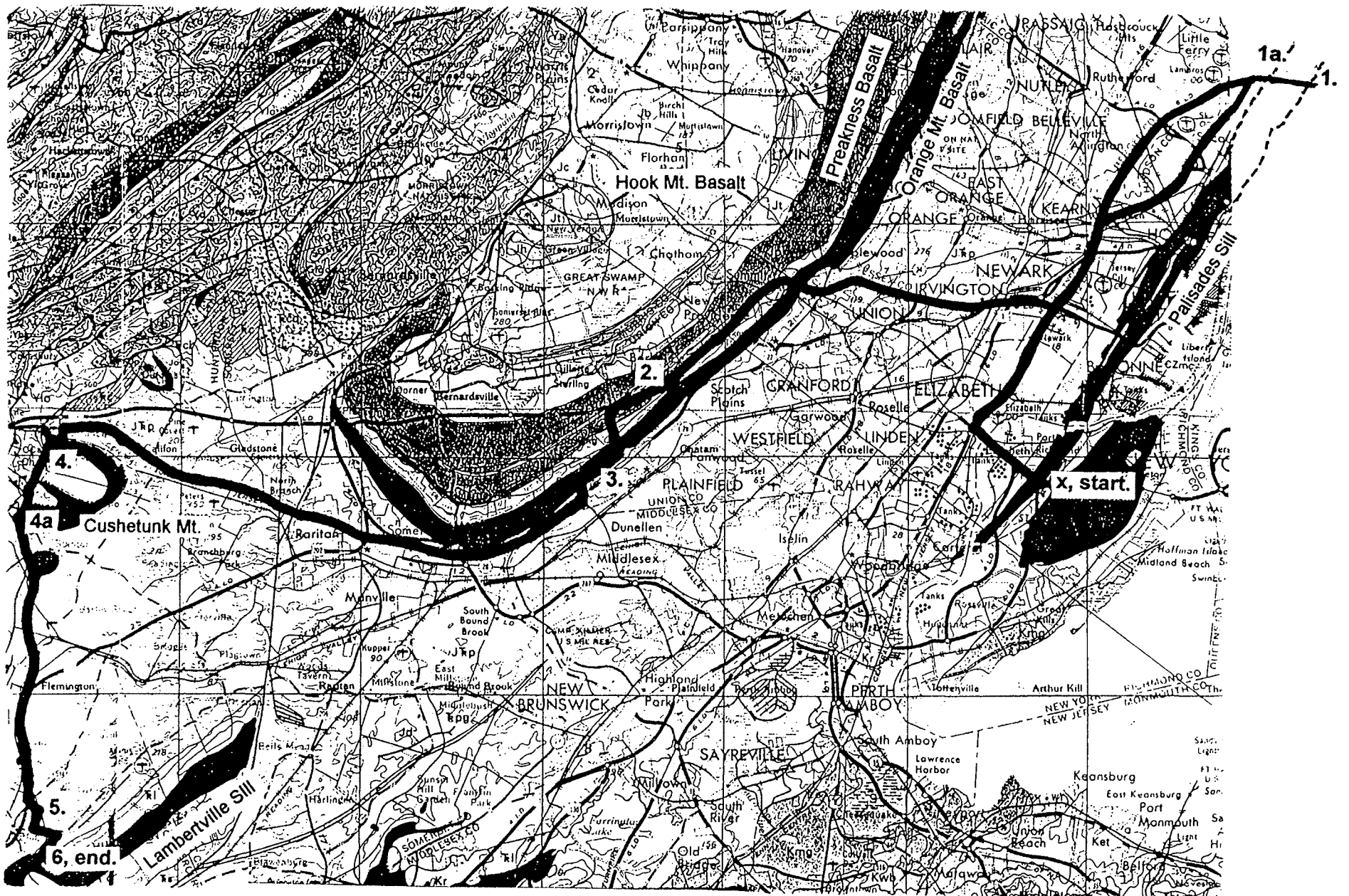


Figure 1. A portion of the Newark 1° x 2° quadrangle by Little and Epstein (1987) with field trip route and numbered stops.

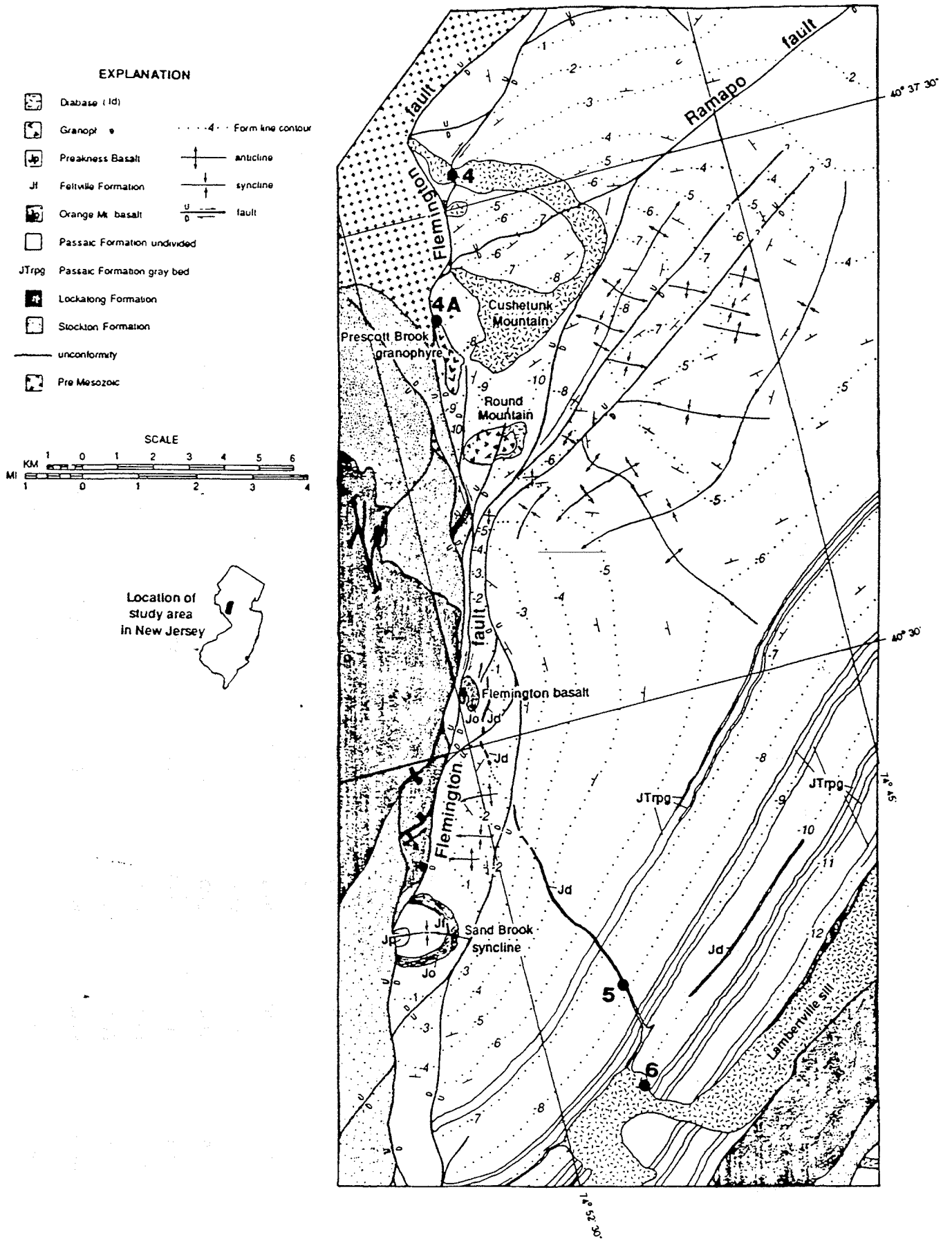


Figure 2. Geologic map (from Houghton and others, 1992) for stops 4-6, central Newark basin, New Jersey. Dotted lines are stratigraphic thickness contours of distance below the OMB. Numbered dots are stop locations.

TABLE 1. NEWARK BASIN DIABASE CHILL AND ENA-HTQ TYPE BASALT COMPOSITIONS

	1	2	3	4	5	6	7	8	9
SiO ₂	52.88	52.52	52.47	52.57	53.18	52.88	52.55	52.69	52.65
TiO ₂	1.13	1.11	1.17	1.15	1.13	1.17	1.22	1.11	1.13
Al ₂ O ₃	14.26	14.22	14.69	14.16	13.73	14.29	14.64	14.57	14.37
FeO*	10.13	9.98	9.95	10.15	10.16	10.30	10.40	9.97	10.58
MnO	0.16	0.16	0.18	0.17	0.19	0.17	0.16	0.20	0.19
MgO	7.91	8.16	7.69	7.82	7.99	7.49	7.67	7.83	7.49
CaO	10.26	11.02	10.93	10.66	10.48	10.56	10.44	10.90	10.78
Na ₂ O	2.01	2.08	2.16	2.29	2.30	2.19	2.06	1.99	2.15
K ₂ O	1.12	0.61	0.62	0.84	0.70	0.82	0.89	0.61	0.67
P ₂ O ₅	0.13	0.14	0.14	0.18	0.14	0.13	0.14	0.12	---
Ba	156	147	154	149	166	158	195	160	---
Cr	298	281	258	279	311	240	315	302	277
Cu	99	105	107	113	122	124	110	121	111
Ni	92	89	87	96	98	81	95	89	81
Rb	37	16	15	33	32	32	---	25	21
Sc	36	36	37	38	36	37	37	---	---
Sr	189	169	208	229	170	195	175	187	186
V	265	264	266	255	285	273	235	310	---
Zr	101	94	104	102	102	115	120	115	92

Major elements normalized to 100 weight percent anhydrous. Trace elements in ppm.

*All iron as FeO. 1=average Quarry dike chill (Husch and Schwimmer, 1995); 2=Byram (Point Pleasant) diabase chill (Husch and others, 1984); 3=Lambertville sill chill-northeast section (Husch and Roth, 1988); 4=average Lambertville sill chill-Delaware River section (Eliason, 1986); 5=average Baldpate Mountain diabase chill (Trione, 1985); 6=Cushetunk Mountain diabase chill (Keely and Husch, 1993); 7=Palisades sill chill (Walker, 1969); 8=average York Haven type basalt (Smith and others, 1975); 9=average ENA-HTQ basalt (Weigand and Ragland, 1970)

TABLE 2. FRACTIONATION MASS-BALANCE MODELS (continued)

3.5-2 Weight Percent MGO Interval										2-1 Weight Percent MGO Interval				
Parent: L ₃		Model 1			Parent: L ₃		Model 2			Parent: L ₄		Daughter: L ₃		
Solution		% Cumulate			Solution		% Cumulate [†]			Solution		% Cumulate		
3.5%	1.000				3.5%	1.000				2%	1.000			
CPX	-0.118	29.194			CPX	-0.104	21.409			CPX	-0.039	21.058		
OPX	0.016	4.083			OPX	-0.149	30.824			OPX	-0.013	6.715		
PLAG1	-0.251	62.157			PLAG1	-0.282	58.297			PLAG2	-0.072	38.537		
MAG	-0.018	4.402			MAG	-0.029	6.092			MAG	-0.044	23.477		
ILM	-0.001	0.164			ILM	-0.002	0.367			ILM	-0.015	7.890		
2%	0.597				OL	0.082	-16.988			AP	-0.004	2.325		
					2%	0.518				1%	0.814			
		R ² = 0.413					R ² = 0.032					R ² = 0.331		
		Daughter	Calc.	Resid.		Daughter	Calc.	Resid.		Daughter	Calc.	Resid.		
SiO ₂		56.40	56.87	-0.47	SiO ₂	56.40	56.48	-0.08		SiO ₂	61.56	61.26	0.30	
TiO ₂		2.51	2.53	-0.02	TiO ₂	2.51	2.51	0.00		TiO ₂	1.56	1.56	0.00	
Al ₂ O ₃		11.94	12.03	-0.09	Al ₂ O ₃	11.94	11.95	-0.01		Al ₂ O ₃	12.06	11.96	0.10	
FeO*		15.36	15.48	-0.12	FeO*	15.36	15.39	-0.03		FeO*	12.63	12.57	0.06	
MnO		0.23	0.24	-0.01	MnO	0.23	0.21	0.02		MnO	0.22	0.21	0.01	
MgO		1.91	1.87	0.04	MgO	1.91	1.91	0.00		MgO	1.03	1.07	-0.04	
CaO		5.62	5.62	0.00	CaO	5.62	5.62	0.00		CaO	4.66	4.67	-0.01	
Na ₂ O		3.50	3.28	0.22	Na ₂ O	3.50	3.57	-0.07		Na ₂ O	3.39	3.86	-0.47	
K ₂ O		2.00	1.71	0.29	K ₂ O	2.00	1.95	0.05		K ₂ O	2.41	2.41	0.00	
P ₂ O ₅		0.54	0.35	0.19	P ₂ O ₅	0.54	0.41	0.13		P ₂ O ₅	0.48	0.44	0.04	
				R _D ²				K _D					K _D	
Ba	445	395	50	0.244	Ba	445	442	3	0.238	Ba	489	530	41	0.154
Cr	16	4	12	3.891	Cr	16	1	15	5.803	Cr	14	10	4	3.331
Cu	241	298	-57	0.289	Cu	241	329	-88	0.292	Cu	278	272	6	0.404
Ni	18	18	0	2.487	Ni	18	17	1	2.258	Ni	18	3	15	9.974
Rb	67	54	13	0.065	Rb	67	62	5	0.057	Rb	72	82	-10	0.041
Sc	31	36	-5	0.878	Sc	31	35	-4	0.977	Sc	20	31	-11	1.026
Sr	169	173	-4	1.338	Sr	169	175	-6	1.246	Sr	145	175	-30	0.833
V	104	309	-205	1.089	V	104	244	-140	1.427	V	25	46	-21	5.019
Zr	255	248	7	0.146	Zr	255	281	-26	0.141	Zr	301	300	1	0.213
La	31.5	24.8	6.7	0.242	La	31.5	27.4	4.1	0.253	La	43.0	35.0	8.0	0.486
Sm	9.20	7.33	1.87	0.250	Sm	9.20	8.24	0.96	0.233	Sm	11.8	10.3	1.5	0.445
Eu	2.45	1.04	1.41	1.246	Eu	2.45	1.06	1.39	1.161	Eu	2.82	2.46	0.36	0.978
Lu	0.73	0.53	0.20	0.260	Lu	0.73	0.58	0.15	0.276	Lu	0.92	0.81	0.11	0.492

*All iron reported as FeO.

[†]Cumulate values are weight percents of the minerals in the fractionated mineral assemblage removed from the parent composition.

[‡]Trace-element bulk distribution coefficients and abundances calculated on the basis of perfect fractional crystallization and the mineral abundances from the major-element solutions.

TABLE 2. MINERAL FRACTIONATION MASS-BALANCE MODELS

8-5 Weight Percent MGO Interval						5-3.5 Weight Percent MGO Interval								
Model 1			Model 2			Model 1			Model 2					
Parent: L ₁	Daughter: L ₂		Parent: L ₁	Daughter: L ₂		Parent: L ₂	Daughter: L ₂		Parent: L ₂	Daughter: L ₂				
	Solution	% Cumulate [†]		Solution	% Cumulate [†]		Solution	% Cumulate [†]		Solution	% Cumulate [†]			
Chill	1.000		Chill	1.000		5%	1.000		5%	1.000				
CPX	-0.107	63.960	CPX	-0.117	49.962	CPX	-0.090	28.545	CPX	-0.090	28.545			
OPX	-0.060	36.040	OPX	-0.071	30.372	OPX	-0.037	11.775	OPX	-0.037	11.775			
5%	0.833		PLAG1	-0.042	17.819	PLAG1	-0.188	59.389	PLAG1	-0.188	59.389			
			MAG	-0.003	1.487	ILM	-0.001	0.385	ILM	-0.001	0.385			
			ILM	-0.001	0.360	5%	0.683		5%	0.683				
			5%	0.766										
		R ² = 0.264			R ² = 0.040						R ² = 0.012			
	Daughter	Calc.	Resid.	Daughter	Calc.	Resid.	Daughter	Calc.	Resid.	Daughter	Calc.	Resid.		
SiO ₂	53.15	52.82	0.33	SiO ₂	53.15	53.18	-0.03	SiO ₂	53.84	53.78	0.07			
TiO ₂	1.30	1.30	0.00	TiO ₂	1.30	1.30	0.00	TiO ₂	1.77	1.77	0.00			
Al ₂ O ₃	16.25	18.49	-0.24	Al ₂ O ₃	16.25	16.27	-0.02	Al ₂ O ₃	15.09	15.07	0.02			
FeO*	10.03	9.97	0.06	FeO*	10.03	10.03	0.00	FeO*	12.42	12.41	0.01			
MnO	0.17	0.16	0.01	MnO	0.17	0.17	0.00	MnO	0.18	0.21	-0.03			
MgO	5.11	5.32	-0.21	MgO	5.11	5.11	0.00	MgO	3.61	3.61	0.00			
CaO	10.33	10.42	-0.09	CaO	10.33	10.33	0.00	CaO	8.90	8.90	0.00			
Na ₂ O	2.71	2.51	0.20	Na ₂ O	2.71	2.53	0.17	Na ₂ O	2.88	2.95	-0.07			
K ₂ O	0.80	0.83	-0.03	K ₂ O	0.80	0.88	-0.08	K ₂ O	1.09	1.09	0.00			
P ₂ O ₅	0.15	0.17	-0.02	P ₂ O ₅	0.15	0.18	-0.03	P ₂ O ₅	0.21	0.22	-0.01			
			K _D [†]			K _D [†]					K _D [†]			
Ba	182	186	-4	0.031	Ba	182	199	-17	0.093	Ba	267	243	23	0.237
Cr	41	42	-1	11.572	Cr	41	31	10	9.316	Cr	18	10	8	4.696
Cu	122	121	1	0.407	Cu	122	192	-7	0.364	Cu	206	180	46	0.280
Ni	55	47	8	4.747	Ni	55	37	17	4.415	Ni	39	40	-1	1.853
Rb	28	30	-2	0.021	Rb	28	32	-4	0.033	Rb	33	40	-7	0.063
Sc	33	29	4	2.144	Sc	33	30	3	1.726	Sc	34	34	0	0.933
Sr	214	217	-3	0.071	Sr	214	213	1	0.403	Sr	206	192	14	1.279
V	269	264	5	1.048	V	269	258	11	1.109	V	324	327	-3	0.485
Zr	114	113	1	0.204	Zr	114	122	-8	0.182	Zr	159	158	1	0.138
La	12.1	12.6	-0.5	0.053	La	12.1	13.5	-1.4	0.108	La	16.7	16.6	0.1	0.165
Sm	3.71	3.80	-0.09	0.320	Sm	3.71	4.07	-0.36	0.284	Sm	4.96	5.05	-0.09	0.189
Eu	1.17	1.18	-0.01	0.321	Eu	1.17	1.17	0.00	0.569	Eu	1.18	1.10	0.08	1.157
Lu	0.33	0.33	0.00	0.416	Lu	0.33	0.36	-0.03	0.358	Lu	0.36	0.45	-0.09	0.201

PART ONE: THE PRHL AND OTHER DIABASE SHEETS

The Palisades sill intruded approximately 201 million years ago (Sutter, 1988; Dunning and Hodych, 1990). Although the Palisades is largely conformable along most of its exposed strike length in northern New Jersey (Stop 1), it clearly is discordant north of Nyack, New York, eventually reaching the Jurassic paleosurface near Suffern, New York (Kodama, 1983; Ratcliffe, 1988). Also highly discordant are the central sections and southwestern ends of the Rocky Hill diabase and Lambertville sill (Figs. 1 and 2) Stop 6; two-dimensional gravity and magnetic models by Pappano and others (1990) confirm the crosscutting nature of these intrusions in the subsurface as well. Husch and others (1988) and Husch (1992) have shown that both the Rocky Hill diabase and Lambertville sill are extremely similar chemically and mineralogically to the Palisades sill (*sensu stricto*) of the northern Newark Basin. In addition to compositional similarities, structural, geophysical, and well-log data (Darton 1890; Bascom and others, 1909; Sandberg and others, 1996; Klewsaat and Gates, 1994) show the Lambertville sill and Rocky Hill diabase to be southwestern continuations of a single Palisades-Rocky Hill-Lambertville (PRHL) "megasheet," extending ~150 km from southeastern New York to eastern Pennsylvania (Husch, 1992). Thus, the PRHL megasheet is exposed at various structural levels, ranging upward from just above the angular unconformity with the underlying basement to just below the Jurassic paleosurface over which the OMB flowed. A separate, presumably contemporaneous HTQ-derived intrusion, the Cushetunk Mountain diabase (CMD; Stop 4), also exhibits similar structural relief (Houghton and others, 1992; Keely and Husch, 1993; Jakubicki and Husch, 1995).

There appears little question that the PRHL megasheet is a composite body, involving as many as four separate magma pulses, with each causing distinct reversals of whole-rock and mineral variation trends (Walker, 1969; Puffer and others, 1982; Shirley, 1987; Husch, 1992; Steiner and others, 1992; Gorrington and Naslund, 1995). The dominant (and perhaps only) magma type involved appears to be the HTQ type, although LTQ-related rocks may be present at sporadic localities (Husch, 1992). Furthermore, the genetic relationship between the HTQ magma type and the apparent magma pulse that formed the (in)famous olivine zone (OZ) of the Palisades sill section of the PRHL (Stop 1) is ambiguous (Husch, 1990, 1992; Gorrington and Naslund, 1995). Regardless, what is certain is that the OZ does not represent the gravity driven, in-situ accumulation of olivine derived from the overlying magma of the PRHL megasheet. Rather, it appears to be a distinct and slightly later injection of olivine-rich magma that may (Gorrington and Naslund, 1995) or may not (Husch, 1990; 1992) be comagmatic with the HTQ magma found at all chilled margins.

Petrography

As reported by Walker (1969), Shirley (1987), Houghton and others (1992), Husch (1992), Steiner and Others (1992), and Gorrington and Naslund (1995), textures within the PRHL megasheet and other diabase intrusions vary from partly glassy, fine-grained basalts to coarsely crystalline gabbros. Subophitic intergrowths of plagioclase and clinopyroxene are common, except in the OZ where the texture can be strongly poikilitic (Gorrington and Naslund, 1995). Other than in the OZ, where olivine may be as abundant as 28 modal percent (Gorrington and Naslund, 1995), olivine is conspicuously rare or absent. Most diabase samples are composed predominantly of plagioclase (An_{45-70}), clinopyroxene (augite and pigeonite), orthopyroxene (En_{65-80}), and Fe-Ti oxides. Accessory minerals include biotite, apatite, quartz, alkali feldspar, sphene, and various opaque sulfides. In granophyric samples, clinopyroxene may be replaced by hornblende and biotite, plagioclase typically is much more sodic, and quartz and alkali feldspar occur in graphic micropegmatitic intergrowths. Most coarse-grained rocks, especially granophyric compositions, exhibit at least some amount of deuteric alteration, as evidenced by the saussuritization of plagioclase and the uralitization, epidotization, and/or chloritization of pyroxene and olivine.

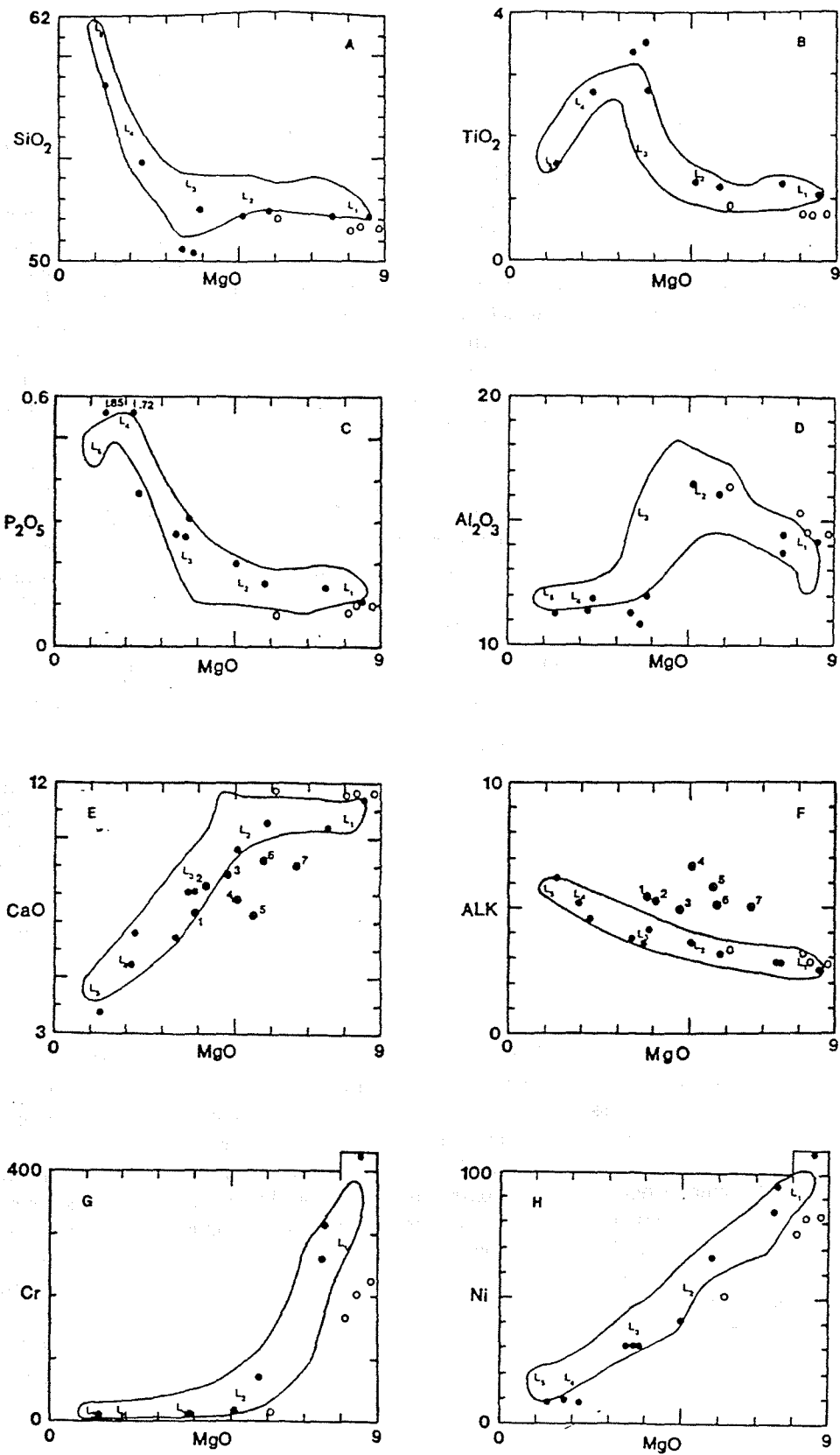


Figure 3. Selected whole-rock oxide and trace-element vs. MgO variation trend fields (from Husch, 1992) for diabase from the PRHL of the central Newark basin and associated sheets. Olivine-free samples from the Palisades section of the PRHL (solid circles, Walker, 1969) and possible LTOQ-related samples from central New Jersey (open circles) also are shown. L_1 , L_2 give positions of average compositions used in mass-balance models (see Tables 2 and 3). Samples numbered in E and F exhibit geochemical evidence (anomalously low calcium and high alkali contents) of contamination. ALK is total alkali ($Na_2O + K_2O$). Oxide concentrations have been normalized to 100 weight percent anhydrous and trace elements are given in ppm.

Whole-Rock Geochemistry

Whole-rock geochemical data for the PRHL and other diabase sheets have been presented by numerous workers (e.g. F. Walker, 1940; K. Walker, 1969; Puffer and others, 1982; Shirley, 1987; Husch and others, 1988; Houghton and others, 1992; Husch, 1992; Steiner and others, 1992, Gorrington and Naslund, 1995). Selected major- and trace-element versus MgO variation trends from Husch (1992) are presented in Figures 3A-H. Although the fields shown are constructed largely from data for the central Newark Basin portion of the PRHL megasheet, the trends are extremely similar to those found for the northern Newark basin (Palisades) section. The trends shown do not include samples with greater than 9 wt% MgO or any samples from the OZ. The former are believed to be mafic enriched because of the accumulation of orthopyroxene and clinopyroxene, while the latter are greatly enriched in modal olivine (see below).

Although coarse-grained whole-rock compositions are quite variable, all fine-grained chilled margin samples are extremely similar, exhibiting a very restricted range of HTQ compositions (Table 1). This is in contrast to the multiple ENA magma types represented by fine-grained diabase and basalt samples from the Gettysburg, Hartford, and Culpeper Basins (Smith and others, 1975; Philpotts and Martello, 1986; Froelich and Gottfried, 1988) and the northern Newark basin (Puffer, 1988, 1992; see Part Two). The compositions of the fine-grained chilled margin samples are assumed to give the best available approximation of the HTQ magma parental to the PRHL and other diabase sheets and is labelled L1 in Figures 3A-H.

A number of the PRHL variation trend fields shown in Figures 3A-H have major inflection points, occurring at MgO contents of approximately 5, 3.5, and 2 wt%. Average whole-rock compositions approximating the points of inflection are labelled L2, L3, and L4, respectively. The point labelled L5 is the average composition of four granophyre-rich samples and is believed to approximate the final end-product of magma differentiation.

Crystal Fraction Models

In an attempt to quantify earlier differentiation models, Husch (1992) completed a series of major-element mass-balance calculations, utilizing the least-squares matrix inversion routine and the trace-element crystal-liquid distribution coefficients of Geist and others (1985). Results for compositions L1-L5 are summarized here and shown in Table 2, including the trace-element abundances produced by the major-element models. The agreement of calculated trace-element abundances with measured abundances provides an independent measure of the validity of the models.

Between 8 and 5 wt% MgO, two models are preferred. One produces the lowest calculated trace-element residuals while the other minimizes major-element residuals. Both models indicate that the early fractionation of the PRHL megasheet was dominated by pyroxene, with clinopyroxene being removed preferentially over orthopyroxene; plagioclase and Fe-Ti oxides may or may not have been involved. The removal (or addition) of olivine is not required and only increases trace-element residuals. For the 5 to 3.5 wt% MgO interval, the most significant change found is the dramatic increase in the required amount of fractionated plagioclase, averaging about 60% in all models run. Including olivine in the models improves major-element residuals only slightly, while increasing trace-element residuals significantly. For the 3.5 to 2 wt% MgO interval two models are preferred. One, with no olivine involvement, results in a fractionation assemblage similar to the one for the previous MgO interval. A second, where olivine is added (or resorbed), substantially reduces the major-element residuals. The preferred model for the 2 to 1 wt% MgO interval contains two significant changes. First, Fe-Ti oxide fractionation increases dramatically, and second, a small amount of apatite removal is required.

If the preferred interval models are combined, the total amount of crystallization needed to produce the most fractionated composition is 70-80%. The preferred models also show that the early fractionation assemblage is dominated by pyroxene, particularly clinopyroxene. Subsequent assemblages are dominated by plagioclase with Fe-Ti oxide and apatite fractionation becoming important only for the lowest MgO rocks. Although there are obvious uncertainties and simplifications inherent in these models, there are independent lines of geochemical evidence that support these conclusions. For example, Rayleigh fractionation models for

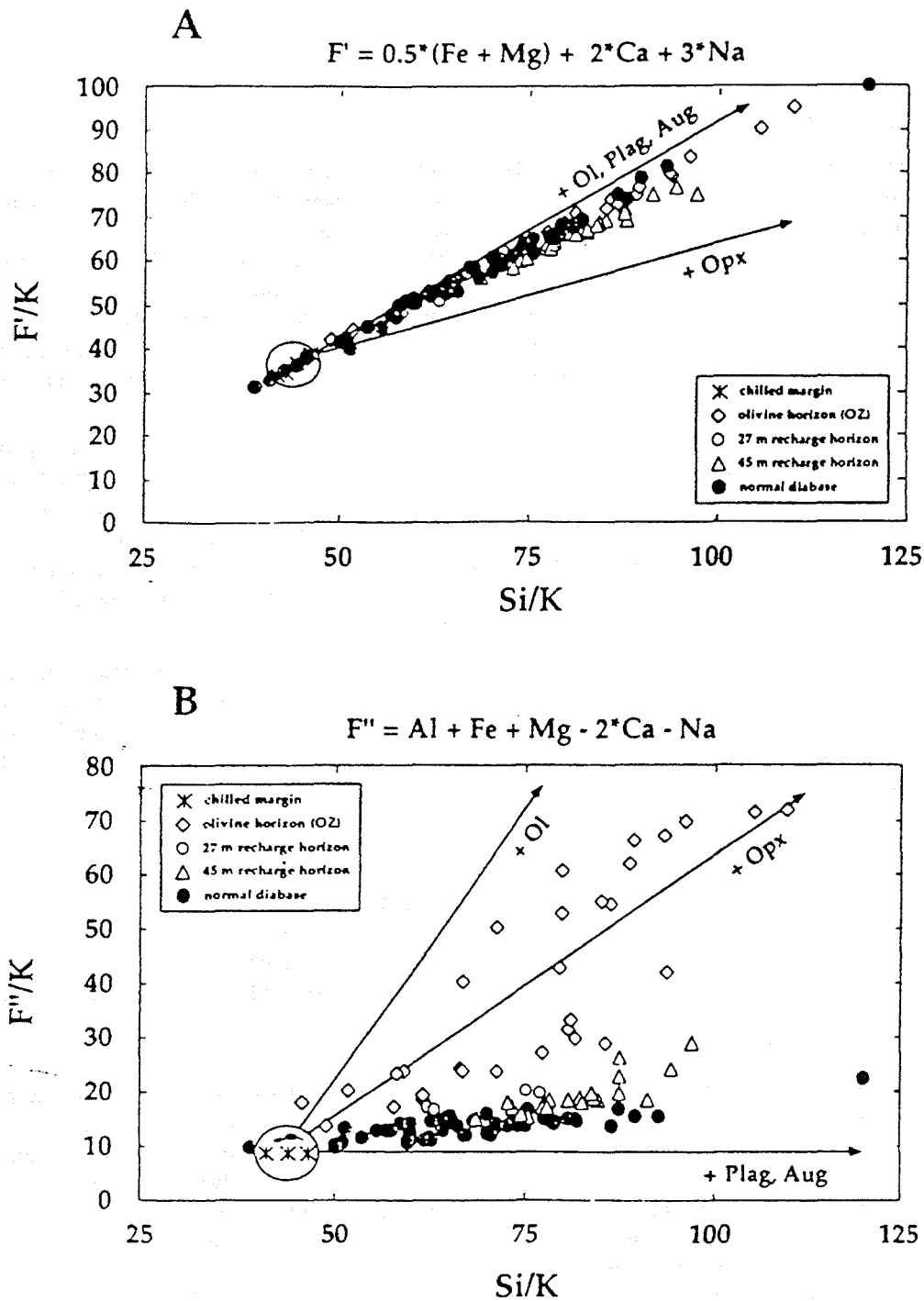


Figure 4. Pearce Element Plots (from Gorrington and Naslund, 1995) for the Fort Lee, NJ section of the Palisades. Although olivine control can not be determined in A, most, if not all, OZ rocks (open diamonds) in B require the addition of olivine in order to produce the fractionation trends observed. All non-OZ rock compositions can be produced by the addition or removal of clinopyroxene, orthopyroxene, and plagioclase without the participation of olivine.

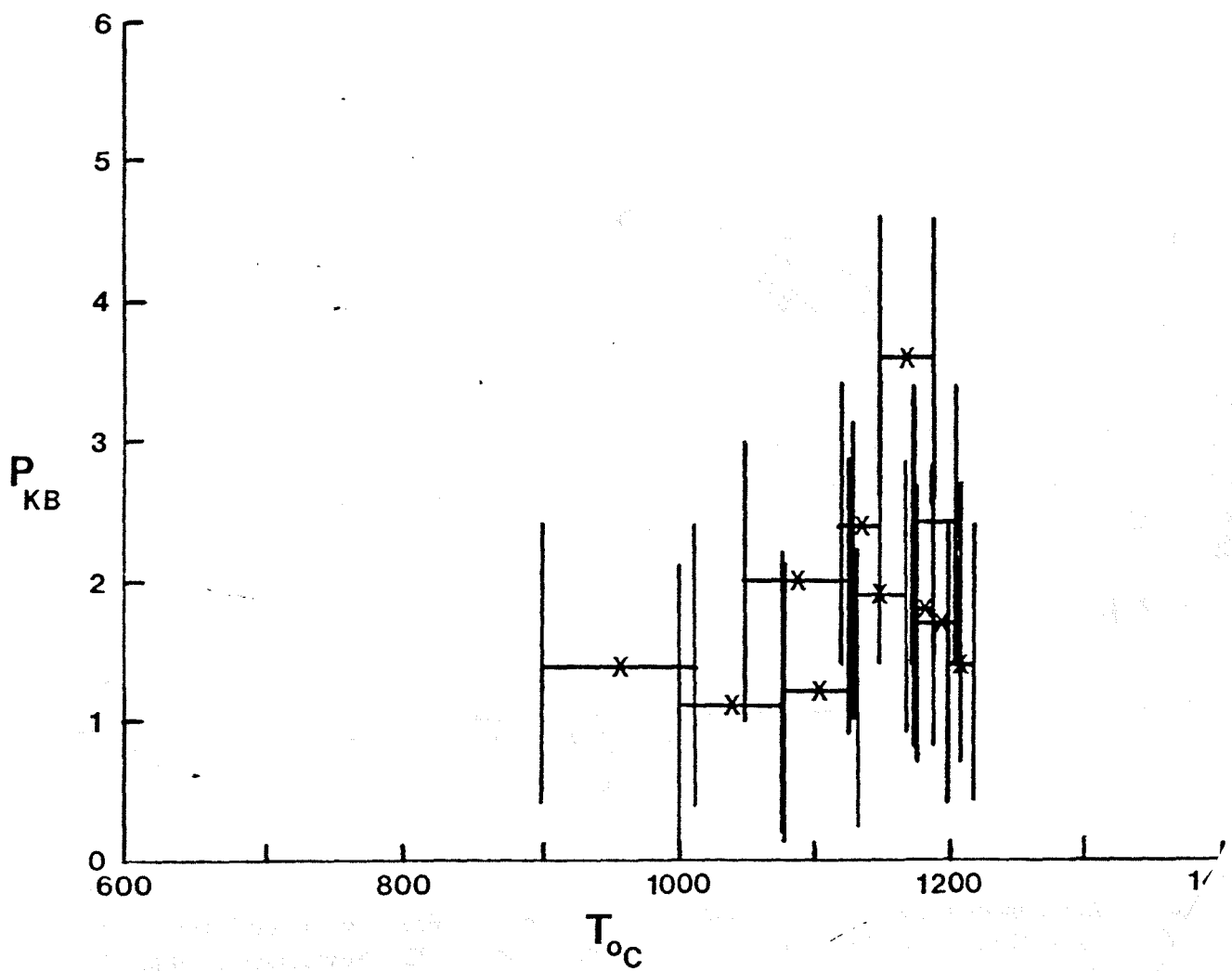


Figure 5. P-T determinations (with uncertainty estimates) for clinopyroxenes from c Newark basin diabase (from Husch, 1991). Median pressure value of 1.7 Kb is ap for a depth of approximately 5 km.

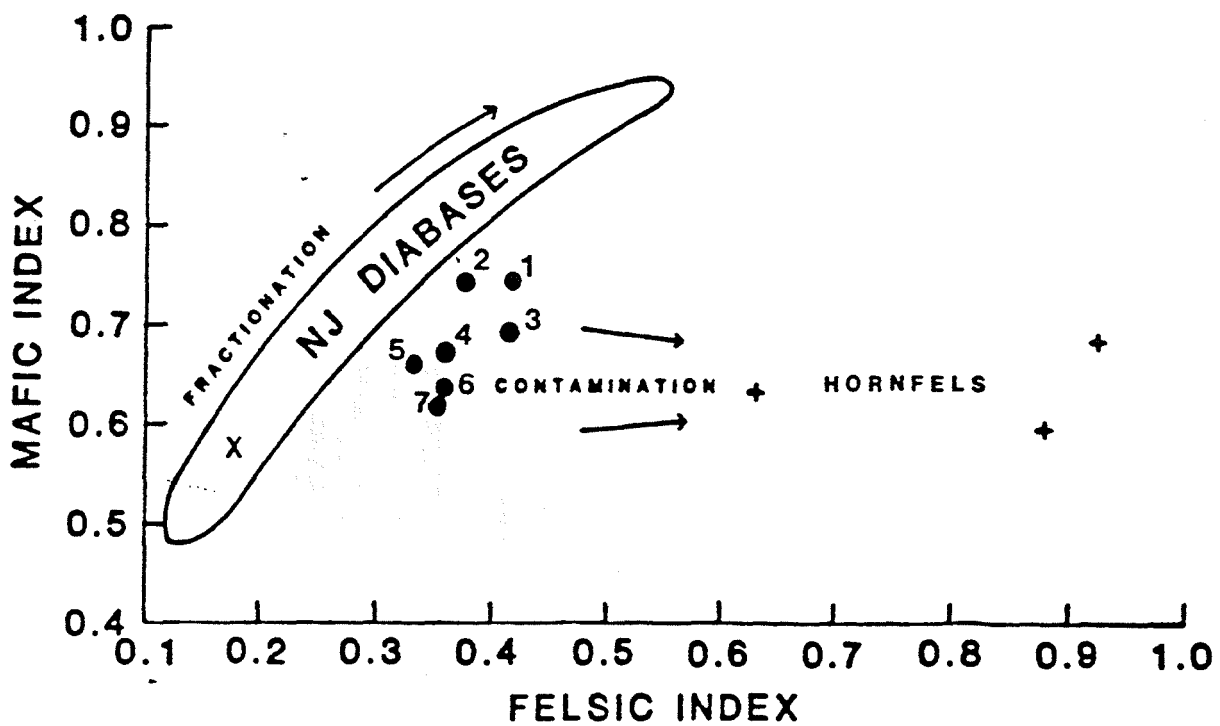


Figure 6. Mafic index ($\text{Fe}_2\text{O}_3^*/\text{Fe}_2\text{O}_3^* + \text{MgO}$; all iron reported as Fe_2O_3) vs. felsic index ($\text{Na}_2\text{O} + \text{K}_2\text{O}/\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$) variation diagram (from Husch, 1992). New Jersey diabase field includes data for Palisades from Walker (1969). Numbered samples exhibit evidence of contamination and are the same as in Fig. 3E-F.

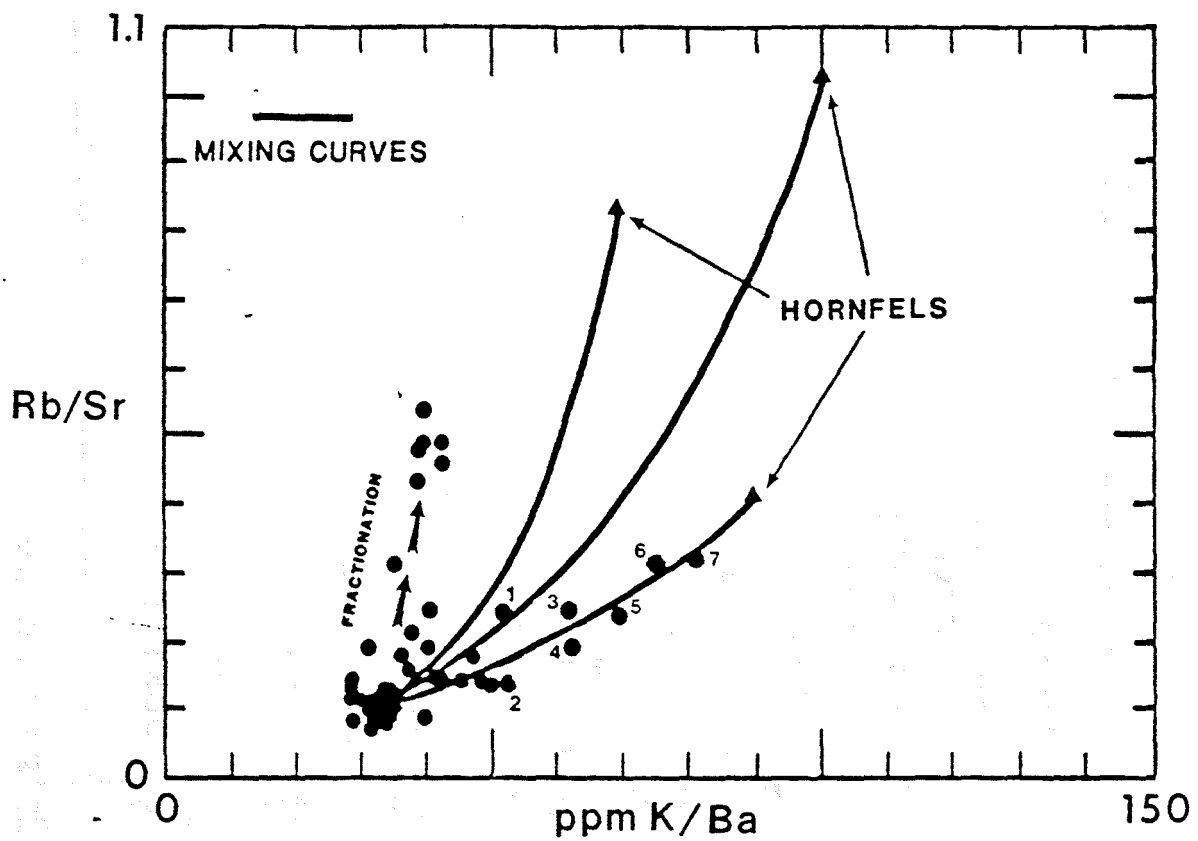


Figure 7. Rb/Sr vs. K/Ba variation diagram (from Husch, 1992). Three mixing curves, extending from average chill composition to each of three analyzed hornfels compositions, calculated using the general equations of Langmuir and others (1978). Numbered samples exhibit evidence of contamination and are the same as in Fig. 3E-F.

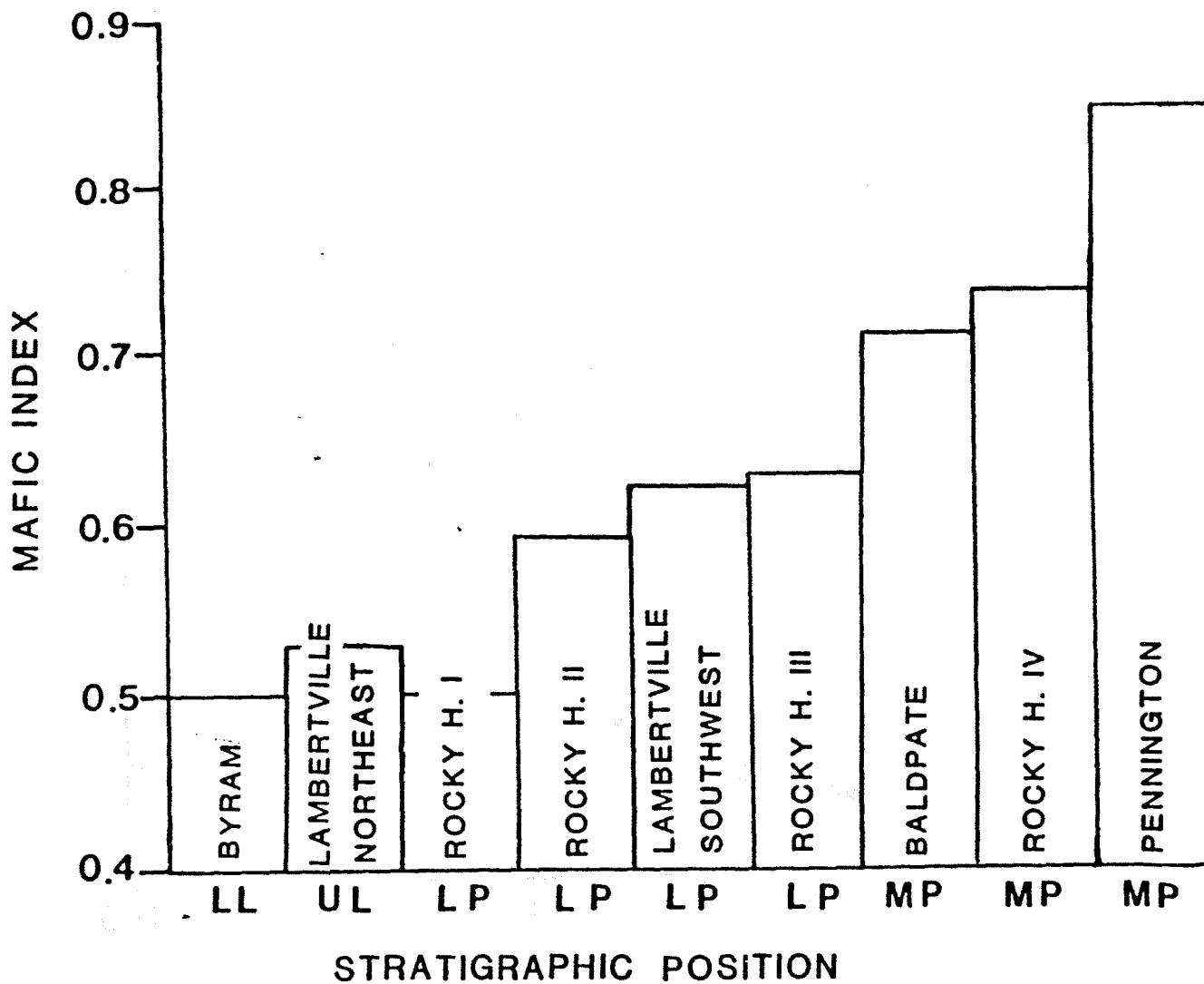


Figure 8. Average mafic index ($\text{Fe}_2\text{O}_3^*/\text{Fe}_2\text{O}_3^* + \text{MgO}$: all iron reported as Fe_2O_3) vs approximate stratigraphic level of emplacement for various exposures of central Newark basin diabase. Rocky H. I-IV averages represent separate sampling areas through the Rocky Hill diabase as it cuts up section. LL=Lower Lockatong Formation; UL=Upper Lockatong Formation; LP=Lower Passaic Formation; MP=Middle Passaic Formation.

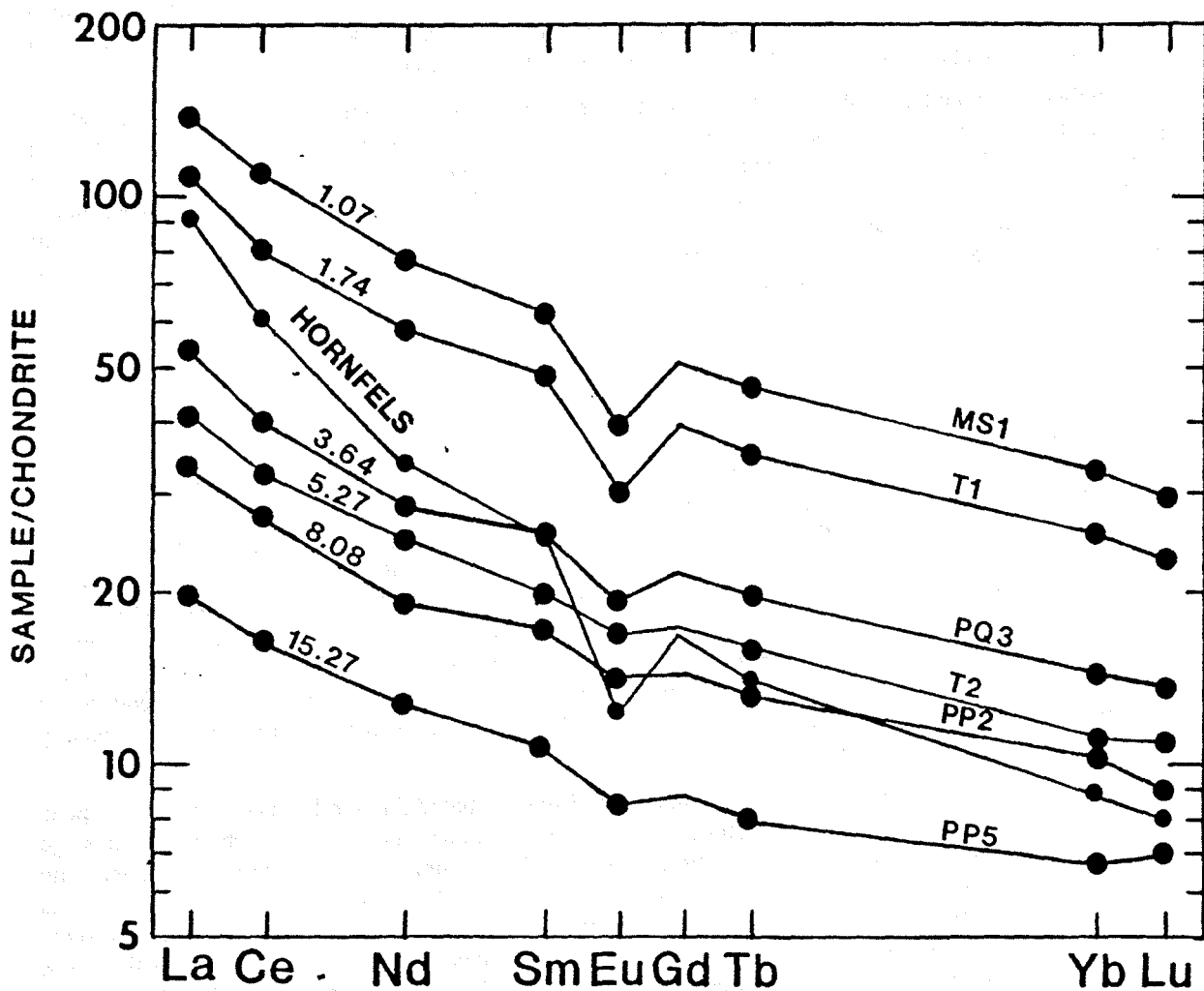


Figure 9. Chondrite-normalized REE distribution patterns for selected diabase samples from the central Newark basin and one hornfels sample (after Husch, 1992). MgO contents in weight percent of the diabase samples are shown at the left of each pattern. Note distinctly higher slope for the hornfels sample compared to diabase, particularly granophyric ones (low MgO rocks).

Ba, Rb, and Zr also require about 75% crystallization in order to produce the most fractionated compositions (Husch and others, 1988). Furthermore, Husch (1992) showed that a number of the important features of measured REE distributions patterns can be reproduced by the combined preferred models. Finally, the combined fractionation scheme generally agrees with other HTQ-related diabase fractionation models proposed by Steiner and others (1992), Gorrington and Naslund (1995), and Woodruff and others (1995).

Mafic-Rich Samples

Mass-balance calculations (Table 3) also show that many high-MgO (>9 wt%) samples result from the accumulation of variable amounts of clinopyroxene and orthopyroxene in the average PRHL chilled margin composition (Husch, 1992). For one sample, LS2, the added cumulate minerals are almost identical in their proportions to one of the preferred fractionation models for the 8 to 5 wt% MgO interval (cf. Tables 2 and 3), suggesting they may be complementary compositions. A rare olivine-rich rock, sample CH2, from the Rocky Hill diabase segment of the PRHL does require olivine to be added in an amount that matches its modal abundance. Gorrington and Naslund (1995) also show that OZ rocks require the addition of olivine (along with clinopyroxene, orthopyroxene, and plagioclase), whereas non-OZ mafic-rich rocks do not (Fig. 4).

Whether the modelled crystal fractionation and mineral accumulations took place at the present level of exposure, at depth, or as a combination of the two has not been determined unambiguously. Gorrington and Naslund (1995) believe the mineral accumulations required to produce the rocks of the OZ took place in a differentiating sub-PRHL, HTQ-derived magma chamber and did not occur in situ. On the other hand, pyroxene thermobarometry studies by Husch (1991) on non-OZ rocks from central New Jersey suggest that diabase differentiation took place within the PRHL megasheet at a pressure of 1-2 kb (Fig. 5), consistent with the sheet's typical stratigraphic level of emplacement beneath approximately 5 km of Triassic sediments.

Localized Contamination and Origin of Cross-Cutting Leucocratic Dikes

A number of samples from the PRHL and other diabase sheets contain anomalously high alkali and low Ca for a given value of MgO (Benimoff and Sclar, 1984, 1988; Husch and Schwimmer, 1985; Husch and others, 1988; Husch, 1992); seven of these are labelled in Figures 3A-H. These samples also plot consistently to the right of the main diabase variation trend on a mafic index vs. felsic index variation diagram (Fig. 6) and along one of the calculated mixing curves on a Rb/Sr vs K/Ba variation diagram (Fig. 7). As detailed by Benimoff and Sclar (1984, 1988) and further documented by Husch (1992), the anomalous compositions apparently were produced by the selective diffusion of alkalis from a contaminant, best approximated by hornfels of Passaic or Lockatong Formation, and of calcium from the enveloping diabase magma into a leucocratic anatectic melt derived from the contaminating material. Although Sr isotopic ratios are increased by this contamination process, many elements, including Al, Cr, Mg, Ni, Ti, and the REEs, appear completely unaffected (Husch and Schwimmer, 1985; Husch, 1992).

Benimoff and others (1989) and Benimoff and Sclar (1990) proposed that the leucocratic anatectic melts produced by the partial fusion of contaminating xenoliths were intruded into cooling fractures as late-stage dikes that cross-cut the sheets at numerous localities. The very similar compositions of the dikes and anatectic melts, particularly their extremely low K_2O/Na_2O values (typically <0.05) and REE distribution patterns (Benimoff and Sclar, 1992), support this model. F. Walker (1940), on the other hand, believed the late-stage dikes (or "white veins") were derived from residual granophyric magmas produced by crystal fractionation, whereas K. Walker (1969) concluded they were hydrothermal in origin. Laney and others (1995) sampled a number of sodic dikes and veins from the northeastern end of the Lambertville section of the PRHL megasheet and discovered at least three distinct compositional groups. One (low- K_2O) group appears derived from anatectic melts of xenolithic origin, a second (high- K_2O) group appears to be produced by intruding magmas residual to diabase crystal fractionation, and a third group has transitional characteristics and may be hybrid in origin. Evidently, as with cats, there is more than one way to derive a dike!

TABLE 3. MASS-BALANCE MODELS FOR MGO-RICH ROCKS

Parent: L ₁		Daughter: LSR5		Parent: L ₁		Daughter: LS2	
	Solution		% Cumulate		Solution		% Cumulate
Chill	1.000			Chill	1.000		
CPX	0.237		62.963	CPX	0.293		44.429
OPX	0.094		24.817	OPX	0.231		34.945
PLAG1	0.039		10.269	PLAG1	0.127		19.183
MAG	0.007		1.813	MAG	0.006		0.975
ILM	0.001		0.138	ILM	0.003		0.469
LSR5	1.377			LS2	1.660		

R² = 0.062

R² = 0.006

	Daughter	Calc.	Resid.		Daughter	Calc.	Resid.
SiO ₂	52.22	52.33	-0.12	SiO ₂	52.34	52.35	-0.01
TiO ₂	0.95	0.95	0.00	TiO ₂	0.89	0.89	0.00
Al ₂ O ₃	11.64	11.68	-0.04	Al ₂ O ₃	11.45	11.45	0.00
FeO*	10.32	10.35	-0.03	FeO*	10.00	10.00	0.00
MnO	0.19	0.18	0.01	MnO	0.17	0.17	0.00
MgO	10.69	10.69	0.00	MgO	11.91	11.91	0.00
CaO	11.50	11.51	-0.01	CaO	11.08	11.08	0.00
Na ₂ O	1.91	1.70	0.21	Na ₂ O	1.67	1.62	0.05
K ₂ O	0.50	0.51	-0.01	K ₂ O	0.46	0.44	0.02
P ₂ O ₅	0.08	0.10	-0.02	P ₂ O ₅	0.03	0.08	-0.05

Parent: L ₁		Daughter: PP5		Parent: L ₁		Daughter: ELS11	
	Solution		% Cumulate†		Solution		% Cumulate†
Chill	1.000			Chill	1.000		
CPX	0.263		18.881	CPX	0.278		73.714
OPX	0.819		58.672	OPX	0.071		18.827
PLAG1	0.305		21.831	PLAG1	0.028		7.505
ILM	0.008		0.599	MAG	-0.002		-0.538
PP5	2.395			ILM	0.002		0.493
				ELS11	1.378		

R² = 0.058

R² = 0.027

	Daughter	Calc.	Resid.		Daughter†	Calc.	Resid.
SiO ₂	52.61	52.77	0.16	SiO ₂	52.47	52.57	-0.10
TiO ₂	0.75	0.75	0.00	TiO ₂	0.94	0.94	0.00
Al ₂ O ₃	10.31	10.35	-0.04	Al ₂ O ₃	11.49	11.52	-0.03
FeO*	9.65	9.68	-0.03	FeO*	9.89	9.91	-0.02
MnO	0.18	0.17	0.01	MnO	0.18	0.18	0.00
MgO	15.42	15.44	-0.02	MgO	10.68	10.69	-0.01
CaO	9.05	9.06	-0.01	CaO	11.89	11.91	-0.02
Na ₂ O	1.57	1.40	0.17	Na ₂ O	1.80	1.68	0.12
K ₂ O	0.35	0.33	0.02	K ₂ O	0.53	0.51	0.02
P ₂ O ₅	0.11	0.06	0.05	P ₂ O ₅	0.12	0.10	0.02

Parent: L ₁		Daughter: CH2	
	Solution		% Cumulate†
Chill	1.000		
OL	0.108		23.279
CPX	0.164		35.289
OPX	0.099		21.179
PLAG1	0.087		18.725
MAG	0.009		1.877
ILM	-0.002		-0.348
3.5%	1.466		

R² = 0.047

	Daughter	Calc.	Resid.
SiO ₂	51.46	41.46	0.00
TiO ₂	0.82	0.82	0.00
Al ₂ O ₃	11.84	11.82	0.02
FeO*	10.48	10.49	-0.01
MnO	0.18	0.15	0.03
MgO	12.58	12.58	0.00
CaO	10.38	10.39	-0.01
Na ₂ O	1.54	1.70	-0.16
K ₂ O	0.63	0.49	0.14
P ₂ O ₅	0.08	0.10	-0.02

*All iron reported as FeO.

†Cumulate values are the relative weight percents of the minerals added to L₁.

TABLE 4. FLEMINGTON DIKE AND FLEMINGTON BASALT COMPOSITIONS

	1	2	3	4	5
SiO ₂	52.65	53.09	52.11	52.34	50.42
TiO ₂	1.13	1.13	1.11	1.13	1.26
Al ₂ O ₃	14.37	13.96	14.17	14.38	14.91
FeO*	10.58	10.06	9.89	9.90	11.27
MnO	0.19	0.16	0.16	0.17	0.20
MgO	7.49	7.94	8.14	7.94	7.98
CaO	10.78	10.29	10.41	9.53	8.08
Na ₂ O	2.15	2.00	1.86	2.36	5.08
K ₂ O	0.67	0.86	0.68	1.53	0.65
P ₂ O ₅	---	0.16	0.14	0.12	0.14
Ba	---	146	143	182	300
Cr	277	300	303	316	292
Ni	81	83	79	83	70
Sr	186	201	191	188	188
Zr	92	102	97	109	99

Major elements normalized to 100 weight percent anhydrous. Trace elements in ppm.

*All iron as FeO. 1=average ENA-HTQ basalt (Weigand and Ragland, 1970); 2, 3, and 4=Flemington dike samples FD2, FD5, and FD8, respectively (Crohe, 1996).

5=Flemington basalt (Houghton and others, 1992).

Table 5

Pangean Flood Basalts

samples	HTQ Large Igneous Province					Other Pangean			
	Orange Mt. NJ	Talcott Conn	Mt.Zion VA	North Mt Nova Scoti	H Atlas Morocco	Algarve Portugal	S.Parana Brazil	Norilsk Siberia	Lesotho S. Africa
	7	7	18	3	14	2	12	58	49
Wt %									
SiO ₂	50.93	51.16	51.89	50.86	51.51	50.71	51.91	50.28	51.5
TiO ₂	1.15	1.06	1.15	1.14	1.16	0.99	0.94	1.12	0.95
Al ₂ O ₃	14.25	14.08	14.42	13.78	14.03	14.11	15.82	15.17	15.69
FeOt	9.8	10.71	10.03	8.6	9.34	10.12	9.81	9.8	9.86
MnO	0.16	0.16	0.18	0.12	0.16	0.16	0.16	0.17	0.16
MgO	7.75	7.87	7.7	7.94	7.93	7.73	7.39	7.2	7.01
CaO	10.68	11.09	10.34	9.92	10.71	10.97	10.75	10.13	10.69
Na ₂ O	2.43	2.03	2.78	2.23	2.05	2.26	2.18	2.17	2.17
K ₂ O	0.48	0.49	0.27	1.01	0.51	0.53	0.76	0.89	0.7
P ₂ O ₅	0.14	0.13	0.13	0.18	0.17	0.14	0.15	0.06	0.16
LOI*	1.16	1.38		2.3	1.31	1.79		2.86	
Total	98.93	100.16	98.89	98.08	98.88	99.51	99.87	99.85	98.89
ppm									
Ba	182	174	145	143	109	386	272	370	177
Cr	337	322	282	224	240	241		130	283
Ni	85	86	79	73	87	87		120	94
Rb	27	22	11	17	20	20	34		12
Sr	192	186	191	201	187	235	236	240	192
Zr	101	87	99	102	103	98	96		94
La	10.9	11.1	10.8	12.4	10.6	14.6	14	16.5	9.9
Ce	25.1	23.9	24.1	26.1	22.5	29.7		36	23.7
Sm	1.09	3.66	3.51	3.65	3.3	4.11		4.3	3.25
Eu	1.2	1.15	1.13	1.16	1.11	1.23		1.2	
Yb	2.3	2.35	2.3	2.23	2.19	2.29		2.4	
Lu	0.39	0.33	0.34	0.35	0.33	0.37		0.6	

Non-Pangean Flood Basalts

samples	Imnaha	Lolo	loSnakeR	upSnakeR	loDeccan	upDeccan	loEast Rift	upEast Rift	lKeeween	uKeeween
	Wash	Wash	Idaho	Idaho	India	India	Ethiopa	Ethiopa	L.Superior	L.Superior
	21	29	1	1	1	1	81	5	1	1
wt. %										
SiO ₂	51.11	50.04	46.18	45.89	50.56	47.93	50.5	47.8	48.55	49.54
TiO ₂	2.04	3.2	2.06	3.33	2.57	3.05	3	2.7	1.86	2.14
Al ₂ O ₃	14.92	14.37	14.47	14.63	13.83	14.96	14.2	15.4	9.02	15.05
FeOt	13.16	14.04	12.17	14.81	12.41	11.78	11.89	11.54	12.57	12.28
MnO	0.23	0.24	0.19	0.21	0.17	0.17	0.2	0.19	0.24	0.17
MgO	5.08	5.25	9.99	6.46	5.12	4.53	5.5	6.6	11.69	5.05
CaO	9.55	8.91	9.68	9.37	9.62	9.73	9.6	10.5	11.29	8.38
Na ₂ O	2.76	2.29	2.63	2.84	2.65	2.89	3	2.9	1.62	2.67
K ₂ O	0.68	1.03	0.61	0.65	0.93	1.49	1	0.6	0.71	1.29
P ₂ O ₅	0.28	0.67	0.44	0.69	0.22	0.34	0.5	0.46	0.25	0.29
LOI*						2.47	1.2	0.96	1.77	2.54
Total	99.81	100.04	98.42	98.88	98.08	99.34	100.59	99.65	99.57	99.4
ppm										
Ba	277	477	298	464	239		537	201		
Cr	78	78	256	107	44		107		890	207
Ni	28	40	193	44	44		31	5.6	240	90
Rb	15	28	13.7	10.4	15		22	248	46	50
Sr	238	298	285	370	219		521		389	235
Zr	193	195	167	295	203		264	28	207	
La	14.4	27	18.3	32.3	19.3	36.4	28	55	29.4	19.4
Ce	33.8	56	41.2	74	43	69.8			77	44.4
Sm	5.72	8	5.6	9.4	7.6	6.53		1.8	8.66	6.74
Eu	1.88	2.55	1.94	3.35	2.47	2.49	3.2		2.29	1.91
Yb	4.06	3.88	2.78	4.06	3.63	2.58			2.36	3.6
Lu	0.61	0.59	0.42	0.61	0.53	0.37			0.26	0.54

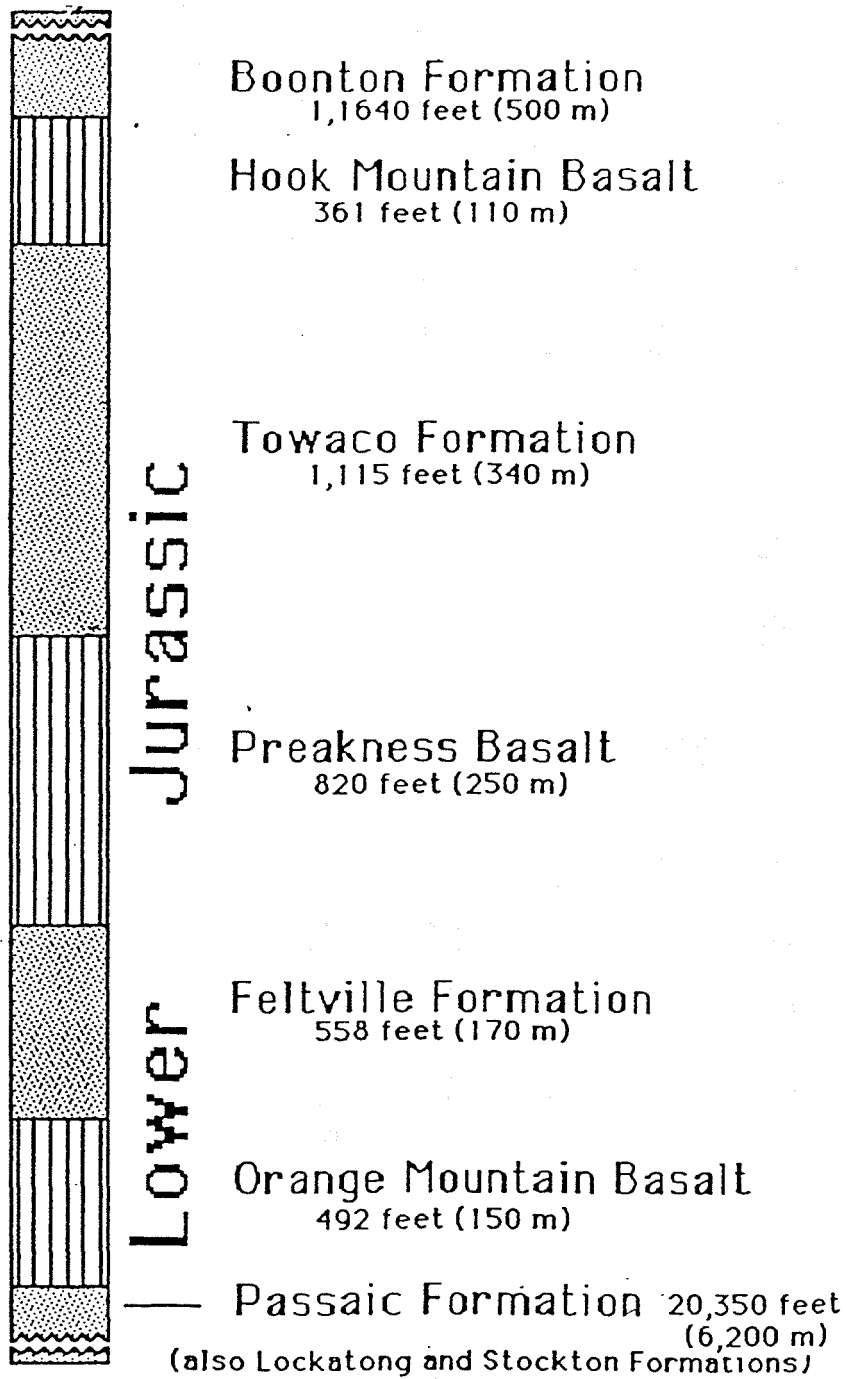


Figure 10. Stratigraphic column for the Newark basin after Tollo and Gottfried (1992). Thickness data are from Olsen and others (1989).

Lateral Compositional Variations and Migration of Residual Magmas

It now is widely accepted that many sections through the diabase sheets (including the PRHL) of the Newark, Gettysburg, and Culpeper Basins are not in mass balance with their HTQ or LTQ parent (Smith, 1973; Froelich and Gottfried, 1985, 1988; Husch and others, 1988; Husch, 1992; Mangan and others, 1993; Woodruff and others, 1995) and that significant lateral and up-dip migrations of residual magmas must have occurred. The calculated average compositions for these sections across individual diabase exposures support what is obvious in the field; those sections with significant pyroxene-rich zones lack complementary residual, granophyric compositions, and those that do have large volumes of granophyric rock lack significant, if any, amounts of pyroxene-rich rocks.

Murphy and Husch (1990) and Husch (1992) further showed that the lateral variations in average PRHL diabase composition could be correlated with the emplacement level of the megasheet within the surrounding Triassic sedimentary rocks; the higher in the stratigraphy the exposed section is located, the more fractionated its average composition (Fig. 8). Three localities where this relationship has been documented in detail are: 1) along the continuously exposed discordant western end of the Rocky Hill diabase section of the PRHL megasheet (Murphy and Husch, 1990); 2) at three separate sections across the Lambertville sill section of the PRHL megasheet, particularly as found at a centrally located stope-like structure (Szemplé, 1996; Stop 6); 3) along the highly discordant and continuously exposed northeastern arm of the CMD (Stop 4), a dike-like structure that traverses over 6000 ft of the Triassic sedimentary section (Keely and Husch, 1993). For all three cases, true granophyric rocks are found only at the highest exposed structural levels of each sheet.

A similar situation appears to be the case for the Palisades section of the PRHL, where the mildly fractionated northern dike-like extension in southeastern New York is emplaced relatively high up in the Late Triassic section (Puffer and others, 1982; Ratcliffe, 1988). This contrasts with the northern New Jersey segment (Stop 1), where the sheet is much more conformable and emplaced at its lowest level in the Basin (Stockton Formation). In this region, mafic-rich rocks, including those of the geographically restricted OZ (Husch, 1990), are much more common and lateral variations in composition are much reduced (Shirley, 1988).

As discussed by Husch (1992), there is no evidence to suggest that the observed lateral compositional variations and their consistent relationship with structural or stratigraphic level of emplacement were produced by the intrusion of variable parental magma compositions, the in-situ large-scale anatexis of surrounding country rock, the localized fractionation of varying mineral assemblages, or the large-scale contamination of sections of the sheets. For example, chilled margin compositions are extremely constant (Table 1) and all of the HTQ type, granophyric rocks have REE distribution patterns similar in slope to those for all other diabase compositions and distinctly different than those for the country rock (Fig. 9). Furthermore, differentiation trends are similar from throughout the region, as are the proposed crystal fractionation models that produce them, and recognized country-rock contamination and associated anatexis appears volumetrically minor and restricted to a limited number of localities.

There also is no evidence to suggest that significant amounts of late-stage, fractionated granophyric magmas were erupted onto the surface as part of the OMB, PB, or HMB (see Part Two). Rather, it appears that once the PRHL and other diabase sheets were intruded contemporaneously with the OMB, they remained relatively closed systems with little, if any, residual magmas being ejected. An excellent example of this relationship is found at the stope-like structure of the Lambertville sill section of the PRHL (Stop 6) and its associated Flemington dike (Fig. 5); the dike cross-cuts over 9000 ft of the Late Triassic sedimentary section, feeding the Flemington basalt, an OMB equivalent. Crohe (1996) documents that the composition of the Flemington dike is reasonably constant except for increasing signs of contamination with decreasing depth, and is essentially the same as the HTQ-type magma found at all sampled PRHL chilled margins and the Flemington basalt (Table 4); no fractionated compositions are seen anywhere in the dike-basalt system. This is despite the fact that the dike emerges from the sheet at the same general location where significant amounts of granophyric compositions are found (Szemplé, 1996). So, although it appears that while the PRHL sheet internally differentiated for some period of time (hundreds to a few thousand years; Shirley, 1987; Husch, 1992; Gorrington and Naslund, 1995), the feeder system to the surface flows shut down almost immediately upon the contemporaneous intrusion of the parental HTQ magma. Residual granophyric magmas could then only migrate to the highest structural levels within the sheet in which they were generated. Thus, the picture that is now

emerging is one of a very short-lived, though multiple, sheet injection event of a regionally constant HTQ magma, followed by the dynamic, but self-contained, differentiation of the individual sheets.

PART 2: THE WATCHUNG FLOOD BASALTS

Stratigraphy

The Watchung basalt flows are grouped into three units (Orange Mountain, Preakness, and Hook Mountain) separated by Lower Jurassic red-bed siltstone formations (Figure 10).

The Orange Mountain unit consists of three flows (Puffer and Student, 1992), a very thick lower flow and two relatively thin upper flows, totaling 150 m (Olsen and others 1989, 96). The flow contacts are defined by scoriaceous flow tops beneath overlying massive to vesicular flow bottoms and the common presence of discontinuous layers of red-bed sediment between flows.

The Preakness unit consists of five flows defined on the same basis, and in the case of the lowest two flows by a 2 to 4 m thick layer of siltstone. The combined thickness of the five flows totals 250 m (Olsen and others, 1989). The lowest of the five flows is the thickest (about 150 m) overlain by a second flow 80 to 100 m thick and three relatively thin upper flows that total about 40 to 65 m thick (Puffer and Student, 1992).

The Hook Mountain unit consists of three flows separated by thin discontinuous layers of red-bed sediment (Puffer and Student, 1992) for a combined thickness of 110 m (Olsen and others, 1989).

Most of the Watchung flows are subaerial, but pillowed basalt, (particularly within the upper Orange Mountain and portions of the second Preakness flow) is found in the Paterson, New Jersey area where early Jurassic lake waters were deepest.

The three early Jurassic Watchung units correlate with early Jurassic basalt units exposed north and south of New Jersey on the basis of virtually indistinguishable petrography and chemical compositions (Puffer and Philpotts, 1988), and the paleontology of interbedded sedimentary units.

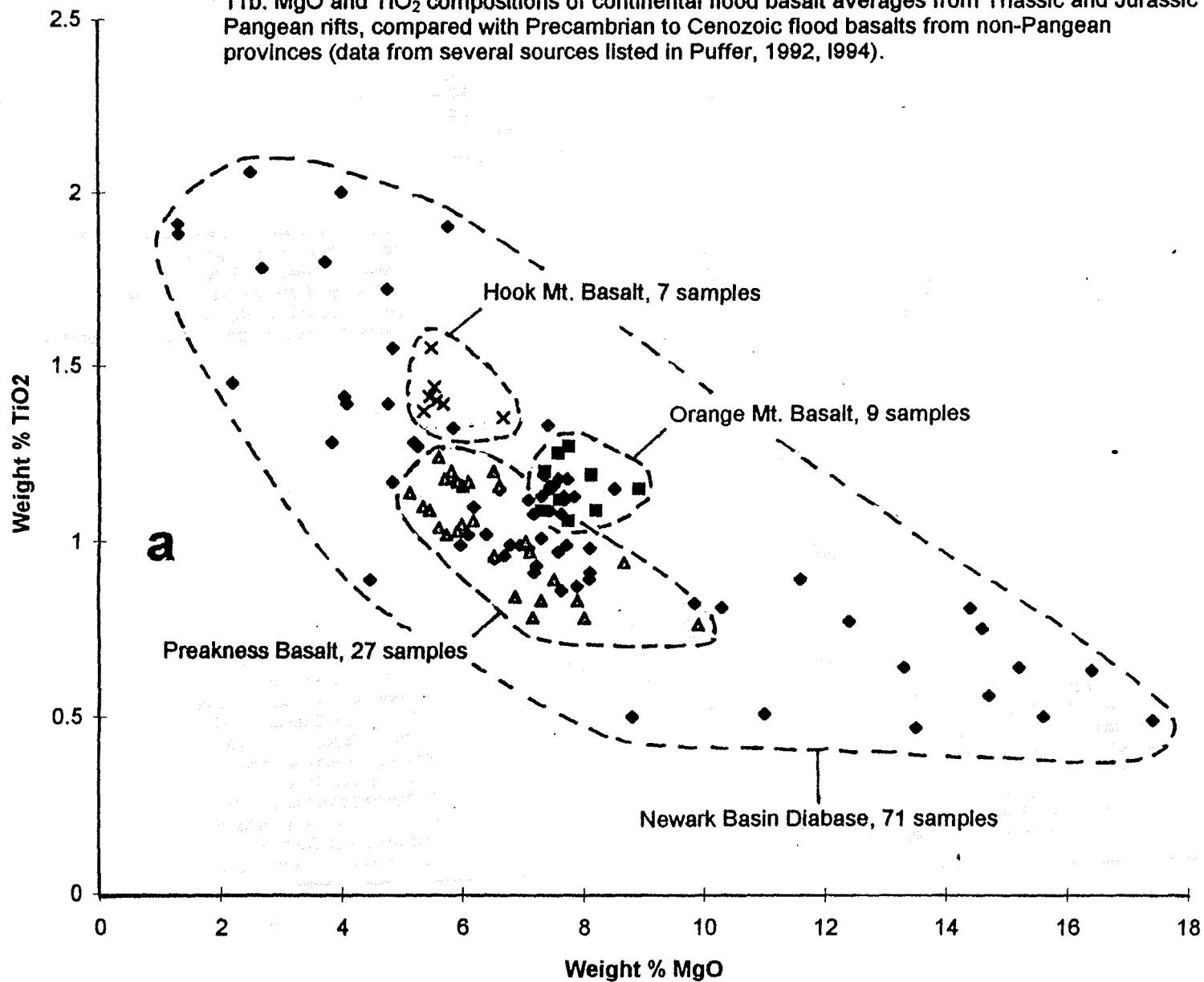
Petrography

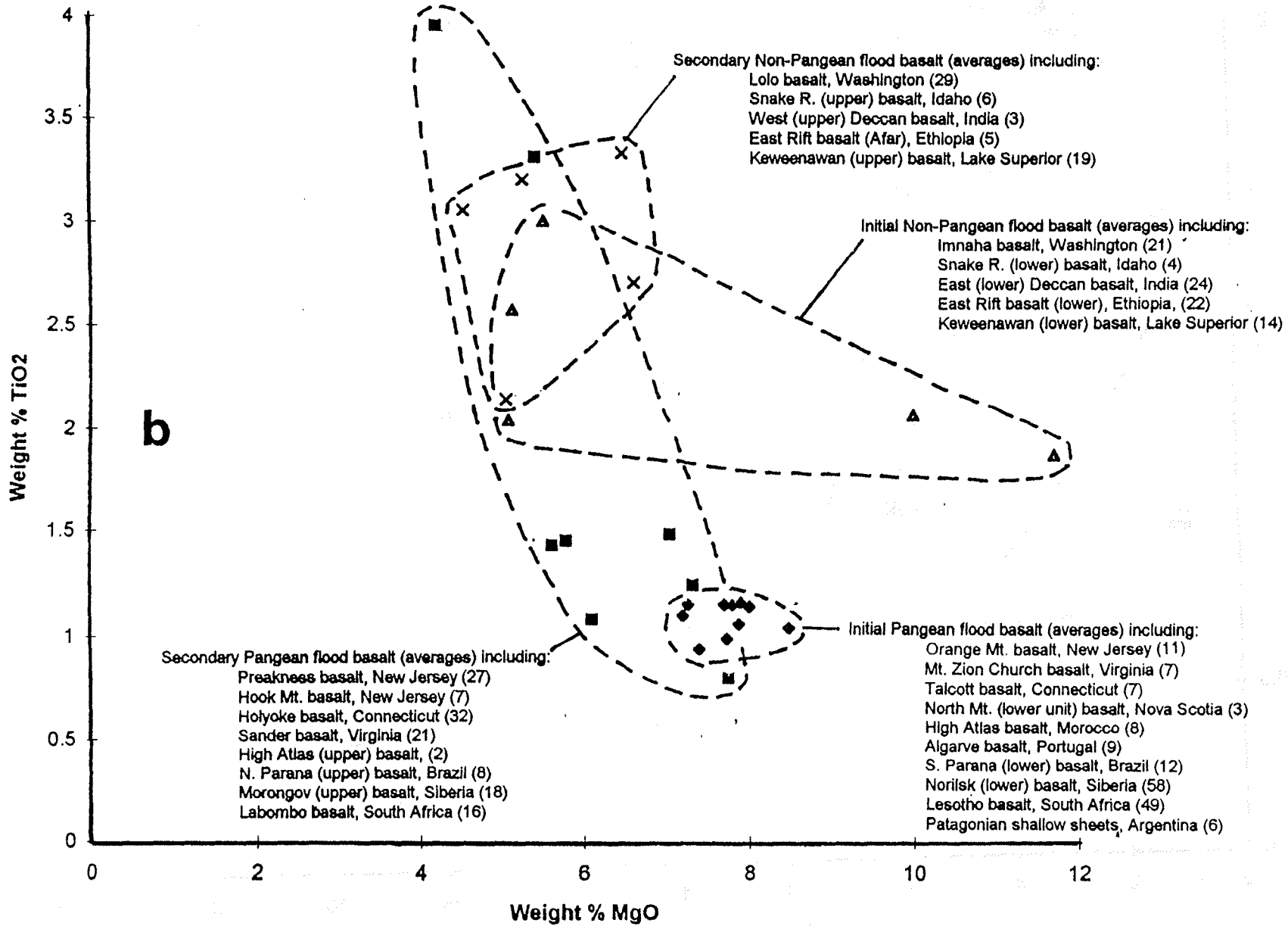
Orange Mountain basalt is petrographically indistinguishable from the Talcott basalt of Connecticut and the Mount Zion Church basalt of Virginia. Most Orange Mountain basalt consists of glomeroporphyritic clusters and intergrowths of subhedral augite and subhedral plagioclase plus common dispersed grains of plagioclase and pyroxene in a dark brown, fine grained to glassy mesostasis. The mesostasis comprises about 5 to 20 percent of the rock and contains abundant skeletal grains of ilmeno-magnetite.

Preakness basalt is typically aphyric to porphyritic and coarser grained than Orange Mountain basalt, but there is a wide variation in textures among the five Preakness flows. The lower two flows are particularly coarse and contain more plagioclase and much less mesostasis than Orange Mountain basalt or the upper three Preakness flows.

Hook Mt. basalt is also coarser grained than Orange Mountain basalt and there is much less textural variation than present in the Preakness. The Hook Mountain is typically aphyric but is locally porphyritic.

Figure 11a. MgO and TiO₂ compositions of diabase from the Newark Basin (Gottfried and others, 1991) compared with Orange Mt, Preakness, and Hook Mt. basalts (Puffer, 1992);
11b. MgO and TiO₂ compositions of continental flood basalt averages from Triassic and Jurassic Pangean rifts, compared with Precambrian to Cenozoic flood basalts from non-Pangean provinces (data from several sources listed in Puffer, 1992, 1994).





Some unusual items found in the Watchungs:

a. Pegmatitic Segregation veins

In addition to the Watchungs, pegmatitic rock has been found in other ENA flood basalts including the North Mountain basalt of Nova Scotia (Greenough and Dostal, (1992), and the Holyoke basalt of Connecticut (Philpotts and Carroll, 1996). It is also found in the Columbia River Basalts, particularly the LoLo (Puffer and Horter, 1993), and in thick lava lake accumulation in Hawaii (Helz and others, (1989).

There are two modes of occurrence of pegmatitic veins, each with a different mode of emplacement. Some pegmatitic rock consistently occurs in the entablature of thick flows at a level about one-third of the way through the flow from the top. These pegmatites are vesicular, and have sharp upper contacts but gradational lower contacts. They are fractionation products of their host basalt consistent with about 20 percent crystallization. They were probably accumulated beneath the upper flow contact as it advanced downward into still molten basalt below. The pegmatitic rock was probably carried by volatiles rising out of the lower crystallization front according to models proposed by Helz and others, (1989); Greenough and Dostal, (1992); and Puffer and Horter, (1993). The coarse grains that they contain presumably grew large in a melt with a viscosity reduced by the volatile content. Most crystal nuclei may have been fused during transport through the hot interior of the flow adding to the likelihood of coarse grains.

Other pegmatitic rock occurs in the lower colonnade of thick flows. These pegmatites are not vesicular, and have sharp upper and lower contacts. They are also fractionation products of their host basalt but represent about 30 percent crystallization. They were probably squeezed (filter pressed) out of a lower colonnade crystal mush and flowed into overlying subhorizontal cracks that opened up during floundering of thick slabs of basalt. Since most crystal nuclei were consumed during partial crystallization at their source, the grain size of the residual pegmatitic rock is increased. This mode of pegmatite (segregation vein) occurs in the Hamden basalt of Connecticut and has been described by Philpotts and Carroll in a series of GSA abstracts, (particularly Philpotts and Carroll, 1996).

b. Platy prismatic joints.

In addition to the columnar shrinkage joints that develop in most subaerial basalt flows according to a process described by Degraff and Aydin (1987), a much more closely spaced set of joints is commonly found at exposures of Preakness basalt and less commonly at exposures of Orange Mountain and Hook Mountain basalt. These closely spaced platy prismatic joints have been described by Faust (1978) and Puffer and Student (1992) and may have been generated by transform shearing forces acting on the basalt during crystallization.

c. Secondary Prehnite and Zeolite mineralization.

Laskowich and Puffer (1990) and Puffer and Student (1992) have described a complex set of hydrothermal alteration and metamorphic processes that have led to the precipitation of abundant zeolites, prehnite, carbonates, amethyst, and sulfides in gas vesicles and between basalt pillows. Most such secondary mineralization is confined to the Orange Mountain basalt and Hook Mountain basalts. Gas vesicles were probably partially filled with hydrothermal sulfates, carbonates, chlorite and clays during the cooling of the flows. Subsequent zeolite facies metamorphism during burial recrystallized this mineral assemblage into an assemblage dominated by prehnite and zeolites.

d. Copper Mineralization

Puffer and Proctor (1994) have described copper mineralization that is concentrated in basalt vugs and shallow lake sediments near the base of the Orange Mountain basalt. A copper bearing mineral assemblage similar to that found in the Keeweenawan basalts of the Lake Superior province was mined at several sites of historic importance in a linear district extending from North Arlington to Chimney Rock, New Jersey. The

copper values correlate with magnesium mineralization, particularly chlorite that may have precipitated out of heated brackish groundwater during and just before Orange Mountain extrusion. The model proposed by Puffer and Proctor (1994) depends on heated brine circulation and, therefore, extrapolates the classic submarine black-smoker model to shallow brackish ponds.

Geochemistry

Whole-rock geochemical analyses of Watchung Basalts (Puffer, 1992) are compared with the major ENA magma types of Weigand and Ragland (1970). The Orange Mountain is consistently HTQ-type basalt and is compositionally uniform. However, the upper Orange Mountain flow is slightly more mafic than the lower flows. The composition of the Orange Mountain basalt (Table 5) closely resembles the chill zones of the PRHL and most other sheets in the Newark basin (see Part 1).

The Preakness basalt is chemically diverse. The lower flows of the Preakness are generally much more highly fractionated than the upper flows. The compositions of the upper flows, typically 0.8 percent TiO₂ and 8.0 percent MgO (Puffer, 1992) are within the LTQ-type range. The lower flows, however, are the product of plagioclase and pyroxene fractionation of LTQ magma and typically contain about 1.1 percent TiO₂ and 6.0 percent MgO (Puffer, 1992).

The Hook Mountain basalt is chemically uniform and is classified as an HFQ-type largely on the basis of its TiO₂ content and mafic index (Puffer, 1992).

The Watchung Flood Basalts as part of the ENA rift related Large Igneous Province

The Jurassic Watchung basalts of New Jersey meet each of the criteria needed to assign them to the category of continental flood basalts (Puffer and Student, 1992). The extreme thickness of most of the flows, their quartz tholeiitic composition, their probable extrusion out of fissures, and the very large aerial extent of the basalt outpourings are some of these criteria. The Orange Mountain basalt is part of an HTQ province (Table 5) that extends from at least as far south as the Culpepper Basin of Virginia (the Mount Zion Church basalt, Puffer and Philpotts, 1988) through New England and eastern Canada to as far north as northern Newfoundland (the Avalon Dike, Papezik and Hodych, 1980). HTQ rocks are not common south of Virginia but a few HTQ dikes may occur as far south as South Carolina (Ragland and others, 1992). The HTQ province probably also includes portions of Morocco (the early Jurassic basalts of the High Atlas mountains; Manspeizer and others, 1976) and Portugal (the early Jurassic basalts of the Algarve basin, Puffer, unpublished data).

The Preakness basalt is part of an LTQ province that extends at least as far north as the Hartford basin of Connecticut (the Holyoke basalt, Puffer and Philpotts, 1988) and into the southeastern US states, as the Sander basalt of Virginia, (Puffer and Philpotts, 1988) and as a major dike swarm in the Carolinas where is closely associated with olivine normative tholeiitic dikes (Ragland and others, 1992). The LTQ province may also extend into Florida and the Blake Plateau off the coast of Florida.

The only well known correlative to the Hook Mountain basalt is the Hampden basalt of Connecticut (Puffer and Philpotts, 1988). The Hook Mountain/Hampden province, therefore, is much more restricted than the huge HTQ and somewhat smaller LTQ provinces. After Hook Mountain/Hampden magmatism very little ENA activity occurred until the Middle Jurassic to Lower Cretaceous with the intrusion of distinctly alkalic rocks including lamprophyric rocks in New England and Atlantic Canada (McHone, 1992). These alkalic rocks, unlike the flood basalt magmatism below appear to be controlled by either hot-spot tracks or long transform faults that may have tapped a magma source unrelated to early Jurassic magma. Presumably while this alkalic magmatism was occurring in New England, some of the first true Atlantic MORB activity was beginning and has continued without much compositional change to the present.

The aerial extent of the HTQ and LTQ provinces as they occurred during the early Jurassic is uncertain but McHone (1996) and McHone and Puffer (1996) have made a first approximation. McHone (1996) has

shown that the status of the ENA basalts should be elevated to that of a world class Large Igneous Province (LIP) and should no longer be ignored by assemblers and modelers of LIPs such as Coffin and Eldholm (1994).

***The Origin of Orange Mountain Basalt (First Watchung):
From Extremely Uniform HTQ-type Magma Melted During Pangean Rifting***

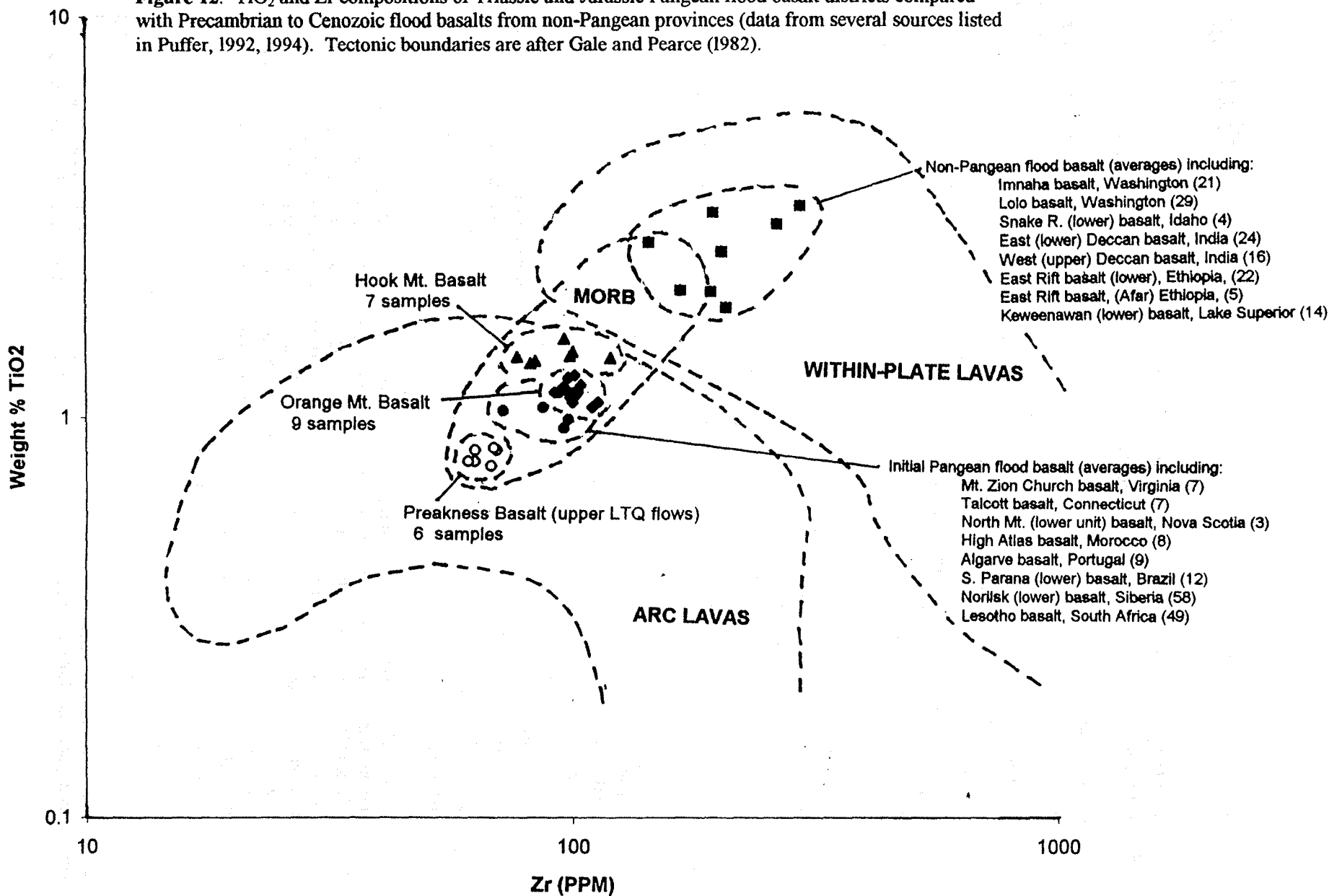
One outstanding characteristic of the HTQ LIP is the extremely uniform composition of each of the basalt flow components (Table 5) and the chill-zones of the feeder dikes. Although most intrusive HTQ sheets (such as the PRHL) have undergone in-situ fractionation or lateral fractionation (see Part-1) and (Figure 11a), there is abundant evidence that the HTQ magma that intruded into these sheets and extruded as flood basalt was chemically too uniform to be the product of fractionation of any more primitive magma (Puffer, 1992, 1994). Although there is no apparent way to prove that some deep fractionation did not occur, perhaps in the mantle or in a magma chamber ponded at the base of the crust, there is no evidence of any mafic cumulate that could account for the huge volume of HTQ magma as a fractionation product. However, the choice of processes that might have generated HTQ magma is highly constrained by its uniform composition on a regional (eastern North America) to perhaps global scale.

The chemical composition of HTQ magma is unlike that of most flood basalts (Table 5) and does not even plot in the continental basalt field of most Pearce-type discriminant diagrams. For example, the Zr/TiO₂ ratios of the HTQ basalts plot within the MORB field of Figure 12. In addition, the MgO/TiO₂ ratios of most if not all Cenozoic, Paleozoic, and Precambrian flood basalts are much different than the HTQ basalt group (Figure 11b). However, there is one group of flood basalts (initial Pangean basalts) that closely resembles HTQ basalts (Figures 11b and 12), and it is probably not a random coincidence that each member of this group was also extruded out of fissures that opened during the initial break-up of Pangea. There seems to be a uniform set of initial conditions that controlled the melting of each of the similar Pangean magmas in Table 5. Those conditions were clearly subcontinental and extensional and very unlike the subduction related conditions associated with andesites, or the mid-oceanic and depleted source conditions associated with MORB, or the hot-spot conditions associated with alkalic basalts. It is less clear just how the sub-Pangean conditions differ from those associated with non-Pangean flood basalts, but the break-up of Pangea was a rapid and unique event. The threshold strength of the Pangean lithosphere during the initial break-up was probably a function of the minimum thickness and maximum mantle heat content requirements that may have been unique to Pangean rift zones. The magnitude of the forces needed to initiate movement of the large pieces of the Pangean super-plate also may have been unique to Pangea. These unique threshold conditions, therefore, may have controlled the rate of ascent of mantle source material under the Pangean rifts and the degree of decompression melting related to the prevailing extensional tectonism.

Although HTQ magma probably intruded quickly (Philpotts, 1992) and avoided much crustal contamination, some assimilation of crustal rock such as described by Puffer and Benimoff (in press) has locally affected HTQ rocks (see also Part -1). As might be expected of crustal contamination, the most highly mobile elements are those that display the most variation among HTQ rocks. Ba, Rb, and K show the most variation among HTQ rocks (Table 5) and could at least partially be the result of late hydrothermal alteration (sericite) and may not have involved much crustal assimilation. Dostal and Dupuy (1984) interpret the negative Nb anomaly that is a characteristic of HTQ rocks as evidence of considerable crustal contamination, but careful examination of the Nb data-base that is commonly used to interpret spider diagrams and discrimination diagrams is suspiciously lacking in credibility (Puffer, unpublished data).

Sr and Nd isotopic data (Puffer, 1992) are somewhat ambiguous and are consistent with either: 1.) some crustal contamination, 2.) an enriched subcontinental mantle source, with enrichment presumably occurring during an earlier subduction cycle (Pegram 1990), or 3.) an undepleted subcontinental mantle source of uniform composition. Of the three choices, Puffer (1992) favors choice 3, again largely on the basis of the uniform composition (including isotopic composition) of Pangean flood basalts that would tend to rule out various

Figure 12. TiO_2 and Zr compositions of Triassic and Jurassic Pangean flood basalt districts compared with Precambrian to Cenozoic flood basalts from non-Pangean provinces (data from several sources listed in Puffer, 1992, 1994). Tectonic boundaries are after Gale and Pearce (1982).



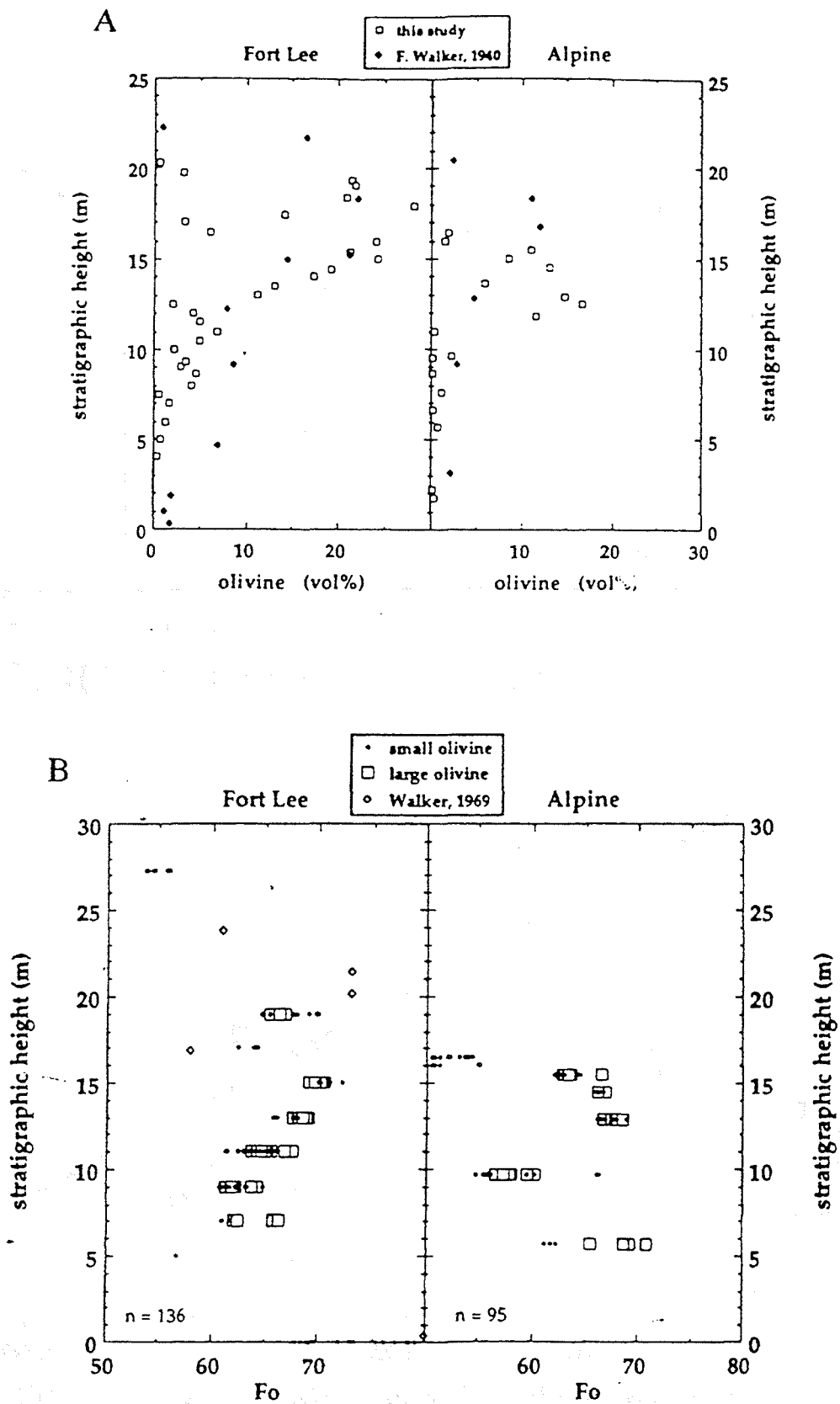


Figure 13. Modal abundance (A) and Fo content (B) of olivine vs. stratigraphic position above lower contact from the Fort Lee and Alpine, New Jersey sections of the Palisades (from Goring and Naslund, L995). Note the presence of two maxims in both A and B, suggesting a double pulse of OZ magma with early formed olivines concentrated near the core of each pulse.

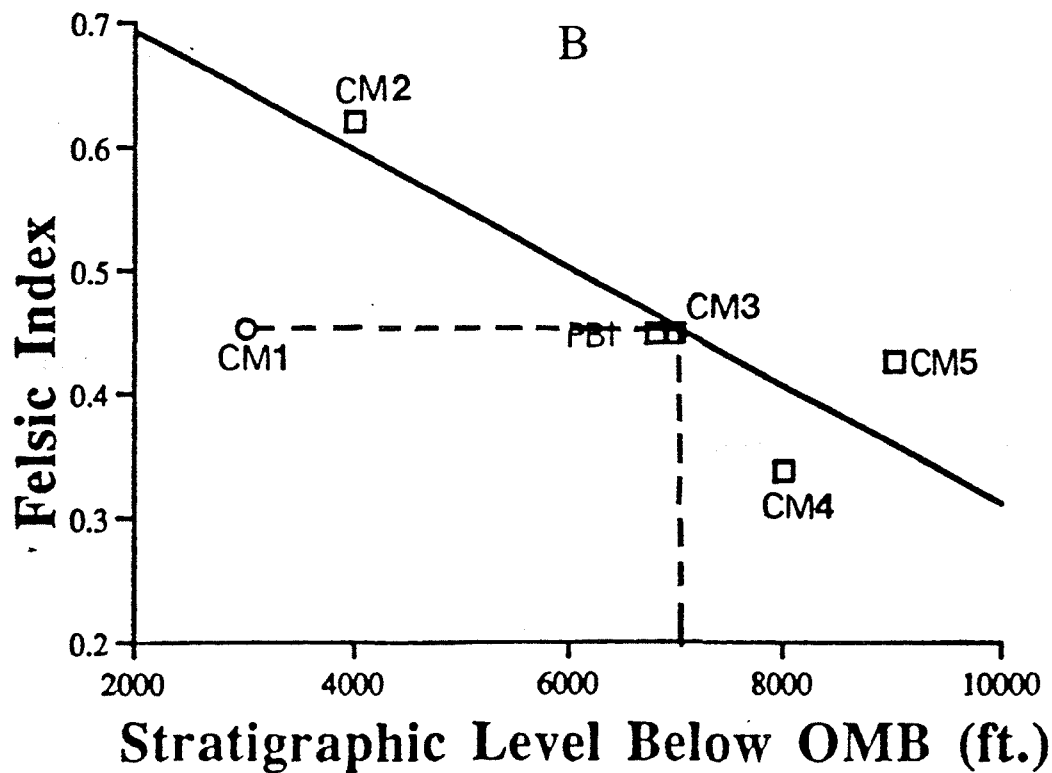
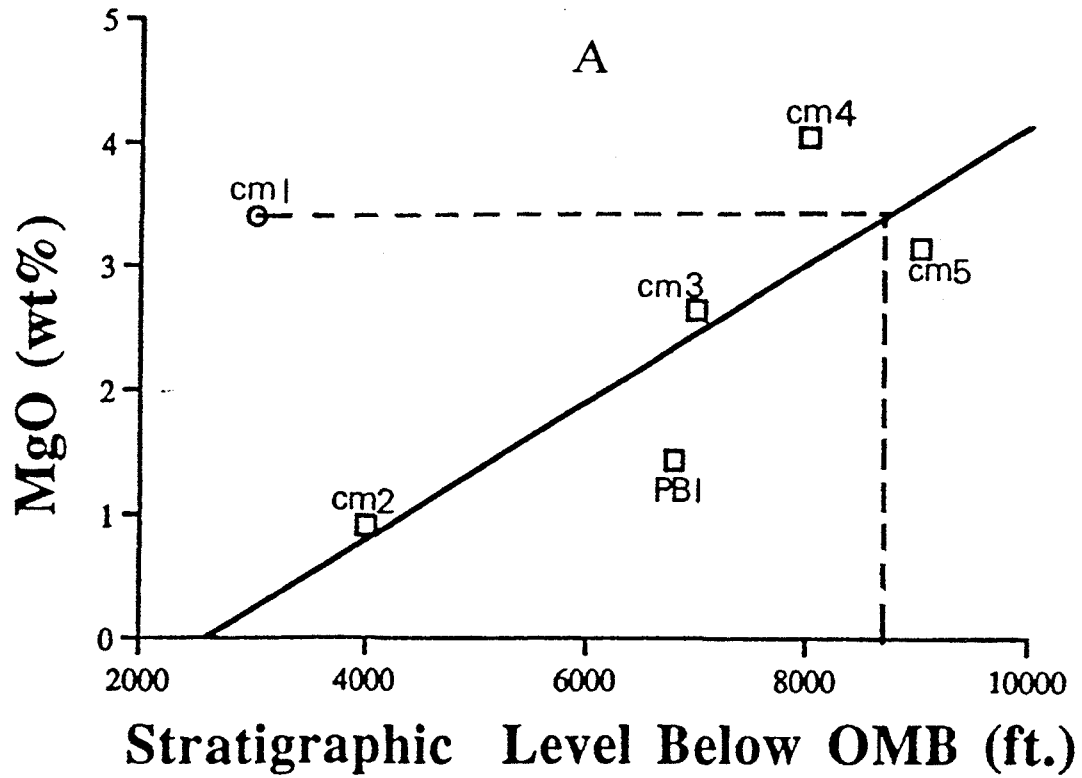


Figure 14. MgO (A) and felsic index ($\text{Na}_2\text{O}+\text{K}_2\text{O}/\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO}$; B) vs. stratigraphic level below the OMB (Orange Mountain Basalt) for the northeastern arm of the CMD (from Keely and Husch, 1993). Solid diagonal lines are least-squared regression of all samples except CM1 (Stop 4). Dashed lines represent estimates of actual stratigraphic position of CM1 prior to post-intrusion normal faulting; an offset of approximately 5000 ft is indicated. Note also the consistency of the position of the Prescott Brook sample (PBI, Stop 4A), suggesting the presence of a subsurface connection of the PBD with the CMD.

degrees of contamination or enrichment. Still another complicating factor is the role that mantle metasomatism may have played as suggested by the isotopic data of Dunn and Stringer (1990).

The Origin of Preakness Basalt (Second Watchung): Four Ways to Generate Diverse LTQ-type Magmas

The Preakness basalt flows clearly consist of LTQ-type rock (upper flows) and fractionated LTQ-type rock (lower flows), however, there are at least four ways to generate LTQ or LTQ-like magma:

1. An independent magma batch.

The chief difference between the HTQ and the LTQ batches is the relatively incompatible element depleted nature of the LTQ batch. Most LTQ-type diabase, basalt, and related fraction products, therefore, are probably the result of a magma batch that was melted from a relatively depleted mantle source compared to the HTQ batch that preceded it, or from a magma batch that represents a higher degree of partial melting than the HTQ batch. On Sun and McDonough mantle normalized spider diagrams where elements are arranged according to their relative incompatibility in the mantle, the Preakness basalt and other LTQ basalts such as the Holyoke of Connecticut and the Sander of Virginia consistently plot well below HTQ levels (Puffer, 1992, 1994). One reasonably likely scenario is that the LTQ magma was generated by renewed decompression melting of the same rising mantle diapir or ridge-like structure that had been previously depleted by earlier HTQ magma generation.

2. Fractionated OLN-type Magma.

Ragland and others (1992) have found several cases of LTQ intrusions that are differentiates of a parent olivine normative type (OLN-type, Weigand and Ragland, 1970) magma that may qualify as a primary melt. Evidence of a genetic link between some LTQ intrusions and OLN magma at some southeastern US locations includes the occurrence of olivine phenocrysts in LTQ diabase and rocks that plot along continuous uninterrupted fractionation trends. Apparently there are two types (batches?) of OLN magma. However, there is a distinct gap in fractionation trends that separates one type of OLN rock from most LTQ rock.

3. Plagioclase and Pyroxene Accumulation and Hydrothermal Alteration of HTQ Magma.

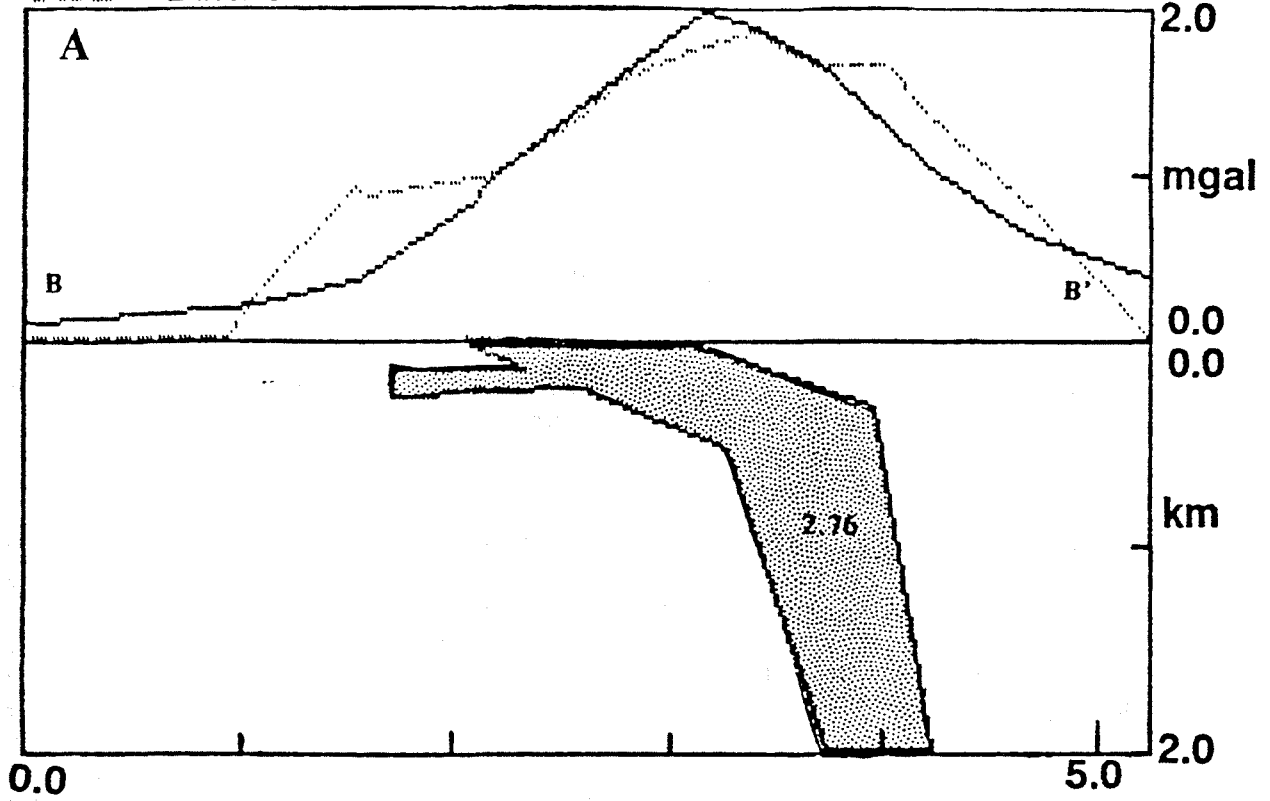
Puffer and Benimoff (in press) have described the geochemistry and petrology of the Laurel Hill diabase intrusion near Secaucus, New Jersey. They have found that plagioclase and pyroxene separated from an HTQ magma have accumulated near the outer margin and have reduced TiO₂ levels to LTQ levels. The TiO₂ levels were reduced still further by hydrothermal precipitation of sericite in the outer margin. The major element chemistry of the resulting rock closely resembles LTQ diabase.

4. Mafic residue remaining after escape of late melt phase during in-situ fractionation.

Philpotts and Carroll (1996) have shown that plagioclase and pyroxene can also become concentrated in HTQ rock without involving movement or accumulation of phenocrysts. They have shown that collapse of increasingly dense partially crystallized rock can occur after about 30 percent crystallization and force the remaining incompatible element enriched melt to become filter pressed out. The resulting enrichment of early pyroxene and plagioclase phases results in a rock containing less TiO₂ and other incompatibles than the expelled liquid phase and would presumably be comparable to LTQ rock.

Of the four ways to form LTQ magma, the preferred application to the Preakness basalt is method 1. There is no evidence of a large supply of OLN magma in New Jersey that could have fractionated into Preakness basalt (method 2), and there is no textural evidence of any accumulation of plagioclase and pyroxene

Obs Calc



Obs Calc

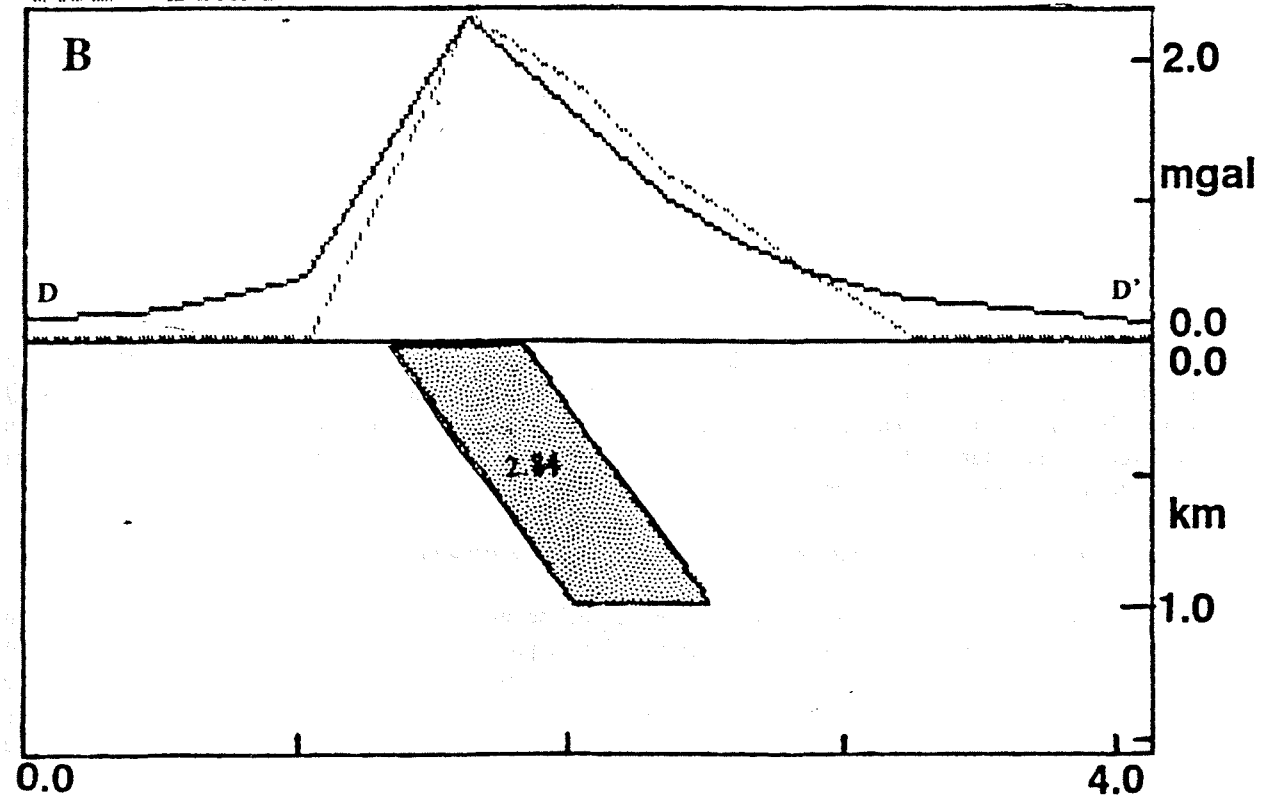


Figure 15. Two-dimensional Bouguer Anomaly models across the northeastern arm of the CMD (from Jakubicki and Husch, 1995) indicating that the intrusion is a ring dike. Center of the CMD is to the left for both profiles. The diabase density required in A (2.76 gm/cc) is less than for B (2.84 gm/cc), consistent with the lower stratigraphic position and more mafic chemistry of the profile location modeled in B. Obs=observed Bouguer Anomaly (light line); Calc=calculated Bouguer Anomaly (dark line) using a reference density of 2.67 gm/cc.

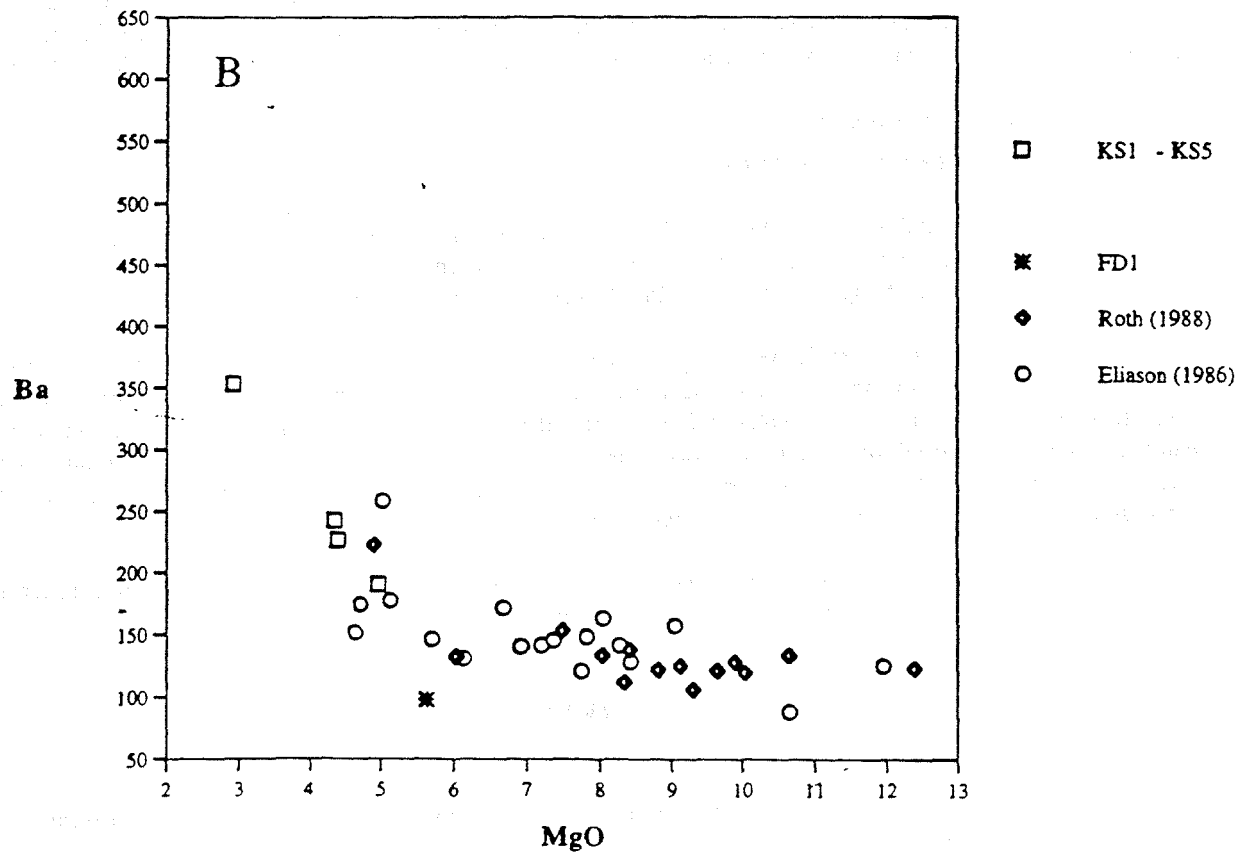
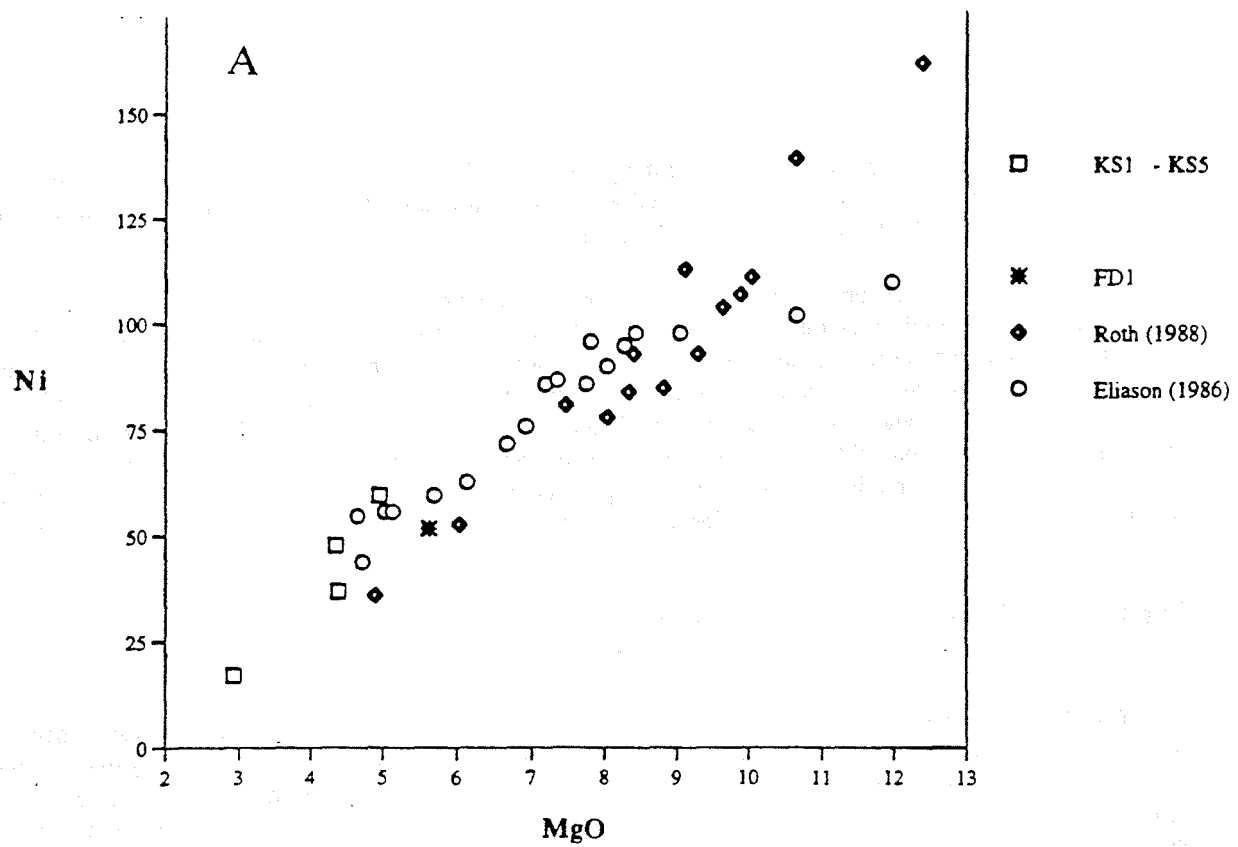


Figure 16. Ni (A) and Ba (B) vs. MgO diagrams for the Lambertville sill (from Szeple, 1996). KS1-5 and FD1 samples are from the stope-like structure (Stop 6). Samples from Roth (1988) and Eliason (1988) are from the northeastern and southwestern ends of the sheet, respectively. Note how only low-MgO, granophyric compositions are found in stope-like structures; northeastern and southwestern sections are dominated by high-MgO rocks with no true granophyre.

phenocrysts (method 3). If enriched melt was filter pressed out of a partially crystallized HTQ source (method 4) the depleted solid residue would be contained as a layer within an HTQ source (in this case the Orange Mountain flows or the PRHL sheet) but the Preakness clearly is not.

Method 2 is a close second choice. OLN rocks are not common in New Jersey but become increasingly common toward the south beginning with the Quarryville dike swarm in Pennsylvania. Some of this olivine normative rock may be mafic cumulates from the fractionation of an LTQ parent magma batch (method 1) and plots on a long, continuous fractionation trend that balances with some highly evolved rocks such as the lower flows of the Preakness and some dike interiors (Figure 11a). But as erosion depths increase toward the southeast into the Carolinas, OLN dikes become abundant and lead to the impression that they are the parent magma, and not simply a mafic cumulate. The LTQ population lacks the compositional uniformity of the HTQ population and there is less compelling evidence that it is a parent magma instead of a fractionation product.

The Origin of Hook Mountain Basalt (Third Watchung): A Third Magma Batch or a Fractionation Product?

The Hook Mountain flows and the Hampden flows of Connecticut are the only two known occurrences of late HFQ magmatism. Although most HFQ rocks are probably fractionation products of HTQ magma, the Hook Mountain and Hampden are not (Puffer and others, 1981). They are instead localized, rather unique outpourings of basalt that do not compare to the widespread dimensions of the underlying flow units. Their chemistry was probably controlled by renewed melting under the complex and highly dynamic tectonic conditions that accompanied the opening of the Atlantic. These rapidly changing conditions are difficult to model and may not have any bearing on the more important magmatism that preceded them and followed them.

Another Unsolved Problem: Where did the Watchungs Come From?

It is quite likely that the Orange Mountain flows extruded out of rifts fed by the same magma that intruded as the underlying PRHL sheet, but before the sheet underwent dynamic but self contained fractionation. All evidence suggests that the Orange Mountain and PRHL sheet are largely co-magmatic HTQ rocks.

The source of the Preakness, however, is less well understood. None of the dikes and sheets exposed in New Jersey are LTQ intrusions that could have supplied the massive quantities of magma required of the Preakness. One possibility is that Preakness flows were fed by conduits that were never exposed by erosion. Another is that the exposed intrusive source was covered by Cenozoic coastal plain sediments. Flow direction studies by Manspeizer (1980) based on curved pipe amygdules found at the base of the Preakness, suggest that the source was to the east, but so far nothing to east has been found.

The source of the Hook Mountain is even more perplexing because flow direction studies suggest a western source. Erosion has penetrated deeply into everything to the west but again, there is no clue.

REFERENCES

- Bascom, F., Darton, N.H., Kummel, H.B., Clark, W.B., Miller, B.L., and Salisbury, R.D., 1909, Description of the Trenton Quadrangle (Trenton folio): U.S. Geological Survey, Geologic Atlas No. 167, 24 p.
- Benimoff, A. I.; Sclar, C. B.; and Puffer, J. H., 1995, Geochemical aspects of the Trondhjemitic-syenitic dikes of the injection zone at the contact of intrusive diabase, Laurel Hill (Snake Hill), Secaucus, N.J.: Geological Society of America, Northeastern Section, Cromwell, Connecticut, v. 27, p. 29.

- Benimoff, A. I., Puffer, J.H., and Sclar, C.B., 1989, A trondhjemite dike in the Palisades sill at the western end of the I-95 cut: Geological Society of America Abstracts with Programs, v. 21, no. 2, p. 4.
- Benimoff, A. I., and Sclar, C.B., 1984, Coexisting silicic and mafic melts resulting from marginal fusion of a xenolith of Lockatong argillite in the Palisades sill, Graniteville, Staten Island, New York: American Mineralogist, v. 69, p. 1005-1014.
- Benimoff, A. I., 1988, The Graniteville Quarry, Staten Island, NY: An exceptional outdoor laboratory for studying igneous phenomena: Northeastern Geology, v. 10, no. 1, p. 30-42.
- Benimoff, A. I., 1990, An albitite dike in the Palisades sill at the south end of the Bayonne Bridge, Staten Island, NY: Geological Society of America Abstracts with Programs, v. 22, no. 2, p. 4.
- Benimoff, A. I., 1992, REE geochemistry of a partly fused xenolith in the Palisades sill, Staten Island, NY: A test of the igneous source-rock concept in REE geochemistry: Goldschmidt Conference Program and Abstracts, The Geochemical Society, p. A-8.
- Bryan, W. B.; Finger, L. W.; and Chayes, F., 1969, Estimating proportions in petrographic mixing equations by least-squares approximation: Science, v. 163, p. 926-927.
- Coffin, M.F., and Eldholm, O., 1994, Large Igneous Provinces: Crustal structures, dimensions, and external consequences: American Geophysical Union, Reviews of Geophysics, v. 32, p. 1-36.
- Crohe, J.K., 1996, Major- and trace-element concentrations across and along strike of the Flemington dike [B.S. Thesis]: Lawrenceville, Rider University, submitted.
- Cummins, L. E.; Authur, J. D.; and Ragland, P. C., 1992, Classification and tectonic implications for early Mesozoic magma types of the Circum-Atlantic, in Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper, v. 268, p 95-118.
- Darton, N.H., 1890, The relations of the traps of the Newark System in the New Jersey region: U.S. Geological Survey Bulletin 67, 82 p
- Dostal, J., and Dupuy, C., 1984, Geochemistry of the North Mountain basalt (Nova Scotia, Canada): Chemical Geology, v. 45, p. 245-261.
- Dostal, J. and Greenough, J.D., 1992, Geochemistry and petrogenesis of the early Mesozoic North Mountain basalts of Nova Scotia, Canada, in Puffer, J. H., and Ragland, P. C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper, v. 268, p 149-160.
- Dunning, G.R., and Hodych, J.P., 1990, U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg sills of the northeastern United States: Implications for the age of the Triassic/Jurassic boundary: Geology, v. 19, p. 795-798.
- Dunn, T., and Stringer, P., 1990, Petrology and petrogenesis of the Ministers Island Dike, southwest New Brunswick, Canada: Contributions to Mineralogy and Petrology, v. 105, p. 55-65.
- Eliason, W.M., 1986, Geochemical variations through the Lambertville sill [B.S. thesis]: Lawrenceville, Rider College, 36 p.
- Faust, G. T., 1978, Joint Systems in the Watchung Basalt Flows, New Jersey: U.S. Geological Survey, Professional Paper 864-B, 46 pp.

- Froelich, A.J., and Gottfried, D., 1985, Early Jurassic diabase, in Robinson, G.R., Jr., and Froelich, A.J., eds., Proceedings of the Second U.S. Geological Survey Workshop on the Early Mesozoic Basins of the eastern United States: U.S. Geological Survey Circular 946, p. 79-86.
- Froelich, A.J., 1988, An overview of early Mesozoic intrusive rocks in the Culpeper Basin, Virginia and Maryland, in Froelich, A.J., and Robinson, G.R., Jr., eds., Studies of the early Mesozoic basins in the eastern United States: U.S. Geological Survey Bulletin 1776, p. 141-150.
- Gale, G.H., and Pearce, J. A., 1982, Geochemical patterns in Norwegian greenstones: Canadian Journal of Earth Sciences, v. 19, p. 385-397.
- Geist, D.J., Baker, B.H., and McBirney, A.R., 1985, GPP: A program package for creating and using geochemical data files (IBM-PC and compatible microcomputers version): Eugene, University of Oregon Center for Volcanology, 33 p.
- Gorring, M.L., and Naslund, H.R., 1995, Geochemical reversals within the lower 100 m of the Palisades sill, New Jersey: Contributions to Mineralogy and Petrology, v. 119, p. 263-276.
- Gottfried, David; Froelich, A. J.; and Grossman, J. N., 1991, Geochemical data for diabase associated with Early Mesozoic basins in the Eastern United States: Western Newark Basin, Pennsylvania and New Jersey: U.S. Geological Survey, Open File Report 91-322-D, 27 pp.
- Helz, R. T., Kirschenbaum, H., and Marinenko, J.W., 1989, Diapiric transfer of melt in Kilauea Iki lava lake, Hawaii: A quick, efficient process of igneous differentiation: Geological Society of America Bulletin, v. 101, p. 578-594.
- Houghton, H.F., Herman, G.C., and Volkert, R.A., 1992, Igneous rocks of the Flemington fault zone, central Newark basin, New Jersey: Geochemistry, structure, and stratigraphy, in Puffer, J.H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 219-232.
- Husch, J. M., 1988, Significance of major- and trace-element variation trends in Mesozoic diabase, west-central New Jersey and eastern Pennsylvania, in Froelich, A. J., and Robinson, G. R., JR., eds., Studies of the early Mesozoic basins of the Eastern United States: U.S. Geological Survey Bulletin 1776, p. 141-150.
- Husch, J. M., 1990, The Palisades sill: Origin of the olivine zone by separate magmatic injection rather than gravity settling: Geology, v. 18 p. 699-702.
- Husch, J. M., 1991, Pyroxene thermobarometry and its implications for the shallow (± 7 km) differentiation of Early Jurassic diabase, central Newark basin. Geological Society of America Abstracts with Programs, v. 23, no. 5, p. A389.
- Husch, J. M., 1992, Geochemistry and petrogenesis of the Early Jurassic diabase from the central Newark basin of New Jersey and Pennsylvania, in Puffer, J.H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 169-192.
- Husch, J. M., Bambrick, T.C., Eliason, W.M., Roth, E.A., Schwimmer, R.A., Sturgis, D.S., and Trione, C.W., 1988, A review of the petrology and geochemistry of Mesozoic diabase from the central Newark basin: New petrogenetic insights, in Husch, J.M., and Hozik, M.J., eds., Geology of the central Newark basin, field guide and proceedings: Geological Association of New Jersey, 5th Annual Meeting: Lawrenceville, New Jersey, Rider College, p. 149-194.
- Husch, J.M., and Schwimmer, R.A., 1985, Major and trace element concentrations across a Mesozoic basaltic dike, New Hope, Pennsylvania: Northeastern Geology, v. 7, p. 144-160.

- Husch, J. M., Sturgis, D. S., and Bambrick, T. C., 1984, Mesozoic diabases from west-central New Jersey: Major and trace element geochemistry of whole-rock samples: *Northeastern Geology*, v. 6, p. 51-63.
- Husch, J.M., and Roth, E.A., 1988, Multiple magma pulses and the petrogenesis of Early Jurassic diabase in the Newark basin: Geochemical and petrographic evidence from the Lambertville sill, New Jersey: *Geological Society of America Abstracts with Programs*, v. 20, no. 7, p. A156.
- Jakubicki, R.G., and Husch, J.M., 1995, 2-Dimensional gravity modeling of the Cushetunk Mountain diabase region, Newark basin, New Jersey: *Geological Society of America Abstracts with Programs*, v. 27, no. 1, p. 57.
- Keely, K., and Husch, J.M., 1993, Geochemistry of the Cushetunk Mountain diabase, Newark basin, NJ: Distribution of residual granophyres: *Geological Society of America Abstracts with Programs*, v. 25, no. 6, p. A-97.
- Klewsaat, D.R., and Gates, A.E., 1994, Faulting, fragmentation, and Cretaceous breaching of the Palisades sill, New Jersey: *Northeastern Geology*, v. 16, no. 3&4, p. 237-250.
- Kodama, K.P., 1983, Magnetic and gravity evidence for a subsurface connection between the Palisades sill and the Ladentown basalts: *Geological Society of America Bulletin*, v. 94, p. 151-158.
- Laney, S.E., Husch, J.M., and Coffee, C., 1995, The petrology, geochemistry, and structural analysis of late-stage dikes and veins in the Lambertville sill, Belle Mead, New Jersey: *Northeastern Geology and Environmental Sciences*, v. 17, no. 2, p. 130-145.
- Langmuir, C.H., Vocke, R.D., Jr., Hanson, G.N., and Hart, S.R., 1978, A general mixing equation with applications to Icelandic basalts: *Earth and Planetary Science Letters*, v. 37, p. 380-392.
- Laskowich, C., and Puffer, J. H., 1990, Volcanic diapers of the Orange Mountain Basalt, New Jersey: *The Bulletin of the New Jersey Academy of Science*, v. 35, p. 1-9.
- Mangan, M.T., Marsh, B.D., Froelich, A.J., and Gottfried, D., 1993, Emplacement and differentiation of the York Haven diabase sheet, Pennsylvania: *Journal of Petrology*, v. 34, p. 1271-1302.
- Manspeizer, W., 1980, Rift tectonics inferred from volcanic and clastic structures: in Manspeizer, W., ed., *Field studies of New Jersey geology and guide to field trips (Proceedings, 52 nd. Annual Meeting of the New York State Geological Association): Newark, New Jersey, Rutgers Univ., p. 314-350.*
- Manspeizer, W., Puffer, J. H., and Cousminer, J. H., 1976, The separation of Morocco and eastern Northern America: A Triassic-Jurassic Stratigraphic Record: *Geological Society of America Bulletin*, v. 80, p. 901-920.
- McHone, J.G., 1992, Mafic dike suites within Mesozoic igneous provinces of New England and Atlantic Canada: in Puffer, J. H., and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper*, v. 268, p. 1-11.
- McHone, J.G., J.G., 1996, Broad-terrane Jurassic flood basalts across northeastern North America: *Geology*, v. 24, p. 319-322.
- McHone, J.G., and Puffer, J.H., (in press), Hettangian Flood Basalts of the Initial Pangean Rift: Aspects of Triassic-Jurassic Rift Basin Geoscience, *Proceedings of a conference to be held Nov. 9 and 10, 1996, at Dinosaur State Park, Rocky Hill, Connecticut.*

- Miller, B.B., and Puffer, J.H., 1972, The cordierite zone of hornfels near the base of the Palisades sill at Weehawken, New Jersey [abs.]: *The Bulletin, New Jersey Academy of Science*, v. 17, p. 46.
- Murphy, K.B., and Husch, J.M., 1990, Geochemical variations along and across the Rocky Hill diabase, central Newark basin, New Jersey [abs.]: *The Bulletin, New Jersey Academy of Science*, v. 35, no. 2, p. 39.
- Naslund, H. R. and Hristov, L. G., 1995, Geochemical modeling of the Palisades Sill: *Geological Society of America, Abstracts with Program, Cromwell, Connecticut*, v. 27, p. 71.
- Olsen, P. E.; Kent, D. V.; Cornet, Bruce; White, W. K.; and Schlische, R. W., 1996, High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America: *Geological Society of America Bulletin*, v. 108, p. 40-77.
- Olsen, P.E., 1980, The latest Triassic and Early Jurassic formations of the Newark Basin (eastern North America, Newark Supergroup): *Stratigraphy, structure, and correlation: The Bulletin, New Jersey Academy of Science*, v. 25, p. 25-51.
- Papezik, V.S., and Hodych, J.P., 1980, Early Mesozoic diabase dikes of the Avalon Peninsula, Newfoundland: petrochemistry, mineralogy, and origin: *Canadian Journal of Earth Sciences*, v. 17, p. 1417-1430.
- Pappano, P.A., Klewsaat, D.R., and Husch, J.M., 1990, Gravity and magnetic anomalies of the central Newark basin [abs.]: *The Bulletin, New Jersey Academy of Science*, v. 35, no. 2, p. 39.
- Pearce, J.A., and Norry, 1979, Petrogenic implications of Ti, Zr, Y, and Nb variations in volcanic rocks,: *Contributions to Mineralogy and Petrology*, v. 69, p. 33-47.
- Pegram, W.J., 1990, Development of continental lithospheric mantle as reflected in the chemistry of the Mesozoic Appalachian tholeiites, USA: *Earth and Planetary Science Letters*, v. 97, p. 316-331.
- Philpotts, A.R., 1992, A Model for Emplacement of Magma in the Mesozoic Hartford Basin: *in* Puffer, J. H. and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268*, p. 137-148.
- Philpotts, A.R., and Martello, A., 1986, Diabase feeder dikes for the Mesozoic basalts in southern New England: *American Journal of Science*, v. 286, p. 105-126.
- Philpotts, A.R., and Asher, P. M., 1993, Wallrock melting and reaction effects along the Higganum diabase dike in Connecticut: Contamination of a continental flood basalt feeder: *Journal of Petrology*, v. 34, p. 1029-1058.
- Philpotts, A.R., and Carroll, Maureen, 1996, Rheology of partially melted tholeiitic basalt: *Geological Society of America, Abstracts with Program, Northeastern Section, Buffalo, New York*, v. 28, p. 91.
- Puffer, J. H., 1988, The Watchung Basalts revisited, *in* Husch, J.M., and Hozik, M.J., eds., *Geology of the central Newark basin, field guide and proceedings: Geological Association of New Jersey, 5th Annual Meeting: Lawrenceville, New Jersey, Rider College*, p. 83-105.
- Puffer, J. H., 1992, Eastern North American Flood Basalts in the Context of the Incipient Breakup of Pangea, *in* Puffer, J. H., and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper*, v. 268, p 95-118.
- Puffer, J. H., 1994, Initial and secondary Pangean Basalts *in* Beauchamp, B; Embry, A.F.; and Glass, D., (editors), *Pangea: Global Environments and Resources: Canadian Society of Petroleum Geologists, Memoir 17*, p. 85-95.

- Puffer, J. H., and Peters, J. J., 1974, Magnetite veins in diabase of Laurel Hill, New Jersey: *Economic Geology*, v. 69, p. 1294-1299.
- Puffer, J. H., and Lechler, P., 1979, The geochemistry of Cushetunk Mountain, New Jersey: *The Bulletin, New Jersey Academy of Science*, v. 24, p. 1-5.
- Puffer, J. H., and Lechler, P. 1980, Geochemical cross-sections through the Watchung Basalts of New Jersey: *Geological Society of America Bulletin*, v. 91, part 1, p. 7-10, part 2, p. 156-191.
- Puffer, J. H., Hurtubise, D. O., Geiger, F. J., and Lechler, P. 1981, Chemical composition and stratigraphic correlation of Mesozoic basalt units of the Newark Basin, New Jersey and the Hartford Basin, Connecticut: *Geological Society of America Bulletin*, v. 92, part 1, p. 155-159, part 11, p. 515-553.
- Puffer, J. H., Geiger, F.J., and Camanno, E.J., 1982, Igneous rocks of Rockland County, New York: *Northeastern Geology*, v. 4, p. 121-130.
- Puffer, J. H., and Philpotts, A. R., 1988, Eastern North American quartz tholeiites: geochemistry and petrology, in Manspeizer, W., ed., *Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean: Developments in Geotectonics 22*, Elsevier Scientific Publishers, Amsterdam, p. 579-606.
- Puffer, J. H., Husch, J.M., and Benimoff, A.I., 1992, The Palisades sill and Watchung Basalt flows, northern New Jersey and southeastern New York: A geological summary and field guide: *New Jersey Geological Survey Open-File Report OFR 92-1*, 27 p.
- Puffer, J. H., and Student, J. J., 1992, The volcanic structure and eruptive style of the Watchung Basalts, New Jersey: *in* Puffer, J. H. and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268*, p. 261-279.
- Puffer, J.H., and Horter, Dawn L., 1993, Origin of pegmatitic segregation veins within flood basalts: *Geological Society of America Bulletin*, v. 105, p. 738-748.
- Puffer, J. H., and Proctor, Theodor, 1994, Distribution of copper in the Orange Mountain Basalt, Related Diabase Dikes, and Underlying Passaic Formation, New Jersey: *Geological Society of America, Annual Meeting, Seattle, Washington, Abstracts with Program*, v. 26, p. A-402.
- Puffer, J. H., and Benimoff, A.I., (in press), Fractionation, wall rock assimilation, and metasomatic effects on an Early Jurassic HTQ intrusion: Snake Hill, New Jersey: *Journal of Geology*, v. xx, p. xx.
- Ragland, P. C.; Cummins, L. E.; and Arthur, J. D., 1992, Compositional patterns for Early Mesozoic Diabase from South Carolina to central Virginia, *in* Puffer, J. H., and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper*, v. 268, p. 309-331.
- Ratcliffe, N.M., 1988, Reinterpretation of the relationship of the western extension of the Palisades sill to the lava flows at Ladentown, New York, based on new core data, in Froelich, A.J., and Robinson, G.R., Jr., eds., *Studies of the early Mesozoic basins in the eastern United States: U.S. Geological Survey Bulletin 1776*, p. 113-134.
- Roth E.A., 1988, Petrographic and geochemical analysis of the early Mesozoic Lambertville sill in the Newark basin: Evidence for compound intrusion on the grand scale [B.S. thesis]: Lawrenceville, Rider College, 76 p.

- Sandberg, S.K., Hall, D.W., Gronberg, J.A.M., J.C., and Pasicznyk, D.L., 1996, Geophysical investigation of the Potomac-Raritan-Magothy aquifer system and underlying bedrock in parts of Middlesex and Mercer counties, New Jersey: New Jersey Geological Survey Report GSR-37, 33 p.
- Sassen, Roger, 1978, The Chimney Rock Quarry, *The Mineralogical Record*, v. 9, p. 25-31.
- Schroeder, B.; Thompson, G.; Sulamowska, M.; and Ludden, J. N., 1980, Analysis of geologic materials using an automated x-ray fluorescence system: *X-Ray Spectrometry*, v. 9, p. 198-205.
- Shirley, D.N., 1987, Differentiation and compaction in the Palisades sill, New Jersey: *Journal of Petrology*, v. 28, p. 835-865.
- Shirley, D.N., 1988, Effects of postcumulus fractionation in the Palisades sheet: Further evidence from Weehawken, New Jersey, in Froelich, A.J., and Robinson, G.R., Jr., eds., *Studies of the early Mesozoic basins in the eastern United States: U.S. Geological Survey Bulletin 1776*, p. 135-141.
- Smith, R.C., II, 1973, *Geochemistry of Triassic diabase from southeastern Pennsylvania [Ph.D. thesis]: University Park, Pennsylvania State University*, 262 p.
- Smith, R.C., II, Rose, A.N., and Lanning, R.M., 1975, *Geology and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin*, v. 86, p. 943-955.
- Steiner, J.C., Walker, R.J., Warner, R.D., and Olson, T.R., 1992, A cumulus-transport-deposition model for the differentiation of the Palisades sill, in Puffer, J.H., and Ragland, P.C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268*, p. 193-217.
- Sun, S., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, in Saunders, A. D., and Norry, M. J., eds., *Magmatism in the ocean basins: Geological Society Special Publication*, v. 42, p. 313-345.
- Sutter, J.F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins, in Froelich, A.J., and Robinson, G.R., Jr., eds., *Studies of the early Mesozoic basins in the eastern United States: U.S. Geological Survey Bulletin 1776*, p. 194-200.
- Szemple, K., 1996, *Geochemistry of the stope-like structure in the Lambertville sill, Rocktown, New Jersey: Distribution of late-stage granophyric rocks [B.S. thesis]: Lawrenceville, Rider University*, 45 p.
- Tollo, R. P., and Gottfried, David, 1992, Petrochemistry of Jurassic Basalt from Eight Cores, Newark Basin, New Jersey: Implications for the Volcanic Petrogenesis of the Newark Supergroup, in Puffer, J. H., and Ragland, P. C., eds., *Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper*, v. 268, p. 233-259.
- Trione, C.H., 1985, *The geochemistry of the Mesozoic Baldplate Mountain diabase, Lambertville, New Jersey (B.S. Thesis): Lawrenceville, Rider College*, 42 p.
- Van Houten, F. B., 1965, Crystal casts in upper Triassic Lockatong and Brunswick formations: *Sedimentology*, v. 4, p. 301-313.
- Van Houten, F. B., 1969, Late Triassic Newark Group, North-Central New Jersey and adjacent Pennsylvania, in Subitsky, S., ed., *Geology of Selected Areas in New Jersey and Adjacent Pennsylvania: Rutgers University Press, New Brunswick, N.J.*, p. 314-347.
- Van Houten, F. B., 1969, Late Triassic Newark Group, north-central New Jersey and Pennsylvania and New York, in Subitsky, S., ed., *Geology of selected areas in New Jersey and eastern Pennsylvania and*

- guidebook of excursions (Geological Society of America 1969 annual meeting guidebook): New Brunswick, Rutgers University Press, p. 314-347.
- Van Houten, F. B., 1971, Contact metamorphic mineral assemblages, Late Triassic Newark Group, New Jersey: Contributions to Mineralogy and Petrology, v. 30, p. 1-14.
- Walker, F., 1940, The differentiation of the Palisades diabase, New Jersey: Geological Society of America Bulletin, v. 51, p. 1059-1106.
- Walker, K.R., 1969, The Palisades sill, New Jersey: A reinvestigation: Geological Society of America Special Paper 111, 178 p.
- Weigand, P. W., and Ragland, P. C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, p. 195-214.
- Wofford, G.T., 1962, Gravity study of Cushetunk Mountain and the surrounding area, New Jersey [B.S. thesis]: Princeton, Princeton University, 41 p.
- Woodruff, L.G., Froelich, A.J., Belkin, H.E., and Gottfried, D., 1995, Evolution of tholeiitic diabase sheet systems in the eastern United States: examples from the Culpeper Basin, Virginia-Maryland, and the Gettysburg Basin, Pennsylvania: Journal of Volcanology and Geothermal Research, v. 64, p. 143-169.

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the success of any business and for the protection of the interests of all parties involved. The document outlines the various methods and systems that can be used to ensure the accuracy and reliability of financial records.

Next, the document addresses the issue of auditing and the role of independent auditors. It explains that auditing is a critical process that helps to verify the accuracy of financial statements and to identify any potential areas of concern. The document provides a detailed overview of the auditing process, including the selection of auditors, the scope of the audit, and the reporting requirements.

The document also discusses the importance of internal controls and the role of management in ensuring the integrity of financial reporting. It highlights the need for a strong internal control system that is designed to prevent and detect errors and fraud. The document provides a comprehensive guide to the development and implementation of an effective internal control system.

Finally, the document discusses the importance of transparency and the role of disclosure in financial reporting. It explains that transparency is a key principle of financial reporting that helps to build trust and confidence among investors and other stakeholders. The document provides a detailed overview of the various disclosure requirements and the importance of providing clear and concise information to all parties involved.

EARLY JURASSIC DIABASE AND BASALT OF THE NEWARK BASIN ROAD LOG

Miles From Start	Miles Between Points	
0.0	0.5	Start at the College of Staten Island parking lot near the outcrop of Palisades diabase, proceed to the exit.
0.7	0.2	Cross over Victory Blvd., proceed north then turn right into the entrance of I-278-west.
4.2	3.5	Proceed west on I-278, cross the Goethals Bridge and follow signs around complex clover-leaf to I-95 north (NJ Turnpike).
5.5	1.3	Take toll card at booth
12.5	7.0	I-95 divides, take east fork toward Lincon Tunnel (but dont enter the Tunnel).
17.3	4.8	Observe Laurel Hill Diabase on both sides of I-95.

View Site: Laurel Hill

Due to the realities of traffic congestion and aggressively enforced trespassing laws throughout the New York City area, Laurel Hill is one of several excellent sites that we will not be able to stop at. But this exposure is at least clear enough to see through the bus windows.

Laurel Hill is an almost completely exposed early Jurassic volcanic neck, consisting of three concentric zones (Puffer and Benimoff, in press). The diverse chemical composition of Laurel Hill diabase overlaps each of the major eastern North American (ENA) Jurassic diabase types. Zone 1 is an irregular, heterogeneous, border-zone characterized by chemistry resembling the low-Ti-quartz-normative type (LTQ) ENA diabase but is interpreted as an alteration product of high-Ti-quartz-normative type (HTQ) diabase. Dilution of HTQ magma with hydrothermal sericite, and with plagioclase and pyroxene that accumulated during fractionation, has reduced the TiO₂ content of Zone 1 from HTQ (1.1 percent) to LTQ levels (<0.9 percent). Localized assimilation of Passaic Formation siltstone is recognized by an enrichment of Zr in some Zone 1 samples. Zone 2, the intermediate zone, is characterized by chemistry typical of HTQ-type diabase. Zone 3, the interior zone, resembles the HFQ-type (High-Fe-quartz-normative) ENA diabase and is interpreted as an HTQ fractionation product.

19.4 over	2.1	Pay toll at Exit 18 "George Washington Bridge" but don't worry you don't have to go over the bridge.
23.9	4.5	I-95 merges with I-80, follow signs to George Washington Bridge.
25.9	2.0	Consistently take local lanes on I-95 toward "Last Exit in NJ".
26.5	0.6	Continue north on I-95; observe the Palisades sill on the east exposed as the north-south ridge in the background.

- 28.4 1.9 Observe upper portions of the Palisades sill on the left. The upper contact is hidden behind vegetation and retaining walls.
- 29.5 1.1 Observe the vertical leucocratic dikes cutting through black Palisades diabase. The relatively thick dikes are composed of trondhjemite while the relatively thin dikes are albatite and calcite. They are described by Benimoff and others (1989) and are interpreted as fusion products of sodic Lockatong argillite host rock. They have a chemical composition similar to the host rock.
- 29.8 0.3 Exit I-95 on right onto Lemoine Ave.; avoid going across George Washington Bridge!!!
- 30.1 0.3 Turn right onto Lemoine Ave.
- 30.3 0.2 From Lemoine turn left onto Main Street, Fort Lee.
- 30.6 0.3 From Main Street turn right onto River Road.
- 30.8 0.2 From River Road turn left into entrance for Palisades Interstate Park.
- 30.9 0.1 Follow park road to the north; observe olivine zone of Palisades Sill on left recognized as an eroded out deeply altered cut at the base of the diabase slope. Stopping on the park road is strictly forbidden, but if you park at the entrance to the park the olivine zone is only a short walk.
- 31.3 0.4 Observe irregular lower contact of the Palisades Sill with the Lockatong Formation.
- 31.4 0.1 Pass under George Washington Bridge.
- 31.5 0.1 Observe additional exposures of the conformable Lockatong/Palisades contact on the left.
- 31.8 0.3 At the circle in the park road at the base of the Palisades Sill take the road which veers off on the right towards Ross Dock.
- 32.1 0.3 Take road down to parking lot at Ross Dock.

STOP 1. Lower Contact Of Palisades Sill With Lockatong Hornfels At Ross Dock, Fort Lee, NJ.

Permission From The Palisades Interstate Park Commission To Stop And Collect Along The Road Is Required.

After admiring the view of the Hudson River and Manhattan Island, walk south from the parking lot along the road to the boat launch, then up the stone steps, through the tunnel under the road, and out onto road level. Walk north along the contact of the lower chilled zone with hornfels of the Lockatong Formation. According to Gorrington and Naslund (1995), the fine-grained diabase chilled zone in the Fort Lee area consists of about 1-2 percent olivine (Fo68-78), 35-55 percent augite, 1-2 percent orthopyroxene (En75-80), and 35-55 percent plagioclase (An65-70; Walker, 1969). The pyroxene-dominated (along with plagioclase), tholeiitic-trend fractionation of this HTQ-type parental magma culminated in the development of a 33 m-thick granophyre layer, or sandwich horizon (Shirley, 1987), 50-100 m below the upper contact of the 330 m-thick sheet. Because this section of the PRHL megasheet is quite conformable, there appears to be little in the way of density driven lateral migrations of residual magmas and nearby sections through the Palisades contain very similar distributions of rock types (Husch, 1990). Some thin leucocratic veins and dikes of quartzofeldspathic material cut the diabase along the road at this locality. As discussed in Part I, these may have multiple origins.

The 3-4 m-thick OZ is exposed approximately 15 m above the road level and is exposed at road level 0.1 mile east of the entrance to the park (mile 30.8). At this locality the lower contact of the OZ is somewhat gradational, although the upper contact is quite abrupt, with olivine modes falling from over 20 percent to zero within less than one meter (Gorring and Naslund, 1995). At other localities along the Hudson river, both the upper and lower contacts of the OZ can be equally sharp (Walker, 1940; Gorring and Naslund, 1995).

Although originally thought by Walker (1969) to be the result of in situ gravitational crystal settling from a second pulse of Palisades magma that produced most (if not all) of the residual, granophyric compositions found higher up in the sheet, recent studies by Husch (1990, 1992) and Gorring and Naslund (1995) indicate that this interpretation is incorrect. Husch (1990, 1992) showed that olivine removal is inconsistent with the geochemical fractionation trends observed for the PRHL megasheet (see Part I) and that there are large-scale features of the OZ that suggest it was a separate olivine-rich intrusion into an already formed, although still largely molten, PRHL sheet. Gorring and Naslund (1995), on the other hand, believe the OZ to have formed as part of the initial injection of the HTQ parent (or at least within 5 years of that event) and that the olivine accumulation took place prior to or during the injection sequence. Based upon the distribution of olivine within the OZ and its composition (Fig. 13), Gorring and Naslund (1995) propose a mechanical sorting of olivine by a flow differentiation mechanism, a process also suggested by Husch (1990).

Beneath the lower contact of the Palisades are contact metamorphosed buff-colored arkoses and platy and laminated siltstones. These metasediments have been described by Olsen (1980) and correlate with other Lockatong Formation exposures to the south. The pelitic layers, in particular, have been affected by thermal metamorphism and have been converted into black hornfels consisting of biotite and albite with minor analcime, diopside, and calcite, or to green hornfels consisting of green diopside, grossularite, chlorite, and calcite with minor biotite, feldspar, amphibole, and prehnite (Van Houten, 1969).

Porphyroblasts of pinite after cordierite commonly occur as small green spots in the black biotite-albite hornfels (Miller and Puffer, 1972). Large tourmaline porphyroblasts and even larger green spherical structures, up to 4 cm across, composed largely of clinozoisite, are less common in the hornfels, but are known from several other hornfels localities in the Newark and Culpeper Basins.

- | | | |
|------|-----|--|
| 32.4 | 0.3 | Proceed to park exit and turn right around circle to the south. |
| 33.4 | 1.0 | Return south to the park exit and turn right onto River Road. |
| 33.6 | 0.2 | From River Road turn left onto Main Street (Rt.11). |
| 33.9 | 0.3 | From Main Street turn right on Lemoine Ave. and continue north over I-95. |
| 34.1 | 0.2 | From Lemoine Ave. turn left onto Cross Street and stay in left lane. |
| 34.3 | 0.2 | From Cross Street turn onto the entrance ramp for I-95, proceed south. |
| 35.6 | 1.3 | <u>Directions to Stop 1A (optional).</u> Follow signs for Interstate 95 Local Lanes. Proceed down the dip slope of the top of the Palisades and pass under the Jones Road viaduct (prominent arch support bridge). Stop on shoulder at western end of outcrop. |

STOP 1A (Optional). Upper Contact Of Palisades Sill Along Westbound Interstate 95 (Local Lanes).

Stopping Along The Highway Other Than For Emergencies Is Illegal In New Jersey. The Police Will Ask You To Leave Immediately (If You Haven't Been Arrested Already).

This rare exposure of the upper contact of the Palisades is visible on both sides of the highway. The chilled margin is almost identical in composition, mineralogy, and texture to that found at the lower contact (Stop 1). Of course, no upper analog to the OZ is seen. Overlying the upper contact are hornfels of the

Lokatong Formation, again similar to those found beneath the lower contact. The contact is highly conformable at this locality with only minor cross cutting "steps" visible; a few minor faults also have offset the contact. In at least one instance, apparent cooling cracks have been filled in with overlying sediments, producing a sedimentary dike structure. Other fractures in the upper contact zone contain copper mineralization and calcite fillings.

As one walks east towards the viaduct, more interior portions of the sheet are exposed and grain size increases, as does the amount of granophyric material. Eventually, pods of pegmatitic granophyre are found within a finer-grained, less differentiated diabase. Looking south across the highway at the opposite cliff (now sheathed in metal netting to keep loose boulders from falling onto the highway) it is possible to see a number of leucocratic dikes running vertically across the face. Benimoff and others (1989) described these dikes as being trondhjemitic in character and concluded, on the basis of geochemical data, that they represented the late-stage injection of anatectic melts, derived from country rock xenoliths, into cooling fractures.

- | | | |
|------|------|--|
| 37.5 | 1.9 | Bear left under sign for I-95 "The Ridgefields"; stay on I-95 south. |
| 44.0 | 6.5 | Pick up toll card at booth and stay in local lanes. |
| 52.2 | 8.2 | Take exit 14 and follow signs for I-78 west. |
| 52.6 | 0.4 | Pay toll at booth and <u>enter express lanes for I-78 west</u> |
| 62.8 | 10.2 | Continue west across valley underlain by Jurassic red-beds of the Passaic Formation. Exposure of Orange Mountain Basalt is on the left with a well defined flow contact identified by an undulating erosion surface, and the contrasting textures of the vesicular upper entablature of the lower flow and the relatively massive lower colonnade of the upper flow. |
| 65.2 | 2.4 | Lower contact of Preakness Basalt on the right. Most of the actual contact has been recently hidden by a new retaining wall and some landscaping but Feltville Formation siltstones exposed here have been thermally metamorphosed by the extrusion of one of the thickest flows of flood basalt anywhere on earth. The contact metamorphism has converted the otherwise consistently red siltstone into a gray layer within 5 meter of the contact and a dark gray hornfels within 1 meter of the contact. The thickness of the lower flow is about 150 m, comparable to the thickness of the Grand Ronde flow of the Columbia River Basalt and thicker than almost any flood basalt. |
| 65.7 | 0.5 | Note vertical strike-slip faults through the Preakness Basalt defined by eroded fault gouge. The fault planes curve below the Preakness flow and do not seem to penetrate into the underlying Feltville Formation. Apparently shearing stresses were absorbed by plastic flow of unlithified Feltville sediments. Similar strike-slip faults are exposed at each of the several trap-rock quarries cut into Orange Mt., Preakness and Hook Mt. basalts in New Jersey. |
| 65.8 | 0.1 | Note the very closely spaced vertical jointing of the lowest of the five Preakness flows. A set of tectonically generated vertical platy-prismatic joints have been superimposed onto the vertical polygonal cooling joints, probably along incipient planes of weakness opened during cooling. The joint patterns have been described and their origin has been discussed by Puffer and Student (1992) and by Faust (1978). |
| 65.9 | 0.1 | The discontinuous exposure of the lower flow of the Preakness Basalt on the right was a virtually uninterrupted exposure 6 miles long during highway construction in 1987, and afforded close inspection and sampling (Puffer, 1992). The chemistry and texture is uniform although there is a slight change in composition across the lower |

colonnade / entablature contact. The upper contact of the flow is clearly defined by a layer of feruginous siltstone. The chemistry of the lower flow is the most highly fractionated of the 5 Preakness flows. The least fractionated flows are the thin upper flows (flows 3,4 and 5) which have typical LTQ compositions.

- 67.1 1.2 Observe the variations in jointing of Preakness basalt exposures on the right and the strike slip fault plains.
- 67.7 0.6 Take I-78 exit-43 (the first Berkeley Heights exit).
- 68.4 0.7 Turn left immediately upon exiting onto the unnamed road marked "DEAD END" that leads to the microwave tower on top of the ridge. The bus can unload along the exposure and turn around at the tower.

STOP 2. Preakness Basalt

The view to the south includes the Orange Mountain basalt of the First Watchung Mountain in the background and the valley eroded into Early Jurassic Feltville Formation red beds in the foreground. While examining the Preakness note:

1. The very uniform medium grained texture consisting largely of plagioclase and pyroxene with only minor glass or mesostasis.
2. The large flat widely spaced joint plains in strong contrast to the very closely spaced platy prismatic joints exposed along I-78.
3. The long curved but subhorizontal step-like parallel structure on the joint surfaces. They are interpreted as the kind of boundaries that join crack segments described by DeGraff and Aydin (1987). The cracks propagate downward through layers of freshly hardened basalt in the entablature as the upper crystallization front of the flow advances down into the largely liquid crystal mush below.
4. The strike-slip fault plain eroded into the Preakness. Note the horizontal striations on the slickenside surfaces.
5. The occurrence of a few rare and small shapeless basaltic pegmatites located between crack segment boundaries, and the occurrence of discontinuous, very thin, vesicular, basaltic pegmatite layers at the crack segment boundaries as described by Puffer and Horter ('993). Although the crack segment boundaries are well defined at this exposure, the pegmatites are not particularly well developed. The size and occurrence of basaltic pegmatite is rather unpredictable but seems to be restricted to unusually thick lava flows. Probably the largest pegmatite layer found in any ENA basalt, as of 1996, was recently mapped by Richard Volkert of the New Jersey Geological Survey at a construction site in the Preakness basalt located near the Chimney Rock quarry. The pegmatite in addition to being huge is highly fractionated with only 2 % MgO and as much as 3 % TiO₂. It also contains considerable glass, but for more details we will wait for Volkert's report.

- 68.8 0.4 Return to I-78 west.
- 69.4 0.6 The Weldon Trap Rock Quarry cut into Orange Mountain basalt is on the left. The basalt here is mineralized with zeolites and prehnite that lines huge vugs over 2 m across. The quality of the zeolites and prehnite is easily of museum grade but access to the quarry was denied. Chemical analyses of several basalt samples collected here are reported by Puffer (1992). Each of the three Orange Mountain flows are exposed in the quarry.
- 71.8 2.4 Proceed on I-78 to exit 40 and turn south (left) onto Rt. 531 (Hillcrest Rd.).
- 73.2 1.4 Proceed south on Rt. 531 and turn right onto Rt. 527 south.

- 73.3 0.1 Stay on Rt. 527 south (Mountain Blvd.) through the traffic circle.
- 74.9 1.6 From Rt. 527 turn left (south) onto Washington Rock Rd. at the sign "Washington Rock"
- 75.5 0.6 Avoid "Dead End" at sharp right turn.
- 76.1 0.6 Proceed south on Washington Rock Road to Washington Rock State Park; park in the lot on the right.

STOP 3. Orange Mountain Basalt

Walk to the monument to General George Washington at the flag pole. The view to the south-east is largely a valley eroded into Triassic red-beds. This entire view area was once occupied by Orange Mountain flood basalt. The Atlantic Ocean (Raritan Bay) is 15 miles to the south/east and can be seen on a clear day. Picnic tables and drinking fountains are available but the rest-room facilities have been closed as a cost cutting measure in defiance of the laws of nature.

The Orange Mountain Basalt exposed near the flag poll is much finer-grained than typical of the Preakness. The basalt here contains common amygdules composed of chlorite and less commonly by quartz. The columnar joint pattern is reasonably clear but lacks the sharp flat surfaces typical of Preakness exposures or the greater degree of clarity at greater depths into Orange Mountain entablatures. The irregular columnar joint pattern and amygdule content are evidence of close proximity to a flow top.

- 76.1 0.0 Exit parking lot and proceed down hill on Washington Avenue. Be careful around sharp curves.
- 77.0 0.9 At light at bottom of hill make right onto Route 22 West. Please keep sophomoric jokes about Texas Wieners (at corner on right) to a minimum.
- 82.3 5.3 Chimney Rock Quarry in OMB on right. This is probably the largest active trap-rock quarry in the Watchung basalts. In addition to a spectacular array of beautiful prehnite and zeolites, particularly heulandite and some of the best natrolite anywhere on earth, there is abundant native copper mineralization in the first Orange Mountain basalt flow and in the Passaic red-beds within a meter of the contact. Sheets of native copper measuring as much as a foot across are easily collected; however, permission for us to collect today was denied. Basalt flow contacts are clearly displayed with very thin layers of red-bed rock between the flows. A description of the mineral collecting here was written by Sassen (1978).
- 82.6 0.4 Intersection with Interstate 287. Stay on 22 West.
- 85.7 2.9 Intersection with Routes 202-206. Stay on 22 West.
- 88.9 3.3 Cross North Branch of the Raritan River.
- 93.8 4.9 Good view to the southwest (left) of the forested ridge, rising approximately 500 feet above the surrounding plain of the Newark Basin, formed by the northeastern arm of the Cushtunk Mountain diabase (CMD).
- 97.4 3.6 Exit left at sign for Lebanon Business Center. Proceed along East Main Street.
- 98.6 1.2 Make left onto Cherry Street (Route 629).

- | | | |
|------|-----|--|
| 98.9 | 0.3 | Pass under railroad bridge. Continue up hill with view of Round Valley North Dam to the left. |
| 99.3 | 0.4 | Park on left in small pulloff at west end of dam directly across road from exposure of CMD on right. |

STOP 4. Fault Zone In Granophyric Rock of the Cushetunk Mountain Diabase, West End of Round Valley North Dam, Lebanon, NJ.

Round Valley Reservoir was filled in the late 1960's and is an important source of water for many municipalities in northern and central New Jersey. It is surrounded on three sides by the arcuate ridge of the CMD. The northwest quadrant of the reservoir is bounded by Precambrian metamorphic rocks, presumably of Grenville age.

Initial geochemical data by Puffer and Lecher (1979) indicated that the CMD chilled margin composition was a quartz normative, high-iron (HFQ) ENA type. However, more recent analyses by Keely and Husch (1993) show that the CMD chilled margin composition is very similar to all other Newark Basin HTQ chills and flows. Keely and Husch (1993) also show that the composition of the interior of the CMD generally becomes more fractionated and granophyre rich as one progresses northward along the intrusion's northeastern arm (Fig. 14). This arm cross-cuts over 5000 feet of the Triassic sedimentary section, rising to within 3000 feet of the OMB, the presumed Early Jurassic paleosurface (Houghton and others, 1992). Reversals in the general fractionation trend, as is found for this stop location (Fig. 14), are believed to be due to post-intrusion normal faulting exposing deeper, less fractionated structural levels of the CMD within the footwall block (Keely and Husch, 1993).

The diabase at this locality is quite granophyric, although less so than the diabase found at the east end of the dam, and contains abundant pink alkali feldspar. Equally obvious at this exposure are numerous fracture surfaces on which well-developed slickensides are observed. Most surfaces indicate a nearly horizontal right-lateral motion, although a few surfaces suggest a normal oblique, right-lateral motion. Houghton and others (1992) map this fault zone as a normal oblique splay fault of the Flemington Fault Zone (Fig. 2). Based upon the geochemical data of Keely and Husch (1993), as much as 5000 ft of vertical offset may have occurred along the fault zone seen here between the footwall block to the west and the headwall block exposed on the opposite side of the dam to the east (see sample CM1, Fig. 14). Jakubicki and Husch (1995), utilizing two-dimensional Bouguer Anomaly modelling, confirmed the normal sense of the vertical offset, but suggested the throw was less, on the order of 1500-2000 feet. The gravity modelling of Jakubicki and Husch (1995) also confirmed the initial findings of Wofford (1962) that the CMD dips outward (Fig. 15) and has the general shape of a ring dike.

- | | | |
|-------|-----|---|
| 100.5 | 1.2 | After continuing south around reservoir on Route 629, make left at stop sign onto Stanton-Lebanon Road (still Route 629). |
| 101.3 | 0.8 | Entrance on left to Round Valley Recreation Area. |
| 102.9 | 1.6 | Crossing Prescott Brook. Round Valley South Dam on left. |
| 103.7 | 0.8 | Make left at Stanton Mountain Road. Park along side of road immediately across from white house. Climb to top of hill on right. |

STOP 4A (optional). Outcrops of Granophyre At Northern End Of The Prescott Brook Diabase, Stanton, NJ.

The diabase at this locality is quite coarse grained and granophyre rich, with MgO concentrations as low as 1.5 weight percent (Keely and Husch, 1993). Approximately 1 km farther south (and structurally lower by approximately 1500 ft) the diabase composition is not quite as fractionated with an MgO content of approximately 3.0 weight percent (Houghton and others, 1992). Again, the chilled margin (not exposed here)

composition for the Prescott Brook diabase (PBD) is typical ENA-HTQ type (Houghton and others, 1992). Keely and Husch (1993) proposed that the PBD was connected at depth to the adjacent CMD to the east, based upon their similar relationships between stratigraphic level of emplacement and composition (Fig. 14). This however, could neither be confirmed nor refuted by the Bouguer Anomaly modelling of Jakubicki and Husch (1995).

Running diagonally across the north-facing slope of the hill is an enigmatic 3 to 5 ft-thick layer that weathers more readily than the surrounding rocks, forming a prominent recess in the hillside. Two of the layer's more noticeable features are its broken, brecciated character and the presence of chevron-like fractures or folds across it. A number of origins have been suggested for this unit, none with any great conviction or certainty. Thus, its origins are unknown at this time and any and all suggestions or ideas, no matter how far-fetched, will be entertained.

- | | | |
|-------|-----|--|
| 103.6 | 0.1 | Return back to intersection with Stanton-Lebanon Road (Route 629) and make left |
| 104.4 | 0.6 | Make right at Payne Road and cross bridge over Prescott Brook. |
| 100.7 | 0.2 | Bear left and remain on Payne Road |
| 105.2 | 0.6 | Make left at light onto Route 31 south towards Flemington. |
| 107.6 | 2.4 | Hill to left is western slope of the Round Mountain diabase (RMD), a HTQ-derived, granophyre-rich intrusion located approximately one mile to the south of the CMD and PBD (Houghton and others, 1992). Gravity data suggests that it is connected at depth to the CMD (Jakubicki and Husch, 1995). |
| 108.7 | 1.1 | Cross over South Branch of the Raritan River. |
| 112.4 | 3.6 | Flemington Circle (don't you just love driving in New Jersey). Go half-way around and continue south on Routes 31-202. |
| 115.5 | 3.2 | Family Golf Center on right. A fairly complete cross section of the Flemington dike (FD) was exposed for a few weeks in the foundation pit during the construction of the center's main building. Samples collected at that time were analyzed by Crohe (1996) for major- and trace-element compositions. Significant contamination affects (see Part I), particularly adjacent to the eastern contact zone of the dike, were found. |
| 115.7 | 0.3 | Road crosses over the FD (now on left) which continues to strike almost due south towards the upper contact zone of the Lambertville sill. |
| 117.2 | 1.4 | Exit right for Reaville and go around jughandle onto Route 514 east. Cross over highway. |
| 117.5 | 0.3 | Make right onto Dutch Lane. |
| 118.3 | 0.8 | Make left onto Back Brook Road. |
| 118.7 | 0.4 | Sharp left turn with float of FD on both sides of road. Park along straight section of road just beyond turn. |

STOP 5. Float Boulders of Flemington Dike, Ringoes, NJ.

All Boulders At This Location Are On Private Property. Many Are In Yards Or Gardens. Please Ask For and Get Permission Before Examining Or Collecting.

Walk across road (west side) to wooded area just to the left of the gray house (Janet and George Holt, 39 Back Brook Road, Ringoes, NJ 08552). There are numerous pieces of FD float lying along the road; there are no known outcrops of the dike exposed at the present time. Please disturb the pieces on the property as little as possible and leave those in the yard and garden alone. Hand samples may be collected from float in the bushes on the east side of the road opposite the house.

All float pieces contain the same fine-grained diabase found along the entire strike length (approximately 7 miles) of the FD. The dike, which is approximately 50-100 feet wide, exhibits little textural or mineralogic variation. Although all samples of the FD have compositions very typical of the ENA-HTQ type (Crohe, 1996), probable wall rock contamination affects, such as elevated concentrations of Na₂O, K₂O, and Ba, and decreased concentrations of CaO, generally become more pronounced as the dike strikes northward towards shallower structural levels. This is not surprising given the fact that the FD traverses over 9000 feet of the Triassic sedimentary section between the Lambertville sill (the dike's source; Stop 6) and the Flemington basalt (Houghton and others, 1992), the OMB equivalent flow that the FD presumably feeds. According to Houghton and others (1992), the Flemington Basalt exhibits striking geochemical signs of contamination, with as much as 5 weight percent Na₂O and 300 ppm Ba.

- | | | |
|-------|-----|--|
| 118.8 | 0.1 | Turn around at entrance to Forthcoming Farm and proceed south and west on Back Brook Road. |
| 119.3 | 0.6 | At stop sign make left onto Dutch Lane. |
| 119.5 | 0.2 | At stop sign make left onto Wertzville Road (Route 602 east). |
| 119.8 | 0.3 | Cross over Flemington Dike. Small pieces of float have been collected from south side of road. Dike strikes south up the hill to the right and intersects the stope-like structure of the Lambertville sill at crest. |
| 120.0 | 0.2 | Make right at Losey Road and proceed up hill. |
| 120.3 | 0.3 | Just beyond gray ranch house (23 Losey Road) on right a dirt road heads west along the crest of the hill. Approximately 0.3 miles up from Losey Road, float from the approximate intersection of the Flemington dike and the Lambertville sill contact zone can be collected. Compositions and textures are very similar to what can be found at Stop 5. |
| 120.5 | 0.2 | Turn right at stop sign onto Rocktown Road. |
| 121.3 | 0.8 | Just after entering trees, stop at outcrop on right. |

STOP 6. Diabase With Pegmatitic Granophyre In The Stope-Like Structure Of The Lambertville Sill, Rocktown, NJ.

This stop is located along the eastern limb of the stope-like structure found in the central portion of the Lambertville sill (Fig. 2). The top of this structure is emplaced approximately 3000 feet higher in the stratigraphy than the adjoining northeastward striking arm of the sill. Consistent with the dynamic fractionation model where residual, fractionated magmas migrate to the highest structural levels within a sheet, Szemplé (1996) found that all diabase samples collected from the stop-like structure are differentiated to some degree, containing between 2.9 and 5.6 weight percent MgO; no MgO-rich samples with elevated pyroxene modes are known. This makes the stope-like structure compositions complimentary to the mafic- (and pyroxene-) rich compositions found in sections at the Lambertville sill's southwestern and northeastern ends by Eliason (1986) and Roth (1988), respectively (Fig. 16). By combining these sections, a regional or sheet-wide mass balance is attained, although at any individual section a local mass balance is lacking.

At this particular locality, the diabase is fairly feldspathic with as much as 19 weight percent Al_2O_3 (Crohe, 1996). However, pods of pegmatitic granophyre, reminiscent of those seen at Stop 1A, are quite common within the host diabase. A more granophyric diabase can be seen in some of the float pieces located across the road and in float located on the other side of Route 31, approximately one mile to the west.

Finally, it should be reiterated here, that it does not appear that any of the residual, granophyric material, so common in this section of the Lambertville sill, was transported into the immediately adjoining Flemington dike or erupted onto the surface as part of the Flemington basalt. This indicates that the emplacement of the HTQ magma into the Flemington dike and its eruption as the Flemington basalt was completed prior to the internal differentiation of the PRHL sheet (as represented locally by the Lambertville sill). Otherwise, granophyric compositions resulting from that differentiation would be more common within the dike and flow.

- 121.4 0.1 Continue west on Rocktown Road and cross one-lane bridge.
- 122.2 0.8 Make right at stop sign onto Route 31 and head north back to Staten Island via. Routes 31, 202, and 287.

STRATIGRAPHY, STRUCTURAL GEOLOGY, AND DUCTILE- AND BRITTLE FAULTS OF NEW YORK CITY

Charles Merguerian
Geology Department
114 Hofstra University
Hempstead, NY 11550-1090
E-Mail: GEOCOMM@HOFSTRA.EDU

INTRODUCTION

Long the center of commerce and culture in the United States, Manhattan is an island around which many geologic units and structural features coalesce. Manhattan's underlying lithology and durable crystalline structure have enabled the construction of enormous towering skyscrapers rooted into glacially-sculpted Paleozoic and older crystalline rock. First studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, the bedrock geology of the New York City area was mapped in systematic detail beginning in the mid- to late 1800's by L. D. Gale, W. W. Mather and F. J. H. Merrill. Merrill, the senior author of the United States Geological Survey New York City Folio (#83) published in 1902, outlined the basic stratigraphic- and structural framework that all succeeding geologists would test, promote, and expound upon.

Today's trip examines the Paleozoic bedrock geology and the ductile- and brittle faults of New York City. The trip consists of seven easily accessible localities ("stops") in Manhattan and the Bronx (Figure 1). All of the outcrop areas are located in public parks or roadcuts which may be easily reached by car, bus, or subway. The seven localities are plotted on segments of the Central Park 7-1/2 minute quadrangle (Figure 2) and UTM grid coordinates are supplied with the stop descriptions. Thus, no detailed road log has been made for this trip. The field-trip stops have been chosen to best identify outcrops critical to my new interpretations of the bedrock geology of New York City, including the results of joint studies with J. E. Sanders that have provided evidence for post-Pleistocene uplift along the footwall of the Mosholu Parkway fault in the Bronx.

GEOLOGIC BACKGROUND

New York City is situated at the extreme southern end of the Manhattan Prong (Figure 3), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terranes of New England. Southward from New York City, the rocks of the Manhattan Prong plunge unconformably beneath predominately buried Mesozoic rocks, Cretaceous sediments, and overlying Pleistocene (glacial) sediments that cap Long Island and Staten Island.

West of Manhattan Island, in New Jersey, a series of gently west-dipping sedimentary rocks of Late Triassic to Early Jurassic ages rests positionally on the deeply eroded bedrock of Manhattan. As indicated in the west-east cross section from New Jersey to the Bronx (Figure 4), the westward tilted Mesozoic sedimentary rocks of the Newark Basin have been intruded by the Palisades Intrusive Sheet whose tilted and eroded edge forms prominent cliffs along the west margin of the Hudson channel. Joint studies by Merguerian and Sanders (1992a, 1994, 1995a, b, and c) suggest that the Palisades sheet is lopolithic in form with a feeder located near Staten Island and was intruded under relatively shallow (~3-4 km) overburden.

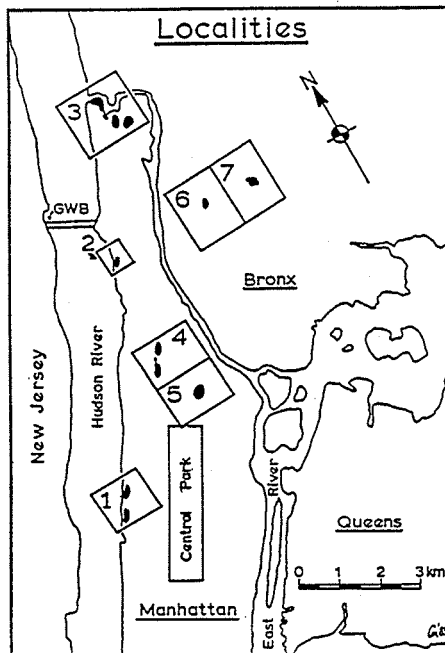


Figure 1 - Locality map of northern Manhattan and adjacent Bronx showing stop-number maps (numbered rectangles), each of which is enlarged on Figure 2.

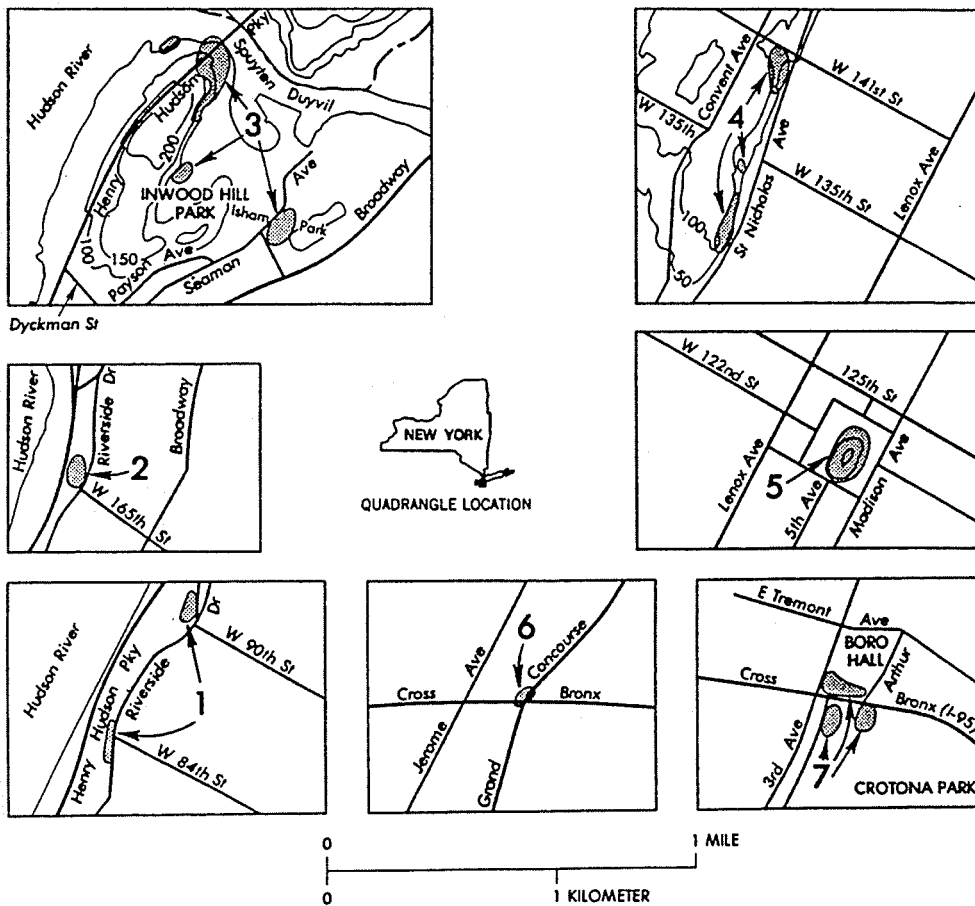


Figure 2 - Outcrop locations for trip stops (shaded areas) shown on segments of Central Park 7.5-minute topographic quadrangle map of U. S. Geological Survey.

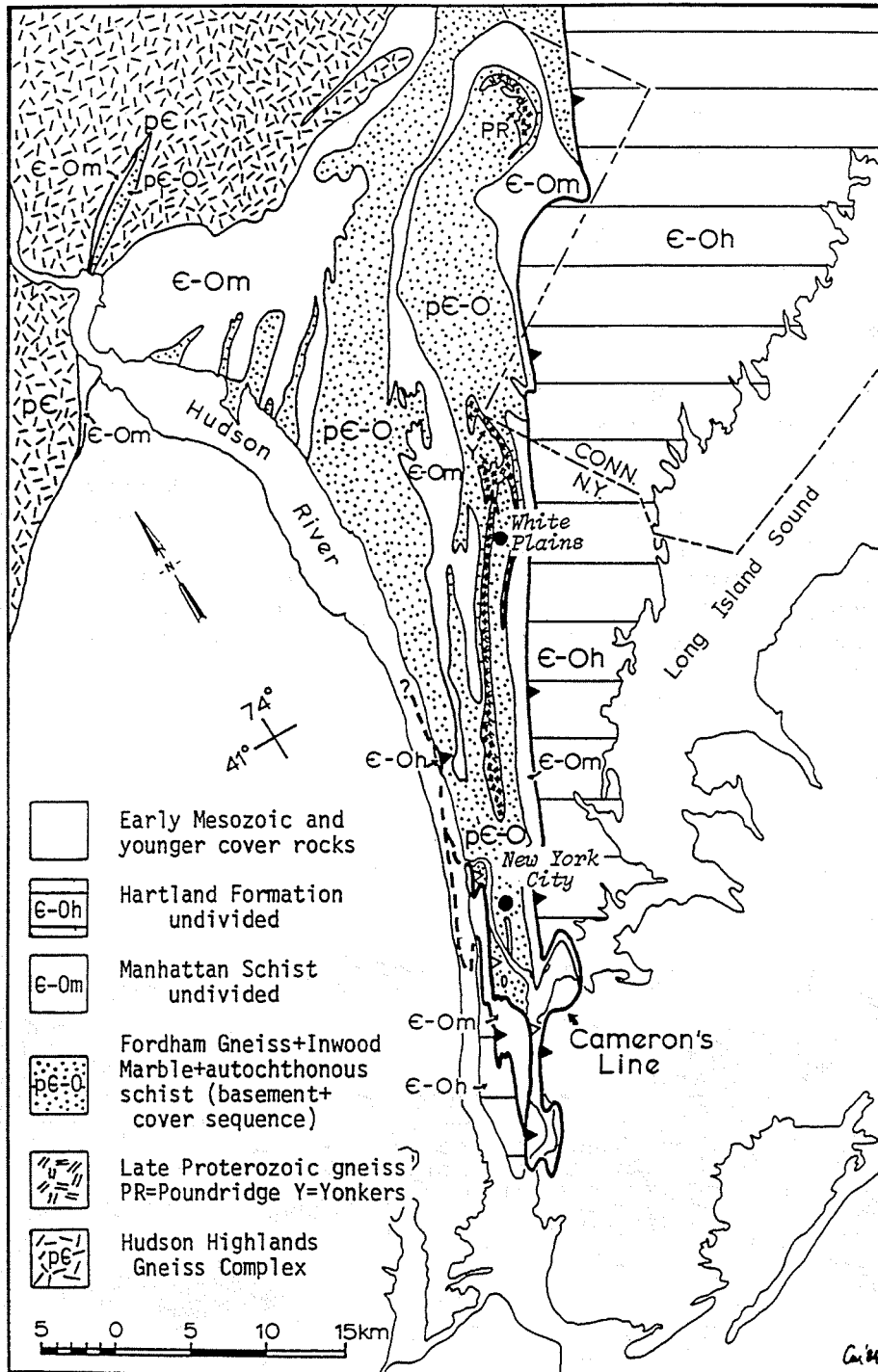


Figure 3 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted. (Mose and Merguerian, 1985, figure 1, p. 21.)

STRATIGRAPHY OF THE BEDROCK UNITS OF NEW YORK CITY

History of bedrock geologic investigations. The first geologic map of the New York City area appeared in W. W. Mather's treatise on the Geology of the First District of New York in 1843. Incorporating L. D. Gale's detailed contributions (1839, and in an addenda in Mather (1843)), Mather's map of Manhattan shows the distribution of Primary granite, gneiss, "limestone of New York County", serpentine (on Staten Island), and alluvial sand and marshland. Mather's Plate 3 included two water-colored geologic cross sections that illustrated the structure of New York City in sections parallel- and perpendicular to strike. Issachar Cozzens' (1848) geologic section through Manhattan shows a continuous granite substrate overlain by gneiss, limestone, amphibolite, serpentine, and glacial "diluvial" strata. Before the turn of the century, many geologists were examining the geology of New York City and vicinity as building construction and industrial development grew exponentially. Reports by Merrill (1886a, b; 1890, 1898a, b, and c), Dana (1880, 1881, 1884), Ries (1895), and Kemp (1887, 1895, 1897), provided important information on the bedrock geology of southeastern New York.

In 1890 (p. 390), Merrill named the Manhattan Schists for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, New York. Merrill and others (1902), produced the United States Geological Survey New York City Folio (#83) and following Dana, chose to use the name Hudson (rather than Manhattan) Schist for the schistose rocks of New York City. The *Silurian* Hudson Schist was successively underlain by the *Cambrian to Silurian* Stockbridge dolomite, the *Cambrian* Poughquag quartzite, and finally the *Precambrian* Fordham Gneiss. This pioneering work by Merrill and coworkers set the stage for a series of detailed investigations by many geologists in the 1900's that helped define the lithology and structure of New York City bedrock units. A complete literature review appears in Merguerian and Sanders (1991, 1993a, b).

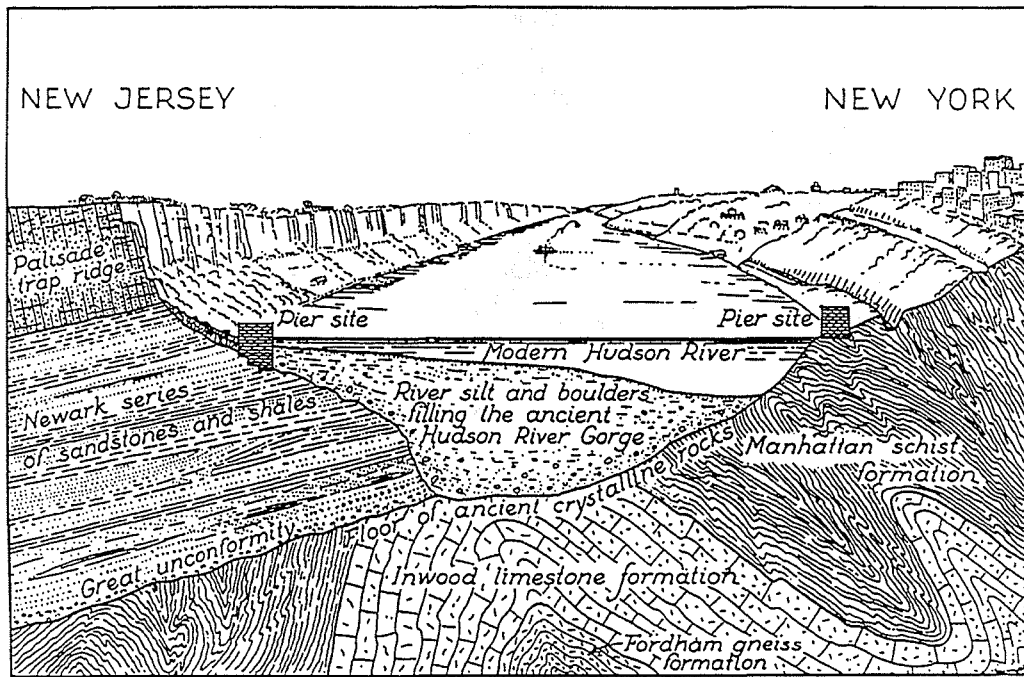


Figure 4 - Interpretive geological section across the Hudson River in the vicinity of the George Washington Bridge. (Berkey, 1948, figure 7, p. 62.)

In 1959, K. E. Lowe edited a series of papers presented at a conference at the New York Academy of Sciences in Manhattan into an annals volume on the geology of New York City (Long, Cobb, and Kulp, 1959; Norton, 1959; and Prucha, 1959). A symposium on the New York City Group of Formations, held at a 1968 meeting of the New York State Geological Association at Queens College, New York, provided discussion for papers by Bowes and Langer (1969), Hall (1968a, b), Paige (1956), Ratcliffe (1968), Ratcliffe and Knowles (1969), and Seyfert and Leveson (1969). Formal "de-Grouping" of the New York City Group of Formations resulted from Leo M. Hall's identification of truncation of subunits of the Fordham Gneiss beneath various members of the Inwood Marble in the Glenville area of Westchester County. Later, a U-Pb age determination by Grauert and Hall (1973) yielded a 1.1 Ga (Proterozoic Y) age for the Fordham gneiss, verifying the field results. The combination of isotopic- and paleontologic evidence proved the Early Paleozoic age of the Inwood Marble. Based on superposition, the Manhattan Schist was considered **younger** than the Inwood but pre-Silurian based on regional relationships and the late medial Ordovician age of the Taconic unconformity.

Based on his work in the Glenville area of Westchester County, Hall (1968a, b, c), proposed subdivisions of the Manhattan Schist into lithically variable members (designated by letters A, B, and C). In Hall's view, the autochthonous Manhattan A, was originally deposited above the Inwood marble and the allochthonous Manhattan B and C (an interlayered amphibolite unit) members were correlated with Cambrian rocks of the Taconic allochthon of eastern New York State. Later, Hall (1976, 1980) suggested that the Manhattan B and C were Early Cambrian (or possibly older) in age, part of the eugeosyncline and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 3, Hall's Manhattan A is included in the basement-cover sequence (pЄ - O) and Manhattan B and C are designated Є - Om. Merguerian (1983a, b; 1986a, b; 1995) has interpreted the Manhattan B and C as a slope-rise-facies that was formerly deposited continentward of the Hartland Formation and now separated from the Hartland by Cameron's Line. Thus, in contrast to Hall's views, Merguerian interpreted the Manhattan B and C and the Hartland as essentially coeval tectonostratigraphic units, and both a part of the **Taconic Sequence**.

In addition to those cited above, studies by Baskerville (1982a, b; 1989a, b; 1992), Merguerian (1994, 1995, 1996a, b, c), Baskerville and Mose (1989), Merguerian and Baskerville (1987), Merguerian and Sanders (1996a, b), Mose and Merguerian (1985), and Taterka (1987), have demonstrated the extreme stratigraphic- and structural complexity of the Manhattan Prong in New York City. Rather significant differences in stratigraphic- and structural interpretation can be found among these studies.

Sequence Stratigraphy of the New England Appalachians. The Lower Paleozoic strata of what is now the Northern Appalachians accumulated along an ancient passive continental margin. During the Cambrian and Ordovician periods, North America lay astride the Earth's Equator; what is now the eastern part of the continent lay in the Southern Hemisphere tropics. The interior of the continent lay to the north, and an open ocean, to the south. Tropical conditions prevailed throughout the time period and a vast sequence of quartzose sands followed by calcareous sediment was deposited above an eroded- and submerged Proterozoic (Grenville) basement complex. The Cambrian- to Ordovician clastics+carbonate passive-continental-margin sequence is known as the **Sauk Sequence** following Sloss (1963), parts of which thinned outward into the NYC area as the protoliths of the Lowerre Quartzite and Inwood Marble Formations.

Starting in the mid-Ordovician, lithospheric plate convergence brought to an end the passive-margin regime that had prevailed since early in the Cambrian Period. An initial, and particularly conspicuous, product of this episode of plate convergence was the appearance of the Northern Appalachian foreland basin. This basin, which developed with unconformity atop the **Sauk Sequence**, saw the influx of deep-water pelitic sediments and intercalated turbidites. This basin, whose origin has been ascribed to the isostatic effects of thrust loading (Quinlan and

Beaumont, 1984) appeared **after** the demise of the carbonate shelf. In New York and adjacent areas, this mid-Ordovician flysch (known as the Normanskill, Walloomsac, Annsville, and Martinsburg formations) constitutes the **Tippecanoe Sequence**.

The original basis for recognizing Taconian thrusting was the juxtaposition of two suites of Lower Paleozoic strata deposited in contrasting paleogeographic settings. One of these suites consists of **Sauk** carbonate rocks. The other is composed of pelitic rocks, deposited beyond the former shelf edge, subsequently interpreted as being products of deposition on a continental rise and generally referred to informally as the **Taconic Sequence**. During the Taconic Orogeny, within the Northern Appalachian foreland basin, both the **Sauk** and **Tippecanoe** sequences became imbricated by low-angle thrusts and older, deeper-water pelites of the **Taconic Sequence** were emplaced above them.

Bedrock stratigraphy of New York City. Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. My field- and laboratory investigations of the bedrock geology in NYC since 1972, based on study of over 500 natural exposures and a multitude of drill cores and construction excavations, define a complex structural history and suggests that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, mappable tectonostratigraphic units. My subdivisions agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-unrecognized, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian, 1981, 1983a, 1985, 1987).

The bedrock stratigraphy of NYC is best explained in the context of sequence stratigraphy. The bedrock underlying Manhattan and the Bronx includes, from the base upward, the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose rocks formally lumped together as the Manhattan Schist. As a result of construction as well as of its very local deposition, the Lowerre is no longer exposed on the surface and the underlying Proterozoic Z Ned Mountain Formation of Brock (1989, 1993) has not been recognized. Metamorphosed miogeosynclinal representatives of the **Sauk Sequence** (including the Inwood Marble (€ - Oi) and the Manhattan Schist (Om) and their Proterozoic cratonic basement rocks occur west of Cameron's Line, a major tectonic boundary in New England. Together, they constitute the autochthonous miogeosynclinal basement-cover sequence of the New England Appalachians (p€ - O in Figure 3) and thus represent metamorphosed sedimentary rocks formerly deposited on crystalline Proterozoic crust (Merguerian and Sanders, 1996a).

Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Rodgers and others 1959, Merguerian 1977, 1985) or the Hutchinson River Group (Seyfert and Leveson 1969, Baskerville 1982a). In contrast to the basement-cover sequence, the Hartland Formation (or **Taconic Sequence**) consists of aluminous schists, granofels, and metavolcanic rocks formerly deposited on oceanic crust (€ - Oh in Figure 3) which became accreted to North America during the Medial Ordovician Taconic orogeny (Hall, 1980; Merguerian 1983b; Merguerian and others, 1984; Robinson and Hall, 1980). Other schistose rocks (€ - Om in Figure 3), originally mapped as the Manhattan Schist and found west of Cameron's Line, are here also interpreted as a part of the **Taconic Sequence** as described below.

Will the Real Manhattan Schist Please Stand Up!. Based on detailed mapping in NYC (Figure 5), Merrill's Manhattan Schist has been subdivided into three roughly coeval, structurally complex, ductile-fault bounded, tectonostratigraphic units of kyanite- to sillimanite grade (Merguerian and Baskerville, 1987; Merguerian and Sanders 1996a).

The structurally lowest unit (**Om = Tippecanoe Sequence**) and crops out in northern Manhattan and the west Bronx. (See Figure 5.) This unit is composed of brown-to rusty-

weathering, fine- to medium-grained, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist containing interlayers centimeters to meters thick of calcite-diopside marble (minerals are listed in decreasing order of abundance). The lower unit is lithically correlative with the Middle Ordovician Manhattan member A of Hall (1968a) because it is a direct lithostratigraphic correlative and is found interlayered with the underlying Inwood at two (possibly three) localities (Stops 3, 5?, and 6), often containing interlayers of calcite ("Balmville") marble near its base. Because it is interpreted as being autochthonous (depositionally above the Inwood Marble), Merguerian informally refers to it as "the Good-Old Manhattan Schist" and has assigned a middle Ordovician age.

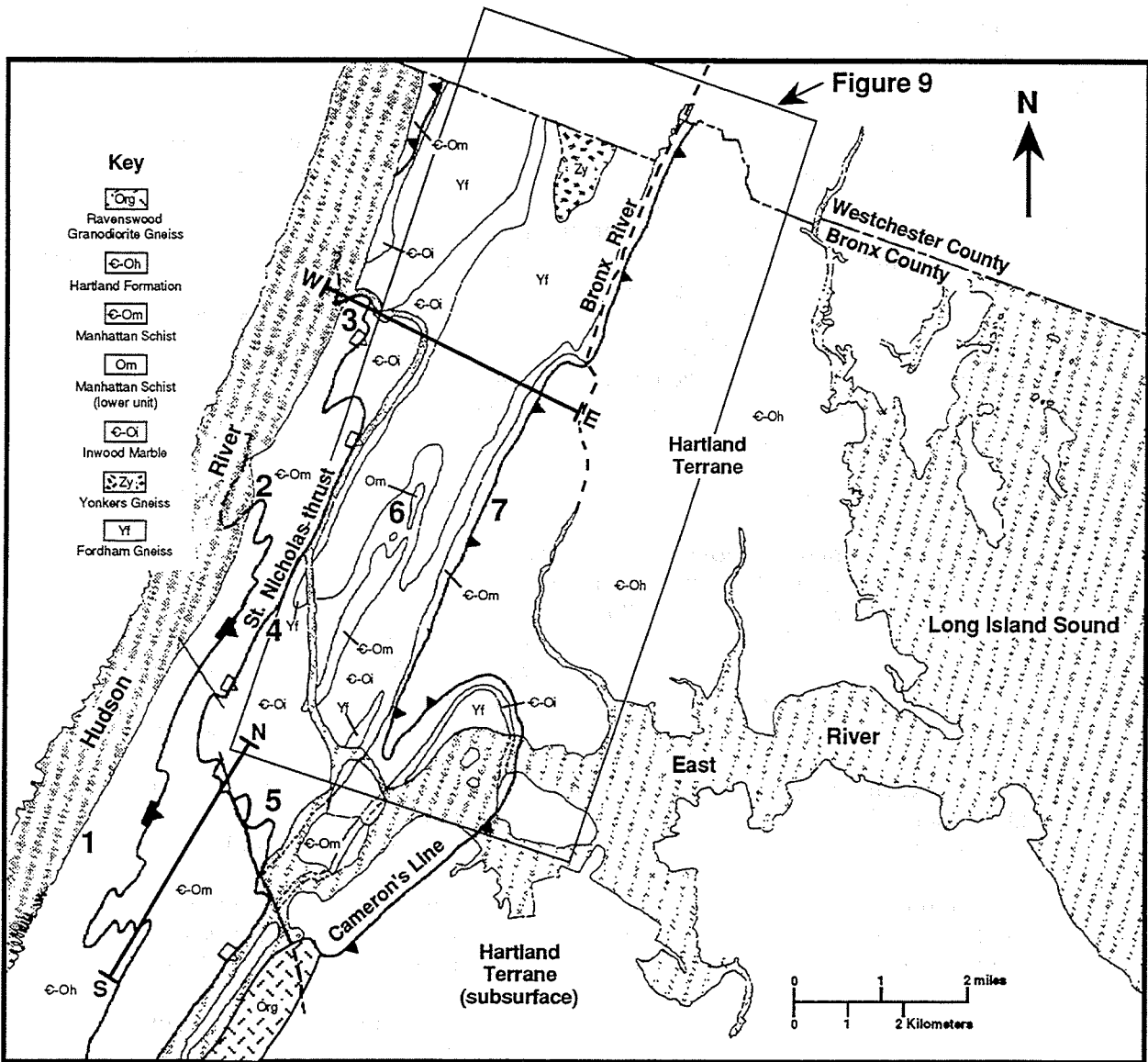


Figure 5 - Geologic map of south end of Manhattan Prong showing Cameron's Line, the St. Nicholas thrust, the Hartland Terrane, and the Ravenswood Granodiorite (Org). Rectangle shows location of Figure 9. Geologic section lines are keyed to Figure 7. The seven field-trip stops are indicated by arabic numerals. (Adapted from Merguerian and Baskerville, 1987, fig. 3, p. 139.)

The lower Manhattan schist unit and the Inwood Marble (**Tippecanoe and Sauk, respectively**) are structurally overlain by the middle Manhattan schist unit (**€ - Om**) which forms the bulk of the "schist" exposed on the Island of Manhattan (Stops 3, 4, 5, 7, and most northern Central Park exposures). (See Figures 1, 2, 5.) The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-grained, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The middle schist unit is characterized by the presence of layers and lenses of kyanite+sillimanite+quartz+magnetite up to 10 cm thick, cm-to m-scale layers of blackish amphibolite, and subordinate quartzose granofels. The middle unit is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Cambrian- to Ordovician ages in New England (Hall, 1976; Merguerian, 1983a, 1985). These rocks, which contain calc-silicate interlayers in western Connecticut (Merguerian, 1977) are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America, and are thus considered a part of the **Taconic Sequence**.

The structurally highest, upper schist unit (**€ - Oh**) is dominantly gray-weathering, fine- to coarse-grained, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and thin- to massive granofels and cotecule, with cm- and m-scale layers of greenish amphibolite+garnet (Stops 1, 2, 3?, 7 and most construction exposures south of Central Park). Together they represent metamorphosed deep-oceanic shales, interstratified lithic sandstones, chert, and volcanic rocks, all a part of the deep-water facies of the **Taconic Sequence**. The upper schist unit, which underlies most of the western edge and southern half of Manhattan and the eastern Bronx, is lithologically identical to the Cambrian and Ordovician Hartland Formation (Rowe, Moretown, Hawley belt) of western Connecticut and Massachusetts. On this basis, they are considered correlative and, in my opinion, extension of the Hartland Terrane into New York City and southeastern New York is a stratigraphic necessity. (See Figure 3.)

Most of the exposed schist on Manhattan Island can be interpreted as part of a transitional slope-rise sequence (**€ - Om**) and as the eugeosynclinal deep-water oceanic Hartland Formation (**€ - Oh**), both a part of the **Taconic Sequence**. Thus, two out of three "Manhattan" schist units, which have been historically lumped together as the Manhattan Schist Formation, need to be separated from in-situ **Tippecanoe** Manhattan (**Om**), which is found only locally interlayered with the Inwood Marble. The "good old Manhattan Schist" (**Om**) is the metamorphosed equivalent of the foreland-basin-filling Normanskill or Walloomsac strata (i. e., that part whose protoliths belong to the **Tippecanoe Sequence**, and were deposited unconformably above the basal Tippecanoe limestones), whereas the overlying schistose rocks are the metamorphosed equivalent of two parts of the **Taconic Sequence** [= the Waramaug (Hoosac) formation (**€ - Om**) and Hartland Terrane (**€ - Oh**)], whose protoliths are basically coeval with the Inwood Marble and owe their structural positions above the marble (and also above unit **Om** of the Manhattan Schist) to displacement along two ductile thrusts (the St. Nicholas thrust and the Cameron's Line thrust).

The Taconic problem in New York City focuses on ductile-fault imbrication of these three amphibolite-grade rock sequences. The St. Nicholas thrust (Taconic frontal thrust) separates lower-plate **Tippecanoe** (**Om**) and **Sauk** (**€ - Oi**) rocks from upper-plate gneiss, schist, and amphibolite of the former Cambro-Ordovician slope- and rise (Manhattan Formation; **€ - Om**). The structurally higher ductile fault known as Cameron's Line, juxtaposes muscovite-rich schist and gneiss, amphibolite, serpentinite, and cotecule of a former deep-water realm (Hartland Terrane; **€ - Oh**) with **€ - Om** rocks. Combined as the Manhattan Schist Formation by past workers, the subunits **€ - Om** and **€ - Oh** are here considered to be allochthonous, ductile-fault-bounded facies of the **Taconic Sequence**.

STRUCTURAL GEOLOGY OF NEW YORK CITY

The three schist units and the underlying rocks have shared a complex structural history which involved three superposed phases of deep-seated deformation (D_1 - D_3) followed by three or more episodes of open- to crenulate fold phases (D_4 - D_{6+}). The synmetamorphic juxtaposition of the various schist units occurred very early in their structural history (D_2) based upon field relationships. The base of the middle schist (ϵ - Om) is truncated by a ductile shear zone, named the St. Nicholas thrust (open symbol in Figure 5). The thrust is exposed at or near Stops 3, 4, and 5. The Hartland (ϵ - Oh) is in probable ductile fault contact with the middle schist unit along Cameron's Line (closed symbol in Figure 5) in the Bronx (Stop 7) and in Manhattan (at Stop 2 and also in Central Park [See Merguerian and Sanders, 1993a, Stop 5]).

Initial deformation and metamorphism of bedrock units occurred during two progressive stages of prograde amphibolite- facies ductile deformation accompanied by isoclinal- and shear folding ($F_1 + F_2$). The F_1 folds are inferred from a locally preserved S_1 foliation (and parallel S_0 layering) which is truncated by zones of D_2 mylonite. Early metamorphism up to garnet-sillimanite grade is overprinted by metamorphism in the kyanite-staurolite-garnet zone. The two Taconian terrane boundaries (the St. Nicholas thrust and Cameron's Line) now occur as steeply oriented, complexly folded, migmatized zones of commingled mylonitic rocks. Formed at the culmination of D_2 , a highly laminated S_2 mylonitic texture formed in the thrust zones producing mylonitic layering, frayed and rotated mica- and feldspar porphyroclasts, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 isoclinal- and shear folds.

During D_2 , the bounding lithologies acquired a penetrative foliation (S_2), growth of kyanite, staurolite, and garnet porphyroblasts (which enclose early stage sillimanite) and growth of distinctive lenses and layers of quartz and kyanite+quartz+magnetite (up to 10 cm thick). The quartzose and aluminosilicate lenses and layers formed axial planar to F_2 folds which regionally deformed the bedrock into a large-scale recumbent structure that strikes $N50^\circ W$ and dips $25^\circ SW$. Stereograms (Figure 6) show the distribution of 245 poles to S_2 , F_2 fold axes and L_2 lineations as measured in the field.

Although the regional S_2 metamorphic grain of the New York City bedrock trends $N50^\circ W$, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25° . (See Figures 5 and 6.) S_3 is oriented $N30^\circ E$ and dips $75^\circ SE$ and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz and kyanite lenses and layers into elongate shapes. Metamorphism was of identical grade with D_2 which resulted in kyanite overgrowths and annealed mylonitic textures (Merguerian, 1988). Stereograms (Figure 6) show the distribution of 238 poles to S_3 , F_3 fold axes and L_3 lineations as measured in the field. Note the great-circle distribution of poles to S_2 and how the pole to that great circle corresponds to the concentration of F_3 axes.

At least three phases of open- to crenulate folds and numerous brittle faults and joints are superimposed on the older ductile fabrics. The effects on map contacts of these late features is negligible but the scatter of poles to S_3 and localized northward plunges of F_3 fold axes and L_3 lineations are deemed the result of post- D_3 deformation. Retrograde metamorphism and production of muscovite pseudomorphs after kyanite were formed during one or more of these later episodes.

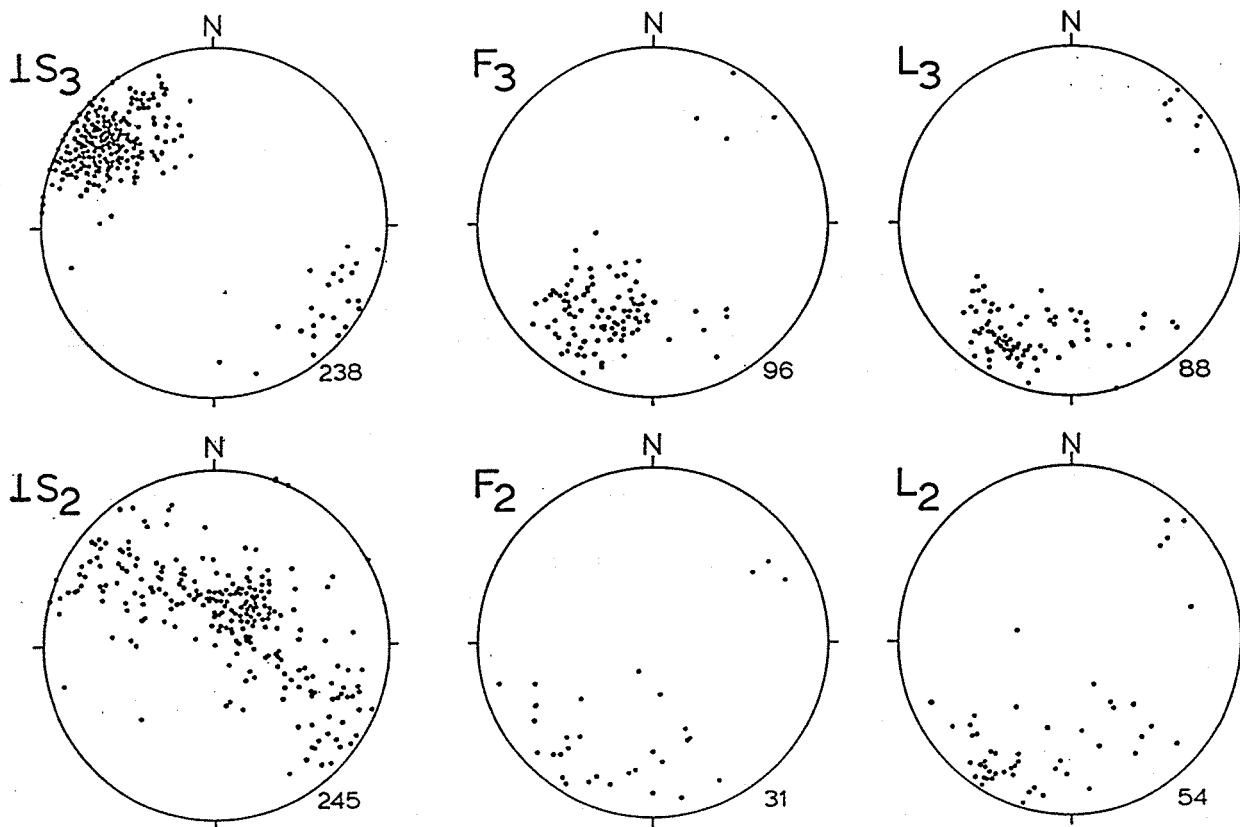


Figure 6 - Equal area stereograms showing the distribution of poles to S_2 and S_3 , the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Merguerian and Sanders, 1991, fig. 26, p. 113.)

Structure Sections. The localities described below offer critical evidence for new structural interpretations of the Paleozoic schists exposed in New York City. Figure 7 presents simplified W-E and N-S structure sections across the New York City area. Keyed to Figure 5, the sections illustrate the complex structural- and stratigraphic interpretation that has emerged over the years. The W-E section shows the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward topping of lithostratigraphic units exposed in central Manhattan and the effects of the late NW-trending upright folds.

Ductile Faults. Synchronous with D_2 , foliated rocks of the Sauk, Tippecanoe, and Taconic sequences were imbricated along two major syntectonic ductile thrust faults (Cameron's Line and the St. Nicholas thrust), and intruded by late-syntectonic calc-alkaline plutons (now orthogneisses such as the Ravenswood Granodiorite Gneiss of Zeigler (1911) and the Brooklyn Injection Gneiss of Berkey (1933, 1948) and Blank (1973). These metaplutonic rocks vary from granitoids through diorite and lesser gabbro and are typically foliated indicating a relatively early intrusion age with respect to structural deformation and regional shearing. Isotopic dating of crosscutting igneous rocks along the length of Cameron's Line indicate a pre-late Ordovician age for development of the mylonitic fabrics (Amenta and Mose, 1985; Merguerian and others, 1984; Baskerville and Mose, 1989).

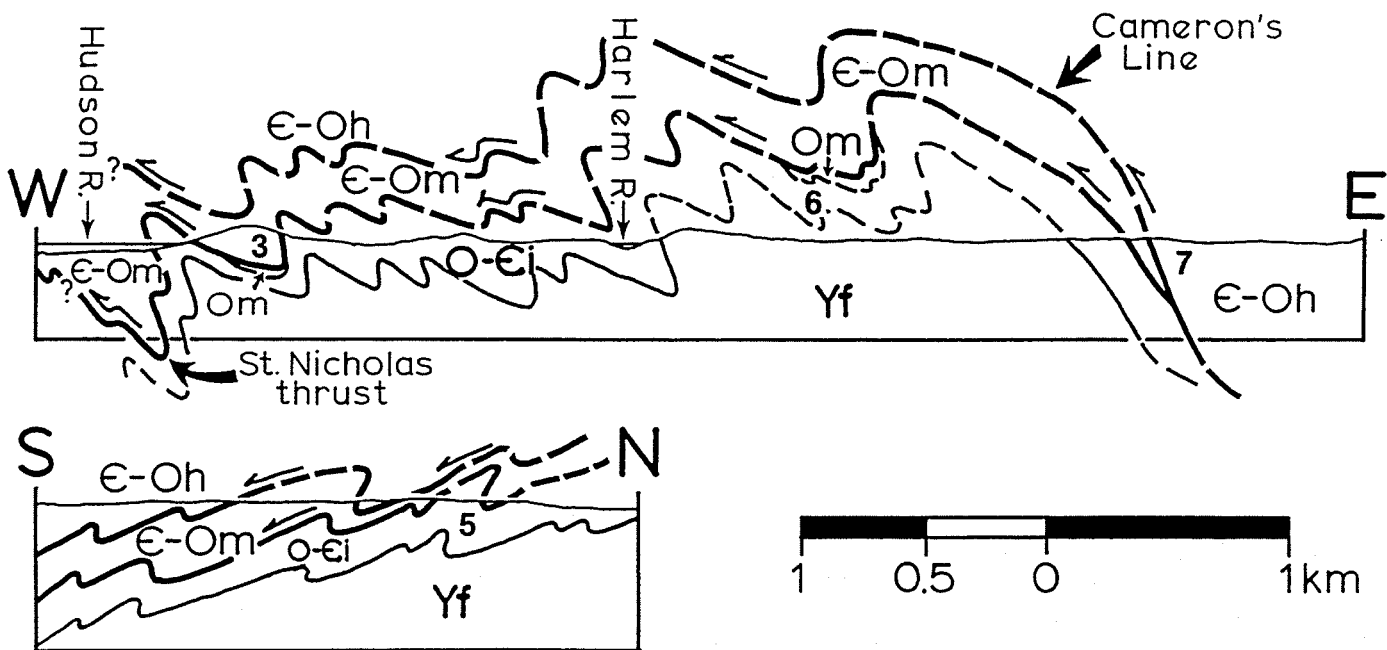


Figure 7 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). Symbols defined on Figure 5. Some field-trip stops are indicated by arabic numerals. (Merguerian and Sanders, 1991, fig. 27, p. 114.)

BRITTLE FAULTS AND SEISMICITY

Geologists and seismologists generally agree that earthquakes produce dislocations known as faults and that preexisting faults tend to localize new earthquakes. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of brittle faults which belong to two contrasting sets oriented NE and NW. These faults cut the New York City area into large fault-bounded blocks. A serious bone of contention among seismologists and geologists revolves around a perceived lack of evidence that surface ground breaks have accompanied historic earthquakes. Many seismologists argue that the bedrock faults that structural geologists map in the field experienced offset at great depth with **no surface connection** and that uplift and erosion have unroofed these structures. Research on the diversion of the Bronx River by Merguerian and Sanders (1996b), summarized below, provides the first demonstration of surface deformation in response to fault motion in geologically recent time.

Two contrasting, near-orthogonal brittle-fault sets cut the isoclinally folded imbricate ductile thrusts (Cameron's Line and the St. Nicholas thrust) and intervening amphibolite-facies metamorphic rocks of New York City. Figure 8A, a stereonet of poles to 118 surface faults, shows a bimodal distribution of moderate- to steep faults although a scattering of gently dipping faults exists. This field evidence and existing subsurface data indicate that the trends of these sets are: 1) approximately N30°E (roughly parallel to the overall trend of lithologic units and the axis of Manhattan Island), and, 2) approximately N45°W (across the NE trend, roughly parallel to the N50°W average S₂ axial surface of the F₂ folds). The trends of brittle faults in the vicinity of New York City are the products of emphatic structural control, as summarized below.

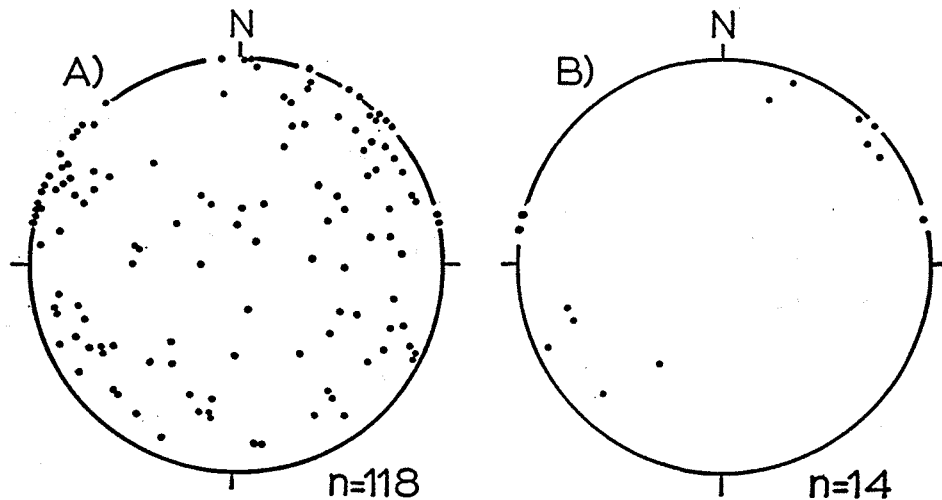


Figure 8 - Equal-area stereonet showing poles to mapped surface faults. Northern half of net used for poles to vertical faults.

A) Poles to 118 faults showing bimodal distribution of NE- and NW-trending fault sets. The dips of the NE-trending set (average trend of N30°E, essentially parallel to the long axis of Manhattan) are steep to moderate. The dips of the NW-trending set (average trend of N45°W) are also steep to moderate.

B) Poles to 14 strike-slip faults with a dominantly NW trend.

NE-trending faults. The NE-trending faults dip steeply to moderately and show dominantly dip-slip motion with offset up to 1 m in zones up to 2 m thick. Locally, where they parallel NE-oriented mylonites (Cameron's Line and the St. Nicholas thrusts), they are found to be cataclastic with greenish clay-, calcite-, and zeolite-rich gouge up to 30 cm thick. Invariably, where the ductile faults are oriented northeasterly, they have been reactivated by brittle faults and marked by fresh clay-rich gouge. Elsewhere, the NE-trending faults have commonly been healed by quartz, calcite, or zeolite minerals. Typically, the NE-trending faults are developed parallel to and commonly disrupt an S_3 transposition foliation or spaced schistosity and/or transposed compositional layering and foliation(s) ($S_0 + S_1 + S_2$).

NW-trending faults. The NW-trending faults (See Figure 5 and Lobeck, 1939, figure on p. 568.) also dip steeply to moderately and show complex movement histories dominated both by left- and right-lateral oblique-slip offset often followed by secondary dip-slip or oblique-slip reactivation. The NW-trending faults contain zeolites, calcite, graphite, and sulfides. Composite offsets along the left-lateral faults average a few cm to more than 35 cm but local offset along the right-lateral faults (such as the 125th Street and Mosholu Parkway faults) exceeds 200 meters in brecciated zones. The famous 14th Street fault controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan south of 23rd Street and north of Canal Street. Figure 8B shows the poles to 14 strike-slip faults. Of these, 80% were left-lateral and 20% were right-lateral, with the latter producing map-scale offset of mapped contacts.

Based on geometric relationships and superimposed slickensides, the movement histories of the northwest-trending faults are typically more complex than those of NE trend. A case in point was observed in the water tunnel beneath the east channel of the East River where a NW-trending, steep NE-dipping left-lateral strike-slip fault bearing sub-horizontal slickensides, showed overprint by N- to NE- plunging slickensides indicating a change from strike-slip to oblique-normal slip movement.

The New York City Water Tunnel #3 cuts through the 125th Street fault beneath Amsterdam Avenue in Manhattan. Here, in an abrupt zone of highly fractured Manhattan Schist 40 m wide, the 125th Street fault dips 55° to 75° SW and cuts orthogonally across the tunnel line and the steeply dipping foliation in the schist. In the overhead roof of the tunnel, 2 to 3 m blocks of the Manhattan, which remained internally coherent within the broad zone of cataclastic rock, showed up to 90° of rotation about a vertical axis. Clearly, this observation indicates that along the 125th Street fault, much of the motion has been strike slip. Indeed, slickensides indicate that right-lateral, normal, oblique slip was the most recent offset sense. Cross-fault offset of the prominent Manhattan ridge indicates over 200 m of composite right-lateral slip.

The NW-trending faults are structurally controlled by an anisotropy produced by A-C joints related to southward-plunging F3 folds and/or by the NW-trending S_1+S_2 regional metamorphic fabric of the bedrock. Thus, the intersection of these two important sets has cut NYC into large, fault-bounded blocks. Of the two, the NW-trending faults show the greatest composite offset but both fault sets are found to cut each other, suggesting that they both harbor potential seismic activity.

DIVERSION OF THE BRONX RIVER IN NEW YORK CITY - EVIDENCE FOR POSTGLACIAL SURFACE FAULTING?

North of the New York Botanical Garden, near the Mosholu Parkway in the Bronx (Figure 9), the NW-SE-trending Mosholu Parkway fault offsets the Bronx River valley (a NNE-SSW-trending strike-valley lowland underlain by the Inwood Marble) from the Webster Avenue lowland (another NNE-SSW valley also underlain by the Inwood Marble). Just at the point of offset of the marble lowland, the Bronx River has abandoned its former wide NNE-SSW-trending strike-valley lowland and currently occupies a narrow N-S-trending gorge, here named the Snuff Mill gorge, cut across the more-resistant Hartland Formation.

Joint studies by Merguerian and Sanders (1996b) suggest that this first-order drainage anomaly was prompted by a blockage induced by postglacial elevation of a bedrock barrier (E. 204th Street Bulge of Figure 9) immediately north of and adjacent to the NW-trending Mosholu Parkway fault. This uplift blocked the marble lowland, dammed the Bronx River, and thus caused a lake to form upstream from the present site of the Mosholu Parkway. Water spilling out of this lake to the south, possibly reoccupying the beginnings of a valley that had been eroded during earlier ice blockage of the Webster Avenue lowland, eroded the N-S-trending Snuff Mill gorge in the New York Botanical Garden, where the Bronx River crosses the Hartland Terrane. Figure 9 shows subsurface contours on the bedrock surface. Note that the Webster Avenue valley is youthful with a narrow, V-shaped profile.

Our studies of subsurface boring records and field examination indicates that the Mosholu Parkway fault is a NW-trending right-lateral oblique-slip fault that projects across the Bronx River channel immediately below the area (near Webster Avenue and E. 203rd Street in the Bronx) where the Bronx River departs from its previous NNE-SSW-oriented channel and N-S-directed flow begins. (See Figure 9.) A NW-trending bedrock high exists at this point as shown by depth-to-bedrock profiles, topographic maps, and surface exposures. The long axis of this basement high (E. 204th Street Bulge) parallels the Mosholu Parkway fault and may, in fact, have been caused by motion along the footwall of the fault. We've proposed that the northern segment may have moved upward in response to normal oblique-slip motion. Such motion would be identical in orientation and magnitude to offset noted for the subparallel 125th Street fault in Manhattan. In support of post-glacial motion, a broad U-shaped valley, similar to that found along the 125th Street fault in Manhattan, does not exist along the Mosholu Parkway fault.

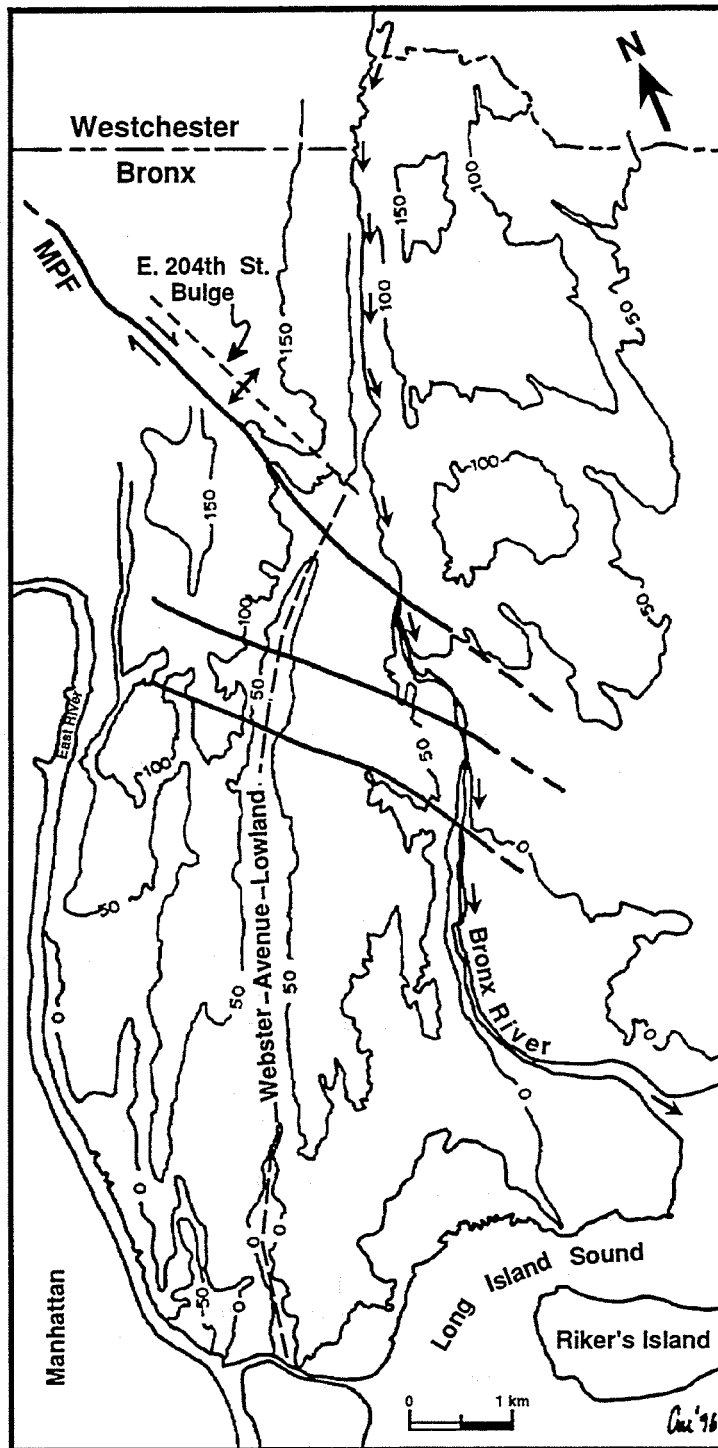


Figure 9 - Index- and bedrock-contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including the Mosholu Parkway fault (MPF), and the 204th Street Bulge. The Webster Avenue Lowland marks the previous course of the Bronx River. Subsurface- and fault data from Baskerville (1992), engineering records of the New York City Subsurface Exploration Section, Hofstra University's Metropolitan New York Drill Core Collection. (Merguerian and Sanders, 1996b, fig. 4, p. 138.)

A postglacial age of diversion is further demonstrated by the absence of glacial polishing and -striae on the jagged walls of the Snuff Mill gorge and by a subsurface unit of clay (lake deposits) that overlies a probable till (glacial deposits) detected north of the bedrock barrier. Significantly, if this explanation for diversion is correct, these data provide the first evidence for induced surface deformation in response to neotectonics in the New York City area. As the well-documented (magnitude ~5) earthquakes of 1737, 1783, and 1884 demonstrate, we live in an area with a recognized history of time-separated seismic events. The potential for a damaging earthquake in the populated areas of New York City **can not** and **should not** be ruled out as earthquakes **have** occurred here, **can** occur here, and **will** occur here. Effective pre-emptive seismic planning is clearly an urban necessity in New York City.

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

The following seven stops (Figures 1, 2) illustrate the evidence for changes in the interpretation of the stratigraphy, structure, and presence of ductile shear zones between the schistose rocks in New York City, as described above.

STOP 1 - HARTLAND FORMATION IN RIVERSIDE PARK *UTM Coordinates: 585.95E/4515.35N northward to 586.35E/4516.10N, Central Park 7-1/2 minute quadrangle.*

The Hartland Formation or upper schist unit (€ - Oh) crops out in Riverside Park from West 75th Street northward to West 116 Street. Described here are exposures near West 90-91 Streets and West 82-85 Streets.

The northernmost outcrops consist of gray-weathering, well-layered and slabby to laminated, lustrous muscovitic schist containing interlayers of quartz-muscovite biotite granofels. Locally, 1 cm thick glassy quartzite interlayers and elliptical pods of recrystallized dark quartz occur. The prominent 2-3 cm scale layering results from original compositional variations and subparallel $S_1 + S_2$ metamorphic recrystallization. The metamorphic layering is parallel to $N48^\circ E, 65^\circ SE$ axial surfaces of long-limbed F_2 isoclinal folds plunging 60° into $S28^\circ E$. A strong down-dip stretching lineation (L_2) composed of quartz ribs and streaked mica lies within S_2 and is deformed by F_3 folds. The F_3 folds are tight, south-plunging "s" folds with abundant shearing along their axial surfaces ($S_3 = N37^\circ E, 78^\circ SE$). L_3 intersection lineations and stretching lineations are parallel to F_3 hingelines which plunge 22° into $S29^\circ W$ and deform the L_2 lineations. S_3 is typically a transposition foliation with oriented mica and migmatite overprinting the older folds and related fabrics. Pre-, syn-, and post- D_3 pegmatites are found throughout the area.

The southern outcrops of the upper schist unit are lithologically identical to the above except the layering is thicker (6-8 cm) and a laminated black-weathering, greenish-black biotite-amphibolite layer (1 m thick) occurs near West 82 Street. Together these outcrops illustrate the penetrative nature of F_3 isoclinal folds with their shallow southward plunges. Apparently the NW-trending, shallow SW-dipping enveloping S_2 metamorphic layering exerted a strong control on the orientation of F_3 hingelines despite the fact that significant transposition occurred during D_3 . The average orientation of S_3 is $N55^\circ E, 75^\circ SE$ with F_3 hingelines and sub-parallel L_3 lineations plunging 20° into $S40^\circ W$. (See Figure 6.) Late, open folds with axial surfaces trending $N47^\circ E, 90^\circ$ are locally developed.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roches moutonnées. Not only are the rock surfaces rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE, consistent with a multiglacier model

proposed recently by Sanders and Merguerian (1991, 1992, 1994a, b) and Merguerian and Sanders (1996c).

STOP 2 - CAMERON'S LINE AND THE HARTLAND AND MANHATTAN FORMATIONS NEAR WEST 165 STREET. *UTM Coordinates: 588.90E/4521.41N, Central Park 7-1/2 minute quadrangle.*

The Manhattan formation (€ - Om) is exposed here in a large outcrop west of Riverside Drive. The Manhattan formation dominates, consisting of rusty- to gray-weathering, coarse-grained biotite-muscovite-plagioclase-quartz-kyanite-sillimanite-garnet-tourmaline gneiss and schist with 2-15 cm interlayers of quartz-biotite-garnet-kyanite-sillimanite granofels. The rock contains porphyroblasts of kyanite +/- sillimanite and garnet (up to 1 cm). Outcrops 350 m to the north show more typical rusty-weathering colors and abundant aluminosilicates of € - Om, yet in November 1985, subsurface construction exposures to the east of Riverside Drive exposed muscovite-rich Hartland lithologies (€ - Oh) cut by brittle faults. These exposures are typical of Cameron's Line, with intercalated lithologies of both bounding units found in close proximity and clear distinction blurred by D₂ tectonic intercalation.

Structurally, at the south end of the outcrop, there is a clear example of a long-limbed intrafolial F₂ reclined fold refolded by F₃ "z" folds. Here, F₂ folds an S₁ biotite foliation and granitoid pods developed parallel to S₂ (and/or S₁) are folded by F₃. S₂ trends N54°E, 44°SE with F₂ plunging 40° into S19°E and S₃ trends N20°E, 75°SE with F₃ axes plunging 42° into S10°W. Excellent examples of type-3 interference patterns (Ramsay, 1962) are found on the sloping north-facing portion of the outcrop. Cameron's Line passes above our heads as we stand in the core of a south-plunging F₃ fold, exposing € - Om at street level. Hartland rocks crop out to the south and east.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roches moutonnées. This particular rock knoll probably was a splendid example of a roche moutonnée many years ago, but cannot be considered as such any longer. The diamond-drill holes along the rock face by the sidewalk indicate that the SE side of this knoll was blasted away to make way for the street and the sidewalk. Not only has the rock surface been rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE.

STOP 3 - ST. NICHOLAS THRUST AND CAMERON'S LINE, INWOOD HILL AND ISHAM PARKS *UTM Coordinates centered on: 590.50E/4525.00N, Central Park 7-1/2 minute quadrangle.*

Inwood Hill Park is located in the extreme northwest corner of Manhattan Island. The park is bordered by Dyckman Street on the south, the Hudson River on the west, Spuyten Duyvil (Harlem Ship Canal) on the north, and Payson and Seaman Avenues on the east. Isham Park occupies the flat area northeast of Inwood Hill Park extending eastward to Broadway between Isham and West 214 Streets.

The area of Manhattan north of Dyckman Street is known as the Inwood section. Except for Inwood Hill Park, the region is underlain by the Inwood Marble marking the name-locality (originally called the Inwood Limestone by Merrill 1890). Isham Park contains near continuous exposure of the Inwood Marble (€ - Oi). Several lithologies occur such as coarse-grained dolomitic marble, fine-grained calcite marble, foliated calc-schist, and marble containing siliceous layers and calc-silicate aggregates that stand in relief as knots on the weathered surface. The marble ranges from white- to blue-white to gray-white. Depending on the amount of impurities, it

weathers gray or tan and produces a sugary-textured surface on outcrops which ultimately develops into a residual calcareous sand. In addition, the outcrops illustrate differential weathering with dolomite-silicate units standing in high relief and calcite marble forming depressions.

The Inwood trends N45°E, 73°SE and forms the eastern overturned limb of a large F₃ synform which is cored to the west by the middle schist unit (€ - Om) of Inwood Hill Park. Tight south-plunging F₃ folds are locally developed. Older structures are not obvious but can be found (especially after, or during, a rain) as long-limbed F₂ isoclinal folds. Abundant examples of boudinage of the siliceous and calc-silicate layers into lenses occur due to the marked ductility contrast between them and the surrounding marble.

Enter Inwood Hill Park following the path past the playground. The first (of two) prominent ridges is composed of kyanite-garnet gneiss and schist of the middle schist unit (€ - Om) which is structurally separated from the Inwood Marble by the St. Nicholas thrust (not exposed here). Follow the path to where it curves around to the west side of the ridge and enters a valley underlain by a south-plunging F₃ antiform which exposes tan weathering, gray-white Inwood Marble striking N40°E, and dipping 58°NW.

Along the path going north (up-slope) along the westernmost ridge, massive, brown-weathering, blackish amphibolite of the middle schist unit crops out. Rocks exposed on the ridge (€ - Om) are massive muscovite-biotite-plagioclase-quartz-garnet-kyanite gneiss and schist with weathered kyanite+quartz+sillimanite nodules. The structure of the ridge is a south-plunging F₃ synform overturned toward the northwest. The S₃ foliation in the middle schist unit is related to F₃ folds with axial surfaces oriented N41°E, 75°SE and south-plunging hingelines. The F₃ structures are superimposed on an older S₂ metamorphic layering which trends N50°W, 25°SW. Atop the ridge, a few exposures of muscovitic schists that are strikingly "Hartland-ish" occur. If they are indeed Hartland rocks and not minor muscovite-rich zones in the Manhattan (which do occur, locally), a case may be made for skirting the top of the ridge with a klippe underlain by Cameron's Line.

Along the N-facing backslope of the western ridge, the contact between the middle (€ - Om) and lower (Om) schist units (the St. Nicholas thrust) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. Structurally beneath the middle schist unit a 0.5 m layer of mylonitic amphibolite is deformed by F₃ folds. Unlike the amphibolite in the middle schist unit above, which contains subidioblastic hornblende, this amphibolite has been retrograded by intense shearing parallel to the S₂ foliation. Green hornblende porphyroclasts are set in an anastomosing S₂ foliation consisting of colorless clinoamphibole, biotite, and quartzose ribbons.

Directly beneath the bridge, where a dirt trail leads down to the river, a coarse-grained gray-white calcite marble with differentially eroded calc-silicate nodules is exposed at low tide. It is unknown whether the marble exposed at the low-tide mark is a "Balmville" interlayer in the lower schist unit (Om) or a faulted part of the Inwood Marble.

Physically above the marble exposure, the lower schist unit consists of biotite-quartz-plagioclase and kyanite with abundant garnet porphyroblasts. Here the lower schist unit contains an S₂ mylonitic foliation composed of mm-scale ribboned and polygonized quartz with recrystallized reddish pleochroic biotite. Produced in the axial planes of F₂ reclined folds, the S₂ foliation strikes N45°E and dips 55°SE with a strong down-dip lineation plunging 50° in a S34°E direction. The thrust zone is structurally complex consisting of intercalated lithologies of the lower- and middle schist units together with mylonitic amphibolite.

STOP 4 - ST. NICHOLAS THRUST AND MANHATTAN FORMATION IN ST. NICHOLAS PARK *UTM Coordinates: 588.45E/4518.28N northward to 588.75E/4519.15N, Central Park 7-1/2 minute quadrangle.*

The St. Nicholas thrust separates the middle schist unit (€ - Om) from the Inwood Marble (€ - Oi) along the east edge of St. Nicholas Park situated west of St. Nicholas Avenue between West 129 and West 141 Streets. Excellent outcrops of the schist form the steep ridge of the park. The southernmost outcrops consist of rusty-weathering biotite- and muscovite-rich gneiss and schist with abundant aluminosilicate nodules, interlayered biotite-quartz-garnet granofels, and thin amphibolite. The Inwood Marble is not exposed but, based on drill core data and geomorphology, underlies the lowland immediately east of the park.

Outcrops atop the ridge on St. Nicholas Terrace contain flattened aluminosilicate layers folded by F₃ folds. Northward, F₂ isoclinal folds with subhorizontal axial surfaces are also deformed by F₃ folds. S₃ trends N30°E, dipping 70°SE and is locally warped by several generations of late crenulate and open folds.

A penetrative S₂ mylonitic layering occurs at the northeasternmost exposures in the park. Tight- to isoclinal F₃ folds deform and locally transpose the S₂ mylonitic foliation into parallelism with S₃. In addition, the F₃ folds deform pegmatite sills injected sub-parallel to S₂ + S₁, thin lit-par-lit foliated syn-D₂ granitoids, aluminosilicate layers, and quartz veins. Because of the combined effects of D₂ and D₃ the rocks are highly recrystallized and locally migmatitic.

The contact between the middle schist unit and the Inwood Marble is never observed but the presence of unusually penetrative S₂ fabrics in the schist at the eastern edge of the park and the apparent absence of the lower schist unit together suggest that the St. Nicholas thrust may be marked by the abrupt break in slope to the east.

STOP 5 - ST. NICHOLAS THRUST AND THE MOUNT MORRIS PARK OUTLIER *UTM Coordinates centered on: 589.13E/4517.25, Central Park 7-1/2 minute quadrangle.*

The Mount Morris Park Outlier, a hill protruding above the Harlem Valley centered at West 122 Street and Fifth Avenue, consists of an erosional remnant of the middle schist unit (€ - Om). The Inwood Marble (€ - Oi) crops out on the Madison Avenue (east) side of the park. The marble is gray- to tan-weathering and contains schistose zones with layers and nodules of diopside+tremolite+ quartz. The middle schist unit is composed of rusty- and locally, maroon-weathering, gray, biotite-muscovite-plagioclase-quartz-kyanite-garnet-sillimanite gneiss and schist with kyanite layers, zones of porphyroblastic kyanite+garnet, and layers of biotite-quartz-plagioclase+garnet granofels.

The overall structure of the park is a south-plunging klippe of the middle schist unit produced by the superposition of an F₃ synform and a late, NW-trending synform. The klippe of € - Om is terminated along its southern margin by a brittle fault (splay of the 125th Street fault?) exposed at street level trending N69°W, dipping 84°SW. Slickensides in the fault surface are oriented N70°W @ 22° clearly indicating a strike-slip movement sense although a component of reverse motion is suggested by faint dip-slip slicks and the presence of Inwood Marble to the south. Along the east-face of the exposure, the St. Nicholas thrust is found between the Manhattan schist and Inwood Marble and is marked by 10° truncation of lithologic layering and an early S₁ foliation in the marble, extreme flattening, 2-3 cm scale annealed mylonitic layering, shearing and imbrication of lithologic units (including small tectonic slivers and interlayers of schist unit Om?), and quartz veins.

Developed during thrusting and deformed by F₃ folds, the S₂ enveloping surface is variable but on average trends N30°W, 20°SW and marks the axial surface of reclined and isoclinal folds found both above and beneath the St. Nicholas thrust contact. Disharmonic F₃ folds of mylonite developed at the thrust contact are exposed at the northern edge of the klippe. They trend N32°E, 80°NW to 70°SE and plunge 23° into S25°W.

STOP 6 - "BALMVILLE" MARBLE AND LOWER MANHATTAN SCHIST UNIT - GRAND CONCOURSE AND THE CROSS BRONX EXPRESSWAY, BRONX. UTM Coordinates: 591.65E/4521.95N, Central Park 7-1/2 minute quadrangle.

An excellent exposure of the lower schist unit (Om) occurs west of the Grand Concourse in an overpass above the Cross Bronx Expressway (I-95). Here, fine- to medium-grained, massive but locally friable, tan- to brown-weathering muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist and granofels is found interlayered on the scale of 3-4 m with calcite and dolomite marble containing 2-3 cm diopside+tremolite calc-silicate and siliceous layers. Massive Inwood Marble (€ - Oi) occurs in the roadcut forming the south wall of I-95 beneath the overpass. This locality, together with exposures described earlier in Inwood Hill Park (Stop 3) and a few other outcrops south of I-95 paralleling the Grand Concourse (C. A. Baskerville, personal communication), are interpreted as the autochthonous portions of the "Tippecanoe" Manhattan Schist.

STOP 7 - CAMERON'S LINE - BORO HALL AND CROTONA PARKS, CROSS BRONX EXPRESSWAY. UTM Coordinates centered on: 593.00E/4521.80N, Central Park 7-1/2 minute quadrangle.

Boro Hall Park in the Bronx is surrounded by East Tremont Avenue on the north, Third Avenue on the west, Arthur Avenue on the east, and East 175th Street on the south. The last-named also serves as the westbound service road for the Cross Bronx Expressway (I-95). This park is situated on an important subdivision of the metamorphic schistose rocks of the Bronx. On the 1971 edition of the Geologic Map of New York (New York State Museum and Science Service) places a queried dashed line through the center of the park as the contact between the New York City Group on the west from the Hutchinson River Group on the east. Seyfert and Leveson (1969) discuss the contact as a thrust fault and argue that it is on strike with Cameron's Line. Based on lithologic correlations, Baskerville (1982a, b, 1992) first identified the contact as Cameron's Line; Merguerian and Baskerville (1987) defined the structural relationships discussed below.

Along East 175th Street the outcrop nearest Third Avenue is a brown- to rusty-weathering, medium-textured, gray, biotite-muscovite schist of the middle schist unit (€ - Om) containing several pegmatite dikes. The foliation strikes N40°E, and dips 70°SE. Test borings for the I-95 overpass near this locality indicate that marble occupies the Third Avenue valley to the west. East of the middle schist unit is a soil-covered shallow swale, 30- to 40 m wide, that trends N40°E. The Hartland Formation (€ - Oh) crops out to the east of the swale and also south of the expressway in Crotona Park (described below). The Hartland rocks are brown- to tan-weathering, gray muscovite-biotite-quartz-plagioclase-garnet schist and gneiss with granitoid sills and thick layers of greenish amphibolite.

The contact between the middle schist unit (€ - Om) on the west and the Hartland Formation (€ - Oh) is never exposed but presumably occupies the swale between the outcrops. Rocks on either side of the contact are highly flattened; as a result of recrystallization during D₃, the microscope shows little evidence for mylonitization. Microscopically, brittle fractures are well-developed in the minerals, suggesting the contact may be a brittle fault reactivating an older ductile

contact. The contact between these units is known as Cameron's Line, a ductile fault separating allochthonous sequences of the Taconian Hartland and Manhattan formations.

Dr. Patrick W. G. Brock of Queens College, who took a class to this stop, collected specimens, and examined the rocks petrographically, detected a corroded grain of corundum that had been highly retrograded by higher-crustal-level metamorphic overprinting. Although it was not in contact with quartz and clearly had undergone retrograde reactions, the corundum discovery suggests that the rocks in this region had initially experienced metamorphism at least up to K-feldspar-sillimanite grade.

To the south of the Cross Bronx Expressway, in Crotona Park, Cameron's Line again separates schist, gneiss, and amphibolite of the Hartland Formation (€ - Oh) on the east from westerly exposures of schist and gneiss of the middle unit of the Manhattan Schist Formation (€ - Om). The rocks are not found in direct contact but, similar to exposures to the north, are separated by a soil-covered interval. The Manhattan exposures are mylonitized, however, with shear folds and laminated textures well displayed.

ACKNOWLEDGEMENTS

This field guide was prepared utilizing data gathered from natural exposures, tunnels, and construction excavations in Manhattan and the Bronx, together with some additional data from the Bronx provided by Dr. Charles A. Baskerville, formerly of the United States Geological Survey. Discussions with Drs. Leo M. Hall, Nicholas M. Ratcliffe, Pamela and Patrick Brock, and John E. Sanders have been of great assistance in developing the lithostratigraphic views presented here on the schists of Manhattan. Additional information from study of Hofstra University's Metropolitan New York Drill Core Collection helped verify geologic contacts mapped in the field. Access to the New York City Water Tunnel system was arranged by Michael Greenberg and Scott Chesman of the City of New York and by the Schiavone Construction Company and use of the archived data of New York City's Subsurface Exploration Section was facilitated by Lawrence Ebbitt and Michael Greenman. Over the years, I have been assisted in the field by Diane Dennis, Eileen Schnock, James Harris, Norma Iturrino, Christopher and Mickey Merguerian, and P. LaJuke and have received abundant subsurface data from local municipal agencies and engineering firms too numerous to mention here individually. Figures 5 and 9 were computer-enhanced and the manuscript was reviewed by Dr. J Bret Bennington, my colleague at Hofstra University.

REFERENCES CITED

- Amenta, R. V., and Mose, D. G., 1985, Tectonic implications of Rb-Sr ages of granitic plutons near Cameron's Line in western Connecticut: *Northeastern Geology*, v. 7, no. 1, p. 11-19.
- Baskerville, C. A., 1982a, Adoption of the name Hutchinson River Group and its subdivisions in Bronx and Westchester Counties, southeastern New York: *United States Geological Survey Bulletin 1529-H, Stratigraphic Notes, 1980-1982, Contributions to Stratigraphy*, p. H1-H10.
- Baskerville, C. A., 1982b, The foundation geology of New York City: p. 95-117 in Legget, R. F., ed., *Geology under cities, Reviews in Engineering Geology*, Geological Society of America, Boulder, Colorado, v. 5, 131 p.
- Baskerville, C. A., 1989, New York City: juxtaposition of Cambrian and Ordovician miogeoclinal (*sic*) and eugeoclinal rocks: p. T361:39-T361:48 in Baskerville, C. A. ed., *Geology and engineering geology of the New York Metropolitan area, International Geological Congress, 28th, Washington, D. C., Guidebook to Field Trip T361*, 59 p.
- Baskerville, C. A., 1992, Bedrock (*sic*) and engineering geologic (*sic*) maps of Bronx County and parts of New York and Queens counties, New York: U. S. Geological Survey Miscellaneous Investigations Series Map I-2003 (scale 1:24,000).

- Baskerville, C. A.; and Mose, D., 1989, The separation of the Hartland formation and the Ravenswood granodiorite from the Fordham gneiss at Cameron's Line in the New York City area: *Northeastern Geology*, v. 11, p. 22-28.
- Berkey, C. P., 1933, Engineering geology of the City of New York: *in* Berkey, C. P., ed., Guidebook 9, New York Excursions, New York City and vicinity: 16th International Geological Congress, United States, 1933, Washington, D. C., United States Government Printing Office, p. 77-123.
- Berkey, C. P., 1948, Engineering geology in and around New York: *in* Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America, 61st Annual Meeting, New York City, p. 51-66.
- Blank, H. R., 1973, Observations on the Brooklyn injection gneiss and related formations: *New York Academy of Sciences, Transactions, series II*, v. 35, no. 8, p. 645-660.
- Bowes, D.; and Langer, A., 1969, Polyphase deformation in the schists of the Bronx, New York City: *in* Alexandrov, E. A., ed., Symposium on the New York City Group of Formations, Geological Bulletin 3, Queens College Press, p. 17-31.
- Brock, P. J. C., 1989, Stratigraphy of the northeastern Manhattan Prong, Peach Lake quadrangle, New York-Connecticut, p. 1-27 *in* Weiss, Dennis, ed., New York State Geological Association Annual Meeting, 61st, Field trip guidebook: Middletown, NY, Orange County Community College, Department of Science and Engineering, 302 p.
- Brock, P. J. C., 1993, Geology of parts of the Peach Lake and Brewster quadrangle, southeastern New York and adjacent Connecticut, and basement blocks of the north-central Appalachians: New York, NY, City University of New York Graduate Faculty in Earth and Environmental Sciences, Ph. D. Dissertation, 494 p., 6 plates.
- Cameron, E. N., 1951, Preliminary report on the geology of the Mount Prospect Complex: *Connecticut Geology and Natural History Survey Bulletin* 76, 44 p.
- Cozzens, Issachar, 1843, A geological history of Manhattan or New York Island: New York, NY, 114 p. (includes map).
- Dana, J. D., 1880, On the geological relations (sic) of the limestone belts of Westchester County, New York: *American Journal of Science*, 3rd series, v. 20, p. 21-32, 194-220, 359-375, 450-456; v. 21, p. 425-443; 1881, v. 22, p. 103-119, 313-315, 327-335.
- Dana, J. D., 1881, Origin of rocks of the Cortlandt series: *American Journal of Science*, v. 22, p. 103-112.
- Dana, J. D., 1884, Note on the Cortlandt and Stony Point hornblendic (sic) and augitic rock [N. Y.]: *American Journal of Science*, v. 28, p. 384-386.
- Gale, L. D., 1839, Report on the geology of New York County, p. 177-199 *in* New York (State) Geological Survey, Annual Report, 3rd: Albany, New York, 339 p.
- Gale, L. D., 1843, Diary of a geological survey of the Island of New York, p. 581-604 *in* Mather, W. W., The geology of New York, Part I. Comprising (sic) the geology of the First Geological District: Albany, Carroll & Cook, Printers to the Assembly, 653 p., 46 pl.
- Gates, R. M., 1951, The bedrock geology of the Litchfield quadrangle, Connecticut: *Connecticut Geological and Natural History Survey Miscellaneous Series* 3 (Quadrangle Report 1), 13 p.
- Grauert, B., and Hall, L. M., 1973, Age and origin of zircons from metamorphic rocks in the Manhattan Prong, White Plains area, southeastern New York: *Carnegie Institute Yearbook*, Washington, D.C., v. 72, p. 293-297.
- Hall, L. M., 1968a, Trip A: Bedrock geology in the vicinity of White Plains, New York, *in* Finks, R. M., ed., Guidebook to Field Excursions: New York State Geological Association, Annual Meeting, 40th, Queens College, Flushing, New York, p. 7-31.
- Hall, L. M., 1968b, Geology in the Glenville area, southwesternmost Connecticut and southeastern New York, Section D-6, p. 1-12 *in* Orville, P. M., ed., Guidebook for field trips in Connecticut: New England Intercollegiate Geological Conference, Annual Meeting, 60th, New Haven, Connecticut, October 1968: *Connecticut Geological and Natural History Survey Guidebook* 2
- Hall, L. M., 1968c, Times of origin and deformation of bedrock in the Manhattan Prong, p. 117-127 *in* Zen, Ean; White, W. S.; Hadley, J. B.; and Thompson, J. B., Jr. eds., *Studies of Appalachian geology, northern and maritime*: New York, Wiley-Interscience Publishers, 475 p.

- Hall, L. M., 1976, Preliminary correlation of rocks in southwestern Connecticut, *in* Page, L. R., ed., Contributions to the stratigraphy of New England: Geological Society of America Memoir 148, p. 337-349.
- Hall, L. M., 1980, Basement-cover relations (sic) in western Connecticut and southeastern New York, p. 299-306 *in* Wones, D. R., ed., International Geological Correlation Project, Proceedings, Project 27: The Caledonides in the U. S. A.: Blacksburg, Virginia, Virginia Polytechnic Institute and State University, Department of Geological Sciences, Memoir 2, 329 p.
- Kemp, J. F., 1887, The geology of Manhattan Island [N. Y.]: Transactions of the New York Academy of Sciences, v. 7, p. 49-64.
- Kemp, J. F., 1895, The geological section of the East River, at Seventieth Street, New York: New York Academy of Sciences Transactions, v. 14, p. 273-276.
- Kemp, J. F., 1897, The glacial or postglacial diversion of the Bronx River from its old channel: New York Academy of Sciences Transactions, v. 16, p. 18-24, map.
- Lobeck, A. K., 1939, Geomorphology. An introduction to the study of landscapes: New York and London, McGraw-Hill Book Company, Inc., 731 p.
- Long, L. E., Cobb, J. C., and Kulp, J. L., 1959, Isotopic ages on some igneous and metamorphic rocks in the vicinity of New York City: Annals of the New York Academy of Sciences, v. 80, p. 1140-1147.
- Mather, W. W., 1843, Geology of New York. Part I. Comprising (sic) the geology of the First Geological District: Albany, Carroll & Cook, Printers to the Assembly, 653 p., 46 pl. (Includes report of Prof. L. D. Gale on New York Island based on survey of 1828 and 1829.)
- Merguerian, Charles, 1977, Contact metamorphism and intrusive relations of the Hodges Complex along Cameron's Line, West Torrington, Connecticut: M.A. dissertation, The City College of New York, Department of Earth and Planetary Sciences, 89 p., with maps; also on open-file Connecticut Geological Survey, Hartford, Connecticut.
- Merguerian, Charles, 1983a, Tectonic significance of Cameron's Line in the vicinity of the Hodges Complex - an imbricate thrust model for Western Connecticut: American Journal of Science, v. 283, p. 341-368.
- Merguerian, Charles, 1983b, The structural geology of Manhattan Island, New York City (NYC), New York (abs.): Geological Society of America Abstracts with Programs, v. 15, p. 169.
- Merguerian, Charles, 1985, Geology in the vicinity of the Hodges Complex and the Tyler Lake granite, West Torrington, Connecticut: *in* R.J. Tracy, ed., Guidebook for fieldtrips in Connecticut, New England Intercollegiate Geological Conference, New Haven, Connecticut, p. 411-442.
- Merguerian, Charles, 1986a, The bedrock geology of New York City (NYC) (abs.): *in* Symposium on the Geology of Southern New York, Abstracts with Programs, Hofstra University, New York, p. 8.
- Merguerian, Charles, 1986b, Tunnel vision - a deep view of the bedrock geology of New York City (NYC) (abs.): Geological Society of America Abstracts with Programs, v. 18, p. 54-55.
- Merguerian, Charles, 1987, The geology of Cameron's Line, West Torrington, Connecticut, p. 159-164 *in* Roy, D. C., ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, Volume 5, 481 p.
- Merguerian, Charles, 1988, Annealed mylonitic textures in polyphase deformed metamorphic terrains (abs.): Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A214.
- Merguerian, Charles, 1994, Stratigraphy, structural geology, and ductile- and brittle faults of the New York City area, p. 49-56 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 23 April 1994, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.
- Merguerian, Charles, 1995, The Taconic problem - alive and well in New York City (NYC) (abs.): Geological Society of America Abstracts with Programs, v. 27, no. 1, p. 68.
- Merguerian, Charles, 1996a, Cameron's Line mylonite zone in Connecticut and New York City - evidence for Taconian accretionary tectonics (abs.): Geological Society of America Abstracts with Programs, v. 28, no. 3, p. 81.

- Merguerian, Charles, 1996b, Evidence for post-glacial surface faulting in New York City (abs.): Geological Society of America Abstracts with Programs, v. 28, no. 3, p. 81.
- Merguerian, Charles; and Baskerville, C. A., 1987, The geology of Manhattan Island and the Bronx, New York City, New York: in D.C. Roy, ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, p. 137-140.
- Merguerian, Charles; and Sanders, J. E., 1991, Geology of Manhattan and the Bronx: Guidebook for On-The-Rocks 1990-91 Fieldtrip Series, Trip 16, 21 April 1991, Section of Geological Sciences, New York Academy of Sciences, 141 p.
- Merguerian, Charles; and Sanders, J. E., 1992, Xenoliths as indicators of paleoflow and paleoenvironmental conditions in the Palisades sheet, New York and New Jersey (abs.): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 62-63.
- Merguerian, Charles; and Sanders, J. E., 1993a, Geology of Cameron's Line and the Bronx Parks: Guidebook for On-The-Rocks 1993 Fieldtrip Series, Trip 26, 08 May 1993, Section of Geological Sciences, New York Academy of Sciences, 103 p.
- Merguerian, Charles; and Sanders, J. E., 1993b, Geology of southern Central Park, New York City: Guidebook for On-The-Rocks 1993 Fieldtrip Series, Trip 28, 26 September 1993, Section of Geological Sciences, New York Academy of Sciences, 143 p.
- Merguerian, Charles; and Sanders, J. E., 1994, Implications of the Graniteville xenolith for flow directions of the Palisades magma (abs.): p. 59 *in* A. I. Benimoff, ed., The Geology of Staten Island, New York, Field guide and proceedings, The Geological Association of New Jersey, XI Annual Meeting, 296 p.
- Merguerian, Charles; and Sanders, J. E., 1995a, NE-, not SE-, directed paleoflow of the Palisades magma north of Staten Island: new evidence from xenoliths and contact relationships, p. 64-77 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 22 April 1995, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.
- Merguerian, Charles; and Sanders, J. E., 1995b, Late syn-intrusive clastic dikes at the base of the Palisades intrusive sheet, Fort Lee, NJ, imply a shallow (~3 to 4 km) depth of intrusion, p. 54-63 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 22 April 1995, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.
- Merguerian, Charles; and Sanders, J. E., 1995c, Geology of the Palisades and the Newark Basin: Guidebook for On-The-Rocks 1995 Fieldtrip Series, Trip 34, 29 April 1995, Section of Geological Sciences, New York Academy of Sciences, 120 p.
- Merguerian, Charles; and Sanders, J. E., 1996a, Contrasting styles of the Taconic orogeny in New York: deep- vs. shallow thrusts, p. 116-130 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 20 April 1996, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 177 p.
- Merguerian, Charles; and Sanders, J. E., 1996b, Diversion of the Bronx River in New York City - evidence for postglacial surface faulting?, p. 131-145 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 20 April 1996, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 177 p.
- Merguerian, Charles; and Sanders, J. E., 1996c, Glacial geology of Long Island: Guidebook for On-The-Rocks 1996 Fieldtrip Series, Trip 39, 01 + 02 June 1996, Section of Geological Sciences, New York Academy of Sciences, 130 p.
- Merguerian, Charles; Mose, D.; and Nagel, S., 1984, Late syn-orogenic Taconian plutonism along Cameron's Line, West Torrington, Connecticut (abs.): Geological Society of America Abstracts with Programs, v. 16, p. 50.
- Merrill, F. J. H., 1886a, On the geology of Long Island: New York Academy of Sciences Annals, v. 3, p. 341-364.
- Merrill, F. J. H., 1886b, Some dynamic effects of the ice sheets: American Association for the Advancement of Science Proceedings, v. 35, p. 228-229.
- Merrill, F. J. H., 1890, On the metamorphic strata of southeastern New York: American Journal of Science, 3rd series, v. 39, p. 383-392.
- Merrill, F. J. H., 1898a, The geology of the crystalline rocks of southeastern New York: New York State Museum Annual Report 50, v. 1, p. 21-31.

- Merrill, F. J. H., 1898b, The origin of serpentinites in the vicinity of New York: New York State Museum Annual Report 50, v. 1, p. 32-44.
- Merrill, F. J. H., 1898c, The geology of greater New York (abs.): Transactions of the New York Academy of Sciences, v. 16, p. 370-371.
- Merrill, F. J. H.; Darton, N. H.; Hollick, Arthur; Salisbury, R. D.; Dodge, R. E.; Willis, Bailey; and Pressey, H. A., 1902, Description of the New York City district: United States Geological Survey Geologic Atlas of the United States, New York City Folio, No. 83, 19 p. (Includes colored geologic map on a scale of 1:62,500).
- Mose, D. G.; and Merguerian, Charles, 1985, Rb-Sr whole-rock age determination on parts of the Manhattan Schist and its bearing on allochthony in the Manhattan Prong, southeastern New York: Northeastern Geology, v. 7, no. 1, p. 20-27.
- Norton, M. F., 1959, Stratigraphic position of the Lowerre Quartzite: p. 1148-1158 *in* Lowe, K. E., chm. and consulting ed., Modern aspects of the Geology of New York City and environs: New York Academy of Sciences, Annals, v. 80, art. 4, p. 1047-1169.
- Paige, Sidney, 1956, Cambro-Ordovician age of the "Inwood" limestone and "Manhattan" schist near Peekskill, New York: Geological Society of America Bulletin, v. 67, no. 3, p. 391-394.
- Prucha, J. J., 1959, Field relationships bearing on the age of the New York City Group of the Manhattan Prong, p. 1159-1169 *in* Lowe, K. E., chm. and consulting ed., Modern aspects of the Geology of New York City and environs: New York Academy of Sciences, Annals, v. 80, art. 4, p. 1047-1169.
- Quinlan, G. M.; and Beaumont, Christopher, 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the Eastern Interior of North America: Canadian Journal of Earth Sciences, v. 21, no. 9, p. 973-996.
- Ramsay, J. G., 1962, The geometry and mechanics of formation of "similar" type folds: Journal of Geology, v. 70, p. 309-327.
- Ratcliffe, N. M., 1968, Contact relations (sic) of the Cortlandt complex at Stony Point, New York, and their regional implications: Geological Society of America Bulletin, v. 79, p. 777-786.
- Ratcliffe, N. M., and Knowles, R. R., 1969, Stratigraphic relations (sic) along the western edge of the Cortlandt intrusives and their bearing on the Inwood-Manhattan problem, p. 49-54 *in* E. A. Alexandrov, ed., Symposium on the New York City Group of Formations: Flushing, N.Y., Geological Bulletin 3, Queens College Press, 83 p.
- Ries, Heinrich, 1895, On a granite-diorite near Harrison, Westchester County, N.Y.: New York Academy of Sciences Transactions v. 14, p. 80-86.
- Robinson, P.; and Hall, L. M., 1980, Tectonic synthesis of southern New England, p. 73-82 *in* Wones, D. R., ed., International Geological Correlation Project, Proceedings, Project 27: The Caledonides in the U. S. A.: Blacksburg, Virginia, Virginia Polytechnic Institute and State University, Department of Geological Sciences, Memoir 2, 000 p.
- Rodgers, John; Gates, R. M.; and Rosenfeld, J. L., 1959, Explanatory text for the preliminary geological map of Connecticut, 1956: Connecticut Geological and Natural History Survey Bulletin 84, 64 p.
- Sanders, J. E.; and Merguerian, Charles, 1991, Pleistocene tills in the New York City region: new evidence confirms multiple (three and possibly four) glaciations from two directions (NNE to SSE and NW to SE) (abs.): Geological Society of America, Abstracts with Programs, v. 23, no. 1, p. 123.
- Sanders, J. E.; and Merguerian, Charles, 1992, Directional history of Pleistocene glaciers inferred from features eroded on bedrock, New York metropolitan area, SE NY (abs.): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 72.
- Sanders, J. E.; and Merguerian, Charles, 1994a, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island, p. 103-116 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 23 April 1994, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.
- Sanders, J. E.; and Merguerian, Charles, 1994b, Glacial geology of Staten Island (abs.): p. 271 *in* A. I. Benimoff, *ed.*, The Geology of Staten Island, New York, Field guide and proceedings, The Geological Association of New Jersey, XI Annual Meeting, 296 p.

Seyfert, C. K., and Leveson, D. J., 1968, Structure and petrology of Pelham Bay Park, p. 175-195 *in* Finks, R. M., ed., New York State Geological Association, Annual Meeting, 40th, Queens College, Flushing, New York, Guidebook to Field Excursions, 253 p.

Seyfert, C. K., and Leveson, D. J., 1969, Speculations on the Hutchinson River Group and the New York City Group, p. 33-36 *in* Alexandrov, E. A., editor, Geological Bulletin 3, Symposium on the New York City group of formations: New York State Geological Association, Annual Meeting, 40th, Flushing, New York, Queens College: Flushing, New York, Queens College Press, Department of Geology, 83 p.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, no. 2, p. 93-114.

Taterka, B. D., 1987, Bedrock geology of Central Park, New York City: M.S. dissertation, Department of Geology and Geography, University of Massachusetts, Amherst, Massachusetts, Contribution 61, 84 p. with maps.

Ziegler, V., 1911, The Ravenswood grandiorite: New York Academy of Sciences Annals, v. 21, p. 1-10.

...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...

A Survey of the Natural and Urbanized Shorelines on Long Island, New York - A Dilemma in Coastal Management

Manfred P. Wolff(1), Nicholas K. Coch(2), Robert W. Johnson(3)

1) Geology Department, Hofstra University

(2) Department of Geology, Queens College, CUNY

(3) Biology Department, Hofstra University

INTRODUCTION

This trip will examine six stops on the barrier island beaches along the south shore of Long Island (Figure 1). Such beaches were probably first formed during the Pleistocene glaciation from eroded and reworked continental Cretaceous-Tertiary strata 100 Km. seaward of their present location. They were then gradually submerged and modified into shoals, lagoons, barrier islands and inlets by the current marine transgression. During the past 25,000 years of glacial melting and deposition the rising sea reached the outer edge of the glacial outwash and moraine deposits, perhaps 3-5 Km. seaward of their present location (Wolff, 1982). It is this newer source of Pleistocene glacial sediments that continue to undergo the transitory processes that modify them into the current coastal features. Ultimately, they will be eroded and deposited offshore, on the shoreface, and below wavebase on the inner continental shelf--as the Holocene transgression continues.

We accept the concept of "barrier island migration" with the rising sea, and will provide evidence for it. This emphasizes the idea that the barrier islands have not been "drowned" but instead, continue to be preserved by progressive landward sand migration. This migration occurs during the shoaling associated inlet formation, and during the flooding and overwash deposition associated with the wave surge from major storms (Wolff, 1989).

Anthropogenic changes brought on by coastal habitation during this century have seriously curtailed the influence of these natural processes in maintaining the sporadic pattern of inlet formation and landward barrier island migration. Management philosophy has instead substituted a policy that now emphasizes mechanisms that attempt preservation of all the natural environments through coastal stabilization. While most of our field stops are on urban beaches, they are maintained by different levels of government (state, county, city and town) and the management policies may also differ. We will review the history of development (natural and urban) at each of these stops, examine the methods used for the artificial (and temporary) stabilization of the dunes and beaches, and discuss the impact of storms in promoting either the destruction or the preservation of these natural features in the future.

Most field trips at this meeting will examine outcrops visited by geologists for over 100 years; the road cuts remain the same-- but the interpretation changes. For our trip, the interpretation has remained the same, but the "outcrops" continuously change (in shape, form or position). As this is written the authors realize that the effects of a nor'easter or hurricane before October could significantly change the form or location of our "outcrops". Most of our stops were within the "zone of breaking waves" within the past few years but all of them have been recently "restored" by beach nourishment. Coastal inhabitants-- particularly park managers and home owners on or near beaches demand a permanent position for their beaches, and have in place a powerful political lobby (at all levels of government) that will fight "beach erosion" and promote coastal maintenance and stabilization (which we realize only promotes more beach erosion).

But nature still remains a powerful influence for coastal change. The most obvious one is the coastal storm that erodes barrier island beaches, breaches dunes, overwashes barrier terraces and marshes, creates inlets, and floods mainland beaches. It floods or destroys all the "permanent" anthropogenic infrastructure, but only temporarily disturbs the habitats of the natural flora and fauna. As with a forest fire, after the initial devastation, the habitats are frequently extended and improved as the cycle of biological and physical evolution is renewed.

The less obvious change is the influence of the rate of sea level rise. It is now 0.6 m./100 years and is estimated to be increasing to 1.5 m./100 years because of the global warming. Yet coastal management

policies still reflect the "status quo"--the demands of the coastal managers and the communities. Because of the intense coastal development, they remain oblivious to the benefits of the storms, (which provide the natural sand migration) and because we haven't had a major hurricane crossing over this region in more than fifty years. There is never a discussion for the initiation of a policy that would emphasize the relocation or abandonment of destroyed structures after a major storm--only renourishment and renewed stabilization of the beach, and the return of larger (and more expensive) structures. In the meantime, the storms and sea level rise will continue. Thus, the dilemma!

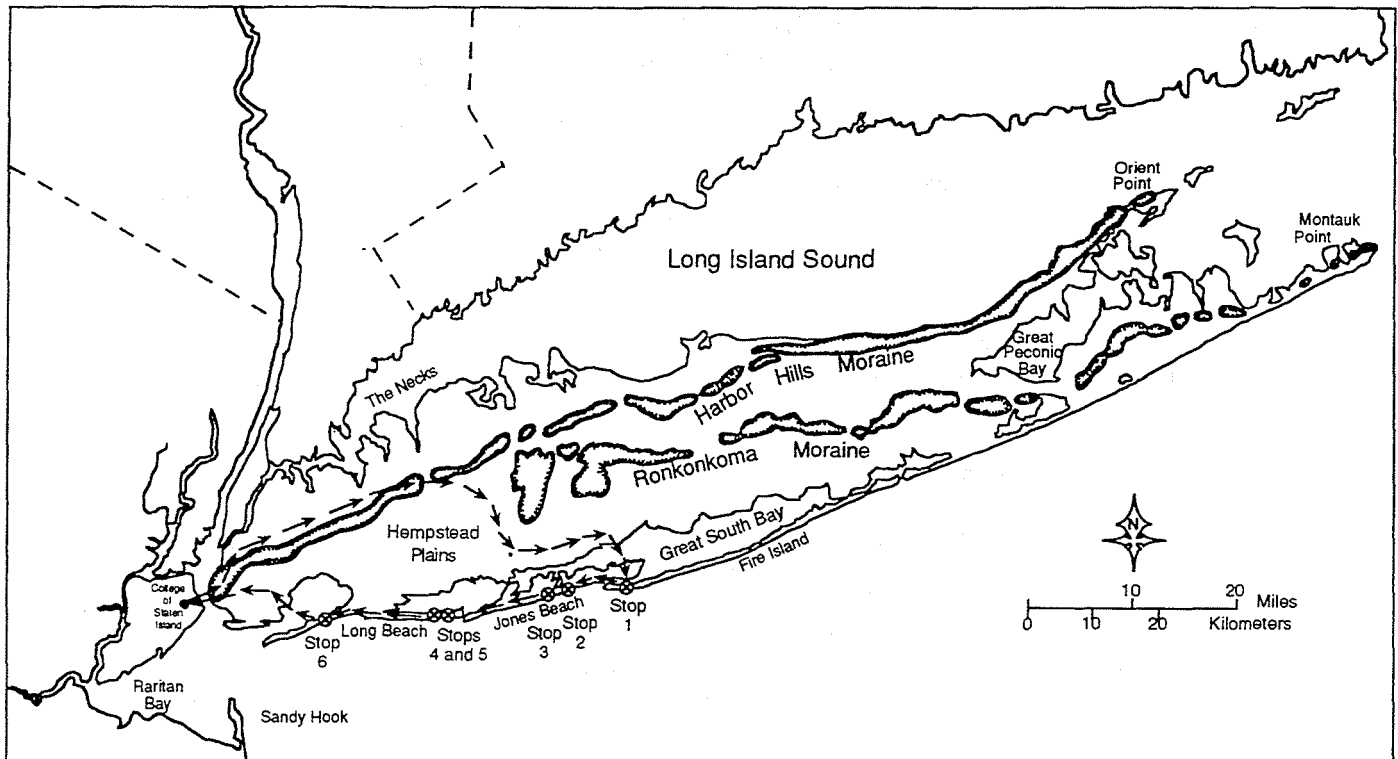


Figure 1. Geographic and geomorphic features, road traverse, and field trip stops related to the south shore of L.I. (See road log for more detailed description of traverse).

GLACIAL AND COASTAL GEOMORPHOLOGY

The glacial history and origin of Long Island (L.I.) was first described by Fuller (1914) and updated by Flemming (1935); Donner (1964); Jensen and Soren (1974), and Sirkin, (1982,1986). The nearly 1000 Km. of L.I. shoreline occurs in the transitional area between the glaciated coasts of New England and the unglaciated coastal plain beaches that extend from northern New Jersey - southward. The northern third of L.I. had the maximum extent of Wisconsinan glaciation with the formation of a series of continental ice lobes fronted by terminal or recessional moraines and kame deltas (Sirkin, 1982) - see Figure 1. Perhaps there were even earlier periods of glaciation that reached L.I. (Sanders and Merguerian, 1994). But it was the most recent interglacial stage that produced the meltwaters that formed the major and minor distributary outwash channels that spread across L.I., and well beyond the present edge of the mainland (Wolff, 1982).

These can be observed in the lobate shoreline configuration of the L.I. mainland behind the western section of barrier islands and marshes (Figure 1). This shape suggests the presence of submerged outwash lobes that originally extended much farther out into the Atlantic Ocean. Additional evidence for these eroded and submerged outwash deltas comes from the preglacial drainage channels cut into the Cretaceous bedrock and then filled with coarse meltwater sediments (Jensen and Soren, 1974). The location of the thalweg for these channels was determined by Williams (1976) and extended from the mainland to the shoreface by Wolff (1982).

SEDIMENT SOURCES FOR THE COASTAL BEACHES

Originally, most of the sand on the beaches was believed to come only from the receding glacial headlands of eastern L.I. As they eroded, the sediments were being continuously moved westward, from one barrier island to the next, by the influence of relatively persistent longshore currents (Colony, 1932; Taney, 1961; Krinsley, et al. 1964; McCormick, 1973; Williams, 1976). This would account for the long, persistent "chain" of barrier islands. However, recognition is now given to the presence of an offshore source that also supplies an important contribution.

The global volume of water within the Wisconsin ice sheets was large enough to lower sea level by over 100 meters, positioning the present shoreline of New Jersey, New York, and Connecticut about 100 Km. seaward of its present location (Milliman and Emery, 1968). This lowered sea level allowed the south-flowing New England and New Jersey rivers to erode the Cretaceous and Tertiary highlands, drain across the Atlantic coastal plain (now the inner continental shelf) and disperse their sediments into the distant ocean. With the rising sea, these strata became the first offshore source of sediment for the initial beaches (Williams & Meisberger, 1987). Therefore, during the early phase of the Holocene coastal transgression, the initial barrier islands did not contain glacial sediments, but were composed of only reworked Cretaceous and Tertiary deposits. The sporadic occurrence of zones of glauconite in the recent sediments on the inner continental shelf may still be a reflection of this.

The melting that ensued at the end of the Wisconsin epoch extended the outwash lobes at least another 5 Km. seaward of the present coastline, and these became the second sediment source. The glacial deposits could not be modified into barrier island-marsh sediments until they were reached by this transgression. Gradually, they became submerged, first beneath the bay and later, as landward barrier island migration continued, the upper 5-10 m. of glacial material was mixed with the older Cretaceous deposits and became part of the reworked Holocene sediments of the ancient barrier islands. The process of eroding old, submerged, mainland strata on the seaward side of a barrier island has been termed "ravinement" (Stamp, 1921). As sea-level rise continued, they were exposed on the shoreface, (the narrow, steeply-sloping seaward extension of the beach and nearshore bar, that extends out to a depth of about 10m.) Here they became an important new source of sediment. Once exposed, storm activity could move this glacial sand landward into the bays by inlet breaching and overwash during the flood surge, promoting deposition. Some of it is also moved seaward, back onto the shoreface during the ebb surge, to produce coastal erosion (but shoreface deposition). Some submerged areas may still contain inlet-filling sediments not entirely eroded beneath the shoreface (Sanders and Kumar, 1975; Williams, 1976; Rampino and Sanders, 1981; Wolff, 1982) though this has been questioned at Fire Island (Panageotou and Leatherman 1986). Such relict sediments would also provide evidence for the progressive landward migration (and not submergence) of the barrier islands.

As the sea level rise continues, the sand on the beach, nearshore zone, and shoreface is gradually moved offshore to form the ridge and swale topography of the inner continental shelf--the nearly horizontal zone beyond the shoreface (Swift, 1976).

The significant point is that not all of the sand for the coastal deposits of western L.I. came from the eastern mainland. The importance of this source and the dominant westward-flowing longshore current cannot be denied. But the more landward lateral offset between each of the barrier islands (Figure 1) also demonstrates the relative importance of onshore sand transfer by flood tides and storms.

The shoreface is also known as a source of sediment transfer (Duane et al., 1972). While long recognized as a depository for coastal sediments, it can also be a contributor (Swift, et al., 1973; Swift, 1976; Williams,

1976). An estimated 6 billion cubic yards of sand is available for recovery--but it tends to occur off the stable beaches, not the unstable ones currently undergoing erosion (Williams, 1976).

MARINE PROCESSES AFFECTING THE BARRIER ISLANDS

While most of the central Atlantic coastline has a north-south orientation, this pattern changes to an east-west one at New York City (Hudson River) and remains this way along Long Island, Connecticut, and Rhode Island. This right-angle bend, known as the N.Y. Bight, changes the direction and the influence of the oceanic processes that affect the shoreline. Onshore winds vary with the seasons, but the dominant set-up favors those from the northeast to the southwest. This produces the westward flowing longshore currents that move the sand (as the littoral drift) from Fire Island toward Rockaway. Interference with this process at any point will create sand starvation (ie. beach erosion) west of that point. This is typically noted at any of the stabilized inlets.

Low frequency waves are associated with fair weather conditions (May-Oct.) and these return the sediment from the offshore "breaker bars" back into the inlets and onto the beaches. Onshore sand transfer can also occur from the flooding and overwash processes that form with the storm surge during hurricanes and nor'easters. This surge, if superimposed on a rising tide, can breach dunes and even barrier islands, producing large overwash lobes and flood tidal deltas in the new inlets (Leatherman, 1981).

More often, it is the high frequency waves, associated with storm conditions, (Nov.-Apr.) that move the sediment from the beaches back into the nearshore zone as submerged "breaker bars". While all storms create erosion, it is the major storms (the "spikes" in the record of time transgression) that also promote the large scale landward sand deposition needed to preserve the barrier islands for future generations. Storms do not strictly produce beach erosion - only sand migration either towards, or away from the rising sea.

HISTORY OF URBAN DEVELOPMENT ON THE BARRIER ISLANDS

The progressive growth of communities from New York City (Manhattan) onto western L.I.(Brooklyn) and eventually eastern L.I. (The Hamptons) is also reflected in the urbanization of the barrier islands. Development started with the filling-in of the marshes behind Coney Island (with its parks and playlands of the 1880's-1920's) creating small plots of shoreline "property". Dunes were removed in many places so homeowners could get a better view of the ocean. Even then, homes were sometimes demolished by storms, but were rebuilt in a more landward location. As homes became blocks and streets became roadways, bridges were built for railroads (and later for cars). Groins and jetties soon followed.

Gradually, there were connections to Rockaway and Long Beach, and from 1910-1940's coastal urbanization on western L.I. spread and flourished. The late 1920's saw the construction of the major parkways, and this included bridges to the newly developed public beaches, pavilions, roadways, and parking lots at Jones Beach State Park. These western islands were originally narrow, irregular, "sand ribbons" with low-moderate dunes, extensive salt marshes (from frequent overwash) and numerous (temporary) inlets. These characteristics are typical of the microtidal transgressive barrier islands described by Leatherman (1982). The establishment of the urban communities on these islands (except Jones Beach) led to the removal of dunes, the closure of the small inlets, and the infilling of salt marshes by bayside dredging. This resulted in straight, wide, barrier islands - now with constant erosion problems and an increase in the construction of streets and houses.

Continuing eastward, we encounter the Jones Beach barrier island. Though its western portion was developed into an urban recreational park (ie. Jones Beach), the eastern part saw the creation of town beaches for the local residents, and the island was spared from further urbanization. Fire Island also experienced urban development, but it remained on a small scale (20 scattered communities) since there was no direct roadway access to the mainland until the construction of the Robert Moses Causeway Bridge in 1963. Development was further restricted by the enclosure western Fire Island into Robert Moses State Park, and central Fire Island into the Fire Island National Seashore (which now incorporates many of the communities).

Most of the island remained unbroken by inlets because of its relatively large volume of sand, creating natural high dunes and wide beaches--until 1933. As inlets were opened and stabilized near its eastern

terminus, habitation increased, and soon, groin fields were added. Sand starvation ensued west of the field, and this region (Westhampton Beach) continues to have severe problems.

Since Fire Island was the only island on Long Island, and the last island on the Atlantic coast to be directly supplied by glacial sediment from longshore currents, it originally was quite high and had few inlets, and few tidal marshes (Wolff, 1980, 1986). Some small stretches still have a forest cover, indicating stability over hundreds of years. Human-induced stabilization has been limited to jetty construction at inlets opened by historic hurricanes, and currently, by frequent beach nourishment from offshore dredging and inlet bypassing. A recent update on the status of the beaches on L.I. has been presented by Wolff (1989).

ROAD LOG

Introduction:

Our 7:30 A.M. departure will provide us time (2 hours) to reach the farthest point at Robert Moses State Park near Fire Island Inlet (Stop 1.) The remainder of the day will be devoted to various stops on the barrier islands of Long Island (Figure 1).

Cumulative

Miles	Miles	Location
00.0	0.0	At CUNY College of Staten Island Parking Lot.
0.7	0.7	Turn right (east) onto Victory Blvd. and within 500 feet, right again onto S. Gannon Ave. (the spur road leading to Rt. 278, East.
5.2	4.5	Follow Rt. 278 to the Verrazano Bridge toll booths
7.5	2.3	Cross bridge and follow signs to Brooklyn-Queens Expressway - Rt. 278, East.
12.5	5.0	Rt. 278 narrows to two lanes.
14.5	2.0	Junction with Brooklyn Bridge overpass - New York skyline in view for camera shot.
19.5	5.0	Junction with Clearview Expressway (Rt. 495 E.) - get on ramp for Rt. 495 - eastern Long Island.
31.7	12.2	At Nassau County line - Rt. 495 continues as Long Island Expressway (LIE).
37.1	5.4	Pass junction with Northern State - Meadowbrook Parkway (approximately 1 hour since departure).
44.8	7.7	Get off at Exit 44 - junction with Rt. 135 south, Seaford - Oyster Bay Expressway.
50.2	5.4	Once on Rt. 135, get off at Exit 7 E (Hempstead Turnpike - Rt. 24).
51.5	1.3	Once on Hempstead Tpke., turn right onto Rt. 109 (Fulton St.).
52.8	1.3	Enter Suffolk County on Rt. 109.
56.4	3.6	Bear right and follow signs to Sunrise Highway E.
60.5	4.1	Once on Sunrise Highway, get off at Exit 41 - spur road to Robert Moses State Park (bear right onto ramp.)
61.1	0.6	Again, bear right onto ramp for Robert Moses Parkway to - (you guessed it!) Robert Moses State Park
64.0	2.9	Start across bridge over Great South Bay.
66.0	2.0	Leave bridge and enter east end of Jones Beach barrier island. Follow signs to Captree State Park, (NOT Captree Island!)
67.4	1.4	Bear right onto ramp for Captree State Park.
68.2	0.8	Enter Captree parking lot; park near Captree Cove Restaurant for last-minute preparations and a pit stop (Stop 0).
68.2	0.0	Leave Captree lot and head west on Ocean Parkway.
69.7	1.5	Turn right under the overpass onto route for Robert Moses State Park.

- 70.2 0.5 Start across (you guessed it!) Robert Moses Causeway Bridge that crosses Fire Island Inlet (see map) - one of the few parallel inlets on the East coast. Note Fire Island Lighthouse in distance on left; enter Fire Island.
- 70.8 0.6 At traffic circle (and Robert Moses Water Tower) go 20 degrees around circle and bear right - follow signs to "Fields 2 & 3 - Golf Course".
- 72.1 1.3 Go to end of parkway loop; at U-turn for entrance to Field 2 - pull off on shoulder.

STOP 1A. North side of Robert Moses State Park - The use of hard stabilization for erosion protection on the bayside of Fire Island.

Here we will examine the concrete "rubble" and a gabion ramp that is being used as revetment to curtail bayside erosion at the end of the Loop Parkway. The reason for the initial loss of 75 meters of this beach and marsh relates to the curved spit seen at the western end of Fire Island (Democrat Point) in the distance. This was a coast-perpendicular inlet in the 1860's, but the extensive westward growth of the island from the lighthouse (over 6 Km.) has now produced a coast-parallel inlet (Figure 2). By the 1940's, it was in deep-enough water off Oak Beach to enable the flood-tidal currents and wave refraction to form a series of recurved spits at Democrat Pt. that began to constrict the inlet (Wolff, 1975a,b).

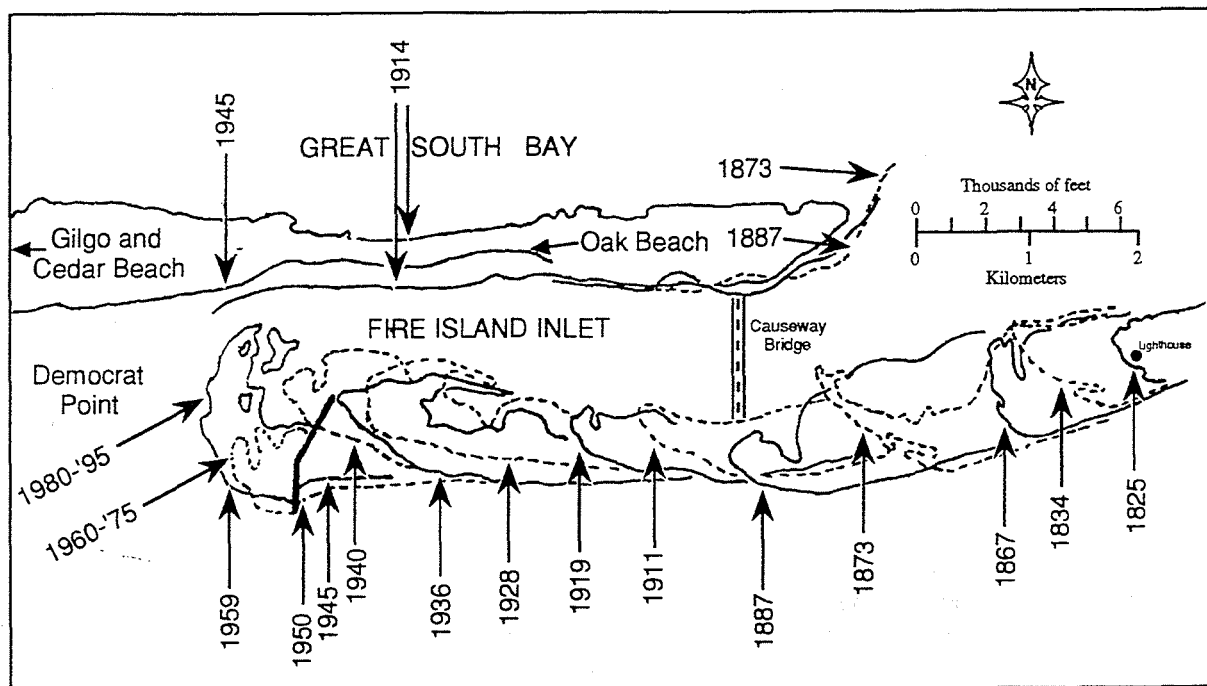


Figure 2. Progressive growth of western Fire Island(1825-1995) and the resulting inlet modifications.

As the tidal channel narrowed and deepened, its velocity increased, and it began forming a curved "meander" shape as it impinged on the Jones Beach barrier at Oak Beach. The resulting erosion required the construction of a jetty at Democrat point (to trap the littoral drift) and the dredging and by-passing of the accumulated sand across the inlet. But during the early 1950's, sand was already passing around the jetty, and by 1959 it was again constricting the inlet (Figure 2.) causing erosion near Oak Beach.

This led to the construction of a reveted sand dike by the U.S. Army Corps of Engineers west of Oak Beach. But this produced deposition and shoaling behind the dike (near Oak Beach) - which again increased the extent of the "meander" curve of the tidal channel. Acting as a "point-bar" in a meandering river, the shoals diverted the tidal currents against the bayside of Fire Island, resulting in the loss of the beach. The rubble and gabion ramp were added in 1986 to curtail the erosion.

The effect of hurricane track near this area would have particularly disastrous regional consequences since there could be a breach anywhere along Oak Beach, as there was in 1901 and 1923 (Wolff, 1975b). Depending on the extent of spit development in front of the Federal jetty, (Figure 2) this could lead to the closure of the present inlet and a deepening and widening of the new one. Such an opening recently occurred at Westhampton Beach, but was soon closed by offshore dredging (Wolff, 1994).

72.1 0.0 Return to bus and continue east on the Loop Parkway back to the water tower.

73.3 1.2 Park on south shoulder of road at traffic circle.

STOP 1B. Water tower in Ocean Parkway loop at Robert Moses St. Park.- use of soft stabilization for erosion protection on the oceanside of Fire Island.

This elongate mound is composed of gravelly sand trucked-in from the mainland under emergency conditions by the N.Y.S. Department of Transportation during the winter of 1990-'91 and again in 1992-'93 when an additional 20,000 cubic yards of sand were added. It is meant to augment the eroded dunes that once protected this traffic circle along the Loop Parkway. The history of beach erosion here dates from the 1940's, but dune erosion did not occur until the 1960's. Wave surge reached the oceanside parking lots east of here by 1973, and this zone of erosion has continued to migrate westward. Using slat fencing with periodic beach scraping, the dunes in front of the parking areas were restored in the 1980's, but erosion here, at this circle continues, necessitating the mainland trucking of gravel against the roadway.

A hurricane path near this area would not breach the barrier island, but it could create extensive damage to the parkway road, and to the water tower. The bridge is unlikely to be affected.

73.3 0.0 Continue north around traffic circle and return to Causeway Bridge; follow signs to "Parkway" North," and recross Fire Island Inlet.

74.6 1.3 Once across the bridge (after signs to "Captree State Park") follow signs to "Ocean Parkway Jones Beach" and bear right on ramp after the overpass.

77.1 2.5 Continue west on Ocean Parkway, with views to Oak Island (right) and Oak Beach (mouth of Fire Island Inlet) on left.

81.0 3.9 Continue west on Ocean Parkway - note region of high dunes on left.

82.2 1.2 Pass entrance to Gilgo Beach and get into left lane for U-turn.

82.7 0.5 Make U-turn for brief "leg" east to Stop 2.

83.6 0.9 Stop on pavement along right shoulder of road near sign for "4 wheel drive vehicular traffic".

STOP 2. Gilgo Beach (Town of Babylon) -use of soft stabilization for erosion protection of Ocean Parkway.

This stop was used by Wolff (1975b) to indicate the process of "ravinement" as described by Swift (1968) in which the active surf zone on a beach, during major storms, will expose old bayside marsh and lagoonal sediments. Such deposits were exposed on this beach during the nor'easters of 1972-73. Here is an area where over 400 meters of beach were eroded in 75 years--it was also used to demonstrate the effects of the process of barrier island "rollover" or landward migration. Once back-bay marsh sediments are buried beneath sands deposited as sand spits (by longshore currents) or overwash (from storm surges) they will later be overlain by sand from the terraces and dunes. As sea level rises, they will ultimately appear beneath the beach--were they can be re-exposed and excavated by the ocean waves (Figure 3). This beach has been renourished periodically since then (Buttner, 1989).

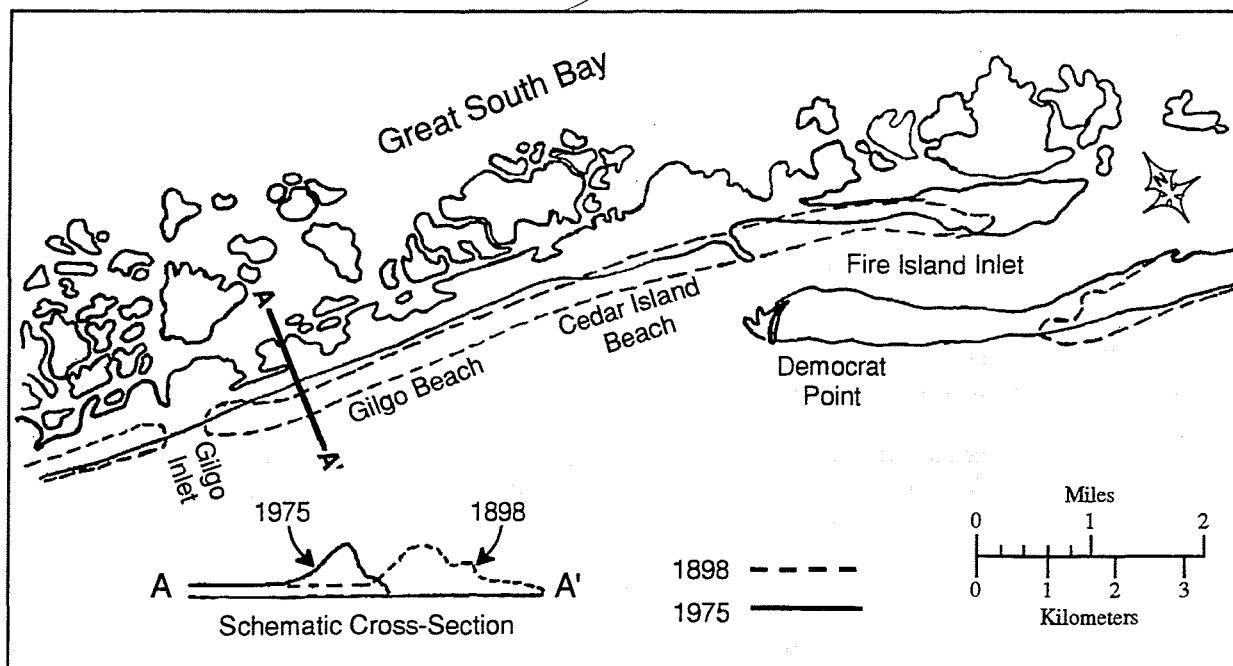


Figure 3. Overlay of 1898 and 1975 Geodetic maps to indicate the ravinement process and landward barrier island migration.

The wide beach at present is a result of several renourishment projects, initiated in 1988, that continue at present. Gilgo is the "feeder beach" for the cubic meters (or yards) of sand dredged and then pumped here from Fire Island Inlet. This sand will naturally feed the western town beaches and Jones Beach through the influence of the littoral drift.

The replenishment volume is as follows (Hanse, 1996):

- 1988 - 1 million cubic yards spread across 10,000 feet of beach
- 1990 - 1 million cubic yards spread across the same area
- 1992 - 1.7 mill. cubic yards spread across 18,000 feet of beach
- 1994 - 1.9 mill. cubic yards spread across 18,000 feet of beach
- 1994-'96 - an emergency stockpile of 20,000 cubic yards.

Note also the elongate ridge of gravelly sand used to replace the dunes along the edge of the Ocean Parkway. During the 1950's N.Y. State had constructed a pavilion near this location. It was being undermined and eroded by the 1970's and was abandoned and dismantled by 1975. The foundation was broken into "rip-rap" to armor the beach, and acted as a 'stubby' groin that trapped sand east of this location. But this resulted in a loss of beach at this location that, by 1986 was extensive enough to erode the dunes and nearly reach the Ocean Parkway. As at Stop 1B. N.Y.S.D.O.T., using emergency funds, was able to truck-in the gravelly sand from the mainland to save this vital roadway. The roadway is built on sand-clay fill dredged from the bay during its construction in the late 1920's and will erode even more quickly if it is ever undermined by the ocean waves. The replenishment of sand at Gilgo Beach (Stop 1B.) has kept the waves from returning.

The effect of a hurricane path passing near this area could also be quite profound since it was already near the site of a former inlet. While tidal marshes are extensive, the adjacent dredged channel for the boat moorings and the intra-coastal waterway leave this portion of the island quite narrow and susceptible to inlet breaching (Figure 3). There is not enough sand left for overwash. In fact, one of the ironies is that the sand that has been pushed by wind or water onto the Ocean Parkway over the past 30 years is rapidly collected and returned to the beach. Undermining of the south side of the roadway is imminent--but only if the trucking-in of sand and gravel is eliminated.

- 83.6 0.0 Continue east on Ocean Parkway, but get into left lane ASAP for another U-turn and the return to the western route.
- 83.8 0.2 Continue west on Parkway - past entrance to Gilgo Beach.
- 85.9 2.1 Pass sign for entrance into "Nassau County".
- 86.3 0.4 Pass entrance to Tobay Beach and get into left lane for U-turn
- 86.5 0.2 Make U-turn for brief "leg" east to Stop 3A.
- 86.9 0.4 Head east on Parkway and pull into Tobay Beach pavilion driveway.

STOP 3A. Tobay Beach (Town of Oyster Bay) - use of soft stabilization for erosion protection of Tobay Beach and the beach pavilion.

Note the location of the Tobay Beach Pavilion and the line of the eroded natural dunes. Note also the size and "storm-proof" construction of pavilion #4. This site for a pavilion goes back to the 1940's-when the dunes were in front of this location and the beach extended seaward another 115 meters. The construction of the Federal jetty at Democrat Pt. on Fire Island (Stop 1A.) blocked the sand from crossing the inlet, causing erosion along all the beaches of the Jones Beach barrier island during the 1950's. Without inlet bypassing, this pattern will persist. Once the beach and dunes were eroded, various storms undermined and partially destroyed the older pavilion. It was rebuilt, refurbished (and re-destroyed) several times before being completely torn down in 1986. Yet, instead of being rebuilt on the north side of Ocean Parkway, it was rebuilt (because of a need for convenient public access) at the same site in 1987. It has been "embraced" by waves from various storms, but the deep, sturdy concrete pilings assure its preservation - as long as periodic beach nourishment remains available. This one, and all the pavilions and bath houses to the west (ie. at Jones Beach State Park) now occupy sites in front of the natural duneline. Even the huge ocean-side parking lots are now in front of the dunes. This again demonstrates the subtle but continuous pattern of natural sand migration that, without continual stabilization, will ultimately cause all the barrier environments to migrate landward (Figure 4).

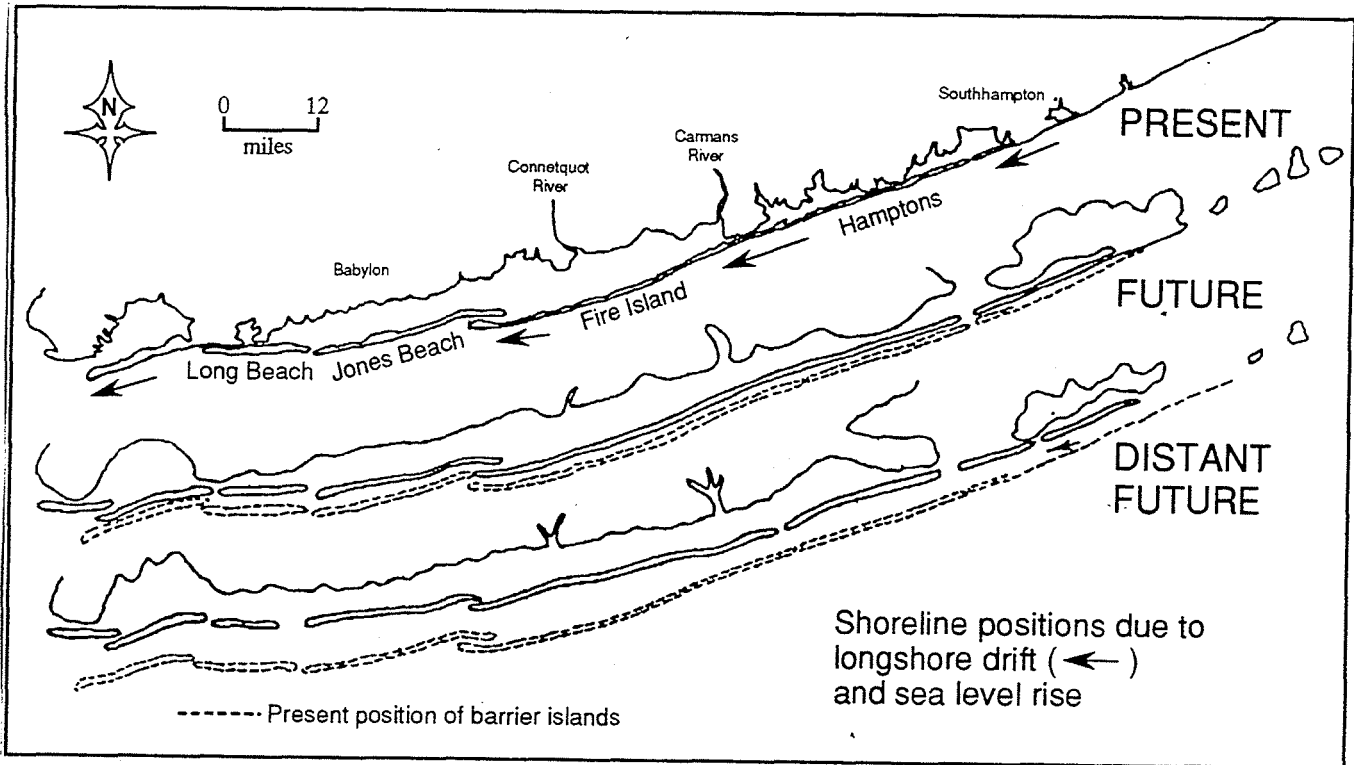


Figure 4. Schematic diagram of pattern of progressive landward migration of bay and barrier island environments during sea level rise from present position (top) to distant future (bottom).

- | | | |
|------|-----|---|
| 86.9 | 0.0 | Return to bus and continue east on Ocean Parkway but again get into left lane ASAP for another U- turn and the return toward the western route. |
| 87.8 | 0.9 | Turn right into entrance of Tobay Beach parking lot, descend ramp, and turn left. |
| 88.4 | 0.6 | Follow single lane road back to J.F. Kennedy Wildlife Sanctuary. |

STOP 3B. Tobay Beach - Wildlife Sanctuary (Town of Oyster Bay) - return of pre-historic inlets into ecologically productive barrier island forests, ponds, and marshes.

This is the site of a pre-historic inlet that retained a large volume of sand and relatively wide dunes and marshes for a long period of time. The result is (on a small scale) the development of freshwater ecosystem in a mature forest - something more characteristic of the mainland. While relatively rare, they demonstrate that certain areas on barrier islands do not rapidly undergo landward migration if enough overwash sand was deposited during prior storms; such areas may remain stable for long periods, and unaffected by the rising sea (Buttner, 1987).

The effect of a hurricane across this region, as before, has more regional than local consequences. Because of the prior overwash and inlet-filling sand, the extensive terraces and secondary dunes, and the wide expanse of salt marsh, a breach through here remains unlikely.

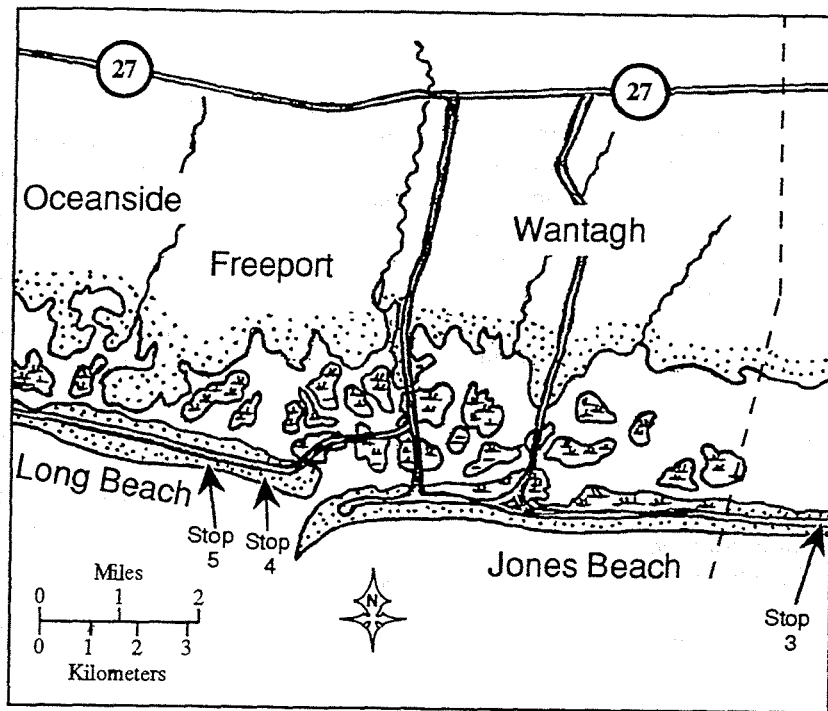


Figure 5. Location map for Stops 3A & B (Tobay Beach) 4 (Hempstead Beach Town Park) and 5 (Lido Beach). (Stops 4 & 5 are on the Long Beach Barrier Island)

- 88.4 0.0 Return on one-lane road to Tobay Beach entrance.
- 89.3 0.7 Return to Ocean Parkway and continue west.
- 91.4 2.1 Pass sign to "Jones Beach State Park".
- 92.7 1.3 Pass opposite entrance to "Field 6" of Jones Beach. Note the location of the dunes versus the location of the parking lot and pavilion.
- 93.4 0.7 Get in left lane and make U-turn just before the traffic circle (and water tower) to again continue east on Ocean Parkway.
- 94.1 0.7 Turn right into entrance at Field 6 and turn right in parking lot for a stop near the pavilion.

(This will be a quick 15 minute pit stop - Lunch can be eaten between here and Stop 4).

- 95.3 1.2 Return to bus for another U-turn and return to the western route - continue lunch aboard bus. Go 180 degrees (ie. straight) around traffic circle and continue west; follow signs to Meadowbrook Parkway.
- 96.5 1.2 Cross over Meadowbrook Parkway Bridge and bear right after underpass for "Loop Parkway" to Long Beach.
- 97.6 1.1 Cross over drawbridge to Long Beach; continue straight on Parkway and cross Lido Beach Blvd. directly into entrance for Hempstead Beach Town Park, Nassau County Park.

98.1 0.5 Bear left after the toll booths, turn left at stop sign, and head toward southeast corner of large parking lot.

STOP 4. Hempstead Beach Town Park, Nassau County- use of hard stabilization for erosion protection at Jones Inlet.

Note the distance (over 350 meters) between the major roadway and the dunes. Though an urban park, there is a large "buffer zone" between the community and the beach - all urban development on barrier islands should have a management plan that will lead to this zonation. Once on the beach, view the shoreline from the last groin. Observe the wide beach and extensive dune field on the east (Jones Inlet) side of the groin. Note the large beach "re-entrant" and lack of dunes on the west side. This area was under water at various times during the 1970's and '80's, threatening the Town Pavilion (seen in the distance). Only the periodic sand bypassing from the inlet has prevented its annihilation. The last nourishment program ended in the spring of '96. You can already see the development of a beach scarp and the lowered profile as the swash undercutting continues to undermine the beach. Dune rebuilding through the use of slat fencing and *Ammophila* (beach grass) has been quite successful here, but only for a limited period.

This beach, near Jones Inlet, has a history similar to that of Oak Beach at Fire Island Inlet (Stop 1A.) The westward littoral drift from Jones Beach, as it moved into the deeper water in the inlet, created a series of recurved spits. By the 1950's the narrowing of the inlet forced the channel against the beach near the community of Pt. Lookout at the eastern end of Long Beach. Erosion also prevailed along much of Jones Beach. A jetty was now constructed at the western tip of Jones Beach. This led to the restoration of the state park beaches behind the jetty, but it increased the erosion at Pt. Lookout. This later required the construction of three groins east of this park, which trapped the sand supplied by the tidal currents in the inlet. But this also increased the rate of erosion beyond the most western groin - resulting in the need for periodic inlet sand bypassing for beach renourishment.

A description of the regional effects of wave surge from a hurricane passing near this inlet towards Freeport (Figure 5) was detailed by Coch and Wolff (1990). This was based on their observations of inland flooding and destruction of mainland communities behind tidal marshes after Hurricane Hugo in 1989. Less serious mainland inundation was noted along Long Island, opposite the recent opening of Little Pike's Inlet (Wolff, 1994). The extent of the enlarged tidal prism that must enter and exit an inlet during a hurricane are profound! The areal extent of the flood surge for hurricanes of different intensity has been depicted on N.Y. State SLOSH maps, and these depict inundations over hundreds of square kilometers that would affect thousands of houses.

Many beachfront homeowners have some low-level protection from bulkheads and retaining walls. But the ebb surge that follows will have some unexpected consequences. Besides opening barrier breaches into new inlets, it will also scour and erode the areas behind the bulkheads. These structures trap the ebb flood, preventing its return to the ocean. This "wall of water" will cause the houses or bulkheads to be overtopped or undermined as the surge seeks its way back to the ocean (Coch and Wolff, 1990).

98.1 0.0 Leave parking lot by going north, then bear left and follow "Exit" sign back to junction with Lido Beach Blvd., then turn left (west) again.

99.5 1.4 Entrance to Lido Beach Town Park (3rd light after water tower).

99.7 0.2 Turn right, and bear right; follow road to large parking lot. Turn right and park in southwest corner of lot.

STOP 5. Lido Beach Town Park (Town of Hempstead)- use of soft stabilization for erosion protection.

The western edge of this park occurs at the boundary between an area with proper urban coastal management and an area that sees the return of community development directly behind the dunes. This region

has also experienced periods of extensive dune breaching and beach erosion, but the periodic beach nourishment and the extensive care given toward dune development have made it a "healthy" beach. This is the last area within the next 50 Km. where one can see dunes in front of coastal structures. In fact, if we continued across the Hudson River into Staten Island, and then across the Arthur Kill into New Jersey, other than a few short stretches along Sandy Hook, we would travel past the 50 Km. of seawalls in N.J. and all the way to Pt. Pleasant before again encountering dunes of this magnitude in front of houses. What was a coastal dilemma becomes a coastal crisis!

In descending the dune boardwalk "overpass," note the location of the dunes with regard to the gold-painted twin spires of the Lido Beach Towers in the distance - their position aligns itself with the mid section of this building. Dune restoration has been frequently attempted across this section of the "New York Bight" from Long Beach to Sea Girt, but it will always fail because the position of the natural dune line is now well within the first block of houses on the urban streets. Without beach nourishment, all the "beachfront" houses would have been removed by erosion during the 1950's, and development has since increased 3-fold. The rebuilding of the dunes west of this area is an "effort in futility". As described at stops 2 and 3, the original dunes were trapped between the rising sea and the most shoreward anthropogenic structures--boardwalk, roadways, or houses (Figure 6). Other than this local area, any new dune restoration will rapidly be eroded. Not until the relocation or abandonment of the first 1-4 rows of houses can the shoreline adapt an equilibrium position that would retain natural dunes for storm protection.

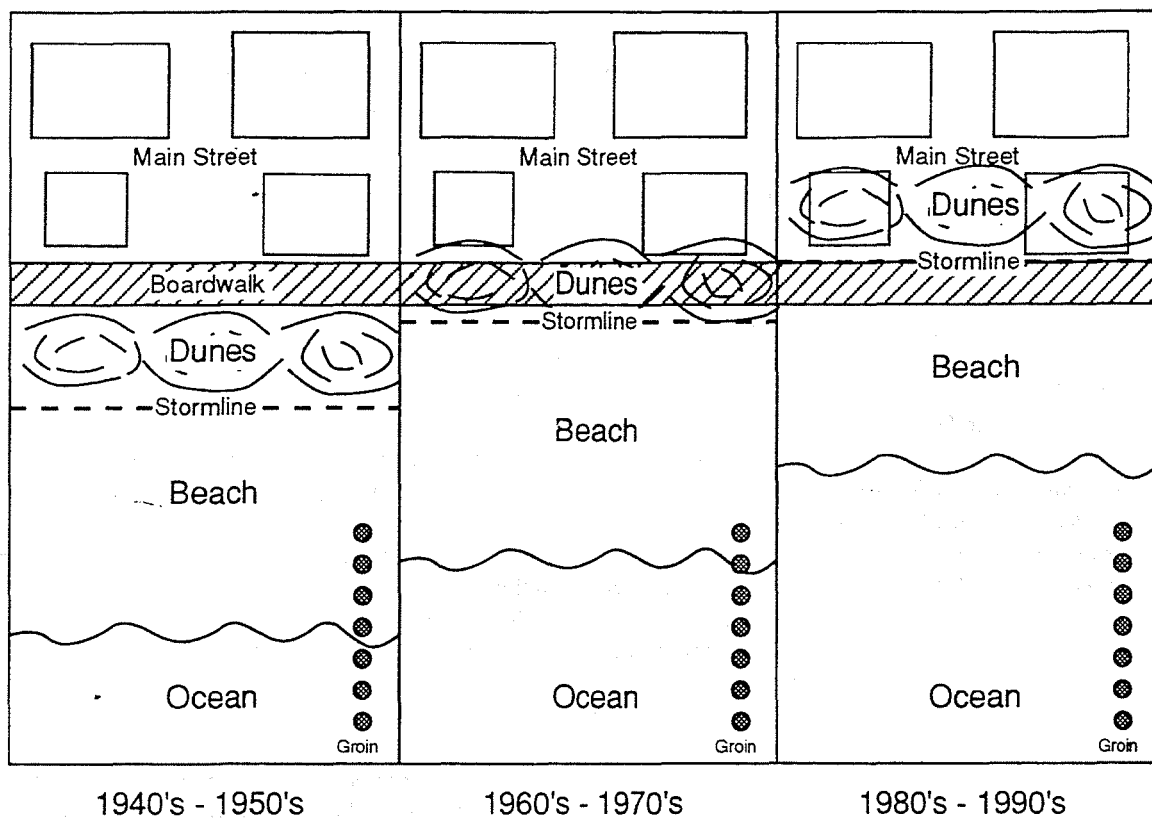


Figure 6. Landward migration of the dunes and stormline along urbanized coasts as the sea-level rises.

The effect of a hurricane path anywhere in the New York Bight, with its large coastal population density, would be overwhelming Wolff,(1992) and Coch,(1995). Though the erosion problems persist, the area

cannot be abandoned, and at, any expense, beach nourishment (without dunes) must continue--therefore, the coastal dilemma!

- 99.9 0.2 Return to Lido Beach Blvd. and turn left (west) into the City of Long Beach.
- 101.2 1.3 Lido Beach Blvd. becomes Park St.
- 104.9 3.7 Turn left 2 blocks after New York Ave. onto Pennsylvania Ave.
- 105.1 0.2 Turn right (west) onto Beech St.
- 107.2 2.1 Continue west on Beech St. and follow signs to Atlantic Beach Bridge.
- 107.7 0.5 Start over bridge - stay in right lane.
- 108.2 0.5 After toll booth - continue right onto ramp to overpass for Rockaway Beach (Sea Girt Blvd.)
- 109.9 1.7 Continue west on Sea Girt Blvd. until under the elevated railroad (El) and make a sharp left onto Rockaway Freeway.
- 110.0 0.1 After two blocks, turn left onto B35th St. and again pass under the El.
- 110.4 0.4 Go one block and turn right (head toward B36th St.); then turn left on B36th to dead end. (Walk out onto boardwalk and beach - then turn left (ea st) and walk to 32nd St. for bus pickup.)

STOP 6 - Edgemere Section of Rockaway Beach - beach dynamics and inlet sedimentation along a highly urbanized shoreline, Rockaway Peninsula, Queens County, New York.

Historical records show that the Rockaway Peninsula was largely pristine until the 1850's. In 1835, large areas were covered by cedar trees and sand ridges rising in places to altitudes of 25-30 feet above sea level. Urbanization, starting in the 1850's, was largely in the form of summer home developments. With the coming of the railroad in 1893, permanent communities became established. The increasing urbanization was to result in drastic changes in the morphology and hydrography of this area.

The Rockaway Peninsula, and the Coney Island barrier island to the east (Figure 7) are the most heavily urbanized and eroded hurricane - prone shorelines in the United States (Coch, 1995). The original dunes covering the Peninsula are long gone and the beaches have receded to such a degree that there is no longer any natural storm surge protection for the high-density structures along this shoreline. The major cause for this continual erosion has been the removal of sand from the longshore drift system by engineering structures and stabilized inlets in the areas to the east. This has deprived the beaches of Western Long Island of a sand supply sufficient to replace that lost to storms. In order to maintain this recreational area and protect the structures, the Army Corps of Engineers must replenish this stretch every 3-5 years.

Our stop will cover the shoreline area from Beach 37th to Beach 25th Streets. We hope to answer the following questions :: 1) how does beach morphology and sediment dynamics differ from that along more pristine shorelines? ; 2) how has this shoreline evolved and what does this imply for the future?; 3) What accounts for the exceptional rate of erosion along this coastal segment? and; 4) how have engineering structures affected sediment dynamics in the vicinity of East Rockaway Inlet.

The area we will be examining today has a history of severe erosion . It was replenished in 1995, when it was built out 140 feet from the boardwalk. By March of 1996 it had eroded back nearly to the boardwalk. Replenishment in June 1996 built the beach out 240 feet from the boardwalk. High waves associated with the passage of Hurricane Bertha in mid-July, 1996, has already caused a beach recession of 40 feet.

The Eastern Rockaway Peninsula has been the subject of a continuing investigation by Queens College students since March of 1996. Examination of the beach section in March of 1966 showed a most unusual stratigraphic section. Sedimentary structures included upper flow regime plane beds, well defined channels oriented in a number of directions and avalanche bedding. The sediments consisted of sand, gravel

and whole shells as well as shell fragments. However, as much as 5-30% of the section consisted of solid waste dating from the 19th Century. The debris included numerous rounded bricks, pieces of drainage pipe, pottery, plates bottles, personal items, animal bones and a few pieces of silverware and coins (Liogys et al, 1996).

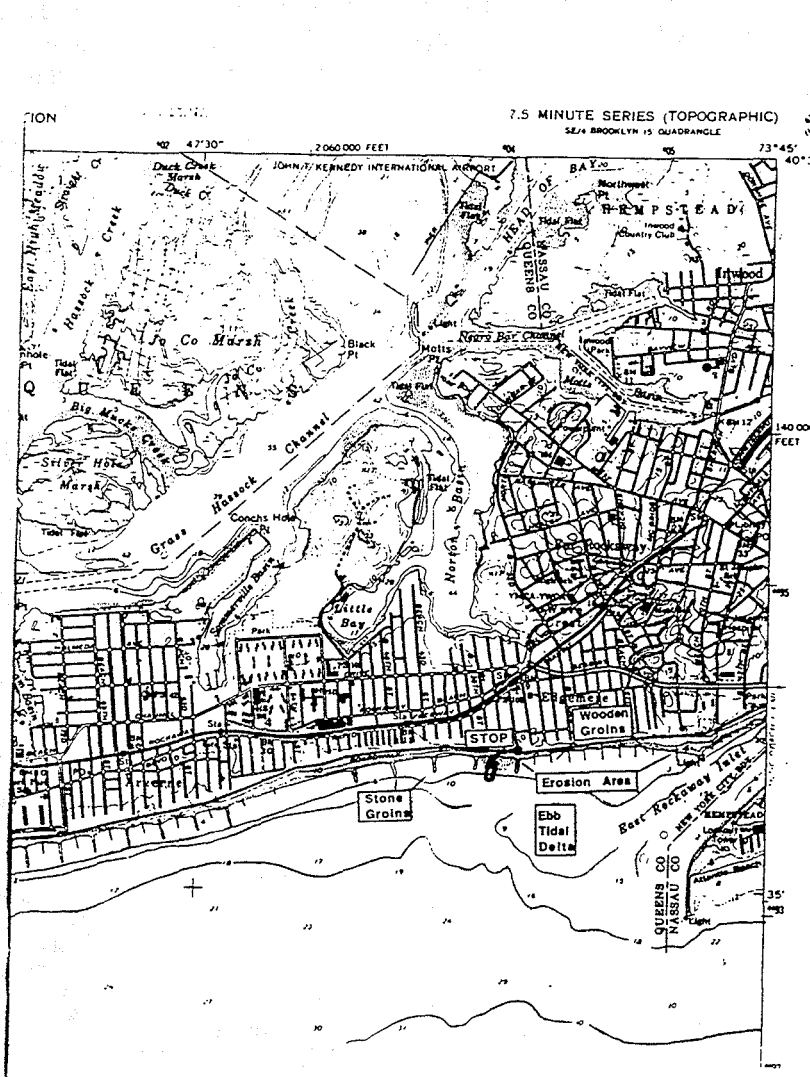


Figure 7. Topographic map of the features associated with Rockaway Inlet at Stop 6.

We considered two working hypotheses to explain this deposit. The dredging could have uncovered an old borrow pit into which solid waste was dumped in the 19th Century. Another possibility is that the debris was washed offshore in the ebb surge of a past hurricane.

Historical records synthesized by Fuqua (1996) indicate that a barrier island (Hog Island) existed 1,000 feet offshore of the Rockaway Peninsula in 1879. A number of recreational facilities existed on Hog Island at that time and they were reached by ferry and causeway from the Rockaway Peninsula. The New York Times of August 21, 1893 reported that a major storm completely inundated Hog Island and it was "the beginning of the end for the island". Later newspaper reports indicate that Hog Island disappeared completely in nor'easter storms in 1893-4. The major storm was probably the "Jamaica Bay Hurricane" of 1893. The eye of that Category 3 storm probably did not pass over Jamaica Bay but crossed the coast in what is now the western part of Nassau County (B. Jarvinen, 1996, personal communication). This would have put the

Rockaway area on the weaker, or left side, of that hurricane, so how can we explain the extraordinary coastal damage that was reported? The wave and surge levels reported were much higher than expected, because of the unique shoreline orientation and offshore bathymetry that occur in this region (Coch, 1994). The obliteration of structures on Hog Island would have provided debris that was washed onto the adjacent sea floor and covered by sand in the following decades. Dredging operations by the Army Corps of Engineers in 1995 (just south of the inferred position of Hog Island) returned this material to the land as part of the hydraulic fill used for beach replenishment. As you look around at the high rise buildings right on the boardwalk, think about the consequences of a major hurricane making landfall again in this highly urbanized area in the future.

Beach sedimentation in this area today consists of swash buildup of the beach face between storms as well as deflation of surface sands by southerly winds. The sand accumulates as drifts against the boardwalk. Some of the sand is blown under the boardwalk to form drifts against eroded vegetated dune remnants with incipient soil profiles. We will examine some of these dune remnants and discuss the inevitable consequence of "barrier rollover" in this area.

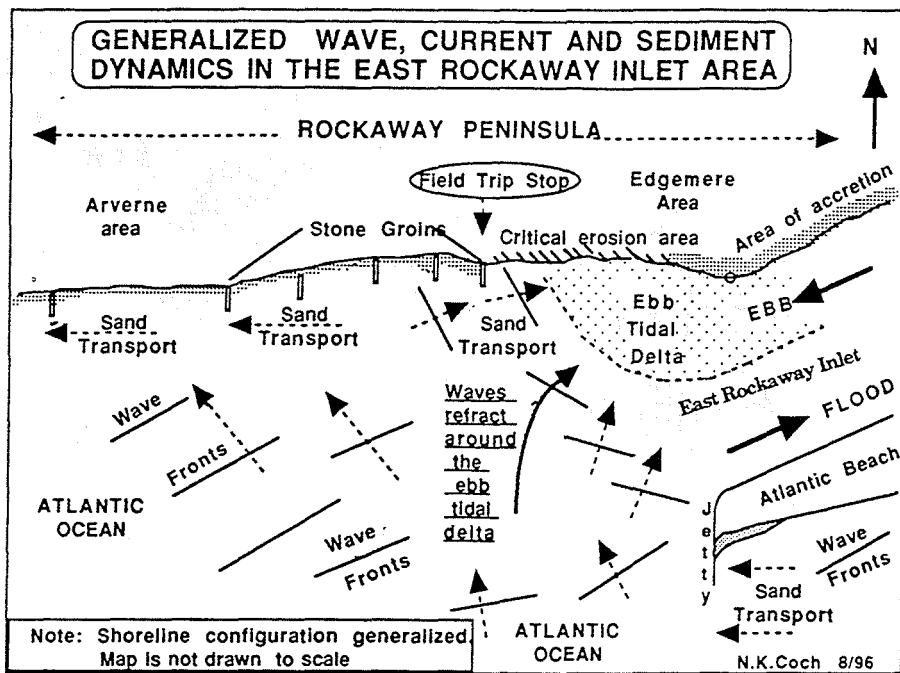


Figure 8. Generalized sediment and water dynamics map of Rockaway Inlet at Stop 6.

There are two sets of groins in the area (Figure 8). The older wooden groins were poorly maintained and are now largely destroyed. The newer stone groins function as effective sediment traps. The most easterly stone groin is at Beach 35th Street at our field trip stop.

A number of factors are responsible for the severe erosion in this area. Observations over several years suggest the following scenario for the water and sediment dynamics in the East Rockaway Inlet area. These dynamics are shown in generalized fashion in Figure 3. Sand moves in the predominant east to west drift toward the jetty at Atlantic Beach. Most of this sand is trapped against the jetty, but a portion is swept across the inlet area toward the Rockaways. Bathymetric contours (Figure 8) indicate shoals that suggest the presence of an ebb tidal delta on the north side of East Rockaway Inlet. Some of the sand moved across East Rockaway Inlet is transported by waves refracted around that ebb tidal delta, and moved towards the inlet. The last stone groin at Beach 35th Street traps some of that sand, but most moves past the area towards the inlet. This sand is deposited in the vicinity of the "light" (Figure 8) where the ebb currents block further penetration

into the inlet. This scenario accounts for the presence of a sand-starved section from Beach 35th to Beach 25th Streets and the severe erosion that occurs continually along that coastal segment.

ROAD LOG FOR THE RETURN TO THE COLLEGE OF STATEN ISLAND.

- 110.4 0.0 Return north on B32nd St. to Sea Girt Blvd. and again turn left.
110.6 0.2 Once beneath the El, again make a sharp left onto the Rockaway Freeway.
115.1 4.5 Continue west on the freeway, past the entrance to Jacob Riis Park, to the junction with Beach Channel Drive.
117.9 2.8 Continue west on Beach Channel Drive to the Marine Parkway Bridge - follow the signs to Brooklyn.
118.8 0.9 Once over the bridge (toll) continue northwest on Flatbush Ave.
120.4 1.6 Cross over the Belt Parkway overpass and continue west on Flatbush Ave.

125.2 4.8 Two blocks after Church St., turn left onto Caton Ave.
126.4 1.2 Continue west on Caton Ave. until it merges.
9 2.5 Follow Fort Hamilton Parkway over the Brooklyn- Queens Expressway (Rt. 278).
129.1 0.2 Turn left at 92nd St. for the spur road to the Expressway (Rt. 278).
131.5 2.4 Return on the Expressway, cross the Verrazano Bridge to the toll booths.
136.0 4.5 Follow Rt. 278 to Victory Blvd. and the return to the College of Staten Island (signs).
136.5 0.5 Return to the college parking lot.

ACKNOWLEDGEMENTS

The authors would like to thank Robert W. Johnson (Biology Dept.) for his field observations and familiarity with most of our stops, and J Bret Bennington (Geology Dept.) for his graphic computer software and expertise in improving our diagrams. Their assistance has immeasurably improved the quality of the article and field trip. Finally, N.Coch would like to thank B.Fuqua for her synthesizing of the historical data, and J.Healy, L.Kiefer and T. Liogys for their field measurements and sample collecting at Stop 6.

REFERENCES

- Bellot, A.H., 1917, History of the Rockaways, Bellot Publications Inc., New York, N.Y. 110 p.
Buttner, P.J.R., 1987, The barrier system of the south shore of Long Island, New York--a response to the expected sea-level rise., *Northeast. Environ. Sci.* v. 6, p.1-22.
Buttner, P.J.R., 1989, Shoreline dynamics of the eastern Jones Beach barrier island, New York: Phase I - Summary of monitoring data base, 1985-1989., *Northeast. Environ. Sci.* v.8, p. 135-173.
Coch, N.K., and Wolff, M.P., 1990, Probable effects of a storm like Hurricane Hugo on Long Island, New York., *Northeast. Environ. Sci.*, v.9, p. 33-47.
Coch, N.K., 1995, Hurricane hazards along the Northeastern Atlantic Coast of the United States, p.115-147, In: Finkel, C.(Ed.) *Coastal Hazards, - Perception, Susceptibility and Mitigation*, Journal of Coastal Research Spec. Public. 12, 372 pp.
Colony, R.J., 1932, Sources of the sand on the south shore of Long Island and the coast of New Jersey. *Jour. Sedim. Petrology*, v. 2, p.150-154.
Donner, J.J., 1964, Pleistocene geology of eastern Long Island, New York. *Amer. Jour. Sci.*, v.262, p.355-376.
Duane, D.B., Swift, D.J.P., & Pilkey, O., 1972, Linear shoals on the Atlantic inner continental shelf, Florida to Long Island., In: *Shelf Sediment Transport*, Dowden, Hutchinson & Ross Pub. Co., Stroudsburg, PA. p.447-498.
Fleming, W.L.S., 1935, Glacial geology of central Long Island. *Amer. Jour. Sci.* v. 30 #177, p.216-238.

- Fuller, M.L., 1914, Geology of Long Island, N.Y., USGS Prof. Paper 82, US Govt. Print. Office, Wash. D.C., 223 p.
- Fuqua, B., 1996, Evolution of the Rockaway Peninsula, Unpublished research report, Queens College, CUNY.
- Hanse, G., 1996, Emergency preparedness manager, Town of Babylon L.I. (personnel communication).
- Jarvinen, B., 1996, Research Meteorologist, Tropical Prediction Center/National Hurricane Center, Miami (personnel communication).
- Jensen, H.M. & Soren, J., 1974, Hydrology of Suffolk County, L.I. New York, USGS Hydrologic Invest. Atlas HA 501.
- Krinsley, D.H., Takahashi, T., Silberman, M.L. & Newman, W., 1964, Transportation of sand grains along the Atlantic shore of Long Island, N.Y.: An application of electron microscopy. *Marine Geology*, v. 2, p.100-120.
- Leatherman, S.P., 1981, (Ed.) Overwash Processes. Benchmark papers in Geology, v. 58, Huthinson-Ross Pub. Co., Stroudsburg, PA.
- Leatherman, S.P., 1982, Barrier Island Handbook, Coastal Public. Series, Univ. of Maryland, College Park, 92 p.
- Liogys, T., Healy, J and Kiefer, L. 1996, Sedimentation and beach erosion in the vicinity of Rockaway Inlet, N.Y., Unpublished research report, Queens College, CUNY.
- McCormick, C.L., 1973, Probable causes of shoreline recession and advance on the south shore of eastern Long Island. In: Coastal Geomorphology, D.R. Coates, (Ed.), Publicat. in Geomorphology, SUNY Binghamton, N.Y., p. 61-72.
- Milleman, J.D., & Emery, K.O., 1968, Sea levels during the past 35,000 years. *Science*, v. 62, 1121-1123.
- Panageotou, W. & Leatherman, S.P., 1986, Holocene-Pleistocene stratigraphy of the inner shelf off Fire Island, New York- implications for barrier island migration. *Jour. Sedim. Petrol.* v. 56, p. 528-537.
- Rampino, M.R. & Sanders, J.E., 1981, Evolution of the barrier islands of southern Long Island, N.Y., *Jour. of Sedimen.* v.28, p. 37-47.
- Sanders, J.E. & Kumar, N., 1975, Evidence of shoreface retreat and in-place "drowning" during Holocene submergence of barrier islands, continental shelf off Fire Island, N.Y., *Geol. Soc. Amer. Bull.* v. 86, p. 65-76.
- Sanders, J.E. & Merguerian, C.M., 1994, The glacial geology of New York City and vicinity. In: A.I. Benimoff, (Ed.) *The Geology of Staten Island, N.Y., Field Guide and Proceed., Geol. Assoc. of N.J.*, 296 p.
- Sirkin, L.A., 1982, Wisconsinan glaciation of Long Island, N.Y. to Block Island, Rhode Island, In: Larson, G. & Stone, B., (Eds.), *Late Wisconsinan Glaciation of New England*, Kendal/Hunt Publish. Co., Dubuque, IA., p. 35-59
- Sirkin, L.A., 1986, Pleistocene stratigraphy of Long Island, N.Y. In: Cadwell, D.H., (Ed.), *The Wisconsinan Stage of the First Geolog. District, eastern, N.Y., N.Y. State Museum Bull. #455*, p. 6-21., N.Y. State Geol. Survey, Albany, N.Y.
- Stamp, L.D., 1921, On cycles of sedimentation in the Eocene strata of the Anglo-Franco-Belgian basin. *Geol. Mag.*, v. 58, p.108-200.
- Swift, D.J.P., 1968, Coastal erosion and transgressive stratigraphy *Jour. Geol.*, v. 76, p. 444-456.
- Swift, D.J.P., 1976, Coastal Sedimentation, In: Stanley, D.J. & Swift, D.J.P., (Eds.), *Marine Sedimentation, Transport and Environmental Management*. John Wiley & Sons, N.Y. Pub., 602p.
- Swift, D.J.P., Duane, D.B., & McKinney, T., 1973, Ridge and swale topography of the Middle Atlantic bight, North America: secular response to the Holocene hydraulic regime., *Marine Geol.*, v. 15, p. 227-247.
- Taney, N.E., 1961, Littoral materials of the south shore of Long Island, N.Y., Tech. Memo. 129, U.S. Army Corps of Engrs., Beach Erosion Board, Wash. D.C., 62p.
- Williams, S.J., 1976, Geomorphology, shallow sub-bottom structures, and sediments of the Atlantic inner continental shelf off Long Island, N.Y., Coastal Engr. Resear. Center, Ft. Belvoir Va., Tech. Paper #76-2. 123 p.

- Williams, S.J., & Meisburger, E.P., 1987, Sand sources for the transgressive barrier coast of Long Island, N.Y. - evidence for landward transport of shelf sediments. In: Coastal Sedimentation, W.W. Division-Amer. Soc. of Civil Engrs., New Orleans, LA., v. 2, p. 1517-1532.
- Wolff, M.P., 1975a, Environmental Geology of Democrat Pt., Fire Island, N.Y., and its influence on adjacent barrier islands. In: M.P. Wolff (Ed.), N.Y. State Geol. Assoc. Guidebook, Public. N.Y. State Geol. Survey, Albany, N.Y., p.73-88.
- Wolff, M.P., 1975b, Natural and man-made erosional and depositional features associated with the stabilization of migrating barrier islands, Fire Island, N.Y., In: M.P. Wolff, (Ed.), N.Y. State Geol. Assoc. Guidebook, Public. N.Y. State Geol. Survey, Albany, N.Y., p. 213-258.
- Wolff, M.P., 1980, Fire Island, Long Island, N.Y., an example of an "unnatural" natural barrier island. N.E. Sect., Geol. Soc. Amer. Abst. w/Program, Philadel., PA., v.12, p. 90.
- Wolff, M.P., 1982, Evidence for onshore sand transfer along the south shore of Long Island, N.Y.--and its implications against the "Bruun Rule". N.E. Geol., v. 4, p. 10-16.
- Wolff, M.P., 1989, An environmental assessment of human interference on the natural processes affecting the barrier beaches of Long Island, N.Y., N.E. Environ. Sci., v. 8, p. 119-134.
- Wolff, M.P., 1992, (Ed.), Hurricane Preparedness Perspectives in an Urban Environment--Are we ready for the BIG ONE?, Hofstra Univ. Research Conf., Geol. Dept., 114 Hofstra Univ., Hempstead, N.Y., 142 p.
- Wolff, M.P., 1994, The role of the shoreface in providing beneficial effects from washovers, inlet breaches (as Little Pike's Inlet) and barrier island preservation through migration. In: Long Island Geolog. Ann. Mtg., Program w/Abstracts, Dept. Earth & Space Sci., SUNY Stony Brook, N.Y., p. 159-165.

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that proper record-keeping is essential for the integrity of the financial system and for the ability to detect and prevent fraud. The document outlines the various types of records that should be maintained, including receipts, invoices, and bank statements. It also discusses the importance of regular audits and the role of internal controls in ensuring the accuracy of the records.

The second part of the document focuses on the importance of transparency and accountability in financial reporting. It highlights the need for clear and concise reporting that provides a true and fair view of the organization's financial performance. The document discusses the various methods used to calculate financial ratios and the importance of comparing these ratios to industry benchmarks. It also emphasizes the need for regular communication with stakeholders and the importance of providing timely and accurate information.

The third part of the document discusses the importance of risk management in financial reporting. It highlights the various risks that can arise from financial reporting, including the risk of misstatement, the risk of fraud, and the risk of non-compliance. The document outlines the various methods used to identify and assess these risks and the importance of implementing effective risk management strategies. It also discusses the role of internal controls in mitigating these risks and the importance of regular monitoring and reporting.

STRATIGRAPHY AND HYDROGEOLOGY OF THE UPPER CRETACEOUS RARITAN, MAGOTHY, AND CHEESEQUAKE FORMATIONS, NEW JERSEY COASTAL PLAIN

PETER J. SUGARMAN
New Jersey Geological Survey
CN-427
Trenton, New Jersey 08625

INTRODUCTION

This field trip (Figure 1) examines some of the remaining pits exposing Cretaceous rocks in Middlesex County. Continuing rapid development of Middlesex County has led to the closure of many of the best geological exposures of the Cretaceous Raritan and Magothy Formations. Fortunately, many of these exposures have been documented and described in previous field guides including Owens and Sohl (1969), Owens et al. (1977), and Olsson (1987), and in geologic maps (Owens et al., 1995; Sugarman et al., 1995).

The stratigraphy of Cretaceous rocks in Middlesex County, New Jersey has been studied for well over a century. Early economic studies concentrated on the use of clay deposits for making earthen and stoneware pottery, and fire brick (e.g., Ries et al., 1904). Because small beds or lenses of clay were economically important, a stratigraphic terminology developed which often had local significance, but lacked criteria for regional correlation.

Later studies focused on the growing importance of these deposits as sources of ground-water (e.g., Barksdale et al., 1943). Ground-water supply and contamination studies continue to be the major focus of recent geologic and geohydrologic studies in the northern New Jersey Coastal Plain, in large part due to increasing ground-water withdrawals, declining water levels, and saltwater intrusion.

This trip will examine outcropping geology of the Cretaceous Raritan and Magothy Formations (Figure 2) to: 1) develop familiarity with the prominent members (or facies) within these formations; and 2) place these facies into a hydrostratigraphic framework. We will also examine the newly named Cheesequake Formation (Litwin et al., 1993).

STRATIGRAPHIC FRAMEWORK

The stratigraphic units listed below will be seen on this trip. Their distribution is shown on the South Amboy quadrangle (Sugarman et al., 1995).

Woodbury Formation

Dark-gray to olive black clayey silt with very fine quartz sand, finely micaceous, with occasional finely disseminated pyrite, lignite, and siderite. Bedding is massive to finely laminated, with alternating layers of very fine sand and clay-silt; typically burrowed. Glauconite sand makes up as much as 5 to 10 percent of the lower part of formation. Grades into the overlying Englishtown Formation. While the Woodbury is overall ~50 feet thick throughout its outcrop belt (Owens et al., 1995), it thins to less than 20 feet in the South Amboy quadrangle.

Wolfe (1976) used palynomorph assemblages, and Gohn (1992) ostracode assemblages, to assign an early Campanian age to the Woodbury. It was deposited in prodelta and inner-shelf environments.

Merchantville Formation

Highly bioturbated quartz-glaucanite sand and clayey quartz silt; thick- to massive-bedded. Layers of fossiliferous siderite concretions are abundant. The Merchantville is the basal transgressive bed of the unconformity-bounded coarsening upward sequence which includes the overlying Woodbury and Englishtown Formations. The contact with the Woodbury is gradational, and is arbitrarily drawn where glauconite sand is no longer a major sand constituent. The unit is thinnest in the north (~20 feet), and thickest in the Trenton area (~70 feet; Owens et al., 1995).

The contact with the underlying Cheesequake Formation is an irregular, burrowed, reworked interval approximately 3 - 4 feet thick, with siderite concretions concentrated near the lower part of the reworked bed. A photo of this contact, from the Oschwald Pit in the adjacent Keyport quadrangle, is shown in Litwin et al. (1993).

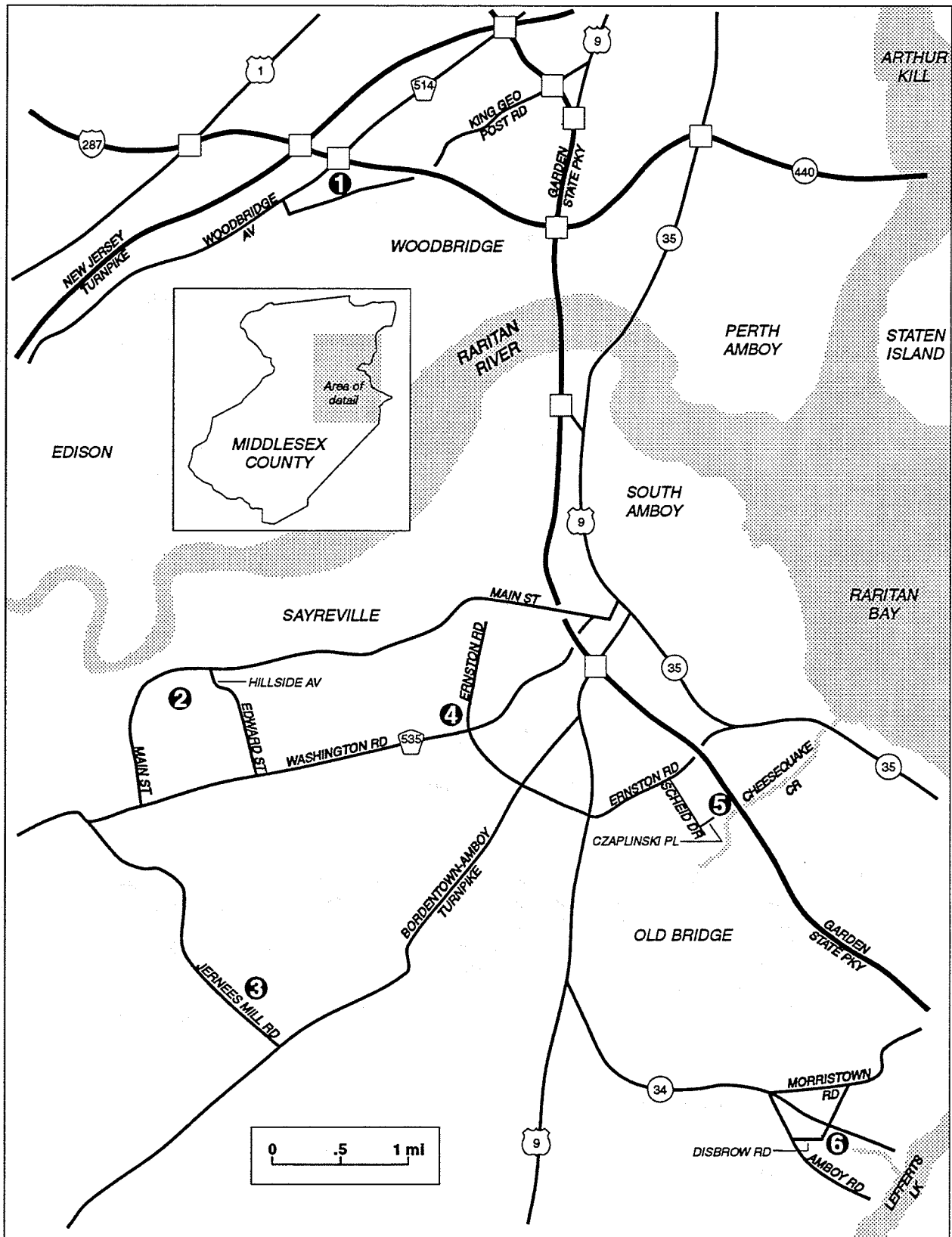


Figure 1. Sketch map showing field-trip route and stops.

The Merchantville is considered lower (but not lowermost) Campanian based on the ammonite *Scaphites hippocrepis* (DeKay) III and *Menabites (Delawarella) delawarensis* (Morton) (Cobban and Kennedy, 1992). It was deposited in a middle- to outer-shelf environment (Olsson, 1987).

Cheesequake Formation

Olive to dark-greenish-gray clay-silt, weathering to moderate brown; massive, burrowed (with lighter colored very fine to fine sand fillings), with mica (mostly clear, some green and brown) and lignite. Grades to olive-gray and dark yellowish-brown (moderate brown where weathered), silty, very fine to fine-quartz sand at top, generally laminated where not extensively burrowed. Very carbonaceous and micaceous, with glauconite (as much as 20%) typically in the basal few feet. Molds of gastropods and layers of large concretions (0.25-1 feet in diameter) are common in the base of the formation. The contact with the Magothy Formation is sharp and disconformable, and is marked by the change from cross-stratified sands and silts below to massive clays, occasionally laminated, with siderite concretions along the boundary.

The Cheesequake is well exposed south of Route 34 in the northwestern tributary of Lake Lefferts. Maximum exposures are 40 - 45 feet thick. Good exposures also occur just north of Route 34 in the southernmost tributaries of Cheesequake Creek. Because of a rapid change in facies in short distances, updip exposures (north of Route 34) generally lack glauconite sand, whereas downdip exposures (south of Route 34) typically contain glauconite sand in the clay-silt matrix. The Cheesequake has been previously placed in the upper Magothy (e.g., Owens et al., 1977; p. 98), and the lower Merchantville (e.g., Weller, 1907). In the subsurface, lack of recognition of the Cheesequake led some workers (e.g., Petters, 1976) to interpret the Magothy and Merchantville as interfingering in the subsurface.

The Cheesequake contains an uppermost Santonian to lowermost Campanian pollen assemblage in the outcrop and subsurface (Litwin et al., 1993). It is a marine unit, with the predominance of woody material and mica suggesting deposition in an inner shelf environment. Where bedding is not obliterated by burrowing, flasers also indicate a possible tidal flat environment.

Magothy Formation

Quartz sand, light colored, commonly interbedded with carbonaceous thin to thick, dark clays and silts. Sand is typically cross-stratified, although laminated sequences are also common. Heavy minerals are dominated by the zircon-tourmaline-rutile (ZTR) suite (Owens and Sohl, 1969). The Magothy contains many lithologies which have been mapped for their economic resources (for example Ries et al., 1904) and hydrologic properties (for example Barksdale et al., 1943). The application of deltaic facies models and palynostratigraphy by Wolfe and Pakiser (1971), Owens and Sohl (1969), Owens et al. (1977), and Christopher (1979) led to a more integrated chronostratigraphic framework for the Magothy and Raritan Formations. Usage follows that of Owens et al. (1977, 1995), and Sugarman et al. (1995) wherein the Magothy includes, from oldest to youngest, the following informal members: South Amboy Fire Clay, Old Bridge Sand, Amboy Stoneware Clay, Morgan beds, and Cliffwood beds. Pictures of the members can be found in Owens and Sohl (1969) and Owens et al. (1977). Although each of these members generally has some distinctive lithologic characteristics, rapid vertical and lateral facies changes complicates mapping; moreover, exposures are limited.

Overall, the Magothy Formation is interpreted as a series of delta-plain and delta-front deposits. This is supported by the abundance of lignite, and interbedded fossiliferous and nonfossiliferous strata (Owens and Gohn, 1985).

Cliffwood beds - quartz sand, light colored, fine to medium, some mica (clear and green), commonly cross-stratified; some horizontal bedding with local *Ophiomorpha* burrows; interbedded with thin dark micaceous and carbonaceous silt containing pyrite. Fossils, primarily crustaceans, in the siderite concretions at the base of the Cliffwood beds in Cliffwood Beach have been described by Weller (1907). The Cliffwood Beach type locality, described in Owens et al. (1977; p. 98), is no longer exposed. Best exposures are in gullies north of Route 34 in the southern section of Cheesequake Park. Maximum thickness of 25 feet. The Cliffwood beds represent delta-front deposits.

Morgan beds - laminated to thinly bedded clay, light to medium gray, typically carbonaceous, and interbedded light micaceous quartz sand. Sands massive or cross-bedded, yellowish-gray (weathered), and predominantly fine grained. Heavy minerals are dominated by ilmenite, leucoxene, and the mature ZTR suite; and to a lesser extent, the staurolite-sillimanite-kyanite (SSK) suite. Clay minerals are mostly kaolinite and illite. Excellent exposures are in the gullies and abandoned pits northwest of Melvins Creek.

Series	Stage	Formation	Member	Hydrogeologic Units	
Upper Cretaceous	Campanian	Woodbury		Merchantville -Woodbury Confining Bed	
		Merchantville			
		Cheesequake			
	Santonian	Magothy	Cliffwood Beds		
			Morgan Beds		
			Amboy Stoneware Clay		
			Old Bridge Sand	Upper PRM Aquifer	
			South Amboy Fire Clay		
	Cenomanian	Raritan	Woodbridge Clay	Confining Bed	
			Farrington Sand	Middle PRM Aquifer	
Potomac		Unit III			
Jurassic	Hettangian	Diabase		Bedrock Confining Bed	
Late Triassic	Rhaetian/ Norian	Passaic			

Figure 2. Stratigraphy (after Owens et al., 1995) and hydrogeologic units (after Zapecza, 1989) for the field trip.

and west of the Garden State Parkway. The Morgan beds are approximately 40 feet thick, and grade into an underlying clay. The Morgan beds are interpreted as tidal delta deposits (Olsson, 1987).

The Cliffwood and Morgan beds have been assigned to the *?Pseudoplicapollis cuneata-Semioculopollis verrucosa* Zone by Christopher (1979), which is equivalent to the upper part of Zone VII of Sirkin (1974). This *?Pseudoplicapollis cuneata-Semioculopollis verrucosa* Zone is considered Santonian to earliest Campanian.

Amboy Stoneware Clay Member - Clay-silt, dark gray to grayish-brown, weathering to white; carbonaceous and micaceous, with grayish-pink fine quartz sand laminae. Fine grained pyrite is commonly associated with the carbonaceous areas. Owens et al. (1977) note that certain beds had large pieces of lignitized logs, and small cylindrical burrows filled with light sand. The Amboy Stoneware is very variable in thickness along strike, in places massive, and appears to have been deposited in lensoidal channels. This unit is ~25 feet thick.

Christopher (1979) placed the South Amboy and upper part of the Old Bridge in his *Pseudoplicapollis longiannulata-Plicapollis incisa* zone, which he considered Coniacian (?) to early Santonian; this corresponds to the lower part of Sirkin's (1974) Zone VII. Sugarman et al. (1995) informally assigned Zone VI to the *Pseudoplicapollis longiannulata-Plicapollis incisa* zone, suggesting that the Amboy Stoneware disconformably overlies the Old Bridge Sand Member. Due to the presence of dinoflagellates in certain localities, the Amboy Stoneware is interpreted as a marginal marine deposit. It may represent an interdistributary bay deposit.

Old Bridge Sand Member- Quartz sand, light gray, weathered to shades of orange and pink, medium to coarse grained, rarely burrowed, with clear mica and sand sized lignite; extensively cross-bedded including trough and planar-tabular cross-bedding varying greatly in size; interbedded with thin- (laminae) to thick-bedded dark discontinuous carbonaceous clay beds as much as 3 feet thick. Heavy minerals include opaques (ilmenite and leucoxene) and nonopaques, dominated by the mature ZTR suite. Exposures of the Old Bridge are poor due to the loose, sandy nature of the beds. Barksdale et al. (1943) estimates a thickness of 80 - 110 feet for the Old Bridge sand, while Owens et al. (1995) gives its thickness in outcrop as 40 feet. This discrepancy may be due to the fact that Barksdale et al. (1943) uses both surface exposures and wells.

The Old Bridge Sand Member is interpreted as a lower delta-plain deposit. The cross-bedded sands are probably distributary channels; the lignitic fine-grained deposits are marsh, swamp, and flood-basin deposits (Owens and Gohn, 1985).

South Amboy Fire Clay - Clay, massive to finely laminated, locally dark gray, but typically oxidized to shades of white and red. Dominated by kaolinite and mixed layer clays (Owens et al., 1977). Contains lignitized, pyritic logs which commonly are flattened. Also contains small fragments of amber in places (Owens et al., 1977). The clay beds generally occur in channels, and are commonly adjacent to cross-bedded, fine to medium grained quartz sands with thin carbonaceous layers containing varisized lignitized material, including logs. Heavy minerals in the sands include opaques (ilmenite and leucoxene); nonopaques are dominated by the ZTR suite.

The South Amboy Fire Clay is the lowermost member of the Magothy. Maximum thickness is 35 feet (Owens et al., 1977). Christopher (1979) recognized a major break in the Normapolles and triporate pollen distribution at the base of this clay, whereas Wolfe and Pakiser (1971) regarded it as the upper member of the Raritan Formation. The South Amboy Fire Clay is assigned to pollen Zone V in this study. The paleoecology of the palynomorph assemblage suggests a coastal lowland swamp with nearby mesic coniferous stands and swampside angiosperms; some brackish water is suggested by a few species of *Baltispaeridium*. This supports the previous interpretation of deposition of the South Amboy clay in abandoned meandering river channels in a subaerial delta-plain (Owens and Sohl, 1969).

The South Amboy Fire Clay is assigned to the *Complexiopollis exigua-Santalacites minor* Zone (Christopher, 1979); this zone was formerly considered Turonian to Coniacian (Christopher, 1979) and later revised to post-Coniacian (Christopher, 1982).

Raritan Formation

The Raritan Formation includes two informal members: the Farrington Sand and the Woodbridge Clay. Owens et al. (1977) included (from oldest to youngest) the Raritan Fire Clay, Farrington Sand, Woodbridge Clay, and Sayreville Sand (of Barksdale et al., 1943) as informal members of the Raritan. The

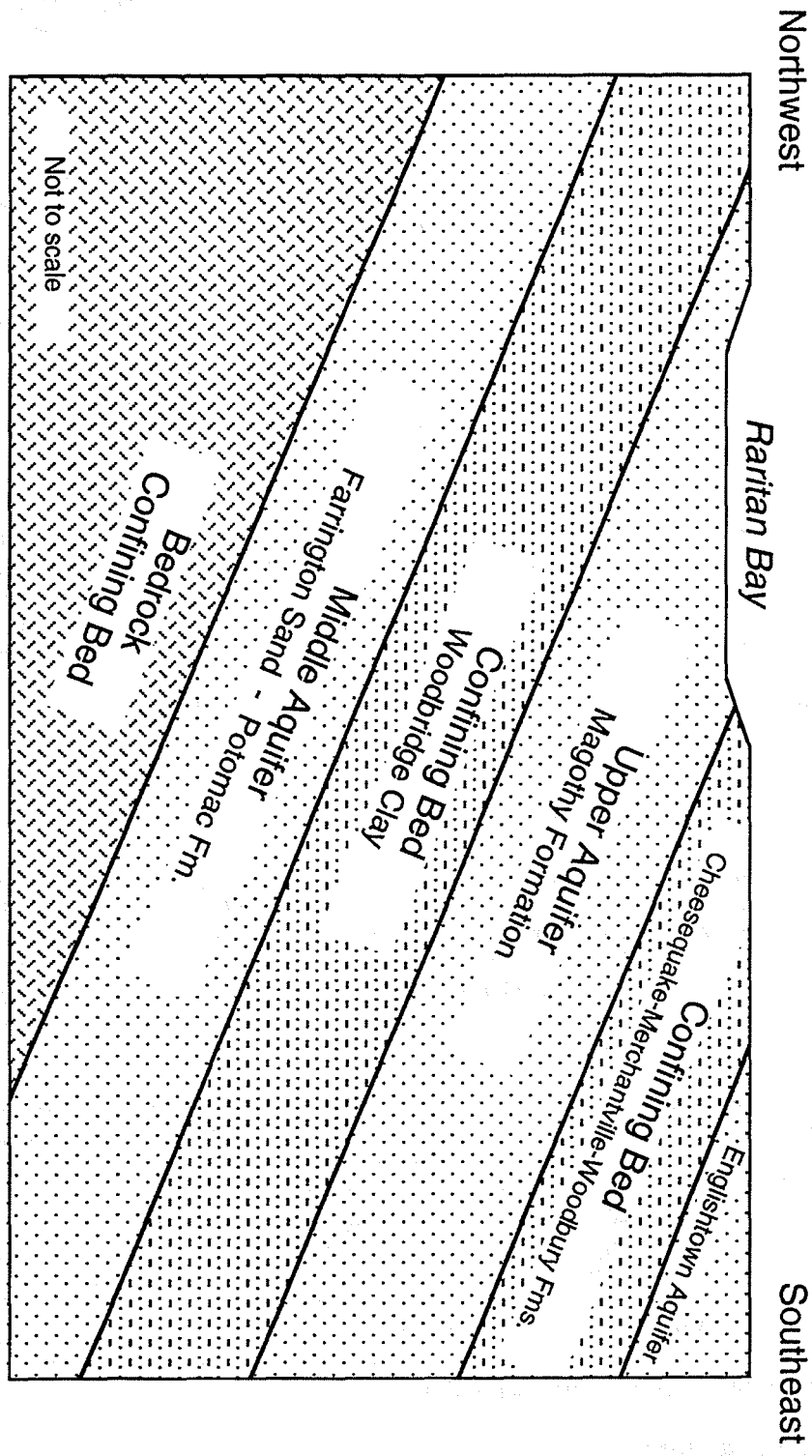


Figure 3. Generalized hydrostratigraphy of the Potomac-Raritan-Magothy aquifer system in the northern New Jersey Coastal Plain. The aquifer system is situated between the Bedrock confining bed and the Englishtown aquifer system. Hydrogeologic units are from Zapacza (1989). Geologic correlations are from Sugarman et al. (1995). Figure modified from Schaefer and Walker (1981).

Raritan Fire Clay, as described in Ries et al. (1904), may, in part, be a residuary clay formed from the decay of the shale, or the product of reworking and redeposition of material prior to the deposition of Cretaceous deposits. The Sayreville Sand was the "Feldspar"- "Kaolin" Sand Bed of Ries et al. (1904). Because the Sayreville is very discontinuous, irregular in thickness, and not recognizable over a large area, it is not mapped as a member of the Raritan anymore. The South Amboy Fire Clay includes a localized cross-bedded sand facies (see preceding discussion), and its limited exposures make it difficult to separate the Sayreville from the cross-bedded sand facies of the South Amboy. Consequently, all the beds above the Woodbridge Clay and below or immediately adjacent to the true clay in the South Amboy Fire Clay are included here in the South Amboy Fire Clay Member.

The contact of the South Amboy Fire Clay and the Woodbridge Clay is best exposed in the abandoned Sayre and Fisher Pit in Sayreville (Stop 2). There is ~25 feet of relief at the contact. The contact is marked by a thin (0.5-1 feet) bed of gravel and clay (white kaolinite) which consists of weathered ripup clasts. An ironstone layer typically overlies this bed.

Woodbridge Clay - Clay-silt, dark gray, massive, burrowed (*Callianassa* borings), with mica (clear, brown, and green), wood (typically fine grained), and pyrite. Occasionally interlaminated with light sand and dark clay-silt. Clay minerals are dominated by a kaolinite-illite assemblage (Owens et al., 1977). Small (less than 3 feet thick) beds and slabs of gray to brown siderite are common. Lignitized trees in growth position have been reported at the base of the Woodbridge in the Sayre and Fisher Pit (Owens and Sohl, 1969), where the best exposure of the Woodbridge remains (Stop 2). Fossil imprints occur near the middle and top of the formation in micaceous siderite sandstone concretions (Owens et al., 1977). Richards (1943) and Stephenson (1954) describe a diverse assemblage of mollusks from these concretions consisting predominantly of bivalves and gastropods. Stephenson (1954) correlates this fossiliferous layer with the Cenomanian Woodbine Formation of Texas. Recently, the upper Cenomanian ammonites *Metoicoceras bergquisti* and *Metengonoceras* sp. were collected from the Sayre and Fisher Pit (Cobban and Kennedy, 1990). The Woodbridge Clay is also the type for the Cenomanian Complexipollis-Atlantopollis assemblage Zone (Christopher, 1979), or Zone IV of Sirkin (1974). Dinoflagellate cysts, including *Cyclonephelium distinctum* and *Hystrichospheridium recurvatum*, occur in the Woodbridge (Sugarman et al., 1995).

The Woodbridge Clay deposit has been interpreted as a lowland swamp (for example, mangrove-type swamp, Owens and Sohl, 1969) with considerable marine influence; or an inner neritic shelf deposit (Sohl, in Owens et al., 1977), and the prodelta or inner neritic shelf deposits related to a delta system dominated by fine-grained sediment. It is 50 - 90 feet thick in outcrop (Owens et al., 1977).

Farrington Sand - Quartz sand, light, micaceous, commonly interbedded with thin gravel beds and thin to thick dark silt beds. It is interpreted as a meandering stream deposit. The Farrington rests unconformably on rocks of Mesozoic age. In the adjacent New Brunswick quadrangle, the Farrington overlies a weathered red clay, which grades downward into a red shale or siltstone of the Newark Group. Approximately 30-35 feet thick (Owens et al., 1995).

HYDROGEOLOGY

The Potomac-Raritan-Magothy aquifer system is the most productive ground-water resource in Middlesex County, accounting for 100 percent of ground-water withdrawals (Vowinkel, 1984). It has been extensively studied because of its importance to water supply. On this trip, we will focus on: 1) correlation of geologic formations and hydrogeologic units in the South Amboy quadrangle, and 2) physical characteristics and depositional environments of these hydrogeologic units.

Figure 3 is a generalized hydrostratigraphic framework for the northern New Jersey Coastal Plain and this trip. Hydrogeologic units are from Zapecza (1989), while geologic interpretations are based on the bedrock geologic map of the South Amboy quadrangle (Sugarman et al., 1995), the bedrock geologic map of the central New Jersey (Owens et al., 1995), and geologic relationships discussed in Barksdale et al. (1943).

Bedrock Confining Bed

The Middle aquifer of the Potomac-Raritan-Magothy aquifer system is confined in this area by the bedrock confining bed. The bedrock confining bed consists of several formations within the Newark Supergroup including the Stockton, Lockatong, and Passaic Formations, and diabase. In the subsurface to

the southeast, the bedrock confining bed consists of undifferentiated pre-Mesozoic crystalline and metamorphic rocks. The transition from Newark Basin Rocks to pre-Mesozoic rocks occurs approximately at South River. A layer of saprolite is common along the contact of this unit with the Middle aquifer; it may be several feet to tens of feet thick. Formations composing the bedrock confining bed will not be seen on this trip.

Middle Aquifer of the Potomac-Raritan-Magothy Aquifer System

The middle aquifer of the Potomac-Raritan-Magothy aquifer system is correlative with the Farrington Sand Member of the Raritan Formation (Pucci et al., 1989). Barksdale et al. (1958) reports transmissivities of 2,300 - 13,440 (feet squared per day), and hydraulic conductivities of 79 - 2000 (feet per day), for the middle aquifer in Parlin and Old Bridge, Middlesex County. In outcrop (e.g., Stop 1 of this trip), the Farrington Sand is an interbedded crossbedded, medium micaceous sand and dark gray, very woody clay-silt. It is typically 30 - 35 feet thick (Owens et al., 1995). Barksdale et al. (1943) describes the Farrington Sand as medium to fine-grained in the upper part, and coarse, arkosic, and pebbly in the lower part. Barksdale et al. (1943) reports the thickness of the Farrington Sand as 80 feet.

While the correlation of the middle aquifer exclusively with the Farrington Sand is correct in the shallow subsurface (down dip from the outcrop of the Farrington Sand), it is problematic in the deeper subsurface. For example, at the Freehold borehole (40° 15' 16", 74° 13' 51", ~17 miles down dip from Sayreville), the Middle aquifer is correlated only with the Potomac Unit III (Pucci and Owens, 1989). Clearly, somewhere between its outcrop and the Freehold borehole, the Farrington Sand is replaced by the Potomac Unit III as the main component of the middle aquifer. The Potomac Unit III is approximately 200 feet thick at the Freehold borehole. It is interpreted as an upper delta plain deposit.

Confining Bed Between the Middle and Upper Aquifers

The confining bed between the middle and upper aquifers is composed predominantly of the Woodbridge Clay. The Woodbridge Clay is the thickest (50-90 feet in outcrop) and most persistent clay in either the Raritan or Magothy Formations (Owens et al., 1977). Zapecza (1989) reports a maximum thickness of 150 feet down dip for the Woodbridge Clay. Farlekas (1979) reports a vertical hydraulic conductivity of 3.6×10^{-2} to 8.6×10^{-6} feet per day for the Woodbridge Clay from model results in the field trip area.

The upper part of confining bed below the upper aquifer may also contain the finer grained (clay-silt) facies of the South Amboy Fire Clay. The South Amboy Fire Clay is thinner (maximum 35 feet) and less widespread (due to rapid facies changes) than the Woodbridge Clay. As discussed above, the Magothy has channeled into the Woodbridge Clay. As described at Stop 2, there is a thin bed of gravel and clay (white kaolinite) which consists of weathered ripup clasts. Water flows into the pit on top of the surface of this contact. So while in places the South Amboy Fire Clay and the Woodbridge Clay form the confining bed between the middle and upper aquifers, water may be channeled along the base of the stratigraphic contact within the confining bed. As seen on Stop 2, the rapid facies changes in the South Amboy Fire Clay makes it a poor confining unit by itself.

Upper Aquifer of the Potomac-Raritan-Magothy Aquifer System

The upper aquifer coincides with the Magothy Formation (Zapecza, 1989). In and near the outcrop belt, the Upper Aquifer is considered correlative with the Old Bridge Sand. In fact, the aquifer has been termed the "Old Bridge" aquifer (Schaefer and Walker, 1981), because of its equivalence with the Old Bridge Sand Member of the Magothy Formation (Zapecza, 1989). The transmissivity ranges from 1,760 - 19,400 feet squared per day, while the lateral hydraulic conductivities are from 4 - 483 feet per day in the upper aquifer (Pucci et al., 1989).

The hydrogeologic and geologic relationships in the upper part of the Magothy Formation (Amboy Stoneware, Morgan Beds, Cliffwood Beds) are complex due to rapid vertical and lateral facies changes. This is characteristic for sediments deposited in an upper delta plain and delta front environment. This complexity is not really addressed in simple hydrogeologic correlations (e.g., aquifer, confining unit). For example, by placing the Amboy Stoneware, Morgan Beds, and Cliffwood Beds within the Merchantville-Woodbury confining unit, it is implied that the Morgan and Cliffwood are relatively impermeable units. As will be seen on this field trip (Stop 5), considerable interbeds of fine-grained quartz sand are present in the Morgan Beds. The Cliffwood beds (not seen on this trip) are typically fine to medium grained horizontally bedded to crossbedded sand (Owens et al., 1995).

Of importance to this problem is the thickness and continuity of the Amboy Stoneware Clay Member. The Amboy Stoneware Clay is approximately 25 feet thick, but tends to pinch out along strike.

An excellent example of this relationship used to be visible in the former South River Sand & Gravel Pit where a thin lense of the Amboy Stoneware is channeled into the underlying Old Bridge Sand. Where the Amboy Stoneware is present, it should behave as a confining unit. Where it is absent or thinned due to either beveling, nondeposition, or facies changes, and the Morgan and Cliffwood beds are juxtaposed on the Old Bridge Sand, there exists the possibility that sand beds in the Morgan and Cliffwood may be capable of transmitting water to the Old Bridge Formation through these gaps. Although there is a large percentage of sand in the Cliffwood and Morgan beds, the uniformly fine grained nature of the sand precludes large yields for the wells tapping it. Therefore it does not have significance as an aquifer, except possibly for domestic supply (Barksdale et al., 1943).

Merchantville-Woodbury Confining Bed

The Merchantville-Woodbury confining bed includes the Cheesequake, the Merchantville, and Woodbury Formations. It may also include all or parts of the Amboy Stoneware Clay, Morgan beds, and Cliffwood beds in its lower part, and clays in the lower portion of the Englishtown Formation in its upper part. Vertical hydraulic conductivities of this confining unit were estimated from model results at 4.3×10^{-6} feet per day for the Northern New Jersey Coastal Plain (Nichols, 1977). This extensive confining bed functions between the upper aquifer of the Potomac-Raritan-Magothy aquifer system and the Englishtown aquifer system (Zapeczka, 1989).

STRATIGRAPHY AND HYDROGEOLOGY OF THE UPPER CRETACEOUS RARITAN, MAGOTHY, AND CHEESEQUAKE FORMATIONS, NEW JERSEY COASTAL PLAIN

Road Log

Road Log (Fig. 1) starts at the New Jersey side of the Outerbridge Crossing (Route 440S).

0.0	0.0	Continue westward on Route 440S
3.3	3.3	Route 514W exit sign
0.6	3.9	Exit onto Route 514W (left exit)
0.5	4.4	Exit right lane for Raritan Center
0.2	4.6	Turn left on King George Post Road
0.6	5.2	Park at the Business Center at Edison, and cross road to gully.

STOP 1: Raritan Center, Edison Owner: Federal Business Centers.

In the drainage ditch on the Federal Business Centers, ~30 feet of the Raritan Formation are exposed. This formation is capped (at ~100 feet) by 5 feet of surficial material consisting of cross bedded sand and gravel. At this stop, the Raritan Formation consists of (from top down):

- 10 feet of interbedded black laminated to thin bedded clay.
- 10-15 feet of pale yellowish orange to grayish orange cross-bedded fine to coarse sand, occasionally micaceous.
- 10 feet massive black clay-silt; very lignitic, with pyrite, occasional 2 inch diameter siderite concretions, and interbedded fine sand.
- 1 foot of white, very clayey sand with possible burrows or roots. Contact of this white clayey sand and black clay above is irregular.

No marine fossils have been collected at this site. Pollen collected from black clays has been assigned to Pollen Zone IV of Sirkin (1974). This zone is equivalent with the Complexiopollis-Atlantopollis Assemblage Zone of Christopher (1979) which is predominantly middle to upper (?) Cenomanian.

Prior to recent industrial development, the Farrington Sand Member of the Raritan Formation was exposed across the road at lower elevations.

- 5-10 feet of an interbedded crossbedded, medium micaceous sand and dark gray, very woody clay-silt, which can be both massive and bedded. Interpreted as meandering stream deposit. Also

assigned to Pollen Zone IV. At the base of the pit (~20-30 feet elevation), the Farrington was in contact with a red shale and clay.

0	5.2	Turn around on King George Post Road
0.7	5.9	Turn right at first light
0.1	6.0	Turn right onto Route 514E
0.2	6.2	Bear right onto Route 440N
1.5	7.7	Exit onto Route 9S
3.8	11.5	Bear right and continue on Route 9S
1.7	13.2	Exit onto Ernston Road
0.1	13.3	Turn right onto Ernston Road West
1.1	14.4	Turn left onto Washington Street (Route 535S)
2.8	17.2	Turn right onto MacArthur Avenue
1.1	18.3	Turn left onto Main Street
0.4	18.7	Turn off on right side of road.

STOP 2: Abandoned Pit of the Sayre & Fisher Brick Company

Owner: K-Land Corporation #5

The Sayre & Fischer brick pit offers the best exposure of the Woodbridge Clay Member in New Jersey. It also contains the contact of the Raritan and Magothy Formations in the southeastern part of the pit. This stop has been previously described by Owens and Sohl (1969), Owens et al. (1977) and Olsson (1987, 1980). The Woodbridge Clay at the pit contains:

30-40 feet of black laminated silts and clays containing many layers of siderite- and iron-oxide-cemented sand. Laminations destroyed by burrowing in the top section. Fossil imprints occur near the middle and top of the Woodbridge Clay in micaceous siderite sandstone concretions (Owens et al., 1977). Pyrite and lignite are scattered throughout the Woodbridge.

5-6 feet of sand and clay containing wood (often in an upright position) were previously exposed at the base of the pit and are now below the upper level of the pond.

Richards (1943) and Stephenson (1954) describe a diverse assemblage of bivalves and gastropods. Stephenson (1954) correlates this fossiliferous layer with the Cenomanian Woodbine Formation of Texas. Sohl (in Owens et al., 1977) interprets this fossil bed to be the result of a winnowed storm deposit, placing an infaunal-dominated molluscan assemblage into a marginal marine environment. Recently, the upper Cenomanian ammonites *Metoicoceras bergquisti* and *Metengonoceras* sp. were collected from the Woodbridge Clay at this pit (Cobban and Kennedy, 1990). The Woodbridge Clay is also the type for the Cenomanian Complexipollis-Atlantopollis assemblage Zone (Christopher, 1979).

0	18.7	Turn left back on Main Street
0.4	19.1	Turn right onto MacArthur Ave
0.1	19.2	Continue straight on Jernee Mill Road
2.4	21.6	Turn left onto Bordentown Avenue
0.3	21.9	Turn right into the Sayreville Recreational Complex.

STOP 3: Sayreville Recreational Complex.

Owner: The Borough of Sayreville

The closing of the South River Sand and Gravel Pit (see Owens et al. 1977 for a description) several years ago eliminated the finest exposure of the Old Bridge Sand in New Jersey. This exposure of the Old Bridge Sand member of the Magothy Formation is a good (but slumped) outcrop showing a major sand channel in the Old Bridge Sand. To the east of this exposure is a graded, seeded bank which offers a partial view of the very carbonaceous, laminated clay-silt and fine sand which was better exposed at the South River Sand and Gravel Pit, and is a common facies of the Old Bridge. The Old Bridge Sand (and thin surficial cap) at this site consist of:

0-5 feet of light brown surficial sand and gravel. At the contact of the surficial unit and the Old Bridge Sand (~90 feet elevation) is an ironstone layer.

25 feet of medium (occasionally coarse) micaceous cross bedded sand. Cross-beds consist of small 2-3 inch troughs, sometimes with thin clay stringers, and occasional thin lignitic cross-lamina.

0	21.9	Turn left onto Bordentown Avenue
1.9	23.8	Turn left onto Cheesequake Road
1.3	25.1	Turn right onto South Minisink Avenue
0.3	25.4	Turn right onto Washington Road (535N)
1.2	25.6	Turn left into John F. Kennedy Park

STOP 4: John F. Kennedy Park - Lunch

The park is the site of an old pit where there used to be an excellent exposure of the South Amboy Fire Clay Member of the Magothy Formation. This member was described at this location by Owens et al. (1977; p. 96) as:

"...a tough, white, light -blue to gray or red-mottled clay. Locally it may be quite dark and contain some lignite...". "Sulfur-balls" (round, ball-like aggregates of pyrite, 1 to 4 inches in diameter) are found in many places, and disseminated pyrite is common throughout the unit. At some localities, small pieces of amber occur near the base of the South Amboy".

On the other side of Washington Avenue we passed the DuPont plant on the way to Kennedy Park. A split spoon well from the site, described below, gives thickness and description of strata outcropping at the park, as well as in the shallow subsurface.

DuPont Parlin FW-5 (Ground Elevation 107 ft; depths reported below land surface).

Pennsauken Formation (~40 feet thick)

5-7': Yellowish red poorly sorted fine -very coarse sand, some rock fragments, trace granules and clear mica, 1% opaques.

10-12': Reddish yellow (7.5 YR 6/6) gravel (maximum 3/4"), gravely sand, some silt, poorly sorted, with rock fragments and feldspar, 2% opaques.

15-17': Light brown (7.5 YR 6/4) gravel (maximum 1.25"), gravely sand, and some rock fragments, with more large gravel.

20-22' Light gray (10YR 7/2) sand, well sorted, mixed with sandy gravel.

25-27': Very pale brown (10YR 7/3) moderately sorted sand, mostly fine with some medium, trace mica.

30-32': Light reddish brown (5YR 6/3) sand, poorly sorted, mostly medium, trace of clear and green mica.

35-37': Reddish yellow (5YR 6/6) clayey gravely sand; gravel to 1" maximum.

Magothy Formation - Old Bridge Sand (~55 feet thick)=====

40-42': Light gray (10YR 7/2) sand, well sorted, fine, clear quartz, trace medium, some fine opaques.

45-47': Same as above.

50-52': Light gray sand, medium.

60-62': Light gray sand, medium, some fine and coarse, minor mica and carbonaceous material..

65-67': As above, medium to coarse, trace gravel to 1/4".

70-72': Light gray to light brownish gray coarse to very coarse sand, trace mica.

75-77': Sand, clayey, medium to -very coarse, with some 1/2" gravel, becoming light yellowish brown.

80-82': Sand, light gray, coarse, with occasional gravel.

85-87': Yellowish gray (5Y 7/2) to light brown (5YR 5/6) interbedded clay and fine to medium sand.

90-92': Light gray sand, medium to coarse, poorly sorted, with some mica.

Magothy Formation - South Amboy Fire Clay (~32 feet thick)=====

95-97': White (N9) - pinkish gray (5YR 8/1) sand, very fine to fine, trace silt.

100-102': Yellow gray to light brown sand, very fine to fine, laminated, trace silt.

105-107': Yellowish gray (5Y 7/2) silty fine sand, with mica.

110-112': Sand, silty, fine to medium, with some coarse to very coarse.

115-117': As above, various shades of orange (10YR 8/2, 8/6, 7/4).

120-122': Light gray (N7) silty sand, very fine, well sorted, 1% clear mica, trace lignite.

125-127': Medium dark gray laminated clay-silt, 5% fine sand, 1% pyrite, mica, trace lignite.

Raritan Formation - Woodbridge Clay (~100 feet thick)=====

130-132': Light to medium light gray clay-silt, some very fine to fine sand, with some elongated lignite pieces.

135-137': Medium-dark (N6-N3) gray, as above, with more clay, carbonaceous material, and mica.

140-142': Light gray (N7) silt, 1-2% very fine sand, 2% mica (white).

145-147': Light olive gray (5Y 6/1) very fine to fine sand, some silt, white mica, and trace of fine carbonaceous matter.

150-152': Light olive gray (5Y 6/1) laminated silt, with abundant finely disseminated mica and carbonaceous material, some siderite.

155-157': As above.

160-162': Grayish orange (10YR 7/4) sand, very fine-fine, with white mica and some carbonaceous material.

165-167': Light gray silty fine sand, mica and trace wood.

170-172': Dusky yellowish brown (10YR 2/2) clay with some very fine sand laminae, trace mica, with occasional thin siderite lenses.

175-177': Moderate brown weathered siderite stained clay-silt.

180-182': Dark to moderate yellowish brown (10YR 4/2 to 5/4) laminated clay/silt with very fine sand, 2-3% finely disseminated mica and carbonaceous material.

185-187': Light gray (N7) clayey silt, laminated (?), with finely disseminated mica and carbonaceous material.

195-197': Light gray silt, as above, less mica.

205-207': Light olive gray to olive gray (5Y 6/1-4/1) clay, some silt, trace mica; massive.

215-217': Medium dark gray (N4) carbonaceous clay, slightly micaceous.

220-222': Medium dark gray (N4) silty clay with some very fine to fine sand, 2% clear mica, 1% fine carbonaceous material.

Raritan Formation - Farrington Sand (minimum 13 feet thick)=====

227-240': Light gray sand, medium to very coarse, tr. lignite.

0	25.6	Turn left onto Washington Road
0.1	25.7	Turn right onto Ernston Road
1.1	26.8	Continue on Ernston Road past Route 9
0.8	27.6	Turn right onto Nathan Boulevard into La Mer.

STOP 5: Gully by Cheesequake Creek and Garden State Parkway

Owner: Kaplan Companies

The gully contains a complicated arrangement of facies generalized by Olsson (1987) as:

0-29 feet of "...dark gray sands and carbonaceous-rich clays, uniformly cross-bedded sands, intermixed flaser bedding, and layers of rip-up clasts." Sands are very micaceous.

16 feet of "...dark gray laminated clay, dark gray alternating sands and clays, and carbonaceous-rich layers".

0	27.6	Turn left onto Ernston Road
2.1	29.7	Turn right onto Route 9S
1.4	31.1	Exit left onto Route 34S
2.8	33.9	Pull over on right by creek.

STOP 6 Route 34 - Northwest tributary to Lake Leffert

Owner: Russ Weber

When initially entering the creek, the Merchantville and Woodbury Formations are exposed. They are gradational units, with no clear contact between them. Exposed in the northern part of the creek is:

0-5 feet of surficial gravel.

5 feet of massive to laminated slightly glauconitic clay-silt (Woodbury Formation).

2-3 feet of massive, burrowed clayey glauconite sand (Merchantville Formation).

Further down the creek, the contact of the Merchantville and Cheesequake Formations are exposed. The contact is irregular and burrowed with a 3 to 4 foot reworked zone, and siderite concretions along contact. Along the contact is a burrowed brown clay with dark green medium-to-course glauconite sand of the Merchantville Formation in the burrows.

The Cheesequake Formation is exposed in the southern part of the creek (tributary to Lake Leffert). Its total thickness is ~30 - 35 feet; descriptions are developed from composite sections. We will see the upper beds of the Cheesequake at this locality.

4 feet of pale to moderate to dark brown fine sand (lighter colors reflects more weathered sands), laminated with yellowish brown clay-silt, finely burrowed, with much fine dispersed mica (mostly clear) and lignite.

6 feet of massive olive-gray clay-silt with very fine sand, very micaceous and lignitic.

The lower beds down the creek and in gullies just to the north off Morristown Road are more fine grained and glauconitic:

10 feet of massive, dark greenish-gray clay-silt with very fine to fine sand, very lignitic and micaceous (clear, white, green, and brown - very fine to very coarse plates), and glauconitic (4-5%, mostly coarse and immature). Some delicate sand filled burrows are present.

1 foot of olive gray clay-silt, glauconitic (20%, fine to medium, botryoidal and accordion forms), with some very fine sand, very micaceous (mostly clear), and slightly lignitic. Contains 0.25-1 foot in diameter pale to grayish brown siderite concretions. At the base of the unit are clay filled burrows (0.5" diameter), occasional molds of gastropods, and siderite concretions (at basal contact with the Cliffwood Beds).

0 33.9 Turn onto 34N
2.8 36.7 Bear right onto Route 9N and return to Staten Island.

References

- Barksdale, H. C., Johnson, M. E., Schaefer, E. J., Baker, R. C., and DeBuchananne, G. D., 1943, The ground-water supplies of Middlesex County, N. J.: New Jersey State Water Supply Policy Comm. Spec. Report 8, 160 p.
- Barksdale, H. C., Greenman, D. W., Lang, S. M., Hilton, G. S., and Outlaw, D. E., 1958, Ground-water resources in the tri-state region adjacent to the lower Delaware River: New Jersey Department of Conservation and Economic Development Special Report 13, 190 p.
- Christopher, R. A., 1979, Normapolles and triporate pollen assemblages from the Raritan and Magothy Formations (Upper Cretaceous) of New Jersey: *Palynology*, v. 3, p. 73-121.
- Christopher, R. A., 1982, The occurrence of the *Complexiopollis-Atlantopollis* Zone (palynomorphs) in the Eagle Ford Group (Upper Cretaceous) of Texas: *Journal of Paleontology*, v. 56, p. 525-541.
- Cobban, W. A., and Kennedy, W. J., 1990, Upper Cenomanian ammonites from the Woodbridge Clay Member of the Raritan Formation in New Jersey: *Journal of Paleontology*, v. 64, p. 845-846.
- Cobban, W. A., and Kennedy, W. J., 1992, Campanian ammonites from the upper Cretaceous Gober Chalk of Lamar county, Texas: *Journal of Paleontology*, v. 66, p. 440-454.
- Doyle, J. A., 1969, Cretaceous angiosperm pollen of the Atlantic Coastal Plain and its evolutionary significance: *Harvard University Arnold Arboretum Journal*, v. 50, p. 1-35.
- Farlekas, G. M., 1979, Geohydrology and digital-simulation model of the Farrington aquifer in the northern Coastal Plain of New Jersey: U.S. Geological Survey Water-Resources Investigations Report 79-106, 55 p.
- Gohn, G. S., 1992, Preliminary ostracode biostratigraphy of subsurface Campanian and Maastrichtian sections of the New Jersey Coastal Plain, in Gohn, G. S., ed., *Proceedings of the 1988 U. S. Geological Survey Workshop on the geology and geohydrology of the Atlantic Coastal Plain*: U. S. Geological Survey Circular 1059, p. 15-21.

- Kennedy, W. J., and Cobban, W. A., 1994, Ammonite fauna from the Wenonah Formation (Upper Cretaceous) of New Jersey: *Journal of Paleontology*, v. 68, p. 95-110.
- Litwin, R. J., Sohl, N. F., Owens, J. P., and Sugarman, P. J., 1993, Palynological analysis of a newly recognized Upper Cretaceous marine unit at Cheesequake, New Jersey: *Palynology*, v. 17, p. 123-135.
- Nichols, W. D., 1977, Digital computer simulation model of the Englishtown aquifer in the northern Coastal Plain of New Jersey: U.S. Geological Survey Open-File Report 77-73, 101 p.
- Olsson, R. K., 1987, Cretaceous stratigraphy of the Atlantic Coastal Plain, Atlantic Highlands of New Jersey. Geological Society of America Centennial Field Guide-Northeastern Section, p. 87 - 90.
- Owens, J. P., and Sohl, N. F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, in Subitsky, S., ed., *Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions*: Rutgers University Press, New Brunswick, N. J., p. 235-278.
- Owens, J. P., Sohl, N. F., and Minard, J. P., 1977, A field guide to Cretaceous and lower Tertiary beds of the Raritan and Salisbury embayments, New Jersey, Delaware, and Maryland: American Association of Petroleum Geologists, 113 p.
- Owens, J. P., and Gohn, G. S., 1985, Depositional history of the Cretaceous Series in the U. S. Atlantic Coastal Plain: stratigraphy, paleoenvironments, and tectonic controls of sedimentation, in Poag, C. W., ed., *Geologic evolution of the United States Atlantic margin*: Van Nostrand Reinhold, New York, N. Y., p. 25-86.
- Owens, J. P., Sugarman, P. J., Sohl, N. F., Parker, R., Houghton, H. H., Volkert, R. V., Drake, A. A., and Omdorff, R. C., 1995a, Geologic map of New Jersey: Central Sheet: U.S. Geological Survey Open-File Report 95-253.
- Petters, S. W., 1976, Upper Cretaceous subsurface stratigraphy of Atlantic Coastal Plain of New Jersey: American Association of Petroleum Geologists Bulletin, v. 60, p. 87-107.
- Pucci, A. A., Gronberg, Jo Ann, and Pope, D. A., 1989, Hydraulic properties of the middle and upper aquifers of the Potomac-Raritan-Magothy aquifer system in the Northern Coastal Plain of New Jersey: N.J. Geological Survey Report 18, 74 p.
- Pucci, A. A., and Owens, J. P., 1989, Geochemical variations in a core of hydrogeologic units near Freehold, New Jersey: *Ground Water*, v. 27, p. 802 - 812.
- Richards, H. G., 1943, Fauna of the Raritan Formation of New Jersey: *Proceedings of the Academy of Natural Sciences of Philadelphia*, v. XCV, p. 15-32.
- Ries, Heinrich, Kummel, H. B., and Knapp, G. N., 1904, The clays and clay industry of New Jersey: New Jersey Geological Survey Final Report of the State Geologist, v. 6, 548 p.
- Schaefer, F. L., and Walker, R. L., 1981, Saltwater intrusion into the Old Bridge aquifer in the Keyport-Union Beach area of Monmouth County, New Jersey: U.S. Geological Survey Water-Supply Paper 2184, 21 p.
- Sirkin, L. A., 1974, Palynology and stratigraphy of Cretaceous strata in Long Island, New York, and Block Island, Rhode Island: U. S. Geological Survey Journal of Research, v. 2, p. 431-440.
- Stephenson, L. W., 1954, Additions to the fauna of the Raritan Formation (Cenomanian) of New Jersey: U. S. Geological Survey Professional Paper 264-B, p. 25-43.
- Sugarman, P. J., Stanford, S. D., Owens, J. P., and Brenner, G. L., 1995, Bedrock geologic map of the South Amboy quadrangle, Middlesex and Monmouth Counties, New Jersey: New Jersey Geological Survey Open-File Map.
- Vowinkel, E. F., 1984, Ground-water withdrawals from the Coastal Plain of New Jersey, 1956-80: U.S. Geological Survey Open-File Report 84-226, 32 p.
- Weller, Stuart, 1907, A report on the Cretaceous paleontology of New Jersey, based upon the stratigraphic studies of George N. Knapp: New Jersey Geol. Survey, Paleontology Series, 2 v., 1107 p.
- Wolfe, J. A., 1976, Stratigraphic distribution of some pollen types from the Campanian and lower Maestrichtian rocks (Upper Cretaceous) of the Middle Atlantic States: U. S. Geological Survey Professional Paper 977, 18 p., 4 pls.
- Wolfe, J. A., and Pakiser, H. M., 1971, Stratigraphic interpretation of some Cretaceous microfossil floras of the Middle Atlantic States: U. S. Geological Survey Professional Paper 750-B, p. B35-47.
- Zapeczka, O. S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p., 24 pls., scale 1: 500,000.

DEGLACIATION OF CENTRAL LONG ISLAND

LES SIRKIN

Earth Science
Adelphi University
Garden City, NY 11530

ABSTRACT

The moraines of Long Island were deposited during the late Wisconsinan Stage of the Pleistocene Epoch by the lobate margin of the Laurentide Glacier. This glacier advanced into the Long Island region twenty-two thousand years ago (22ka) and deposited the terminal moraine and the outwash plain to the south. Between 22ka and 20ka, the ice receded northward across Long Island, establishing at least two recessional positions. During each stand of the ice, recessional moraines were deposited, proglacial lakes developed between the ice and the moraines, and meltwater carved drainage channels southward across the outwash plain and laterally along the ice front. In central Long Island, these features, which can be identified by tracing the recession of the Connecticut Lobe of the glacier northward from the Ronkonkoma Moraine, the terminal moraine of this lobe, include the Connetquot-Nissequogue meltwater channel that drained north to south through outwash plains and proglacial lake basins, the Stony Brook Recessional Moraine, and finally the last recessional moraine, the Roanoke Point Recessional Moraine, along what is now the northeastern coast of Long Island, and draining of the proglacial lakes in the Long Island Sound basin. The glacial history of the region is the subject of Dr. Sirkin's books "Eastern Long Island Geology" and "Western Long Island Geology."

INTRODUCTION

In the context of geologic time-- over four and one half billion years-- the formation of Long Island is barely a footnote. It took only about two thousand years, between twenty-two thousand and twenty thousand years ago for glacial advance and deposition of the terminal moraine and deglaciation and deposition of the recessional moraines. From twelve thousand years ago to the present, sea level rise and coastal erosion have shaped the moraines and created the characteristic, fish-shaped Island geography. Consequently, the variety of glacial and postglacial features, ranging from ice-contact deposits to relict landforms is readily available for study. This geology is well represented and readily accessible in coastal bluffs and on the surface, and is easily seen from roadways, beaches and trails.

Field Trip Geology

The geology of western Long Island, as seen in its coastal bluffs, gravel pits, and excavations is characterized by glacial deposits and deformation and erosion of the two drift sheets. Exposures of these features allow us to examine the results of glacial and postglacial processes, in sections along the direction of ice advance, north to south, ice retreat, south to north, and across the grain of advancing glacial lobes, from west to east. The major stratigraphic units are the upper (younger) and lower (older) drift sheets, both of which contain tills, outwash and lake beds. They are distinguished first by their relative position, normally the younger, upper drift is superimposed over the older, lower drift. Color and texture are the next considerations: the older drift is fine-grained and in shades of gray; the younger drift is often coarser and more in yellow-brown hues. The colors depend on grain size and mineral content. The upper drift is rich in granitic rock debris owing to its northerly source areas in granitic terrane, and it has abundant till stones and erratics. In this context, "granitic" is used as an arbitrary category that includes rocks with similar color and mineral content, such as granite, granite gneiss, pegmatite and quartzite. The darker color of the lower drift may also be related to clay content.

The oldest sedimentary deposits in the region are beds of sand, clay and gravel of Cretaceous age, which may appear as masses of sediment thrust into the moraines by the last glacier. The Cretaceous clasts were moved by the glacier from the edge of the uptilted strata now submerged beneath Long Island Sound north of Long Island. Next, the lower drift unit is comprised of till, often a variety known as basal or lodgement till, deposited and compacted beneath the glacier. The lower drift may be in place where it was deposited, or as deformed masses of sediment, detached from the main body of drift and ice shoved. Blocks of this sediment have been ripped-up, thrust and engulfed in the outwash of the younger drift. Lake sediments in the lower drift include banded clays that appear as tightly-folded, thin-bedded sequences.

In the upper drift, outwash beds may slope away from the ice or may be folded, steeply inclined, and intercalated with thrust Cretaceous beds and lower drift. The most common, upper drift till is meltout till, which as the name implies has melted out of the ice. It may be partly washed by meltwater, but is still more or less unstratified. Meltout till may overlies outwash and may vary in thickness from several feet to thin layers of till stones. Till interbedded with outwash may be flow till, a variety that flowed in thin layers from the ice along with sand and gravel, or beds of lake clays homogenized by thrusting.

The outwash consists of lenses of sand and gravel coalesced into outwash plains, kames or crevasse fillings, deposited adjacent to or within the glacier by meltwater streams. Fan-shaped deposits of outwash along the ice margins are the heads of broad outwash plains like the main, late Wisconsinan outwash plain of southern Long Island. Some sand and clay layers are deposited from the ice into proglacial lakes to form kame deltas or in lakes away from the ice margin to form deltas. Due to glacial deformation, exposures of glacial deposits may vary in thickness and structure and may change in complexity as coastal erosion and slumping alter dimensions and form, even though the relative position of the beds remains the same.

Postglacial, wind-blown silt, called loess, is found in thick layers covering the glacial deposits. The loess can be a few feet thick and may contain old soil profiles, or paleosols, buried under recent sand dunes. Beach deposits, excluding flotsam, are the result of the interaction of coastal processes and the erosion of bluffs. On beaches that lie below bluffs, berms of coarse gravel, erratics, slump blocks with masses of sediment and vegetation, and slides of sediment from high up the cliffs are common. This eroding part of the coast is in the process of nourishing the beaches. The condition of beaches can also vary with the season or sequence of storms; sand won from the headlands may be pushed ashore by gentle summer waves; massive erosion of beach sand, dunes, and coastal structures usually follow a storm.

This overland trip reveals many surface features resulting from glacial deposition and erosion. The sediments at the surface are likely to be those of the upper drift. The terrain of glacial deposition, erosion, and recessional features, such as meltwater channels, proglacial lakes and ice-contact deposits, is as distinctive as the hummocky topography of the moraines. The moraines form an upland with a crest or ridge line and slopes-- the one facing the glacier is the proximal slope, the one facing away is the distal slope. In addition to these features, the landforms have also been modified by postglacial fluvial erosion and deposition and the formation and movement of sand dunes. These all combine to make the overland geology a fascinating complement to that encountered along the coasts.

FIELD TRIP I: DEGLACIATION OF CENTRAL LONG ISLAND

This trip covers the geology of a south to north transect through the sequence of late Wisconsinan glacial deposits--the Terminal Moraine, Recessional Moraines, Outwash Plains, Proglacial Lakes and a Prominent Meltwater Channel-- in central Long Island. The Connetquot River, which drains southcentral Long Island from north to south, and the Nissequogue River, which flows through northcentral Long Island from south to north, have nearly coalescing drainage basins in central Long Island (Figure 1). The route of this field trip crosses, from south to north, the USGS 7.5' Quadrangle Maps: Bay Shore East, Central Islip and Saint James. These two underfit rivers together cinch the waist of Long Island and reveal an intriguing stream valley system that originated as a late-glacial meltwater channel draining a series of proglacial lakes north of the terminal moraine, flowing through a gap in the moraine and across the outwash plain and continental shelf.

The trip straddles the arbitrary geographic boundary between eastern and western Long Island. Geologically, it is situated east of the late Wisconsinan Interlobate Zone between the Hudson and Connecticut glacial lobes in the vicinity of Huntington. The Interlobate Zone resulted in the complex of interlobate morainal deposits, meltwater channel gravels and proglacial lake, deltaic beds that make up the north-south range of hills: Manetto Hills, Half Hollow Hills and Dix Hills. The route of the field trip lines up roughly with the axis of the last interlobate angle between the receding glacial lobes and trends northward toward the interlobate angle formed at the inferred junction of the Sands Point Moraine of the Hudson Lobe and the Roanoke Point Moraine of the Connecticut Lobe projected beneath Smithtown Bay (Figure 2). The deposits were eroded by meltwater flowing

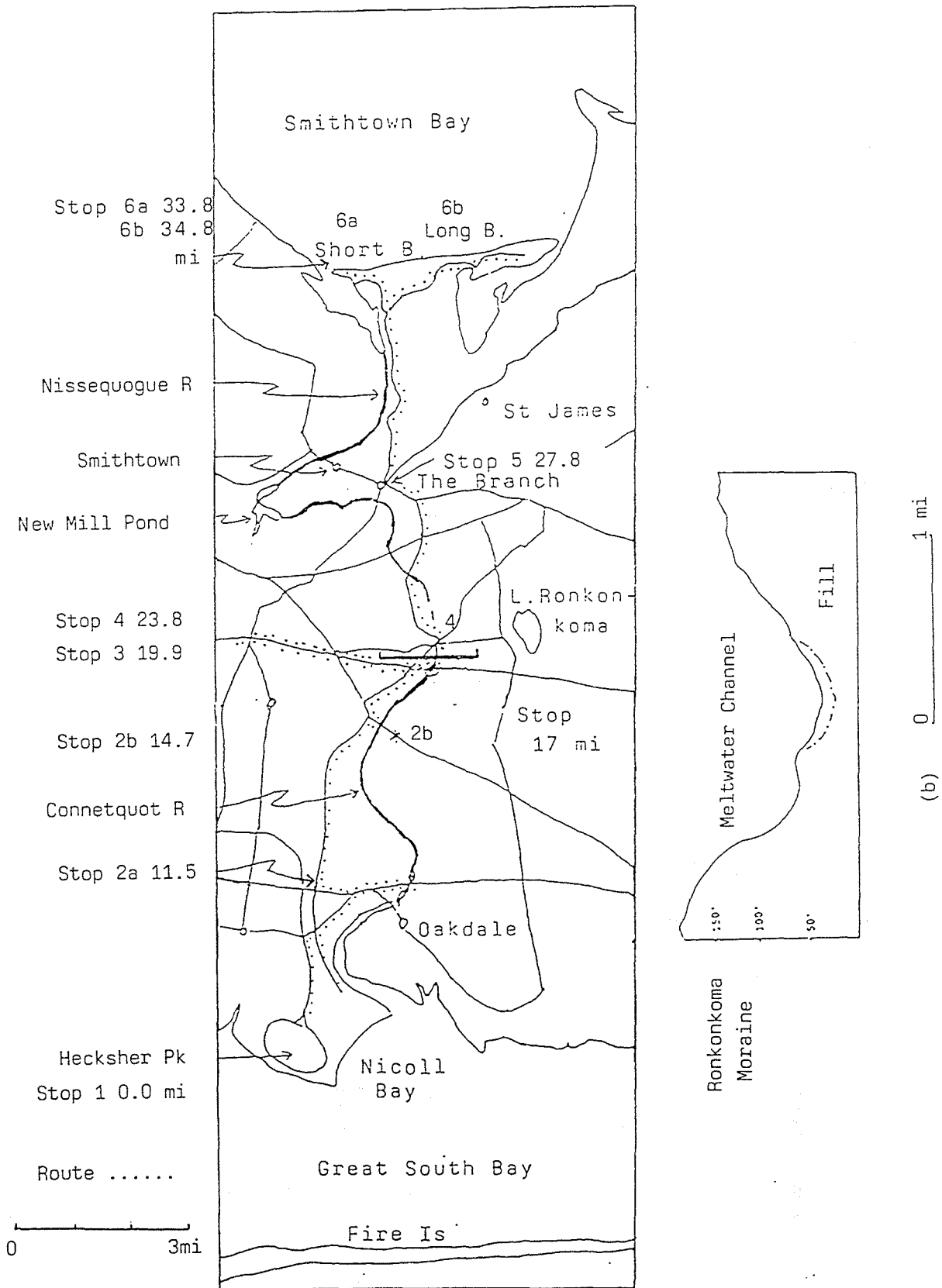
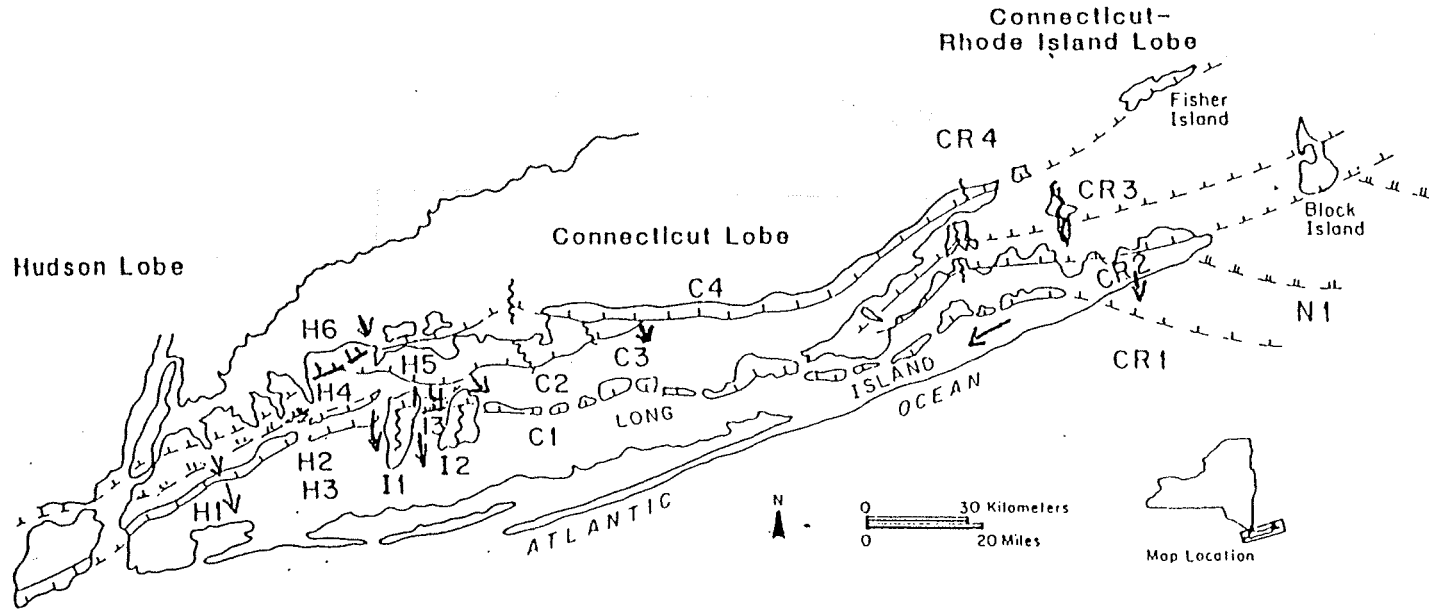


Figure 1. a) Route of Field Trip 1; b) Valley Profile (_____).

Figure 2. Long Island Moraine Map.



Map of Long Island glacial end and recessional moraines and the relative positions of glacial lobes, keyed as follows:

- H1 Harbor Hill Moraine
- H2 Jericho Moraine
- H3 Old Westbury Lobe
- H4 Oyster Bay Moraine
- H5 Northport Moraine
- H6 Sands Point Moraine

Interlobate Moraine

- I1 Manetto Hills Lobe
- I2 Dix Hills Lobe
- I3 South Huntington Lobe
- I4 High Hill Interlobate Moraine

Connecticut Lobe Ice Margins

- C1 Ronkonkoma Moraine - Shinnecock Moraine
- C2 Stony Brook Moraine
- C3 Mount Sinai Moraine
- C4 Roanoke Point Moraine

Connecticut Lobe and Eastern Connecticut - Western Rhode Island Ice Margins

- CR1 Amgansett Moraine
- CR2 Sebonack Neck - Noyack - Prospect Hill Moraine Envelope
- CR3 Robins Island - Shelter Island - Gardiners Island - Moraine Envelope
- CR4 Roanoke Point - Orient Point - Fishers Island Moraines

Narrugansett Lobe

- N1 Montauk Point (Altonian?)

southward from the proglacial lakes, the last is now Long Island Sound, and later submerged by the rising postglacial sea.

While the Connetquot and Nissequogue rivers seem to originate miles apart, as depicted on the topographic maps, their valleys begin on either side of a divide located near a broad gap in the Ronkonkoma Moraine, the terminal moraine, both at elevations of about sixty feet. They are separated by a tract of pitted outwash and meltwater channel deposits formed on residual ice. The two valleys have meandering stream patterns and are incised north and south of the gap into outwash and lacustrine deposits. If interpreted as a single meltwater channel that traversed the Island from north to south, the combined river valley reveals a broad meander pattern eroded into the glacial deposits that form its outside banks. The origin of this drainage is interpreted from the geomorphology and sedimentary deposits of this area.

Stop 1. 0.0 miles. The trip starts at the entrance to Heckscher State Park (Bay Shore East Quadrangle). Follow the roadway loop through the park for four and one-quarter miles.

0.0-5.6 miles. The late Wisconsinan outwash plain underlies the park, salt marshes and the bay to the south. A filled-in, crescent beach forms the south shore of the park. The Connetquot River estuary drains into Nicoll Bay over one mile to the northeast, but prior to Holocene submergence the river probably meandered to the southwest against the Heckscher shore. A few miles to the south, Fire Island forms the barrier beach that encloses Great South Bay.

5.6-5.7 miles. Turn right on Rt 27 and then right again on Great River Road. Great River Road follows the west bank on the outside curve of the southernmost meander of the river, beginning south of Sunrise Highway. The west bank is the steep side (outside) of the meander loop, and it rises about fifteen feet above the river. The topography of the river valley is somewhat obscured by development. Turn around near the golf course and proceed northward to Montauk Highway, Rt 27A.

7.9 miles. Turn right (east) on Rt 27A, essentially following the meander curve but well above the cut bank.

Note: the field trip follows the meanders of the meltwater channel valley in the direction of glacial recession and against the direction of late-glacial meltwater discharge. North of the terminal moraine, the meltwater channel meandered and lengthened as the ice front receded and tributary channels drained proglacial lakes.

9.4 miles. Junction with Sunrise Highway, Rt 27. Turn right (east) on Rt 27 and cross the Connetquot River valley near Lower Pond. The river has been dammed here to form Lower Pond and East Pond. The river bottom is partially hidden by development and highway ramps to the south. To the north, stands of trees and shrubs mask the ponds and the channel. At the next stop light turn left (west) on Rt 27. Proceed westward toward Connetquot Avenue.

Stop 2a. 11.5 miles. Turn right (north) on Connetquot Avenue. Stop where convenient to become oriented to the terrain. Note that while the river meanders are easily followed on the topographic map, extensive housing development hides the valley. The road follows the western margin of the Connetquot valley, passing the Bayard Cutting Arboretum and the Connetquot State Preserve (Central Islip Quadrangle). The Connetquot River, while gently meandering on its flood plain, has been dammed for mill ponds and a fish hatchery. A well defined, west-trending valley meander forms the river's reach and a low eroded bank in the outwash between the Long Island Railroad tracks and the village of North Great River. But it is against the easterly bend of the valley, located in the State Preserve to the south, that meltwater carved a twenty foot escarpment. The breadth of the valley meanders compared with the width of the Connetquot channel shows the river to be decidedly underfit in this segment. Evidently, a much more robust, meltwater-laden river established the meander pattern and shaped this much broader valley (Figure 1b). The fifty-foot contour line and the adjacent contour lines outline the valley morphology from meander to meander northward from the State Preserve to the Ronkonkoma Moraine.

14.5 miles. Connetquot Avenue turns right.

Alternate Stop 2b. Junction with Veterans Memorial Highway, Rt 454. Bear right on Rt 454 about 0.2 miles to sign: "Headwaters of Connetquot River." The valley can be entered from a gate east of the sign with permission from the State Park Preserve, as indicated. Turn back (northwest) on Rt 454.

15.2 miles. Turn right (northeast) on Nichols Road which crosses the outwash plain between the Ronkonkoma Moraine to the north and the rapidly narrowing river valley to the east (Figure 3a).

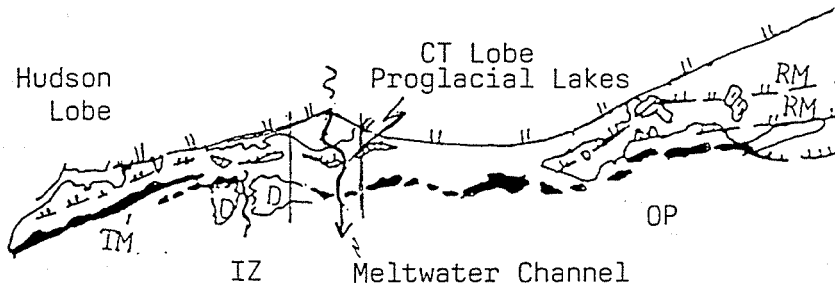
16.5 miles. The Long Island Expressway, Interchange 58. Enter the LIE, westbound ramp.

19.5 miles. Exit the LIE at Interchange 56. Turn left (south) on Rt. 111 for 0.2 miles.

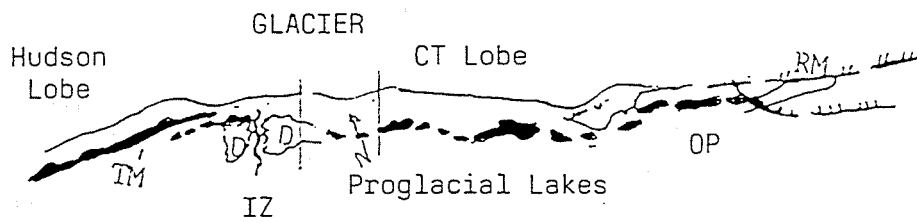
Stop 3. 19.9 miles. Turn right (west) on Central Avenue; proceed for 0.2 miles to sand pit in the Ronkonkoma Moraine. Walk to the west to the remnant exposure in the extensively mined and once two hundred foot high segment of the Ronkonkoma Moraine. Here about twenty feet of outwash is capped by a thin (two to four foot) layer of brown sandy and gravelly till. Erratics are scarce. The thin soil horizon (A?) at the top is formed on loess (Figure 4).

20.3 miles. Return to the LIE, eastbound.

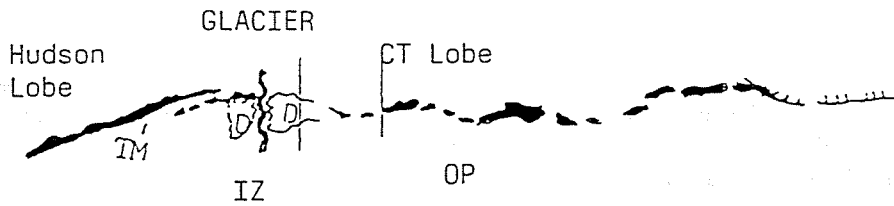
23.3 miles. Exit the LIE at Interchange 58. Turn left (north) on Nichols Road.



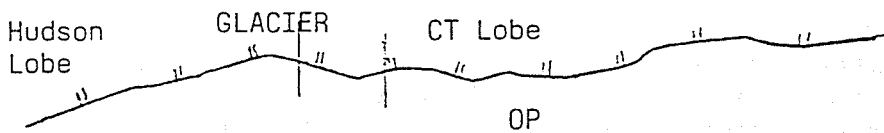
d) Sands Point, Roanoke Point Ice Margin, ca 20 ka



c) Oyster Bay, Northport, Stony Brook, Mt Sinai Ice Margin

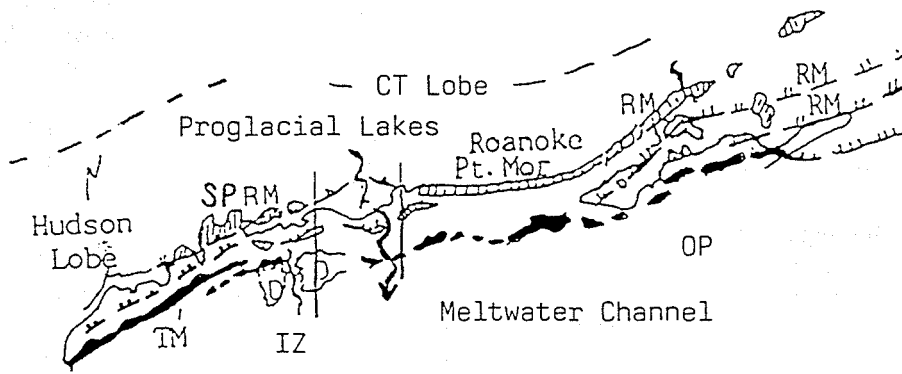


b) Late Wisconsinan Terminal Moraine

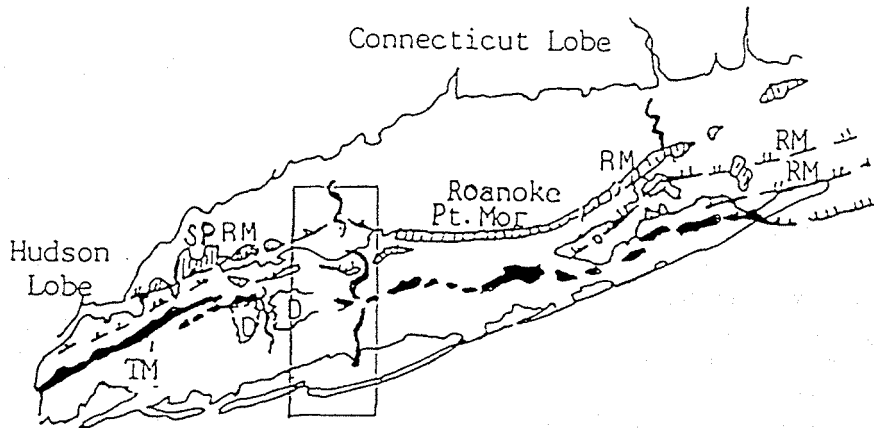


a) Late Wisconsinan Ice Margin, ca 22 ka

Figure 3 a-f. Moraines, Ice Margins, and Proglacial Lakes in Central Long Island.



e) Sands Point, Roanoke Point Recessional Moraines, ca 20 ka

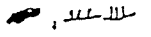
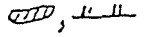



f) Long Island Moraine Map

Legend:

IZ-
 {- Interlobate zone; D: Delta

0 50 mi

TM: Terminal Moraine 
 RM: Recessional Moraine 

 FIELD TRIP AREA

OP: Outwash Plain

Figure 3 a-f. Continued.

Stop 4. 23.8 miles. Roughly where Nichols Road, Terry Road and Vanderbilt Motor Parkway converge in a triangular intersection, about 0.4 miles north of the Long Island Expressway, Rt 495, the headwaters of the Connetquot River drainage are now buried under the roadways. The watershed begins in a significant gap in the Ronkonkoma Moraine. Stop, if traffic allows, as near the gap as possible, even though roads and residential development obscure the view. The late-glacial meltwater channel was incised through the moraine as meltwater carved an easterly meander sixty feet above present sea level (Figure 1b). In a short excursion to the east, Vanderbilt Motor Parkway ascends the Ronkonkoma Moraine (Figure 3a and b). To the west, the Parkway crosses the gap and climbs the meander-scarred moraine--although not easily seen due to the highly suburbanized character of the terrain.

23.9 miles. Turn left (northwest) on Terry Road. The road goes up a hill that follows the meander scar. The evidence of meander erosion shows that meltwater flowed at this higher elevation during the interval of valley widening. Upstream, the valley turns sharply from the northwest against the steep proximal slope of the moraine, incised by a seventy foot-high meander scar.

The northern half of this meltwater-formed meander has become, in the context of the modern drainage, the headwaters of the north-flowing Nissequogue River drainage, a region of wetlands and ponds within the fifty-foot contour line. The river valley casts two broad meanders over the relatively flat basin enclosed by the Ronkonkoma Moraine to the south and the recessional moraines of the last glaciation to the north--the Stony Brook Moraine to the northeast and the Northport Moraine to the northwest). These moraines may be recessional moraines of the Connecticut and Hudson lobes of the glacier, respectively, or segments of the moraine of a sublobe of the ice front that formed between the main lobes at this stage of glacial recession (Figure 3c and d). This lowland, characterized by meanders incised into a plain of low relief, wetlands and pitted outwash, is underlain by lake clays deposited on the floor of a proglacial lake formed between the terminal moraine and the ice front during deglaciation. Continue northward on Terry Road from the intersection.

24.9 miles. Intersection with Town Line Road. Terry Road enters hummocky, stream-dissected and kamic topography north of the Ronkonkoma Moraine.

25.9 miles. Intersection with and merge left into Smithtown Blvd.

26.4 miles. Intersection with Rt 347, Nesconset-Port Jefferson Highway.

26.8 miles. Note the exposure of a dissected kame or outwash fan on the east side of Terry Road.

27.0 miles. Another possible dissected kame or outwash fan can be seen on the north side of the junction of Terry Road and Rt 25, Middle Country Road. Eroding sand and gravel forms the slopes.

27.2 miles. Intersection with Middle Country Road, Rt 25. Turn left (west) on Rt 25.

Stop 5. 27.8 miles. Junction of Rt 25 with Rt 111, Rt 25A and Nissequogue Road in the village of The Branch, just east of Smithtown. Stop where convenient to consult the topographic map (Central Islip Quadrangle), get your bearings, and consider these features. Terry Road and this segment of Rt 25 follow the edge of a proglacial lake basin that formed between the Ronkonkoma Moraine and the receding ice front during the late Wisconsinan. The roads curve against the meander-cut valley wall. The underfit channel of the Northeast Branch of the Nissequogue River first wanders northward through (former) wetlands before making a broad northward curve.

The channel is divided into several small ponds formed from dammed-up stream segments. It then heads westward, south of Smithtown, to New Mill Pond, also the result of a dam, and then turns northward across the flat channel bottom and flood plain deposits where the valley narrows significantly. While clearly seen on the topographic map, the channel is obscured on the east side by housing, office buildings and a shopping center. The poor drainage on the proglacial lake-bottom clay beds, cf. the Smithtown Clay, of late Wisconsinan age, serves as a reminder of the geologic history of this lowland. Emerging from the lake basin southwest of Smithtown, the valley turns northeastward. The narrow river channel is incised into the outwash with high banks on either side. The river can be seen south of and parallel to Rt 25, west of the Rt 25-Rt 25A fork, west of Smithtown, where it flows northeastward through a young hardwood forest established on the flood plain. It then crosses Rt 25 just east of the Rt 25-Rt 25A fork, about one mile west of the Rt 111 intersection.

The narrow valley persists through a broad eastward meander north of Smithtown where the meltwater channel cut through the recessional moraine. The modern Nissequogue River actually meanders in a confined belt on its own marsh-covered flood plain, but through steep valley walls of the meltwater channel up to one hundred feet high. The river becomes tidal near Mill Creek, and tidal flats cover channel deposits northward to the river mouth. Where the Nissequogue River enters Smithtown Bay, it is restricted by sand bars from both the east and west sides. On the east side, a northwest-hooking spit, Short Beach, indicates the dominant direction of littoral drift. The spit has forced the river outlet to bend further westward; the west sand spit has, in turn, confined the westward discharge.

A proglacial lake basin extends to the northeast and underlies much of the Saint James region. This basin drained, in part, to the southwest via narrow channels into the Nissequogue meltwater channel in the Village of the Branch and Smithtown, and eroded the interfluvies into narrow ridges. One such ridge was described by Fuller

(1914) as an esker which bordered a driftless area [i.e. the proglacial lake bed of the current model] and was somehow seen as evidence of the greater age of that terrain.

27.9 miles. Immediately after crossing the intersection take the left fork, Nissequogue River Road, and proceed northward (Saint James Quadrangle). Pass the old cemetery on the right.

Within a short distance, the road rises onto the distal slope of the recessional moraine, the Stony Brook Moraine. The river lies near the interlobate angle, but Nissequogue River Road and adjoining roadways cut through successive, washboard ridges and swales of the Stony Brook Moraine for over three miles between here and the north shore. This segment of the Stony Brook Moraine is typically hummocky and has a number of kettles. The east-west washboard texture is probably the result of stillstands of the ice front during recession and postglacial channel deepening.

30.1-30.4 miles. A good view of the river to the west (left) and the eroding roadcut in the moraine on the east (right) side. Merge with River Road.

30.8 miles. Views of Nissequogue tidal estuary to west.

32.4 miles. River Road intersects Moriches Road.

Route to Stop 6a. Northwest to Short Beach. Bear left into Horse Race Lane, and then Boney Lane at 32.9 miles.

33.6 miles. The road descends the kame moraine to the level of the salt marsh, and then enters Smithtown Short Beach.

Stop 6a. 33.8 miles. Park and walk to the beach. Consider the variety of coastal landforms. To the southwest, a bluff has been cut into the moraine by coastal processes. To the northeast, you can see the topography of the Roanoke Point Recessional Moraine forming distant bluffs on the Old Field headland. The successive ridges of this eroded westernmost extension of the moraine are apparent from this perspective. Try to imagine the confluence of the Roanoke Point and Sands Point moraines to the north in what is now Smithtown Bay in late-glacial time before the deposits were erased by meltwater streams and later by coastal currents. To the east, large erratics in the Bay are a reminder of the continuing erosion of the moraine and recent increments of sea level rise. Today, bay currents are dominantly east to west along this beach.

From the parking lot follow the dune ridge westward to the river edge and the boat ramp.

34.0 miles. Here you can observe the estuary and the meanders of the meltwater channel valley south of the Short Beach spit. The Nissequogue River estuary, the drowned and silting mouth of the north-flowing river, is confined by two sand bars. Short Beach trends east to west and then northwest on the east side and forces the river to the northwest; the opposing Sunken Meadow Beach on the west side channels Sunken Meadow Creek eastward parallel to the bar and into the estuary.

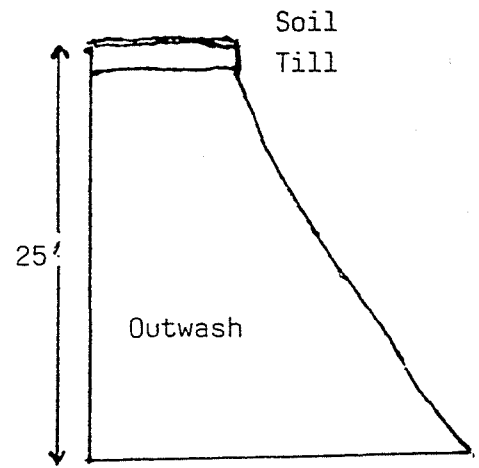
Route to Stop 6b. Northeast to Long Beach.

32.4 miles. Right on Moriches Road.

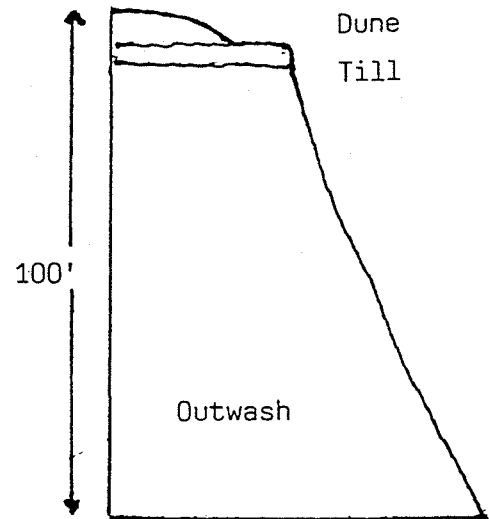
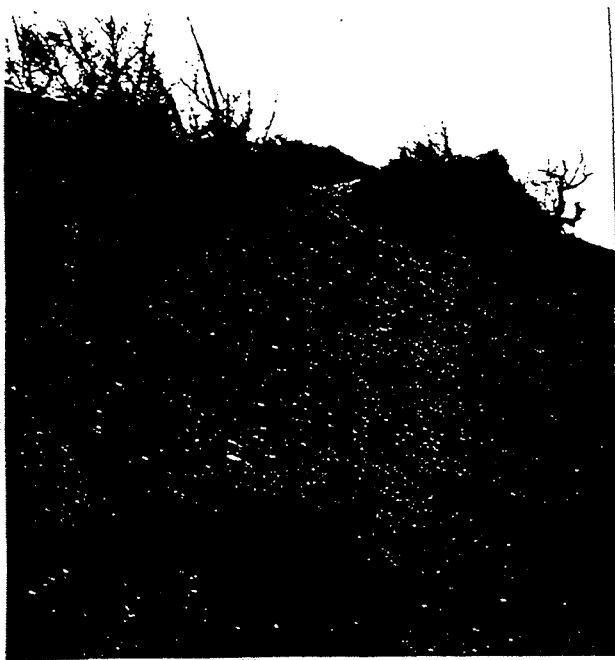
32.9 miles. Left on Long Beach Road. Long Beach Road cuts northeasterly across the last prominent ridge of the Stony Brook Moraine.

Stop 6b. 34.8 miles. The eroded edge of the moraine, at the base of Long Beach, reveals a 100' high bluff with an exposure of thin (2-4 ft), sandy meltout till over outwash, capped by 5-10 ft high sand dunes (Figure 4).

Stop 6b. 34.8-36.3 miles. Long Beach. Stony Brook Harbor, the mouth of a north-trending stream valley cut into the Stony Brook Moraine, is diverted eastward through Porpoise Channel by the one and one half mile long, Long Beach sand bar. This estuary is also silting in. On the east side of Smithtown Bay, Long Beach forms a narrow inlet along with West Meadow Beach, a spit that trends southward along the Setauket coast from the distal margin of the Roanoke Point Moraine at Old Field to the northeast. The Roanoke Point Moraine forms the headland in a series of washboard ridges. As mentioned, the geographic extension of the trends of the Roanoke Point Moraine from the east and the Sands Point Moraine from the west meets in an interlobate angle near the northcentral margin of Smithtown Bay (Figure 3d-f).



a) Ronkonkoma Moraine, Islip.



b) Stony Brook Moraine, Long Beach

Figure 4. Stratigraphy and Cross Sections of the Terminal and Recessional Moraines.

Additional Readings:

Sirkin, L. A., and Mills, H., 1975, Wisconsinan glacial stratigraphy and structure of northwestern Long Island: New York State Geological Association Guidebook 47th Annual Meeting, p. 299-327.

Sirkin, L. 1982, Wisconsinan glaciation of Long Island, New York, to Block Island, Rhode Island. In Stone, B. and Larson G., eds., Late Wisconsinan Glaciation of New England: Dubuque, Kendall/Hunt, p. 35-59.

Sirkin, L., 1986, Pleistocene stratigraphy of Long Island, New York. In Cadwell, D. H., ed., Glacial Stratigraphy of New York State: New York State Museum Bulletin 455, p. 6-21.

Sirkin, L. A., 1987, Palynology and stratigraphy of Cretaceous and Pleistocene sediments on Long Island, New York: U. S. Geological Survey Bulletin 1559, 44p.

Sirkin, Les, 1990, Stratigraphy of the Long Island Platform. In Gayes, P., and others, eds., Long Island Sound: Postglacial evolution and sea level changes: a symposium volume in honor of Walter S. Newman. Journal of Coastal Research Special Issue #10, p. 217-227.

Sirkin, Les, 1995, Eastern Long Island Geology. Watch Hill: The Book and Tackle Shop, 220p.

and cited:

Fuller, M. L., 1914, The Geology of Long Island, New York. U.S. Geological Survey Professional Paper 82. 231p.

Faint, illegible text at the top of the page, possibly a header or introductory paragraph.

Main body of faint, illegible text, appearing to be several lines of a document.

Lower section of faint, illegible text, possibly a conclusion or a separate paragraph.

Highlights of Staten Island Geology

Alan I. Benimoff and Anderson A. Ohan

Department of Applied Sciences

The College of Staten Island

Staten Island, NY 10314

Introduction

Since the 1975 NYSGA field trip on *Staten Island* (see Ohan et al. 1975) there have been many contributions to the geology of Staten Island. Staten Island geology (see figures 1 and 2) is very diverse, consisting of Cambro-Ordovician serpentinite, Jurassic diabase, Newark Group sedimentary rocks, Cretaceous and Pleistocene sediments. In addition, there are numerous wetlands, stream drainage basins and the world's largest landfill. Staten Island has an interesting plate tectonic history as John McPhee notes in his 1993 book entitled *Assembling California* "Southeastern Staten Island is a piece of Europe glued to an ophiolite from the northwest Iapetus floor". The aim of this trip is to give highlights of the geology of Staten Island.

The Staten Island Serpentinite

The Staten Island Serpentinite is a lens shaped, NE-SW trending body, having a dimension of approximately 55 Km and occupies a ridge located in the Northeastern section of Staten Island, reaching an elevation of approximately 135 meters above sea level.

This Serpentinite body is part of a string of similar ultramafic bodies, extending throughout the Appalachian, from Alabama to Newfoundland. The Serpentinite displays a sheared fault contact with the Cambro Ordovician Hartland Formation along its Eastern margin (Little and Epstein 1987) and is unconformably overlain by the Triassic aged Stockton Formation of the Newark Super Group at the western margin. In places, the western contact is faulted. The Southern and Eastern margins of the serpentinite is overlain by the Raritan Formation of Cretaceous age. Pleistocene glacial deposits overly the serpentinite in numerous localities.

In Cross-Section the Serpentinite body is a wedge-shaped pod, extending downward approximately 1.3 kilometers (Yersak, 1977). The Serpentinite is situated on Cameron's line at the base of the Hartland formation (Little and Epstein, 1987).

Hollick (1909) suggested that the Staten Island serpentinite is a fault-bounded horst-block, Crosby (1914) Miller, (1970), Merguerian and Sanders, (1994) share that interpretation. A petrographic study of the Serpentinite was accomplished by Behm (1954). He concluded that the serpentinite body can be subdivided into two major zones as follows:

A Central Zone termed a massive porphyritic serpentinitized peridotite composed of porphyritic enstatite-bastite and olivine in a matrix of antigorite, serphophite and olivine. Magnetite, picotite, anthophyllite, talc and chrysotile occur as accessory minerals. The serpentinite is foliated with antigorite representing the essential foliation-producing mineral. The degree of serpentinitization is variable.

A border zone characterized by a massive talcose serpentinitized peridotite. Serpentinization is more extensive when compared with the central zone, and displays a distinctive increase in talc, anthophyllite, and magnetite. Talc and anthophyllite schists occur in a number of localities. Shearing is pronounced and veins of silica and carbonates are common.

Okulewicz (1979) reported that the serpentinite protolith was hartzburgite, consisting essentially of olivine (90%), enstatite (6%) and magnetite (3%). Some serpentinitized dunites exist in the northern part of this body. Serpentinization occurred under greenschist facies conditions. The most abundant serpentine mineral is lizardite, with chrysotile present as fracture fillings and in veins. Chrysotile shows a small but variable concentration throughout the serpentine body. Benimoff et al. (1992a) reported on a Ni-Cr rich splintery antigorite whereby they analyzed it using **High Resolution Transmission Electron Microscopy**.

Serpentinization produced up to 32% volume increase through the hydration of enstatite and olivine. Tensional stresses were generated producing the existing fault system in the serpentinite

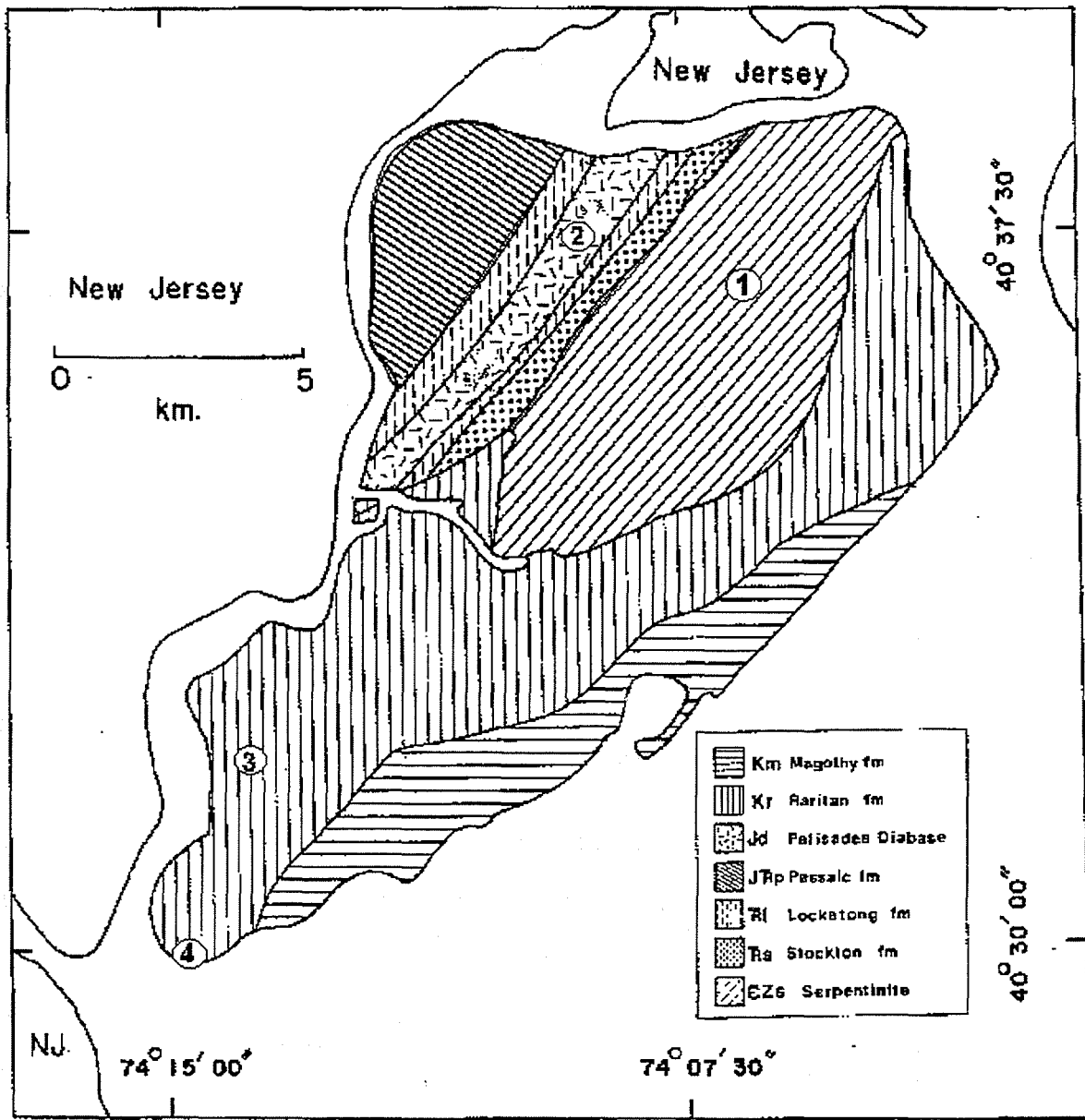


Figure 1. Geologic bedrock map of Staten Island, New York modified from Lyttle and Epstein, (1987). Field trip stops are indicated by numbers.

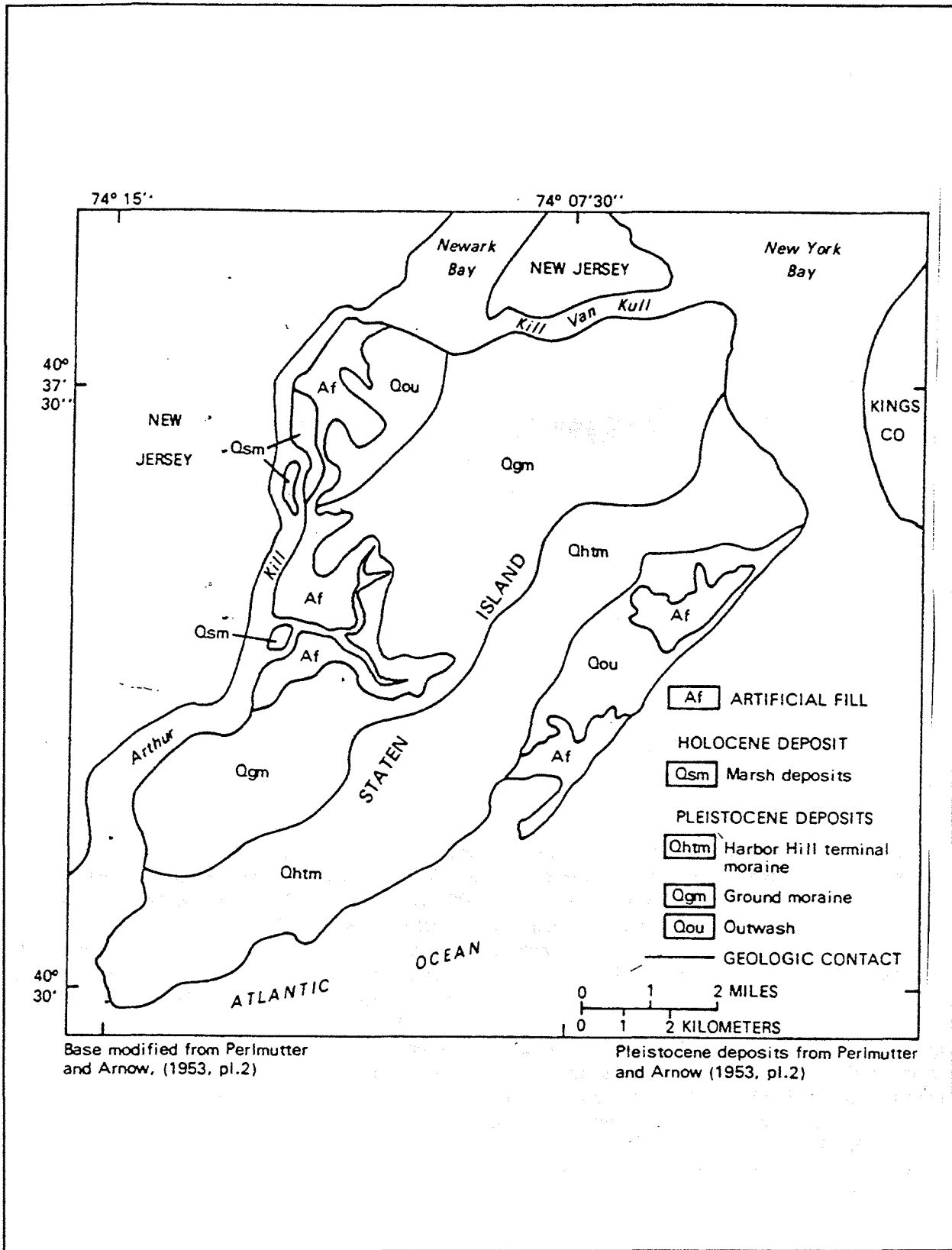


Figure 2. Surficial geologic map of Staten Island, New York (from Soren, 1988)

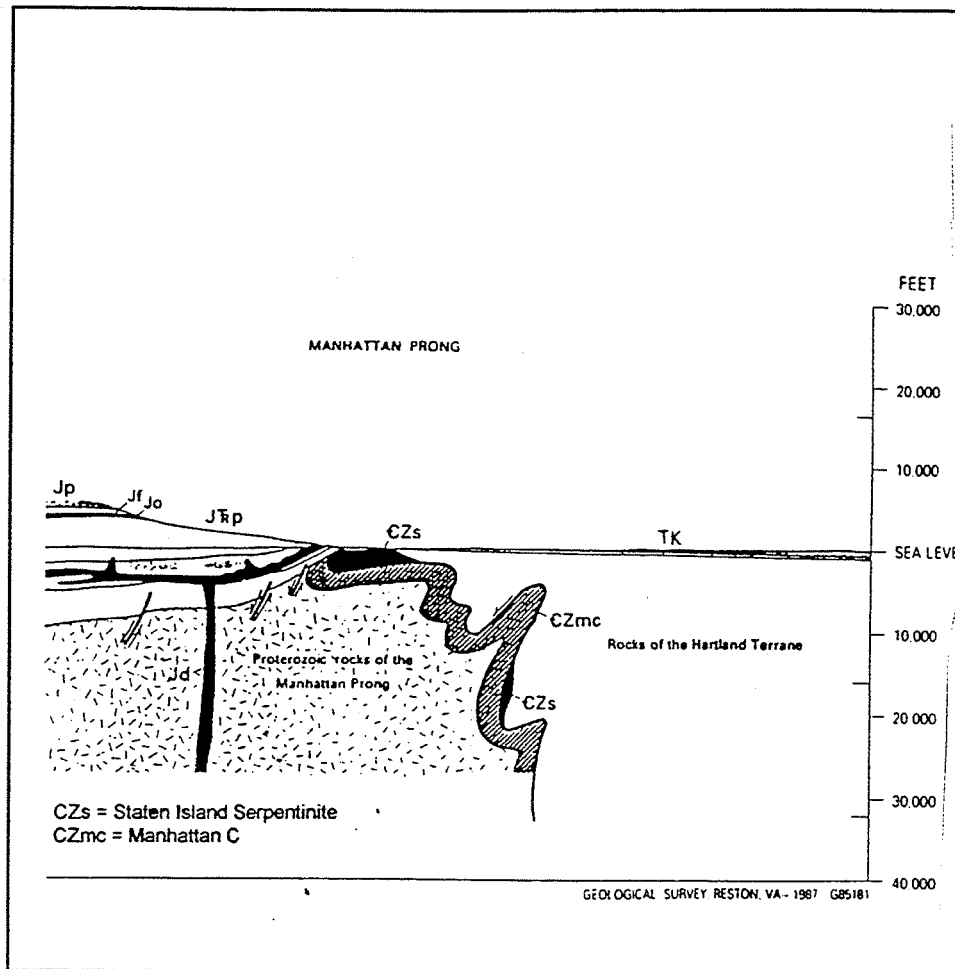


Figure 3. Cross section through Staten Island (From Lytle and Epstein, 1987)

Hess (1955, 1962) recognized the importance of ophiolite belts and their emplacement. Moores and Vine (1988) state "Hess recognized the prime importance of ultramafic rocks in understanding the tectonic development of collisional (alpine type) mountain belts." Okulewicz (1979) also believes that the Staten Island serpentinite represents a slice of an ocean-floor ophiolite suite, that was abducted during the mid-Ordovician tectonic orogeny.

Puffer (1994) methodically examined samples of the Staten Island meta-peridotite from 27 localities. He determined that 66% of serpentinite is lizardite and 27% is chrysotile. The remainder is olivine, chromite, and magnetite. At the I 278 exposure chrysotile makes up 54 volume percent of the serpentinite. He concluded that the serpentinite protolith was Hartzburgite and Dunite. Puffer (1994) compares two mechanisms of serpentinite emplacement. Abduction of an ophiolite-suite member or a metamorphosed olivine cumulate zone in a layered gabbro magma chamber. Puffer supports the abducted ophiolite member origin since the serpentinite is associated with the Hartland schist, which is believed to have a deep-oceanic origin (Little and Epstein 1987). In addition the absence of contact metamorphism as well as any indication of fractionation or layering refutes an intrusive origin.

Puffer (this volume) concludes that the mode of emplacement of the New York area serpentinites is controversial but most evidence tends to favor the Taconic obduction of the base of a Iapetus ophiolite sequence. This would force the placement of the New York area serpentinites into the Taconic suture zone (Cameron's Line) between Hartland terrain (C-Oh) and Manhattan-C terrain (C-Om).

The Mesozoic Igneous Rocks of Staten Island, New York

The early Jurassic Palisades intrusion of the Newark Basin crops out from Haverstraw New York to the northwestern part of Staten Island, a distance of 90 km., and underlies a narrow belt along the western part of Staten Island (Figure 1). Detailed studies of the Palisades Sill were made by Lewis, 1907, 1908a, 1908b; F. Walker, 1940; K. Walker, 1969a, 1969b; Pearce, 1970; K. Walker et al., 1973, Puffer, 1984. and Shirley, 1987. None of these earlier studies included the Staten Island portion of the Palisades intrusion probably because the intrusion is poorly exposed on Staten Island. Recent studies of *Eastern North American Mesozoic Magmatism* in the Newark Basin were made by Puffer (1992), Steiner et al. 1992, Husch (1992), Houghton et al. 1992, Tollo, et al. 1992, Puffer and Student (1992), Hozik (1992) and Puffer and Husch (this volume). These studies were confined to those portions of the Palisades intrusion, exposed in New Jersey and in Rockland County, New York where the intrusion is dominantly a sill. There is general agreement that the sill resulted from several pulses of tholeiitic magma each of which differentiated through gravitational fractional crystallization. The boundaries of the Palisades intrusion on Staten Island are shown in Figure 1. Outcrops of diabase occur at the Graniteville Quarry, the toll plaza of the Bayonne Bridge, the Travis Quarry, and the Teleport. There are no known outcrops of the Newark Supergroup of sedimentary rocks on Staten Island which underlie and overlie the Palisades intrusion. However, on the basis of subsurface drill-core data, Van Houten (1969), and Pagano (1994) show that Locketong argillite overlies and underlies that Palisades intrusion in this area. The reader is referred to Puffer and Husch (this volume) for a comprehensive study of the Palisades-Rocky Hill-Lambertville (PRHL) "megashheet,".

The Graniteville Quarry

It is an exceptional occurrence wherein one can observe the parent of an igneous rock adjacent to that igneous rock. This is the case at the Graniteville Quarry (Stop 2 on this field trip) where marginal fusion of a xenolith of sodium-rich Locketong argillite enclosed in the basaltic magma of the Palisades sill resulted in coexisting silicic and mafic melts. This phenomenon was studied in detail by Benimoff and Sclar, 1978, 1980a, 1980b, 1984, 1988, 1992, 1996 and Sclar and Benimoff (1993), and a summary of these studies is presented below.

A xenolith of Locketong argillite is exposed in the Palisades diabase in a quarry at Graniteville, Staten Island. The xenolith has been recrystallized to a hornfels. It is a vertically dipping slab, 0.3 to 0.5m wide, and some 30 m long. The xenolith strikes N 30° W. The bottom of the xenolith is not exposed. Benimoff and Sclar (1978, 1984) concluded that the xenolith was derived from the Locketong formation below the sill. Between the diabase and the hornfelsed xenolith is a sharply bounded interface zone of coarse-grained igneous rock. The interface zone ranges from 5 to 12 cm in thickness and completely surrounds the xenolith. They have categorized the coarse-grained rock of the interface zone as a melanocratic pyroxene trondhjemite. The chemical analyses of these rocks is shown in table 1.

Table 1. Chemical analyses and CIPW norms of the xenolith and the associated trondhjemite and diabase from the Graniteville Quarry, Staten Island, New York (from Benimoff and Sclar, 1984)

Chemical Analyses, weight % oxides						
	XA	XB	TA	TB	D-1	D-2
SiO ₂	74.8	63.5	58.4	58.2	51.8	52
Al ₂ O ₃	11.6	16.1	6.75	6.91	16.8	16.7
TiO ₂	0.61	0.75	1.63	1.48	1.17	1.13
MgO	0.23	0.3	4.89	5.14	4.91	4.74
FeO	0.1	0.1	4.35	5.6	6.7	7.85
Fe ₂ O ₃	0.31	0.47	1.51	1.93	2.75	1.74
MnO	0.02	0.04	0.14	0.16	0.16	0.19
CaO	2.07	5.6	13.1	11.5	8.79	10.2
Na ₂ O	6.67	9.48	3.76	3.81	3.22	2.58
K ₂ O	0.07	0.12	0.12	0.14	1.4	0.76
P ₂ O ₅	0.09	0.13	0.3	0.09	0.14	0.15
LOI	1.48	3.85	4.71	2.88	1.15	0.23
Total	98.05	100.34	99.66	97.84	98.99	98.27

CIPW Norms						
	XA	XB	TA	TB	D-1	D-2
Q	35.41	7	19.32	16.27	1.42	4.63
Or	0.39	0.72	0.84	8.29	4.51	3.23
Ab	56.4	80.24	35.41	32.25	27.27	21.82
An			0.39	1.34	27.24	31.74
Wo			13.49	15.46	6.48	7.49
En	0.57	0.74	9.19	9.62	3.67	3.72
Fs			3.25	4.92	2.53	3.62
En			2.99	3.18	8.53	8.08
Fs			1.06	1.62	5.87	7.85
mt			2.2	2.8	3.98	2.52
hm	0.34	0.46				
il	0.26	0.09	3.1	2.81	2.22	2.14
tn		1.2				
ru		0.22				
ap	0.19	0.28	0.65	0.19	0.31	0.34
C	0.2					
cc	3.36	8.76	10.71	6.65		
H ₂ O					1.15	0.23
Total	97.59	100.49	99.68	97.85	98.96	98.69

D-1 Diabase: Adjacent to Trondhjemite (TA); D-2 Diabase taken 47 meters S30°W of D-1; TA Trondhjemite: North end of xenolith; TB Trondhjemite: south end of xenolith; XA Xenolith north end of outcrop; XB xenolith south end of outcrop.

The diabase at Graniteville is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34.44}Fs_{17.31}Wo_{35.42}$) (Benimoff and Sclar, 1984). The augite contains exsolution lamellae of pigeonite on (001), and typically exhibits simple contact twinning on (100). A granophyric intergrowth of quartz and K-feldspar is present in minor amounts. Grains of titanomagnetite with oxidation lamellae of ilmenite and discrete grains of ilmenite are common.

The trondhjemite is composed dominantly of quartz-albite granophyre in which are enclosed large discrete crystals of albite and Ca-rich clinopyroxene (Benimoff and Sclar 1984). Minor constituents include interstitial calcite, titanite, ilmenite, optically homogeneous titanomagnetite, nickelian and cobaltian pyrrhotites, apatite, and zinc sulfide (Sclar and Benimoff, 1993). The modal mineral percentages are clinopyroxene 38, albite 38, quartz 18, titanite 2.7, calcite 1.3, and opaques 2.0.

Petrographic examination by Benimoff and Sclar, 1984, shows that the xenolith is now a hornfels and exhibits a granoblastic texture. The hornfels is composed dominantly of albite and quartz and subordinantly of calcite, titanite, apatite, ilmenite, and actinolite. The modal mineral percentages are albite 66, quartz 30, titanite 2.3, calcite 0.9, apatite 0.5, and actinolite 0.3. The bulk composition of the xenolith is variable which is not unexpected for a rock of sedimentary origins. Normative albite ranges from 56.4 to 80.2 wt.%, whereas normative quartz ranges from 7.0 to 35.4 wt.%.

Benimoff and Sclar 1984 concluded that the hornfels was derived from the Newark Supergroup (Olsen, 1980) of sedimentary rocks which encloses the Palisades Sill. This group of rocks consists of the Stockton, Lockatong, and Brunswick formations (Van Houten, 1964, 1965, 1969, 1971). The protolith for the xenolith was probably a silty lacustrine sediment rich in sodium and carbonate, but very low in potassium and iron and these are the chemical characteristics, of much of the Lockatong formation (Benimoff and Sclar, 1984).

Because the diabase magma is markedly different from the trondhjemite, Benimoff and Sclar 1996 studied the concentration of the cations across the liquid - liquid interface because this interface represented a liquid-liquid boundary between two chemically divergent magmas. The boundary is somewhat irregular but is very sharp and there is no evidence of chill zone effects. Hence they have a simple geologic setting involving a natural diffusion couple between two coexisting magmatic liquids of very contrasted chemistry that coexisted for a significant time, and these are not glassy rocks as shown by their phaneritic texture. Despite the relatively coarse grain size and the mineralogy they attempted to obtain the natural concentration profiles across the liquid-liquid interface. So they took several drill cores perpendicular to the diabase-trondhjemite interface, and they sampled the core at two millimeter intervals with a diamond wafering blade in order to obtain enough mass to analyze each slice adequately. They plotted the chemical data.

This occurrence constitutes an exceptional circumstance in igneous petrology in which the source rock (xenolith) and the igneous daughter product (trondhjemite) are contiguous and in which the geological, petrographical, mineralogical, and chemical evidence point unequivocally to a parent-daughter relationship (Benimoff and Sclar, 1992). This setting provides an opportunity to test whether REE signatures reflect the source of an igneous rock. Chondrite-normalized REE plots of the xenolith, the trondhjemite, and the contiguous Palisades diabase were prepared from REE analysis. The trondhjemite and the xenolith plots are characterized by a pronounced negative europium anomaly (Eu 20-30 times chondrites), LREE concentration of 80-100 times chondrites, and HREE concentrations of 30-50 times chondrites. By comparison, the diabase shows a positive europium anomaly (EU 19-26 times chondrites), LREE concentrations of 18-40 times chondrites, and HREE concentrations of 10-17 times chondrites. Benimoff and Sclar, 1992 concluded that the REE signature of an igneous rock (the trondhjemite) does indeed reflect that of the source rock (the Lockatong argillite).

Travis Quarry

A steeply dipping albitite dike 10-15 cm thick in the Palisades Sill at the Travis Quarry, was reported by Benimoff et al. 1988). The dike is exposed continuously on strike for 3.5 meters, and may be traced 30 meters along strike (N 12° E). The leucocratic dike is coarse grained (1 cm). It consists of 85 volume % euhedral to subhedral albite (Ab_{98}), 15 volume % of interstitial subradial prisms of augite ($Wo_{45.49}En_{40}Fs_{16}$), and minor ilmenite. Chemical analyses and CIPW norms of the diabase (TV02) and albitite (TV01) are given in Table 2.

Table 2. Chemical analyses and CIPW norms of the Jurassic Igneous Rocks at Travis, South end of the Bayonne Bridge, Teleport, and CSI Willowbrook Campus, Staten Island, New York from Benimoff and Sclar, 1994)

Chemical Analyses, weight % oxides						
	TV01	TV02	BBAL	BBDB	TL01	CSI01
SiO ₂	62.7	52.3	60.1	52.5	51.88	53.29
Al ₂ O ₃	17.7	12.5	16.2	15.4	16.85	11.0
TiO ₂	0.37	10.1	0.85	1.14	1.06	2.87
MgO	2.21	9.31	0.97	5.42	6.1	4
FeO	1.4	2.33	0.7	8.4	6.72	11.46
Fe ₂ O ₃	0.79	0.72	1.36	1.67	1.68	2.86
MnO	0.07	1.56	0.04	0.17	0.14	0.2
CaO	3.68	8.4	4.55	10.2	10.67	6.79
Na ₂ O	8.79	0.18	9.39	2.48	2.65	3.2
K ₂ O	0.48	0.91	0.36	0.84	0.86	1.83
P ₂ O ₅	0.02	0.11	0.08	0.14		
LOI	1.54	0.77	4.7	0.47	1	2.0
Total	99.75	100.3	99.3	98.83	99.61	99.5

CIPW Norms

	TV01	TV02	BBAL	BBDB	TL01	CSI01
Q	0.27	0.89	1.59	1.08	1.53	5.71
or	2.83	4.25	2.12	4.82	5.08	10.8
ab	74.36	19.71	79.46	20.36	22.42	27.06
an	7.42	21.52	1	27.57	31.53	10.24
di	7.97	22.68		17.07	17.46	19.65
hy	3.1	25.12		16.78	16.13	14.42
en			2.42			
hm			0.42			
mt	1.14	2.27		2.36	2.44	4.15
il	0.7	1.73		2.11	2.02	5.46
tn			2.08			
ru						
ap	0.34	0.24	0.2	0.3		
cc			6.25			
wo				5.85		
C						
pv				0.08		
ac						
Total	98.13	98.42	97.79	98.28	98.61	97.5

Bayonne Bridge Toll Plaza

Another steeply dipping albitite dike 12 cm thick in the Palisades Sill at the south end of the Bayonne Bridge

was reported by Benimoff and Sclar (1990). The dike strikes N 30° E. The leucocratic phaneritic albitite dike is composed dominantly of subhedral albite and subordinately of interstitial augite which is partly altered to actinolite and chlorite. Chemical analyses and CIPW norms of the diabase (BBDB) and the albitite dike (BBAL) are given in Table 2.

Interpretation of the albitite dikes

Based on the chemical and mineralogical characteristics of the leucocratic dikes in the Palisades Sill, Benimoff and Sclar concluded that the parental magma of these dikes was derived from fusion of xenoliths of Lockatong argillite in the Palisades Sill, and that these leucocratic intrusions are not late magmatic differentiates of the diabase sill. Late differentiates are quartz-kspars with a relatively high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio. These leucocratic intrusions probably represent the end stage of a process represented in an arrested state by the partly fused xenolith of Lockatong argillite in the Graniteville Quarry as discussed above. The Lockatong argillite is a chemically unusual sedimentary rock with an exceptionally high $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio. The xenolith - derived dike magmas and the diabase magma did not co-exist as a two-liquid system for a period of time sufficient to permit chemical diffusion across the liquid-liquid interface as it did at Graniteville. Similar occurrences of leucocratic dikes are described by Benimoff et al. (1989), and Puffer et al. (1994).

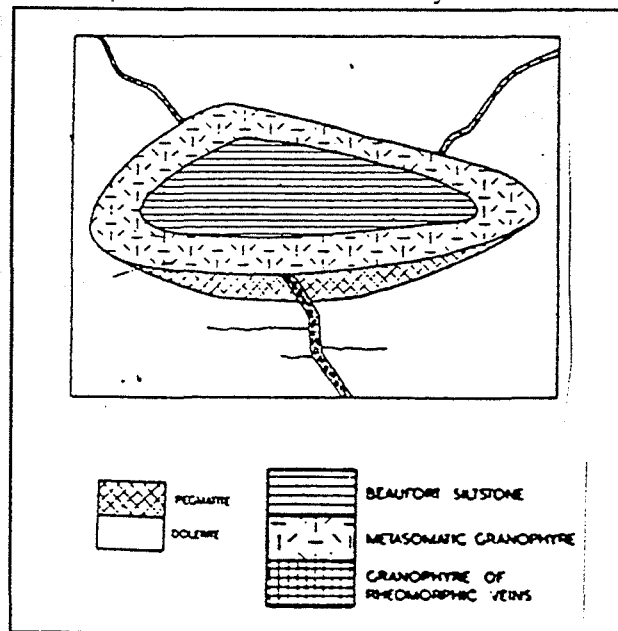


Figure 4. Sketch of the xenolith and pegmatite enclosed in the Karroo Dolerite (from Walker and Poldervaart 1949).

Walker and Poldervaart (1949) studied the field relationships of the reaction products of the Karroo dolerite magma with associated sedimentary rocks and reported that examples of assimilation are rare. They concluded that rheomorphism and transfusion or metasomatism of sedimentary rocks occur more commonly. The former process includes all processes whereby sedimentary rocks are fused sufficiently so that they are capable of flowing, and the latter processes as due to emanations of alkali-rich fluids reacting with minerals of the sedimentary rocks to produce new minerals. They describe (Figure 4) a lenticular siltstone xenolith that measured 15.24 m x 2.43 m about 30 m from the upper contact of a sill 183 m thick. Surrounding the xenolith is a zone of granophyre that exhibits sharp boundaries with the dolerite and the xenolith. They report that "rheomorphic veins" originate from the granophyric zone. Although they propose a transfusion-type of process for the origin of the granophyre, Benimoff et al. (in prep.) propose that it is equally as probable that the granophyre is a fusion product of the xenolith. The spatial arrangement of the "rheomorphic veins" suggest that the granophyric magma is the source of the "rheomorphic veins". If this granophyre is a fusion product of

the xenolith, then some of the leucocratic " veins" that occur in the Karroo dolerite also have their source in the associated sedimentary rocks(Benimoff et al., in prep.).

The New Exposure of Palisades Diabase at the North End of the new CSI Willowbrook Campus

An new exposure of Palisades diabase was revealed in an excavation for a storm runoff retention basin at the north end of the new Willowbrook CSI campus. It was examined by A. I. Benimoff and J. H. Puffer on November, 17, 1993. This exposure is either an outcrop or a large glacial erratic. Although the exposure is near the eastern contact of the Palisades sill, its chemistry(see Table2) is indicative of the highly fractionated diabase of the upper sill. It contains about 20% by volume of interstitial remarkably unaltered granophyre composed of quartz and K-feldspar. On one side of the exposure, there appears a xenolith, but it is so highly altered to actinolite and chlorite that its origin is obscure.

Glacial and Cretaceous deposits

Exposed on the eastern and southern areas of Staten Island are cretaceous deposits of clays, silts, and sands. These upper Cretaceous termed the Raritan formation strike NE-SW and dip 10° SE(Johnson and Richards, 1952) . The raritan formation is characterized by crossbedded, alternating light colored sands and essentially light colored to gray clays. Owens and Sohl(1969) conclude that the Raritan formation environment of deposition was point bar deposits of meandering streams.

Overlying the Cretaceous deposits are glacial deposits of the Woodfordian age(see figure 2 and 5). Most studies of Staten Island glaciation believe the existing erosional and depositional features, including the Harbor Hill Moraine are related to events that occurred during the Late Wisconsin(Woodfordian) events(Sirkin, 1982). Sirkin and Stuckenrath, (1980) report that the late Wisconsin glacier, consisting of at least three major lobes, reached its terminal position around 21,750 years ago.

The Harbor Hill moraine(the end moraine of the Hudson lobe) is the terminal moraine(see figures 2 and 5) on Staten Island(Sirkin, 1986). During deglaciation, proglacial lakes such as Lake Bayonne(Figure 5) formed between the ice lobe and the Harbor Hill terminal moraine(Stanford and Harper, 1991).

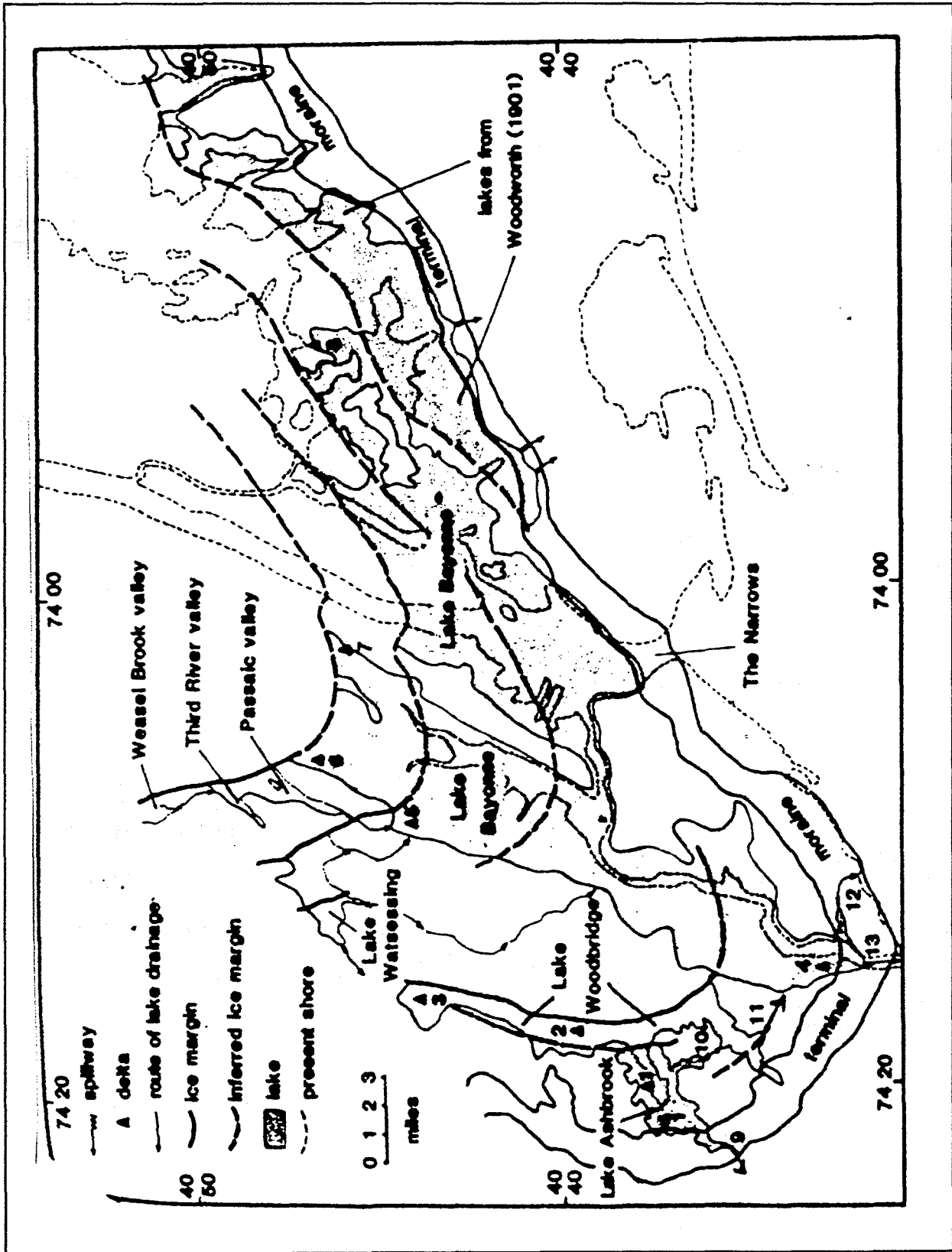


Figure 5. Map showing terminal moraine, inferred ice margins and glacial lakes (from Stanford and Harper, 1991)

References

- Behm J.J., 1954, The petrology of the serpentinite of Richmond County (Staten Island), N.Y., Proc. of the Staten Island Inst. of Arts and Sciences, v. 16, p. 1-39.
- Benimoff, A. I. and Sclar, C. B. (1978) Pyroxene trondhjemite derived by partial fusion of a xenolith of Lockatong argillite in the Palisades sill, Staten Island, N. Y. (abstr.) Geological Society of American Abstracts with Programs, 10, 33.
- Benimoff, A. I. and Sclar, C. B. (1980a) Partial fusion of a xenolith of Lockatong argillite in the Palisades diabase, Graniteville quarry, Staten Island: The petrochemistry of coexisting silicic and basic magmas. Geological Society of American Abstracts with Programs, 12, 24.
- Benimoff, A. I., and Sclar, C. B. (1980b) "Two Chemically Divergent Magmatic Liquids." Cover Story, EOS, Transactions American Geophysical Union, 61.
- Benimoff, A. I. and Sclar, C. B. (1984) Coexisting silicic and mafic melts resulting from marginal fusion of a xenolith of Lockatong argillite in the Palisades sill, Graniteville, Staten Island, New York. American Mineralogist, 69, 1005-1014.
- Benimoff, A. I. and Sclar, C. B. (1988) The Graniteville quarry, Staten Island, N. Y.: an outstanding location for illustrating igneous phenomena. Northeastern Geol. 10, 30-42.
- Benimoff, A. I., Sclar C. B., Okuliewicz, S., and Behm, H. J. (1988) "A Leucocratic Albitite Dike in The Palisades Sill, Travis Quarry, Staten Island, New York" GSA Abstracts with Programs V. 20. No. 1, 5.
- Benimoff, A. I., and Sclar, C. B. (1990) "An Albitite Dike in the Palisades Sill at the South end of Bayonne Bridge, Staten Island, NY. Geological Society of America Abstracts with Programs, 22, No. 2, p. 4.
- Benimoff, A. I., and Sclar, C. B. (1992b) REE Geochemistry of a Partly Fused Xenolith in The Palisades Sill, Staten Island, NY: A Test of The Igneous Source-Rock Concept in REE Geochemistry. V. M. Goldschmidt Conference Program and Abstracts, The Geochemical Society, A-8.
- Benimoff, A. I. and Sclar, C. B. (1994) The Mesozoic Igneous Rocks of Staten Island, New York: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 25-58.
- Benimoff, A. I. and Sclar, C. B. (1996) Natural Cationic Diffusion Profiles Across a Liquid-Liquid Boundary Between Chemically Dissimilar Coexisting Magmas: a Trondhjemite-Diabase Interface. EOS, Transactions American Geophysical Union, Spring Meeting paper V21-04.
- Benimoff, A. I., Moore, P. B., Rice, S. B., and Sclar, C. B. (1992a) A Ni and Cr-bearing splintery antigorite from the serpentinite of Staten Island, N.Y., *Geological Society of America Abstracts with Programs*, 24, (3) 7.
- Benimoff, A. I., Puffer, J. H., and Sclar, C. B. (1989) A Trondhjemite Dike in the I-95 Cut of The Palisades Sill, NJ, GSA Abstracts with Programs, 21, No. 1:4.
- Crosby, W.O. (1914) Physiographic relations of serpentinite with special reference to the serpentinite rock of Staten Island. *Journal of Geology* 22, No. 6 582-592.
- Haskin, L. A., Haskin, M. A., Frey, F. A. (1968) Relative and absolute terrestrial abundances of the rare earth elements. *In Origin and distribution of the Elements*, ed. L. H. Ahrens, pp 889-912. Oxford, Pergamon Press.
- Hess, H. H., 1955, Serpentines, orogeny, and epeirogeny: p. 391-407 in Poldervaart, Arie, ed., *Crust of the Earth (a symposium)*, Geological Society of America Special Paper 62, 762 p.
- _____ (1962) History of ocean basins. Geological society of America, *Buddington Volume* 599-620.
- Hollick, C. A., (1909) Notes in connection with specimens recently obtained from serpentines of Staten Island, N.Y.: *New York Academy of Sciences, Annals*, v. 19, p. 315-317.
- Hozik, M. J. (1992) Paleomagnetism of Igneous Rocks in The Culpeper, Newark, and Hartford/Deerfield Basins *in* Puffer, J. H., and Ragland, P.C., eds., *Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper* 268, 279-308.
- Husch, J. M., (1992) Geochemistry and Petrogenesis of the Early Jurassic Diabase from the Central Newark Basin of New York and Pennsylvania *in* Puffer, J. H., and Ragland, P.C., eds., *Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper* 268, 169-192.

- Johnson, M.E., and Richards, H.G. (1962) Stratigraphy of coastal plain in New Jersey: American Association of Petroleum Geologists Bulletin, v. 36, no. 11, p. 2150-2160.
- Lewis, J. V. (1907) The origin and relations of the Newark rocks. New Jersey Geological Survey Annual Report, 1906, 99-129.
- Lewis, J. V. (1908a) Petrography of the Newark igneous rocks of New Jersey. New Jersey Geological Survey Annual Report, 1907, 99-167.
- Lewis, J. V. (1908b) The Palisades diabase of New Jersey. American Journal of Science, 26, 155-162.
- Lyttle, P. T., and Epstein, J. B., 1987 Geologic Map of the Newark 1° x 2° Quadrangle, New Jersey, Pennsylvania, and New York. USGS Miscellaneous Investigation Series, I-1715.
- Miller, W. H., (1970) Structural geology and tectonism of the Staten Island Serpentine; Brooklyn College of City University of New York, Department of Geology, Brooklyn, New York Master's Thesis, 67 p.
- McPhee, J. (1993) *Assembling California*, Farrar, Straus, and Giroux, New York, 304p.
- Merguerian, C. and Sanders, J. E., (1994) Trip 19: Geology of Staten Island and vicinity, 16 October 1994 : New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 78.
- Ohan, A. A., Kureshy, A.; and Kaarsberg, E., (1975) Geological aspects of Staten Island, New York, p. 195-212 in Wolff, M. P., ed., Guidebook to Field Excursions: New York State Geological Association, Annual Meeting, 47th, Hofstra University, Hempstead, N. Y., October 1975, Hempstead, New York, Hofstra University, Department of Geology, 327 p.
- Okulewicz, S.C., (1979) Petrology of the Staten Island alpine ultramafic body: Masters Thesis, Brooklyn College, New York, 92 pp.
- Olsen P., (1980) Fossil great lakes of the Newark Supergroup in New Jersey: in Manspeizer, W., Ed. Field studies in New Jersey geology and guide to field trips, 52nd Annual Meeting of the New York State Geological Association, Newark College of Arts and Sciences: Rutgers University, p. 352-398.
- Owens, J.P., and Sohl, N.F., (1969), Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey coastal plain: in Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions, Geological Society of America Annual Meeting, Rutgers University Press, New Brunswick, N.J., p. 235-278.
- Pagano, T. S. (1994) The geology of western Staten Island, New York north and south of the fall line: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 61-84.
- Pearce, T. H. (1970) Chemical variation in the Palisades Sill. Journal of Petrology, 11, 24-32.
- Puffer J. H. (1994) The Staten Island Meta-Peridotite: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 1-24.
- Puffer, J. H. and Student, J.J., (1992) Volcanic Structures, Eruptive Style, and Post-eruptive Deformation and Chemical Alteration of the Watchung Flood Basalts, New Jersey *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper 268, 261-278.
- Puffer J. H., Husch, J. M., and Benimoff, A. I. (1992) "The Palisades Sill and Watchung Basalt Flows, Northern New Jersey and Southeastern New York: A Geological Summary and Field Guide". New Jersey Geological Survey, Open File Report OFR 92-1, 27 pages.
- Sanders, J. E., and Merguerian C. (1994) The Glacial geology of New York City: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 93-200.
- Roberts-Dolgin, G. (1989) The Geology of Staten Island and western Long Island, Kings County and Queens counties, New York pages 51-57, in C.A. Baskerville ed., Geology and engineering geology of the New York metropolitan area. 28th International Geologic Congress Field Trip Guidebook T361.
- Slar, C. B. and Benimoff, A. I. (1993) An occurrence of magmatic sphalerite, The Canadian Mineralogist, 31(3) 691-694.
- Sirkin, L. A., (1986), Pleistocene stratigraphy of Long Island, New York, in Cadwell, D. H., ed., The Wisconsin Stage of the First Geological District, eastern New York: New York State Museum Bulletin 455, 6-21.
- Soren, J. (1988) Geologic and geohydrologic reconnaissance of Staten Island, New York: United States Geological Survey Water Resources Investigations Report 87-4048, 22 p.

- Stanford S. and Harper, D. (1991) Glacial lakes of the lower Passiac, Hackensack, and lower Hudson Valleys, New Jersey and New York. *Northeastern Geol.* 13, 271-286.
- Steiner, J. C., Walker, R. J., Warner, R. D., and Olson, T. R., (1992) A Cumulus-Transport-Deposition Model for the Differentiation of The Palisades Sill *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper 268, 193-218.
- Shirley, D. N. (1987) "Differentiation and Compaction in the Palisades Sill, New Jersey", *J. Petrol.* 28, Part 5, 835-865.
- Tollo, R. P., and Gottfried, D., (1992) Petrochemistry of Jurassic Basalts from Eight Cores, Newark Basin, New Jersey: Implications for the Volcanic Petrogenesis of the Newark Supergroup *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper 268, 233-260.
- Van Houten, F. B. (1964) Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation Central New Jersey and adjacent Pennsylvania *Geological Survey Bulletin*, 169, 497-531.
- Van Houten, F. B. (1965) Composition of Triassic Lockatong and associated Formations of Newark Group Central New Jersey and adjacent Pennsylvania. *American Journal of Science*, 263, 825-863.
- Van Houten, F. B. (1969) Late Triassic Newark Group, north-central New Jersey and adjacent In S. Subitsky, Ed., *Geology of Selected Areas in New Jersey and Pennsylvania Adjacent*, p. 314-347. Rutgers University Press. New Brunswick, New Jersey .
- Van Houten, F. B. (1971) Contact metamorphic mineral assemblages, Late Triassic Newark Group, N. J.: *Contributions Mineralogy and Petrology*, 30, p. 1- 14.
- Walker, F. (1940) The differentiation of the Palisades diabase, New Jersey. *Geological Society of America Bulletin*, 51, 1059-1106.
- Walker, K. R. (1969a) The Palisades Sill, New Jersey: A Reinvestigation. *Geological Society of America Special Paper*, 111.
- Walker, K. R. (1969b) A mineralogical, petrological and geochemical investigation of the Palisades Sill, New Jersey. *Geological Society of America Memoir*, 115, 175-187.
- Walker F., and Poldervaart, A., (1949), Karroo dolerites of the Union of South Africa: *Geological Society of America Bulletin*, v. 60, p. 591-706.
- Wasserman, G., (1956), Magnetic survey of the Staten Island serpentinite: New York, New York, New York University, Department of Geology, Masters thesis, 65p.
- Yersak, T.E., (1977) Gravity study of Staten Island and vicinity: Rutgers University, New Brunswick, New Jersey, M.S. thesis, 47 p.

Field Guide to Stops

Mileage	Remarks
<u>Cum.</u>	<u>Inc.</u>
0.0	Leave Parking Lot 4
0.1 0.1	Speed Bump(just installed!)
0.3 0.2	Stop sign
0.6 0.3	turn right at stop sign.
0.7 0.1	turn right onto Victory Boulevard
0.8 0.1	turn right onto South Gannon Avenue
1.1 0.3	enter Staten Island Expressway I-278 East
1.6 0.5	pass Bradley Avenue Exit
2.5 0.9	pass Todt Hill road Exit
2.8 0.3	Outcrops of Staten Island Serpentinite on right and left
3.3 0.5	Exit for Richmond Road, Hyland B'lv'd, Clove Road
3.8 0.5	Turn Left onto Clove Road
3.8 0.0	Turn Left onto Narrows Road
4.2 0.4	Turn Left onto Renwick Avenue.
4.3 0.1	Turn Right onto Milford Drive.
4.6 0.3	STOP 1 The Staten Island Serpentinite

This outcrop represents the largest continuous exposure of the Central-Zone Serpentinite on Staten Island, and is a foliated serpentinitized Hartzburgite, composed essentially of Lizardite (48-71%), chrysotile (15-30%), and olivine (10-15%). Antigorite, anthophyllite, talc and magnetite are present in minor concentration (Puffer & Germine 1994). Numerous veins are filled with carbonates, chrysotile or talc. A number of folds exist displaying a N40°E - N 45°E trend and a NE plunge. Several folds have western limbs that are overturned and are cut by high angle NE-SW trending faults. At this locality, the trend of one hundred and twenty-five fractures were measured and statistically plotted, in an attempt to determine the relationship between the joint patterns and the existing structure. The fractures can be categorized into 3 types based on their orientation to the folds. Type (1) longitudinal joints subparallel to the axial planes of folds, and may be release joints. Cross Joints This joint set is oriented normal to the fold axis and commonly develop in the hinge zone of folding by stretching parallel to the fold axis. Oblique Joints may be conjugate shear sets produced by a shortening normal to the axis of folding (Davis & Reynolds 1996). The fracture pattern relationship with the folds indicates a common origin. It is suggested that the folding, faulting and fracture patterns were produced by a SE-NW oriented compressional stress and may be related to the Mid Ordovician Taconic event.

4.7 0.1	Left Turn onto Renwick Ave.
4.8 0.1	Turn Left onto Little cLove Road
5.2 0.4	Turn Left onto Windsor Road
5.5 0.3	Turn Left onto Slosson Ave.
5.5 0.0	Turn Right onto Narrows Road
5.6 0.1	enter Staten Island Expressway I-278 West
6.1 0.5	Pass Bradley Ave. Exit
6.9 0.8	Pass Victory Boulevard Exit
7.3 0.4	Pass exit for NY 440 North
7.8 0.5	Pass Richmond Ave. Exit

- 8.0 0.2 Exit at South Ave.
- 8.6 0.6 Turn left onto South Ave.
- 9.0 0.4 Turn Right onto Forest Ave.
- 9.7 0.7 **Stop 2 - The Graniteville Quarry.**

At this locality, we see an extraordinary example of two coexisting magmatic liquids, now represented by the diabase of the Palisades Sill and a pyroxene Trondhjemite derived by fusion of the margins of a xenolith of sodium rich Lockatong Argillite (Benimoff and Sclar, 1978, 1980, 1984, 1988, 1992, 1996; Sclar and Benimoff, 1993). The diabase is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34.44}Fs_{17.31}Wo_{35.42}$). The trondhjemite is composed dominantly of quartz-albite granophyre in which are enclosed large discrete crystals of albite ($Ab_{99}An_{0.52}Or_{0.44}$) and Ca-rich pyroxene. Minor constituents include interstitial calcite, titanite, ilmenite, optically homogeneous titanomagnetite, nickelian and cobaltian pyrrhotites, apatite, and sphalerite. The modal mineral percentages are clinopyroxene 38, albite 38, quartz 18, titanite 2.7, calcite 1.3, and opaques 2.0. The xenolith is now a hornfels and exhibits a granoblastic texture. The hornfels is composed dominantly of albite and quartz and subordinantly of calcite, titanite, apatite, ilmenite, and actinolite. The modal mineral percentages are albite 66, quartz 30, titanite 2.3, calcite 0.9, apatite 0.5, and actinolite 0.3. Normative albite ranges from 56.4 to 80.2 wt.%, whereas normative quartz ranges from 7.0 to 35.4 wt.%. Chemical analyses (Table 1) reveal that diffusion of calcium, magnesium, iron, and sodium ions occurred across the liquid-liquid interface.

On the surface of the bedrock in the quarry area, numerous ice-sculpted features are present. These include shallow trough-like grooves, striae, and crescentic marks.

- 10.0 0.3 Pass Richmond Ave.
- 10.1 0.1 Turn right onto Willow Road
- 10.2 0.1 Enter 440 South
- 10.8 0.6 Bear Right NY 440 South/I-278 West
- 11.8 1.0 Exit onto The West Shore Expressway NY 440 South
- 13.3 1.5 Pass South Ave. Exit
- 14.5 1.2 Pass Victory Boulevard Exit
- 15.5 1.0 Fresh Kills Bridge
- 15.9 0.4 Exit at Muldoon Ave-Exit 5
- 16.4 0.5 View Landfill
- 16.8 0.4 Pass Arden Ave.
- 17.3 0.5 Intersection with Arthur Kill Road
- 17.5 0.2 Enter West Shore Expressway
- 17.9 0.4 Exit at Bloomingdale Road
- 18.3 0.4 turn right at Stop sign
- 18.4 0.1 turn left onto Arthur Kill Road
- 18.6 0.2 Arthur Kill Correctional Facility on Right
- 19.4 0.8 road curves to left
- 19.6 0.2 Storer Road on right.
- 19.7 0.1 enter Parking Lot for **Stop 3**

Stop 3 AKR TRUCKING COMPANY, 4288 Arthur Kill Road, Staten Island, NY. The owner is Mr. Frank Agugliaro.

Prolific Pleistocene till overlies most of the older units on Staten Island and the age of these deposits are believed to be late Wisconsin (Roberts-Dolgin 1989). This exposure is approximately 1 mile north of the Terminal Moraine, which exists on the eastern part of Staten Island, extending from the Narrows to Tottenville. Sanders and Merguerian (1994) report red-brown till overlying decayed-pebble outwash, which rests on white, charcoal-bearing Cretaceous micaceous sands and gray clays. At this exposure, glacial outwash is present at the northern section of the driveway. The unit is a tan to red-brown sand, alternating with sandy gravel. The entire outcrop displays abundant trough cross-stratification, and existing rock fragments have an origin from the following sources:

- 1) Diabase and clastic sedimentary rocks from the Triassic-Jurassic Newark Super Group

- 2) Ironstone clastics of Cretaceous Age.
- 3) Granite-Gneiss Precambrian N.Y.-N.J. Highlands.
- 4) Lowerre or Poughquag Quartzite.

The source of these clastics may have been from the north or west.

The rock fragments show advanced stages of chemical weathering. Sanders and Merguerian (1994) believe that and the trough cross-bedding and the extensive chemical alteration indicates this unit was formed in a braided stream during the Early Pleistocene (Nebraskan).

Roberts-Dolgin (1989) concludes this unit is the Pensauken formation which represents a stream deposit formed during an interglacial period. It is suggested that the existing glacio-fluvial deposit is part of a delta that entered Lake Bayonne, a glacial lake that existed between the glacier and the Terminal Moraine. (Stanford and Harper, 1991).

- 20.1 0.4 Road curves to right.
- 20.2 0.1 Road curves to left.
- 20.5 0.3 Pass Veterans Road
- 20.7 0.2 Pass under Outerbridge Crossing
- 21.8 1.1 turn left onto Main St.
- 22.1 0.3 intersection with Amboy Road
- 22.5 0.4 Turn Right onto Hylan Boulevard
- 22.8 0.3 Park on Right for **Stop 4 - The Conference House Park**

Proceed past the conference house to the beach. The late Wisconsin aged Harbor Hill terminal moraine(see figures 2 and 5) is present in the cliffs facing the Raritan Bay. The typical unsorted, unstratified character of glacial till is exposed at this locality. The till is red-brown, with many large boulders intermixed with finer sediments in the moraine, as well as on the beach. The existing erratics display a wide variety in rock type, reflecting a source from the North or Northwest. They are examples of glacial outwash in several areas along the cliff. Merguerian & Sanders (1994) believe The Terminal moraine is Mid-Wisconsinan, (Sangamonian?) These authors believe that overlying the terminal moraine is a Paleosol, with downward extending zones of discoloration. They interpret these zones as tree roots.

- 24.0 1.2 Turn Left onto Page Ave.
- 24.6 0.6 Pass Amboy Road
- 25.4 0.8 Turn left onto NY 440 North
- 25.7 0.3 Enter West Shore Expressway - North: Return to CSI.

...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...

...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...

...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...

...the ... of ...
...the ... of ...
...the ... of ...
...the ... of ...

SEDIMENTARY ENVIRONMENTS IN THE NEWARK BASIN IN NEW JERSEY AND CONTIGUOUS NEW YORK

GERALD M. FRIEDMAN

Brooklyn College and Graduate School of the City University of New York, Brooklyn, New York 11210, and Northeastern Science Foundation affiliated with Brooklyn College of the City of New York, P.O. Box 746, Troy, New York, 12181-0746

INTRODUCTION

As Manspeizer (1988) noted "these are extraordinary times for Triassic-Jurassic researchers of the Atlantic passive margins. Extensive field studies on the African and North American plates during this past decade have yielded a wealth of new data and ideas about rift basins and the origin of passive margins, that but a few years ago would have seemed like childish speculation.

New surface and subsurface basins have been identified, fossils abound in strata that only recently were considered barren, oil exploration is being pursued actively in continental strata of the Richmond - Taylorsville, Sanford and Newark basins, Late Triassic marine strata have been identified in Georges Bank off the coast of Massachusetts, and the roles of wrench tectonics, successor basins and listric normal faults have challenged the classical view that these are simple extensional basins". "Geologic data from the Atlantic passive margins record that continental rifting of central Pangaea occurred during the Late Triassic - Early Jurassic (Liassic), and that sea-floor spreading probably began no later than the Middle Jurassic."

The Newark Supergroup is composed of Late Triassic to Early Jurassic continental sedimentary rocks and interbedded basalts that crop out in a series of elongated basins along the eastern margin of North America (Froelich and Olsen, 1985).

The following sections from Friedman, Sanders, and Martini, (1982, p.44-49) provide background on the Newark basin and their basin-filling strata.

NEWARK BASINS AND THEIR BASIN-FILLING STRATA

Since the beginning of the nineteenth century the Newark rocks of eastern North America have engaged the attention of many geologists. Perhaps more than with any other single large suite of rocks, interpretations of the Newark strata have been closely controlled by the status of ideas prevailing within the fabric of geology. In many ways the changing ideas about the Newark strata have paralleled the intellectual growth and development of the science of geology in the United States.

Throughout all these intellectual developments the Newark rocks have been linked to the Appalachians. This coupling has logically followed from the fact that the Newark rocks occur in belts which follow so faithfully the median parts of the Appalachian chain. A brief review of some salient ideas about the Newark rocks shows a large geologic literature written by several generations of investigators, many of whom clearly were torn between their ingrained geologic "beliefs" (the "geologic fabric") and conclusions contrary to these "beliefs" that arose from their field study of the Newark strata.

AGE OF THE NEWARK STRATA

The term Newark has been applied in a general way to all strata generally referred to as "Triassic." In the later part of the nineteenth century, they were designated as "Jura-Trias" (for example, Dana, 1883). Early in the twentieth century, however, this "untidy" arrangement of a formation crossing a systemic boundary was changed. Instead, the idea became popular that the Palisades "Disturbance" closed the Triassic Period. Therefore, the Newark strata, having been deformed by this "disturbance," were considered to be entirely of late Triassic age.

NEWARK BASIN FILLING-STRATA (UPPER TRIASSIC BUT MAINLY LOWER JURASSIC)

Newark-age strata unconformably overlie metamorphosed Paleozoic strata of Cambro-Ordovician age and are in fault contact with some Precambrian formations. Cobbles and boulders in Newark basin marginal conglomerates (and fanglomerates) include mostly rocks of Middle Ordovician, Silurian, and Devonian age which formerly blanketed the elevated blocks at the NW basin-margin. The thick (possibly 8 or 9 km) strata filling the Newark basin are nonmarine; they include marginal rudites, fluvial sediments, and lake deposits [most notably the massive black argillites of the Lockatong Formation, which attains a maximum thickness of about 450 m in the Delaware River valley exposures]. Interbedded with these sedimentary rocks are three extrusive complexes, each 50 to 200 m thick, whose resistant tilted edges now underlie the curving Watchung Mountains in north-central New Jersey. Boulders of vesicular basalt in basin-marginal rudites locally prove that the lava flows formerly extended across one of the basin-marginal faults and onto a block that was later elevated and eroded. The thick (300m), generally concordant Palisades sheet of mafic igneous rock is located about 400m above the base of the Newark strata.

Extension related to the breakup of Pangea and incipient rifting of North America from Africa resulted in the system of fault-bounded basins of Triassic - Jurassic age that compose the Newark Supergroup. The Newark basin is a half-graben. Sedimentation began during late Middle Carnian time and continued through the Late Sinemurian (Cornet, 1977). The basin contains fluvial, lacustrine, alluvial-fan, and playa deposits together with intrusive and extrusive basalts (Van Houten, 1969).

The Newark basin in New Jersey and contiguous New York is at present an area of active research. For a review of recent references I recommend Froelich and Olson (1984), Husch and Hozik (1988), and Olsen et al. (1996). Olsen et al. (1996), list more than one hundred references relating to the Triassic-Jurassic deposits of the Newark basin.

FIELD TRIP

Figure 1 is a physiographic map which shows the New Jersey highlands and lowlands, the Watchung Mountains, and the location of STOPS 1 and 2. Figure 2 is a profile across the Hudson River; STOP 3 examines Triassic-Jurassic strata beneath the Palisades Ridge shown in this figure. Figure 3 shows the geology and structure under the Hudson River, at the Palisades.

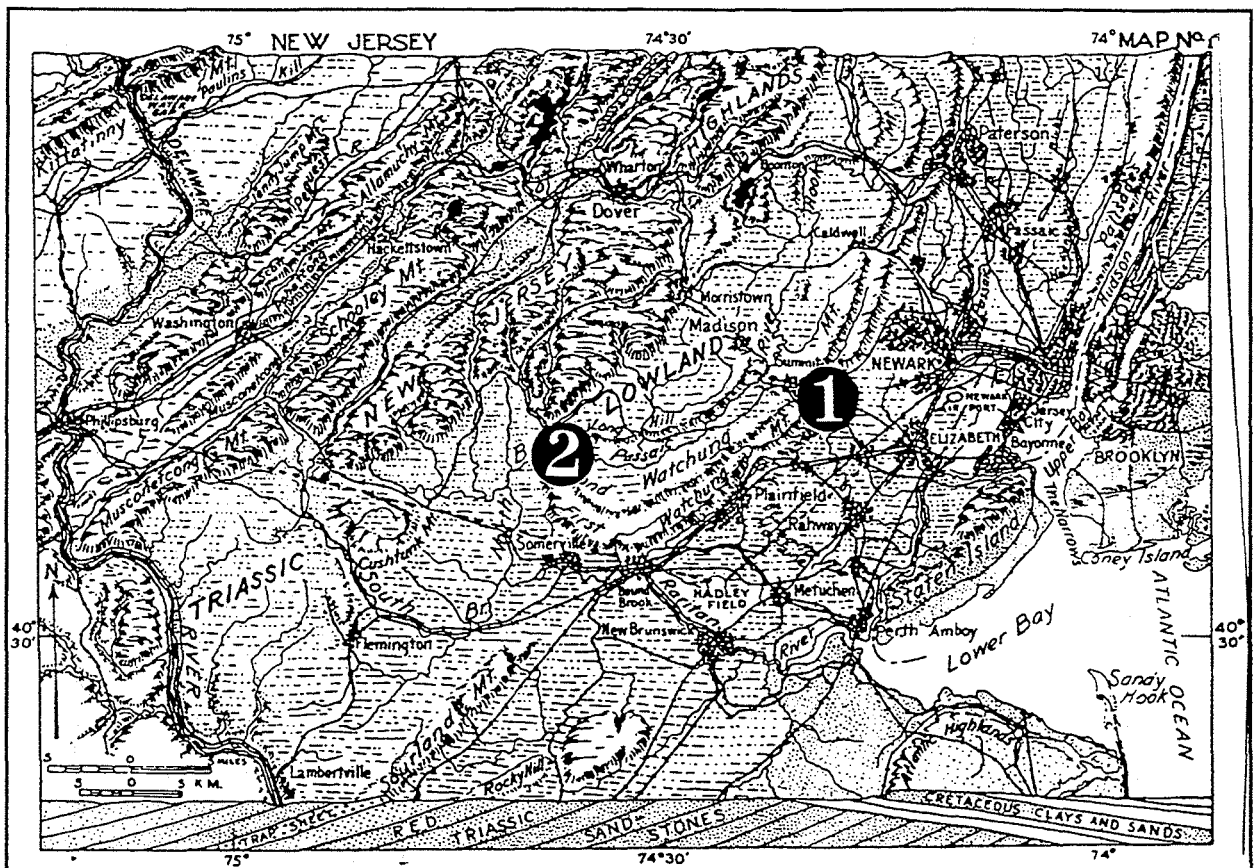


Figure 1. Physiographic map showing the New Jersey highlands and lowlands, the Watchung Mountains, and the location of STOPS 1 and 2.

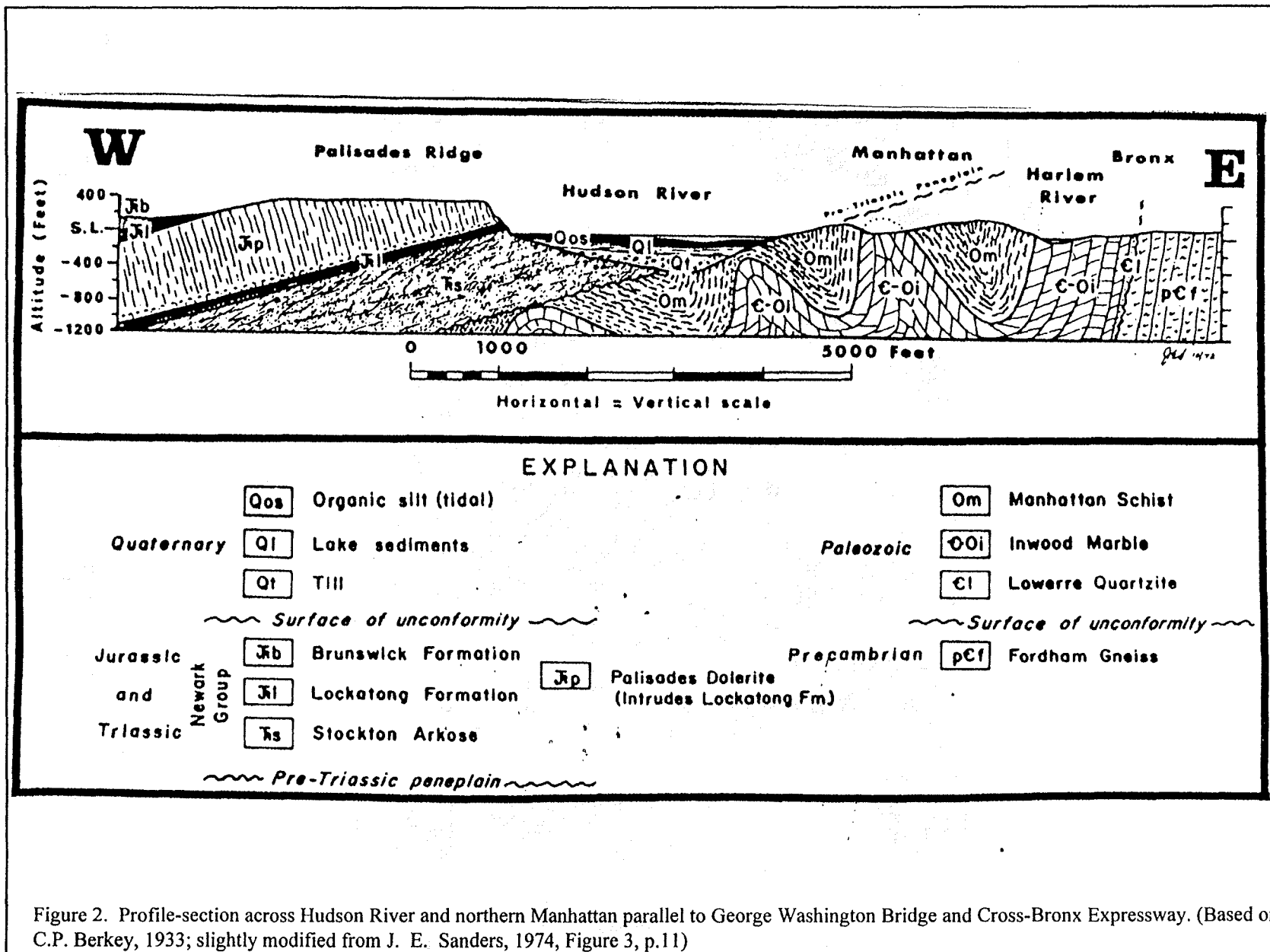


Figure 2. Profile-section across Hudson River and northern Manhattan parallel to George Washington Bridge and Cross-Bronx Expressway. (Based on C.P. Berkey, 1933; slightly modified from J. E. Sanders, 1974, Figure 3, p.11)

ROAD LOG

From the College of Staten Island head to Goethals Toll Bridge and cross Arthur Kill into New Jersey. Take Rte. 82 near Elizabeth to Rte. 24 and proceed to Summit Avenue, Summit. Exit Summit Avenue. The road log starts here.

Mileage Cumulative
Between
Points

1.1	1.1	Traffic light in Summit, head west to Ciba-Geigy Plant.
0.9	2.0	Sign: Junction 512 Union County.
0.2	2.2	At traffic light take 512 west; go to Springfield Avenue.
1.2	3.4	Bear right at traffic light (on to Springfield Avenue).

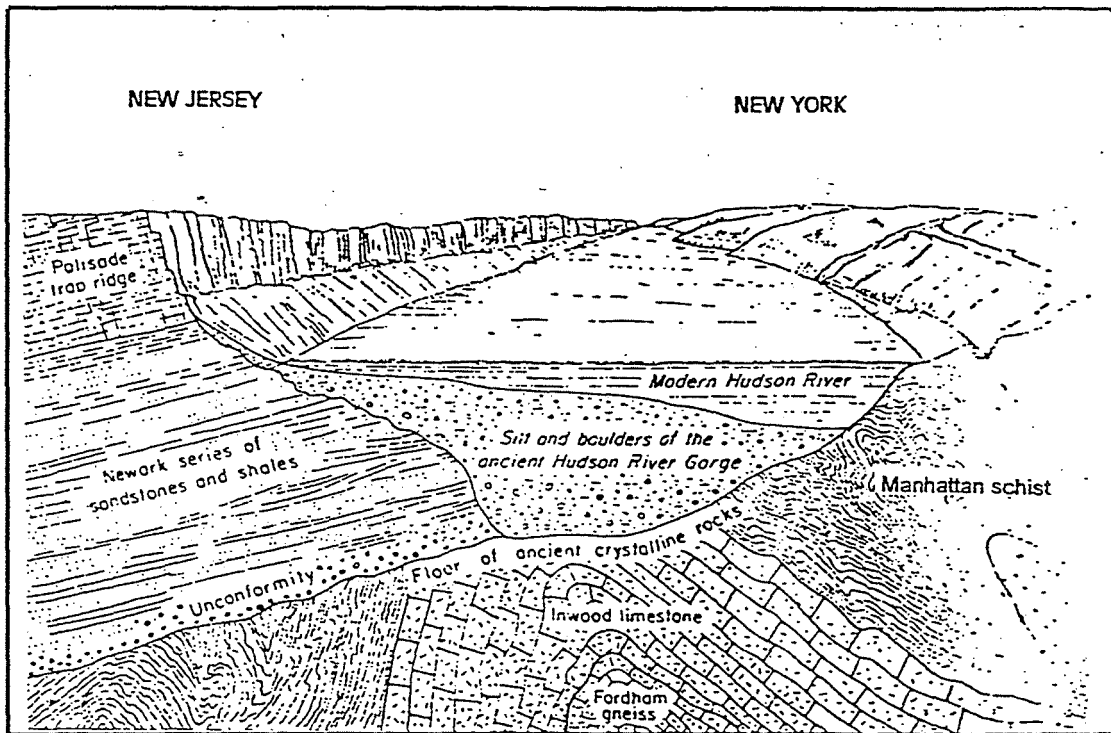


Figure 3. Geology and structure under the Hudson River, at the Palisades. (After Fig. 7 Guidebook, 61st Annual Meeting, Geol. Soc. Am.)

Mileage
Between
Points

1.3	4.7
2.2	6.9

At traffic light take 647 south to Murray Hill, South Street.
Follow South Street south through Murray Hill, past
Bell Laboratories. South Street changes to Glenside

Road. Follow underpass and turn right and make left (south) turn into Union County Park. Continue on road in Union County Park to Parking Lot, passing the abandoned village of Feltville.

0.5 7.4 Park vehicles and walk below parking lot to STOP 1.

STOP 1. Feltville Formation of the Newark Supergroup

On north side of Blue Brook are exposed interbedded micaceous red and gray siltstones and shales with sporadic lenticular channels of quartz sandstones. These exposed strata are part of the type section of the Feltville Formation of the Newark Supergroup. Similar exposures are present an estimated 1/4 to 1/2 mile farther east on south side of the brook, where a tributary meets Blue Brook. In the creek bottom are numerous blocks of quartz-pebble conglomerate.

According to Paul Olsen (personal communication, 1985) the strata at this site carry abundant spores and pollen.

For stratigraphic section see Table 1. Figure 4 shows type section of the Feltville Formation exposed along ravine near Blue Lake; Table 2 provides the key for individual units.

Mileage Between Points	Cumulative	
7.6	15.0	Return to Glenside Road.
0.5	15.5	Turn left (west). Enter road to Interstate 78 West. Follow signs to Interstate 78.
1.1	16.6	Enter Interstate 78.
1.2	17.8	Note exposures of Watchung Basalt, especially spectacular columnar jointing.
9.8	27.6	Note exposures of Watchung Basalt.
0.7	28.3	Ascend road to Scenic Overlook and return to Interstate 78.
1.7	30.0	Exit 29 Interstate 287 North. Follow Interstate 287 North.
5.6	35.6	Exit road to Bernardsville, follow Route 525 North.
2.5	38.1	Enter Bernardsville.
1.1	39.2	Turn left on Route 202 West.
1.2	40.4	Turn left into Anthony Ferranti Quarry for STOP 2.

TABLE 1. LITHOSTRATIGRAPHIC TERMS FOR NEWARK BASIN

Newark Supergroup
(of Newark Basin)

Boonton Formation

Hook Mountain Basalt

Towaco Formation

Preakness Basalt

Feltonville Formation

Orange Mountain Basalt

Passaic Formation

Lockatong Formation

Stockton Formation

(Reproduced from Olsen, Paul E., 1980, Triassic and Jurassic Formations of the Newark Basin in Field Studies of New Jersey Geology and Guide to Field Trips, Warren Manspeizer (ed.), Rutgers University, Newark, N.J., 398 p.)

TABLE 2. TYPE SECTION OF THE FELTVILLE FORMATION AND KEY TO FIGURE 4.

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

(Reproduced from Olsen, Paul E., 1980, Triassic and Jurassic Formations of the Newark Basin *in* Field Studies of New Jersey Geology and Guide to Field Trips, Warren Manspeizer (ed.), Rutgers University, Newark, N.J., 398 p.)

STOP 2. Anthony Ferranti Quarry. (Permission is needed to enter this quarry. Contact Linda Kimler, Public Relations, Anthony Ferranti Quarry, 908-647-8273).

Spectacular outcrops of sandstone, siltstone, and shale of the Feltville Formation occur beneath the Preakness Basalt (see Table 1). Crossbedded sandstones show local channeling. Find sandstones with dinosaur footprints and plant fossils as well as raindrop impressions on mudcracked surfaces. Note small strike-slip faults in quarry.

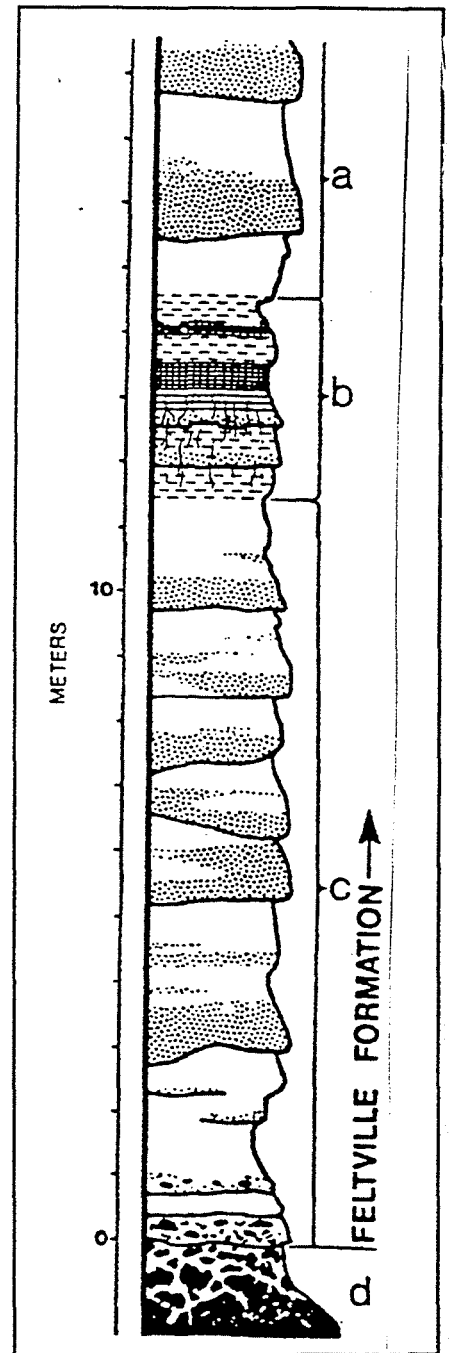


Figure 4. Type section of the Feltville Formation exposed along ravine for Blue Brook about 1 k south of Lake Surprise in the Watchung Reservation, Union County, New Jersey (Olsen, 1980)

Mileage Between Points	Cumulative	
0.2	40.6	Return to Route 202, turn right.
0.6	41.2	Turn right onto Route 525 South.
2.3	43.5	Turn onto Interstate 287 North.
15.6	59.1	Turn onto Interstate 80 East.
24.1	83.2	Take local exit to Palisades Parkway North via Interstate 95 (which changed from Interstate 80), exit 72 at Fort Lee.
3.6	86.8	North on Palisades Int. Parkway (PIP).
15.0	101.8	Exit PIP at NY303 (Orangeburg).
4.0	105.8	North on 303, under Thruway. Road goes uphill; cuts on L side are in Palisades dolerite.
0.3	106.1	Cuts in dolerite, both sides of road.
0.2	106.3	End of cuts in dolerite.
0.1	106.4	Highway sign Valley Cottage.
0.65	107.05	Small dolerite cut on R.
0.05	107.1	Traffic signal; turn R on Lake Road.
0.7	107.8	Wooded hill in distance on R is dip slope on W side of Palisades sill (strike NS, dip 15° W).
0.1	107.9	Jct. Belleville Rd.
0.5	108.4	Traffic signal, Rte. 9W. Cross 9W and enter Rockland Lake State Park. Rockland Lake at L.
0.4	108.8	Wooded ridge ahead is dip slope of Palisades sill.
0.2	109.0	Exposure of dolerite of sill on R; overlain by sill.
0.5	109.5	Exposure of dolerite of sill in slope at R.
0.4	109.9	Intersection; turn R on street marked "Dead End".
0.1	110.0	Barricade; passage for "Official Cars Only". Park vehicles at barrier. Walk down to old quarry and pick up trail down to shore.

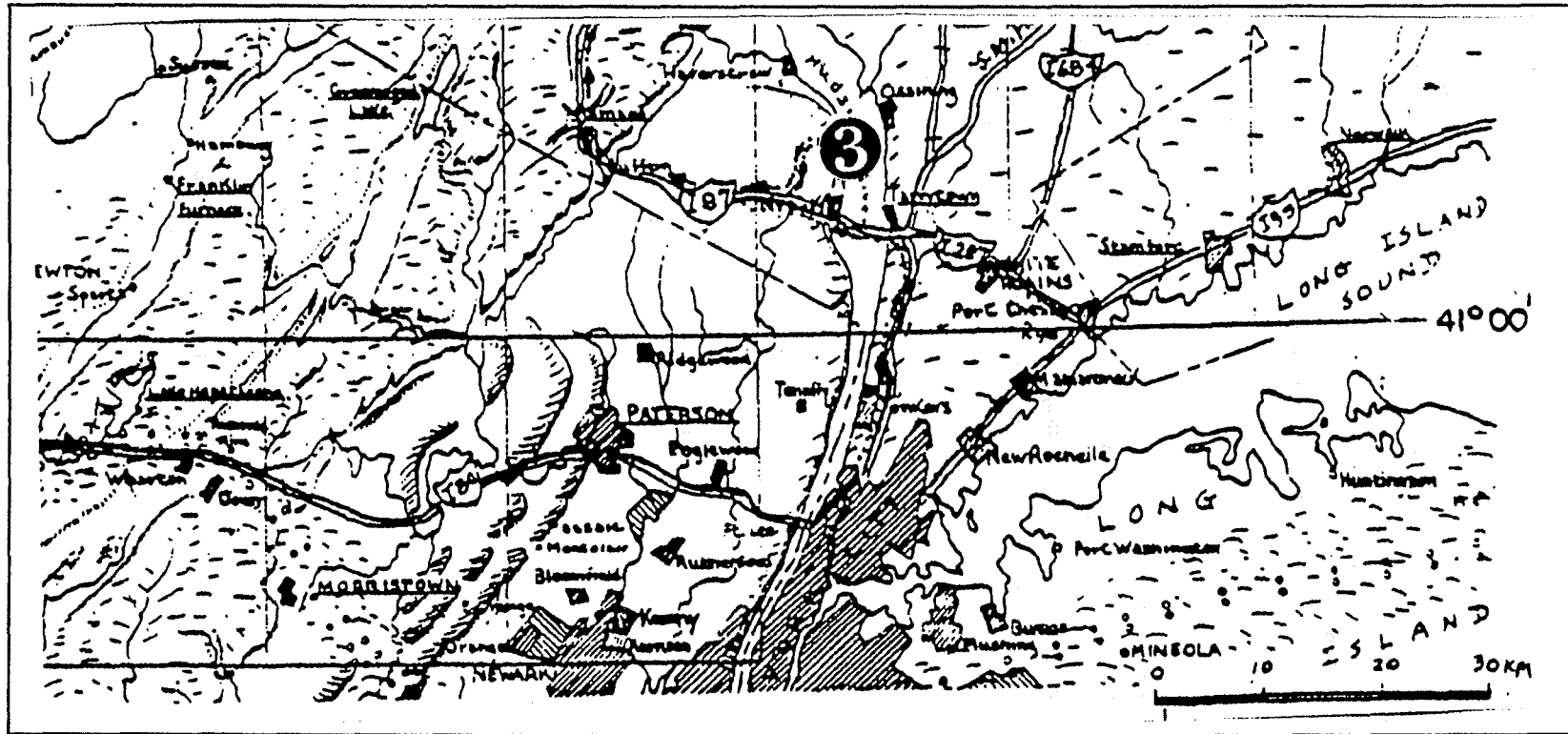
STOP 3. Nyack Landing, Upper Nyack

(SE part of Haverstraw 7 ½ minute quadrangle, along W shore of Hudson River at Long. 73°54'W, from Lat. 41°08'15" to Lat. 41°07'30"N). See Figure 5 for the location of STOP 3. Walk southward on gravel road, along floor of old quarry in Palisades dolerite. Take trail toward Hudson River from S end of quarry. Walk down to lower level and study exposures along lower trail. The level of the old quarry floor lies at an altitude of about 60 ft; the top of the cliff facing the quarry is at an altitude of 510 ft. Thus the face is about 450 ft high. The face extends downward nearly to the contact with the underlying basal Newark sandstones. The contact is not exposed but lies near altitude +50 ft. The descriptions at this stop follow Friedman, Sanders and Martini (1982).

The continuous exposure of dolerite in the face is a noteworthy display of cooling joints, which are inclined off the vertical about the same amount as the base of the sill dips westward, i.e., 12 to 15°. At this locality, no olivine zone is exposed. Farther south the olivine zone, 10 to 15 ft thick, is located about 50 ft above the base of the Palisades sill. The absence of the olivine zone here could mean one of several things: (1) This exposure includes the lower 450 ft of the sill but no such zone ever formed here; (2) This exposure does not include the lowermost 450 ft of the sill, but that much of some part of the interior of the sill lying above the lowermost 60 to 70 ft, hence the olivine zone may be present but is not exposed in the old quarry face. Alternative 2 implies that a fault follows close along the base of the face and throws down on the west by at least 70 ft.

The large institution directly opposite us on the east side of the Hudson River is Sing Sing, the notorious destination of prisoners "sent up the river" (from New York City). The wide expanse of wooded countryside between Ossining and Tarrytown is the Rockefeller family preserve, an area so large that it has been incorporated as a separate

Figure 5. Physiographic diagram drawn by Frank P. Conant, Wesleyan University in 1930's, with major roads added by J.E. Sanders, 1980. Shows the location of Stop 3.



town (Pocantico Hills). Nobody levies local taxes on the Rockefellers but other Rockefellers!

The Croton River enters the Hudson just S of Croton Point, to the NE of us. The till exposed on the tip of Croton Point itself has been interpreted by some as a lateral moraine, but we think this till is part of a drumlin having a N-S axis. Between the till and the mainland is a sandy deltaic deposit which formed when lake water occupied the Hudson Valley to altitude about +60 ft.

The sandstones exposed in a long strike section are situated about 1000 ft above the base of the Newark Group (Upper Triassic to Lower Jurassic)(based on projection from the section at the Tappan Zee Bridge). These sandstones probably belong to the Stockton Arkose (Upper Triassic to Lower Jurassic). The strata strike N20°W and dip 12°SW (determined on base of ledge overhanging the siltstone toward the S end of the exposure). Typical Stockton Arkose is a light gray pebbly coarse rock that contains large-scale cross strata indicating water flow toward the west. Such gray rock interfingers with red siltstones and sandstones containing less feldspar (or even zero feldspar), which form the Brunswick Formation. Farther SW the Newark sequence from base upward is Stockton, Locketong, Brunswick. Locketong, typically a tough black argillite deposit of a former lake, is not exposed north of the George Washington Bridge; the argillite disappears by interfingering with the sandstones and siltstones of the Stockton and Brunswick.

The bluff west of the trail exposes about 20 ft of strata, of which the thickest and most persistent unit is a maroon siltstone 6 to 8 ft thick. This unit is overlain and underlain by various sandstones. At the N end of the exposure only the overlying sandstones are present. These include (upward) a coarse pebbly laminated sandstone about 1 ft thick, a laminated, reddish medium-grained sandstone, 2 to 3 ft thick, and 6 to 8 ft of coarse-grained pebbly sandstone having prominent cross strata dipping (now) 28° toward the direction of S45°W (225° true on a 360° scale). The original dip of the cross strata is about 16°. Hence these are considered to be accretion-type cross strata (in the sense of Imbrie and Buchanan, 1965), of the kind that form by the advance of "washed-out sand waves" (features transitional between the "regular" sand waves of the lower flow regime and the plane-bed condition of the lower part of the upper flow regime).

Below the siltstone unit is a bed, 1 to 1.5 ft thick, composed of greenish, poorly sorted conglomeratic arkose, almost a "pebbly mudstone." Next below is a lenticular arkose having a maximum thickness of about 2 ft.

The interbedding of the siltstones and sandstones probably resulted from the action of a floodplain meandering river. One usually tends to expect such rivers to deposit the coarse sediments in channels and the fine sediment on the floodplain. As the channels migrate, a sheet of sediment is deposited consisting of what has been termed a point-bar sequence. This sequence begins with a channel-floor lag at the base and passes upward through various deep-channel and shallow-channel deposits whose thickness equals the depth of flow in the former channel. Such sequences have been much discussed under the heading of "fining-upwards cycles" (Allen, 1965b; also Friedman, Sanders, and Kopaska-Merkel, 1992).

Closely associated with this typical channel-migration succession are deposits of natural levees and fan-like bodies of coarse sediment that spread over the floodplain from crevasses in the levees where floodwaters erode a gap through the levees. These fans have been termed splay deposits (or crevasse splays). (See summary paper dealing with alluvial sediments by Allen, 1965a).

The upper sandstones west of the trail do not seem to be part of a typical fining-upward cycle deposited by a migrating channel. The laminated, medium-grained sandstone just above the siltstone may be a natural-levee deposit and the coarse, cross-bedded sandstone next above may be a crevasse-splay (idea suggested by John Connolly). The coarse sandstone forms a series of imbricate, overlapping lenses, the upper ones of which extend farther southward than the lower ones. Thus, instead of being incised into the siltstone as in a channel, these sands prograde over the siltstone as would the sediments of a growing fan (or the foreset beds of a delta lobe).

The sandstones underlying the siltstone are not exposed enough to be analyzed in detail. The lenticular sandstone, previously interpreted as a "double-channel" are here considered to be a depositional bedform having positive

relief, a sort of longitudinal sandbar with the long axis parallel to the main direction of current flow.

At the S end of the exposure sandstone and dolerite are in close juxtaposition. The sandstone lacks evidence of contact metamorphism and the dolerite is much too coarse grained for this contact relationship to be explained as intrusive. Accordingly, J.E. Sanders interprets this contact as a normal fault which strikes about NW, is nearly vertical, and throws down on the west by at least 70 ft; this much displacement is inferred in order to drop the olivine zone out of sight. Thus, J.E. Sanders presumes that the olivine zone is present, but is not exposed.

Return to vehicles..

REFERENCES

- Allen, J.R.L., 1965a, Sedimentation to the lee of small underwater sand waves -an experimental study: *Jour. Geology*, v. 73, p. 97-116.
- Allen, J.R.L., 1965b, Some simple experiments to demonstrate wave-motion, flow-separation, helicoidal flow and stationary vortices: *Jour. Geol.Education*, v. 13, p. 78-80.
- Berkey, C.P., 1933, New York City and vicinity: *International Geol. Congress, 16th session, United States, Guidebook 9, New York Excursions*, 151 p.
- Cornet, B., 1977, The palynostratigraphy and age of the Newark Supergroup [Ph.D. thesis]: University Park, Pennsylvania State University, 504 p.
- Dana, J.D., 1883, The origin of the Jura-Trias of eastern North America: *American Journal Science*, 3rd series, v. 25, p.383-386.
- Friedman, G.M. and Sanders, J.E., 1978, *Principles of Sedimentology*. New York, John Wiley & Sons, 792 p.
- Friedman, G.M., Sanders, J.E., and Kopaska-Merkel, D.C., 1992, *Principles of Sedimentary Deposits: Stratigraphy and Sedimentology*. New York, MacMillan Publishing Company, 717p.
- Friedman, G.M., Sanders, J.E., and Martini, I. P., 1982, Excursion 17A: Sedimentary Facies: Products of sedimentary environments in a cross section of the classic Appalachian Mountains and adjoining Appalachian Basin in New York and Ontario, *International Assoc. of Sedimentologists Guidebook, 11th International Congress on Sedimentology, McMaster University, Hamilton, Ontario, August 22-27*, 268 p.
- Froelich A. J, and Olsen, P. E, 1984, Newark Supergroup, a revision of the Newark Group in eastern North America: *U.S. Geological Survey Bulletin 1537-A*, p. A55-A58.
- Husch, J.M., and Hozik, M.J., 1988, Geology of the Central Newark Basin. *Fifth-Annual Meeting of the Geological Association of New Jersey, (October 7-9 1988), Field Guide and Proceedings*, Rider College, Lawrentville, N.J.331 p..
- Imbrie, J., and Buchanan, H., 1965, Sedimentary structures in modern carbonate sands of the Bahamas, p. 149-172, *in* Middleton, G.V., ed., *Primary sedimentary structures and their hydrodynamic interpretation*: Tulsa, Okla., *Soc. Econ. Paleontologists Mineralogists, Spec. Publ. 12*, 265 p.
- Jaffe, H.W., and Jaffe, E.B., 1973, *Bedrock geology of the Monroe quadrangle, Orange County, New York*: New York State Museum and Science Service, *Map and Chart Series 20*, 74 p. (includes colored geologic map on scale of 1:24,000).

Manspeizer, W., 1988. Triassic-Jurassic rifting and opening of the Atlantic: An overview, *in* Manspeizer, W. ed. Triassic-Jurassic rifting, continental breakup, and the formation of the Atlantic Ocean and passive margins, Part A: Amsterdam, Netherlands, Elsevier, p. 41-79.

Olsen, P. E, 1980, Triassic and Jurassic formations of the Newark basin. *in* Manspeizer, W., ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association, 52nd Annual Meeting, Newark; New Jersey, Rutgers University, p. 2-39.

Olson, P.E., Kent, D.V., Cornet, Bruce, Witte, W.K., and Schlische R.W., 1996, High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America): Geological Society America Bulletin, v. 108, p.40-77.

Sanders, J.E., 1960, Structural history of Triassic rocks of the Connecticut Valley belt and its regional implications: New York Academy of Sciences, Transactions, Series II, v. 23, p. 119-132.

Sanders, J.E., 1974, Geomorphology of the Hudson Estuary: New York Academy of Sciences, Annals., v.250, p. 5-38.

Van Houten, F. B, 1969, Late Triassic Newark Group, north-central New Jersey and adjacent Pennsylvania and New York, *in* Subitzki, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions, New Brunswick, New Jersey (Geological Society of America, Field Trip 4): Atlantic City, New Jersey, Rutgers University Press, p.314-347.

Faint, illegible text, possibly bleed-through from the reverse side of the page.

SERPENTINITES OF NEW YORK CITY AND VICINITY

John H. Puffer

Dept of Geology

Rutgers Univ.

Newark, New Jersey, 07102

ABSTRACT

A discontinuous chain of early Paleozoic serpentinites are exposed along the Appalachian Mountains from Quebec Canada, through the New York City area, and into the southeastern states. The Geologic Map of New York, 1970, (Lower Hudson Sheet) shows five serpentinite bodies in the New York City Area: Staten Island, Hoboken, Manhattan, New Rochelle, and Port Chester that are part of this chain. The Staten Island and Hoboken serpentinites are the largest of the five bodies and are known to contain considerable asbestos (Puffer and Germine, 1994). The serpentinites of Staten Island and Hoboken consist of about 95 percent serpentine with minor but highly variable olivine, anthophyllite, talc, magnetite, and trace amounts of several additional minerals.

The chemical range is typical of metamorphosed harzburgite and dunite suites although some unusually low CaO and Al₂O₃ values may be due to hydrothermal leaching and re-precipitation as a network of amphibole and carbonate veins in shear zones.

The mode of emplacement of the New York area serpentinites is controversial but most evidence tends to favor the Taconic obduction of the base of a Iapetus ophiolite sequence. This would force the placement of the New York area serpentinites into the Taconic suture zone (Cameron's Line) between Hartland terrain (C-Oh) and Manhattan-C terrain (C-Om).

The chrysotile content of New York area serpentinites, as determined using a combination of polarized light and transmission electron microscopy and XRD techniques, is highly variable but is typically about 15 to 40 volume percent of the rock (Puffer and Germine, 1994). The widespread distribution of asbestos minerals in the serpentinites may lead to contamination of water and air supplies wherever exposures are being eroded.

GEOLOGIC SETTING

The discontinuous chain of serpentinites along the Appalachian Mountains that extends from Quebec Canada into the southeastern states (Figure 1) passes through the New York City area. The Geologic Map of New York, 1970, (Lower Hudson Sheet) shows five serpentinite bodies in the New York City Area: Staten Island, Hoboken, Manhattan, New Rochelle, and Port Chester that are part of this chain (Figure 2). The Staten Island and Hoboken serpentinites are the largest of the five bodies.

Lyttle and Epstein (1987) stratigraphically place the Staten Island meta-peridotite and the Hoboken serpentinite bodies at the base of the Hartland terrain (Figure 3) on a Taconic suture that overthrusts

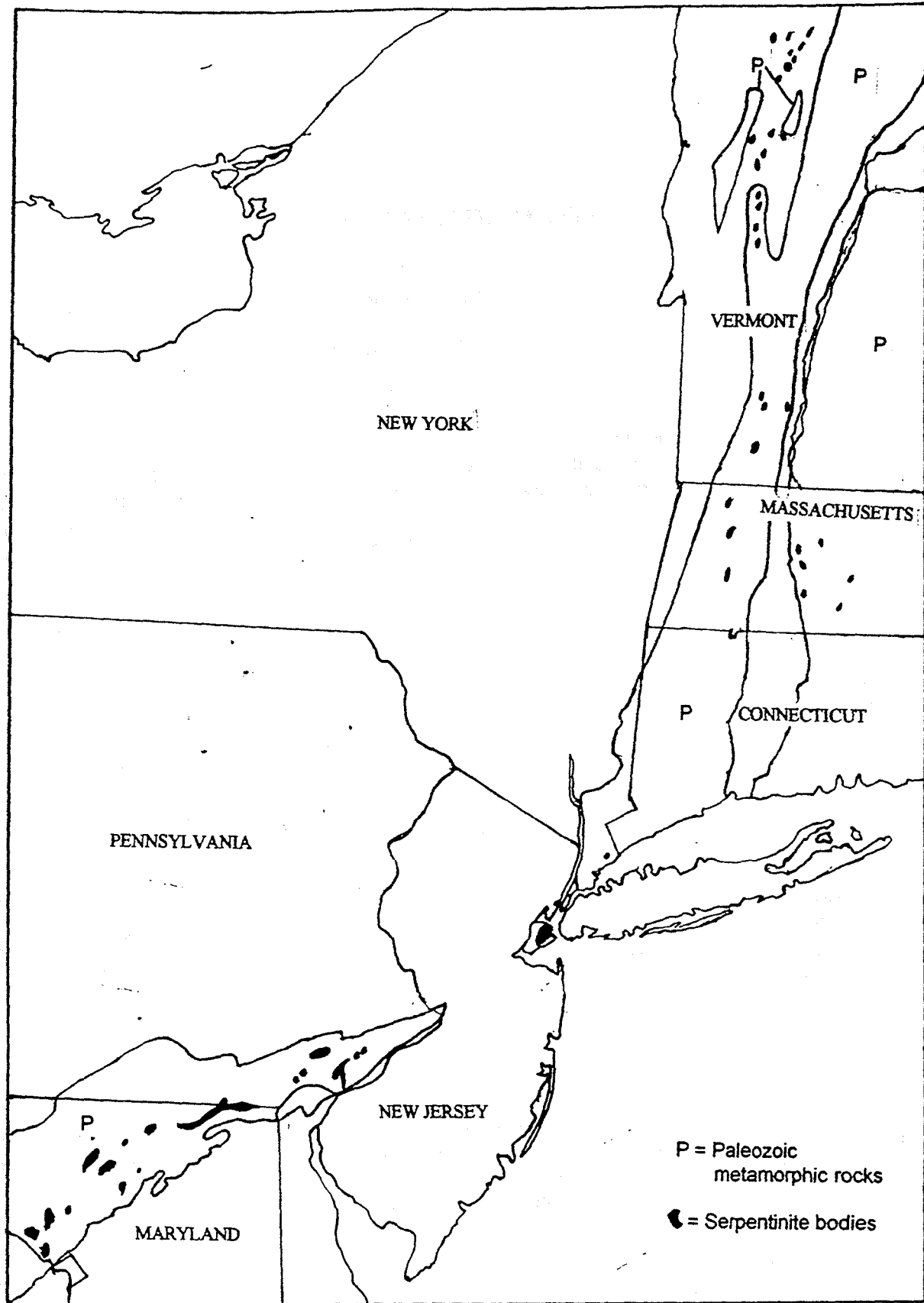


Figure 1. Serpentinite occurrences in the central and northern Appalachians appearing on the USGS "Tectonic Map of the United States" (1962).

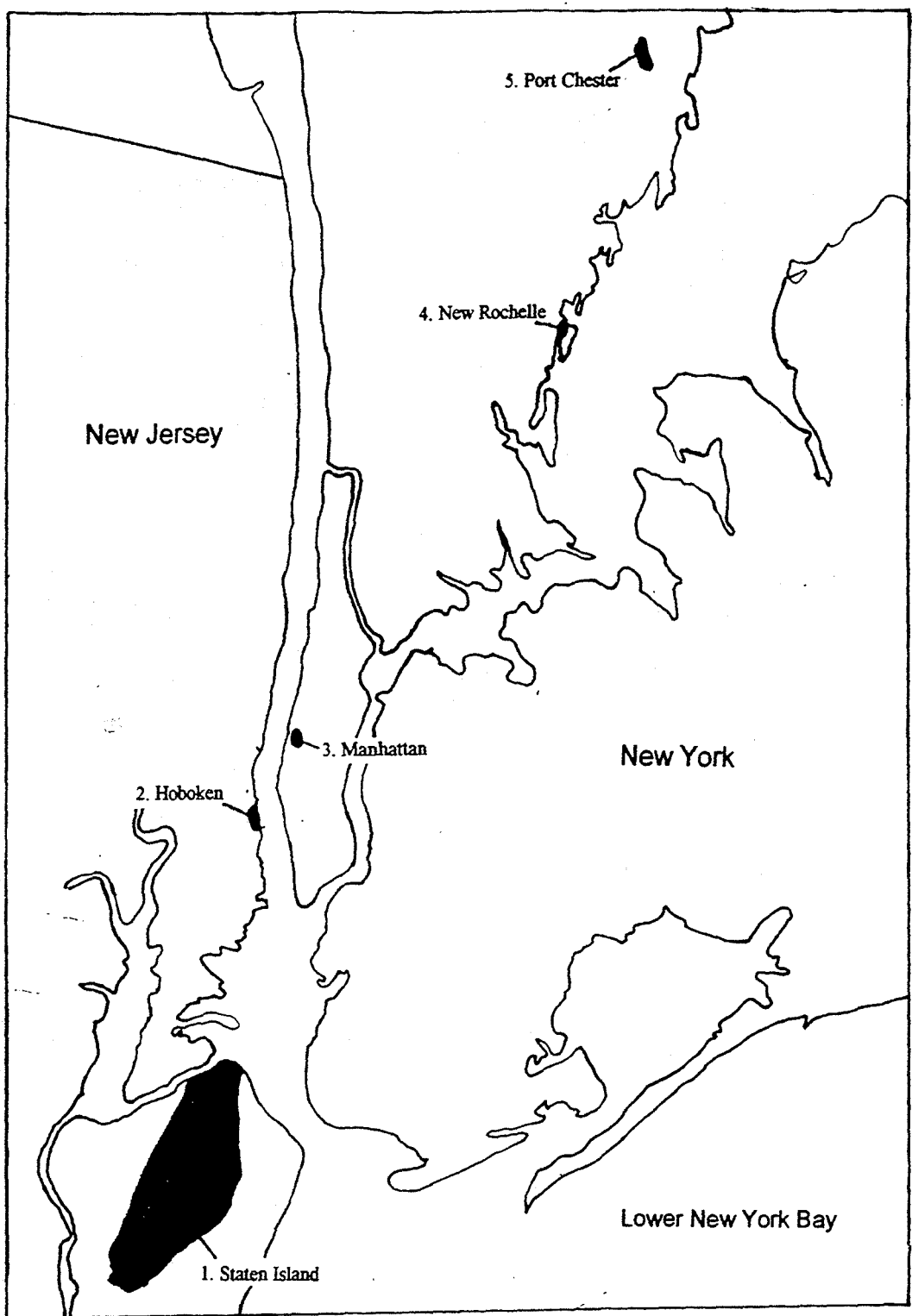


Figure 2. The Serpentinites of New York City and vicinity, based on occurrences mapped on the "Geologic Map of New York", Lower Hudson Sheet (1963).

Member C of the Manhattan Formation. The tectonic suture is presumably Cameron's Line which is defined as the tectonic boundary of the western part of the Appalachian core zone. Merguerian (1983) interprets Cameron's Line as a ductile shear zone or terrain suture that developed at the base of a west-facing Taconic accretionary prism separating Manhattan C from Hartland terrain (Mose and Merguerian, , 1985). Member C of the Manhattan Schist is not exposed on Staten Island but Hartland schist is the bedrock along the eastern edge of the meta-peridotite body on the northern end of the island. Member C of the Manhattan Formation contains common amphibolite lenses (meta-basalt) that were described by Hall (1976) as Member B of the Manhattan Formation. The Hartland Formation also contains common amphibolite lenses that chemically overlap with Member B amphibolite (Eicher and others, 1994; Merguerian and Puffer, unpublished data). Member C is a biotite schist that is petrologically and chemically similar to typical Hartland Formation (Puffer and others, 1994) and both schists overthrust still more biotite schist, the mid-Ordovician Member A of the Manhattan Formation. In addition to the confusing formation names, the stratigraphy is further complicated by overlapping chemical compositions, mineralogies, and petrologic textures among the schists.

For purposes of organizing these units into a tectonic framework, however, it is important to determine their depositional setting. Baskerville (1989) interprets Manhattan C and B as metamorphosed allochthonous transitional slope meta-sediments and discontinuous volcanics in contrast to the meta-eugeosynclinal deep-oceanic shale and interstratified volcanic of the Hartland Formation (Merguerian and Sanders, 1991). The schists of Manhattan A are interpreted as autochthonous miogeosynclinal basement cover rocks. The interpretation of the Hartland Terrain as deep-oceanic rock is based in part on its association with the Staten Island meta-peridotite which Baskerville, 1989 views as part of an ocean-floor ophiolite suite.

PETROLOGIC DESCRIPTIONS OF THE FIVE NEW YORK AREA SERPENTINITES

In general, rocks from each of the five New York area serpentinites are indistinguishable and are probably genetically related.

1. The Staten Island Serpentinite

The Staten Island serpentinite is a wide lens shaped body (Figure 2) that trends NE-SW and comprises the bedrock of northern Staten Island. It is well exposed along a prominent ridge that extends from the northeastern shore of the island toward the southwest. The serpentinite body appears on most geologic maps as either, Cambrian, Cambro-Ordovician, or "relative age unknown". Lytle and Epstein (1987) position the Staten Island Serpentinite above Member C of the Manhattan Schist and at the base of the Hartland Formation but contact relationships are not exposed.

The serpentine content of 36 serpentinite rock samples from 27 locations (Figure 4, with typical examples on Table 1) averages 66 percent lizardite and 27 percent chrysotile (asbestos). Minor talc, anthophyllite, olivine, chromite, and magnetite makes up the remaining 7 percent. The average olivine content of the Staten Island meta-peridotite is about 5 percent. A few samples contain as much as 50 percent olivine but it is absent from most samples. Where present, olivine typically occurs as relic anhedral micro-islands surrounded by serpentine that has replaced most of the individual grains or as larger grains veined by olivine.

Table 1 Thin Section Modes of Serpentinites and Anthophyllite Schist from Staten Island locations (Fig. 1), New York.

	4e	5b	7b	8b	10c	11c	13c
Lizardite	60		65	74	65	4	85
Chrysotile	10		15	15	10	1	15
Anthophyllite		98				65	
Talc	10		5		4	15	tr
Carbonate			5		11	5	tr
Olivine				10			tr
Opaque Oxide	20	2		1	10	10	tr

	14c	15b	15c	21b	23a	27b
Lizardite	60	50		62	70	48
Chrysotile	15	25		18	15	30
Anthophyllite			90			tr
Talc	5	5		5		3
Carbonate	10			10	tr	tr
Olivine		20		tr	15	15
Opaque Oxide	10	5	10	5	tr	4

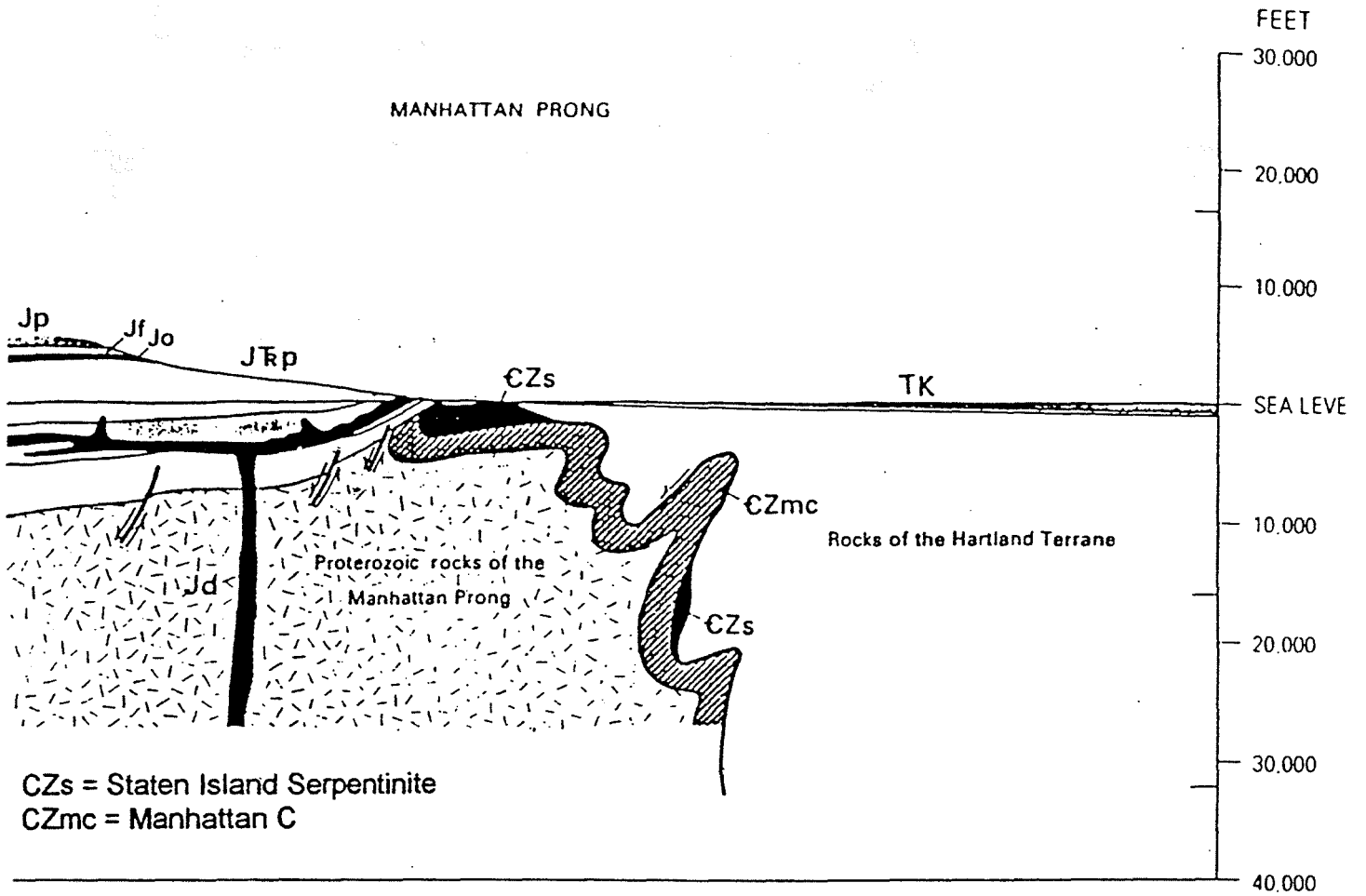


Figure 3. Cross-section through Staten Island Serpentinite (after Little and Epstein, 1987)

Electron microscopic analysis of ten samples from the I-278 outcrop (sample 8, Figure 4), indicates a chrysotile asbestos content of 54 volume percent although it is absent at a few locations. In sample 1 (Figure 4) some evidence of minor antigorite was also found.

Clues as to the original protolith are found in some of the olivine rich samples, particularly from the north-central portion of the ultramafic body. Unaltered pyroxene is rarely observed in any of the rock but phenocrysts of pyroxene that have been partially or completely altered to intergrowths of chlorite, talc and oxide are common in some of the massive serpentinite. These altered pyroxene phenocrysts make up about 15 % of some samples and indicate that such rock was a harzburgite as originally suggested by Behm (1954). However, most samples of massive serpentinite, where primary igneous textures are preserved, do not contain evidence of pyroxene and are probably dunite.

The chemical range of samples from 20 of the largest exposures of serpentinite from Staten Island includes 35 to 44% SiO₂, 0.1 to 0.8% Al₂O₃, 6 to 10% FeO, 34 to 42% MgO, 0.03 to 3.3% CaO, 0.07 to 0.26% Cr, and 0.18 to 0.36% Ni (Table 2). The chemical data confirm a harzburgite and dunite protolith interpretation although some unusually low CaO and Al₂O₃ values may be due to hydrothermal leaching and re-precipitation as a network of amphibole and carbonate veins in shear zones.

2. The Hoboken Serpentinite.

The Hoboken serpentinite body is a lense shaped exposure about 0.7 miles long and 0.15 miles wide located along the Hudson River (Figure 2). The serpentinite is particularly well exposed at Castle Point, along a steep slope into the Hudson at the east edge of the Stevens Institute of Technology campus. The serpentinite body is in fault contact with Member C of the Manhattan Schist (Lyttle and Epstein, 1987). The fault (Cameron's Line) is positioned at the western edge of the Hoboken Serpentinite and extends to the south where it wraps around the Staten Island Serpentinite.

The chemical composition (Table 1) and mineralogy of most of the Hoboken serpentinite exposure is indistinguishable from typical Staten Island serpentinite, although subtle differences can be found, some of which are described in road log section of this chapter.

3. Manhattan serpentinite body.

The Manhattan body is mapped as a small circular area, (Figure 2). The original mapping of the Manhattan serpentinite body may have been based on observations along the Rail-cut near 57th street, or at the excavation sites of buildings that later became John Jay College of Criminal Justice and Roosevelt Hospital. In both cases, however, any previously exposed bed-rock has since been sealed off, paved or landscaped. Baskerville (1982) in describing the Manhattan serpentinite body reports "The Manhattan pod is now covered by streets and buildings."

The Manhattan serpentinite is also described by Cozzens (1843), Britton (1881), Gratacap (1904), and Merrill and others (1902). The credibility of each of these researchers is good (particularly Merrill) and it is unlikely that serpentinite was misidentified or incorrectly mapped. Serpentinite is a distinctive rock that is readily identified by experienced geologists. The Manhattan serpentinite is surrounded by Manhattan Formation (Member C) and may be a tectonic lens within Member C; although due to

Table 2. Chemical compositions of Serpentinites from Staten Island, NY, Hoboken, NJ, and Red Hill, Calif. compared with ophiolite compositions.

samples	New York			New Jersey			California			PCCI	Harzburg	Dunite
	Staten Isl.			Hoboken			Red Hill			1	ave. of 31	ave. of 32
	ave. of 20	max.	min.	ave. of 6	max.	min.	ave. of 45	max.	min.			
Wt. %												
SiO ₂	39.36	44.25	35.00	39.48	43.23	36.78	39.12	44.76	35.21	41.90	43.86	43.86
TiO ₂	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.12	0.01	0.02	0.02	0.01
Al ₂ O ₃	0.39	0.81	0.10	0.42	0.75	0.08	0.33	3.03	0.09	0.74	0.77	0.36
FeO _t	7.67	9.99	5.75	7.74	8.85	6.22	7.95	8.95	5.89	7.81	8.19	8.52
MgO	39.66	41.95	34.20	40.36	42.42	36.95	39.85	50.51	33.79	43.18	45.41	49.50
MnO	0.11	0.13	0.08	0.12	0.15	0.10	0.13	0.16	0.08	0.12	0.11	0.14
CaO	0.09	3.30	0.03	0.11	1.89	0.04	0.11	3.93	0.00	0.51	0.73	0.30
Na ₂ O	0.02	0.27	0.01	0.02	0.17	0.01	0.07	0.45	0.00	0.01	0.11	0.03
K ₂ O	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.09	0.00	0.00	0.02	0.05
P ₂ O ₅	0.00	0.01	0.00	0.00	0.01	0.00	0.004	0.01	0.00	0.00	0.00	0.00
LOI	11.94	18.25	6.20	11.41	12.96	7.42	11.85	17.00	4.63	5.62	0.00	0.00
Total	99.26	100.33	98.27	99.68	100.40	98.97	99.444	100.23	98.37	99.91	100.00	100.00
ppm												
Co	92	135	64	96	140	66				112		
Cr	2184	2571	686	2310	2597	2156	2895	7051	1395	2730	4300	5400
Cu	8	11	1	7	12	4	36	74	6	11		
Ni	2495	3603	1780	2521	2684	2361	2531	3341	1542	2339	3400	3000
Sr	2	7	1	2	6	3				0	1	4
V	25	27	18	29	34	23				30		
Zn	36	42	30	33	39	26				36		
Zr	7	9	6	8	10	5				7		

- Notes:
1. Staten Island samples (after Puffer and Germiné, 1994), Hoboken samples, and California samples were analyzed with Rigaku 3030 XRF unit at Rutgers/Newark.
 2. PCCI is the primary USGS peridotite standard used for analyses performed at Rutgers/Newark.
 3. Harzburgite and Dunite data are averages of meta-harzburgites and meta-dunites from ophiolites recalculated to 100 % anhydrous. (Hyndman, 1989).

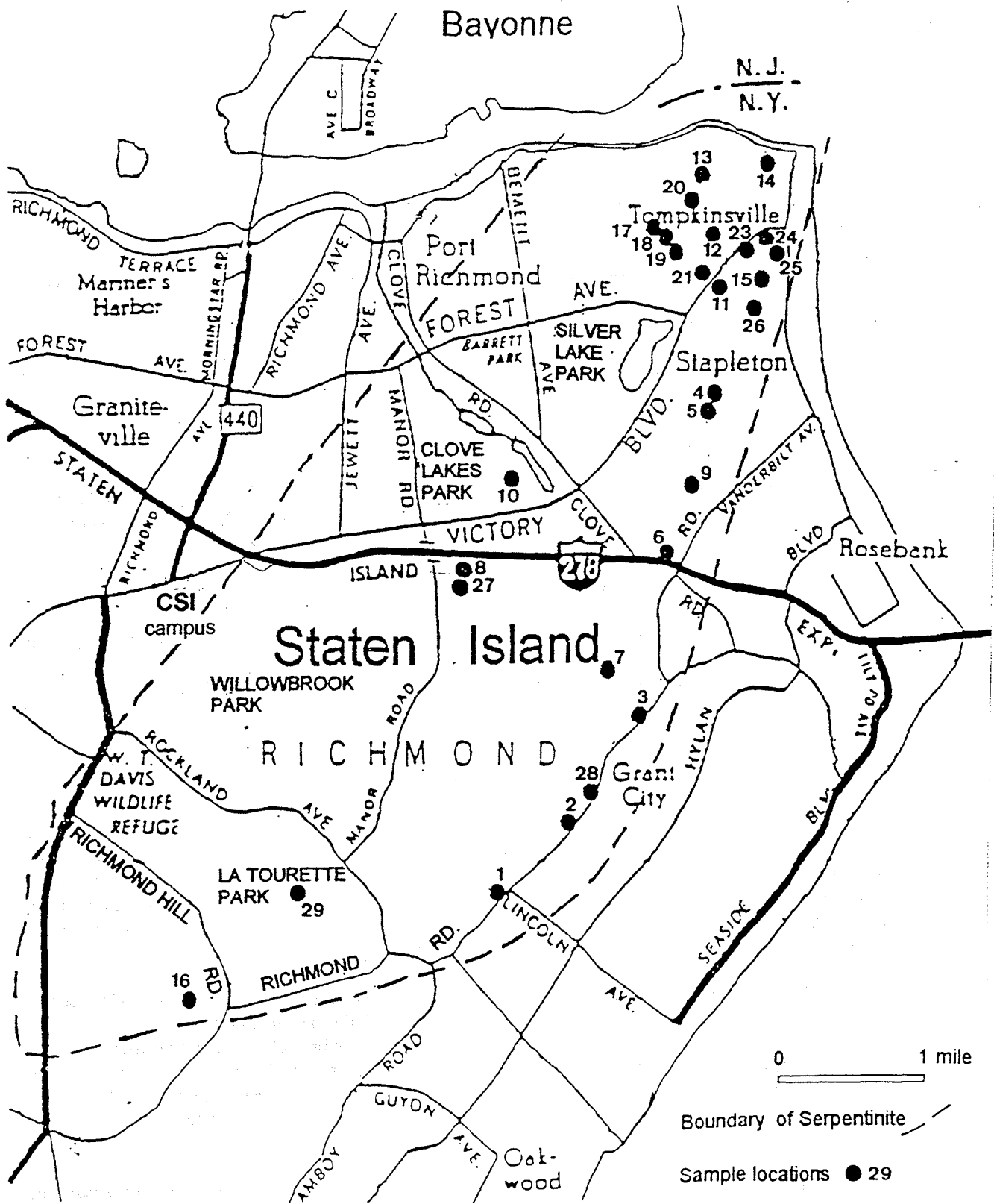


Figure 4. Staten Island Serpentinite: approximate boundaries and sample locations (after Puffer and Germine, 1994).

difficulties in mapping the extremely complex position of Cameron's Line, its placement on the Line can not be ruled out.

A small sample of Manhattan serpentinite was provided by Joseph Peters from the petrology collection of the American Museum of Natural History and was analyzed by Dr. Mark Germiné for asbestos content at Rutgers/Newark. He determined that the sample contained a green serpentine-like material but x-ray and thin section analysis was inconclusive due mainly to small sample size. Chlorite could not be ruled out as an alternative to the probable serpentinite content of the sample. Chlorite and serpentine have overlapping physical and chemical properties and are not easily distinguished.

4. The New Rochelle Serpentinite Body

The New Rochelle serpentinite is a small oval body about 0.5 by 0.25 miles across. It has been mapped along Echo Bay Drive near Echo Bay in Westchester Co about 1.5 miles north of Bronx Co (Figure 2). Very little geologic work has been done on the occurrence since Merrill and others (1902).

5. The Port Chester Serpentinite Body

The Port Chester serpentinite body is a large occurrence almost one mile long and about one-half mile wide (Figure 2) that appears on maps drafted by Merrill and others (1902) and. "The Geologic Map of New York", 1970, (Lower Hudson Sheet) surrounded by "Schists and gneisses, undivided ... relative ages unknown".

ORIGIN AND MODE OF EMPLACEMENT

The interpretation of the Hartland Terrain as deep-oceanic rock is based in part on its association with the Staten Island serpentinite which Baskerville (1989) interprets as part of an abducted ocean floor ophiolite suite. Alternatively, the Staten Island serpentinite may be a metamorphosed olivine cumulate zone formed as part of a layered gabbroic magma chamber or an independent intrusion such as some interpretations of the serpentinites of the Pennsylvania piedmont (including Gates, 1988), although clear evidence is not presented.

Evidence of any clear association with the fractionated gabbroic rocks of a mafic intrusion such as thermal metamorphism at serpentinite contacts or xenoliths within the serpentinite is also absent from Staten Island. In addition, if the serpentinite body was formed at the base of a gabbroic intrusion before it was tectonically displaced, some evidence of the kind of tholeiitic trend fractionation that is a characteristic of layered gabbroic plutons might be preserved. The absence of any clear fractionation trend (Puffer and Germiné, 1992) or any clear layering, such as the cryptic and rhythmic layering of the Bushveld, argues against such a mode of origin.

Merguerian and Sanders (1994) also discuss each of the two principal emplacement mechanisms that have been proposed for the Staten Island serpentinite and are diplomatically non-committal, but seem to favor ophiolitic emplacement over intrusive plutonism. They point out that if the Staten Island body was a pluton its chilled igneous margins and any contact metamorphism would have been obscured by subsequent metamorphism and faulting. Therefore, the absence of such contact relationships are "difficult,

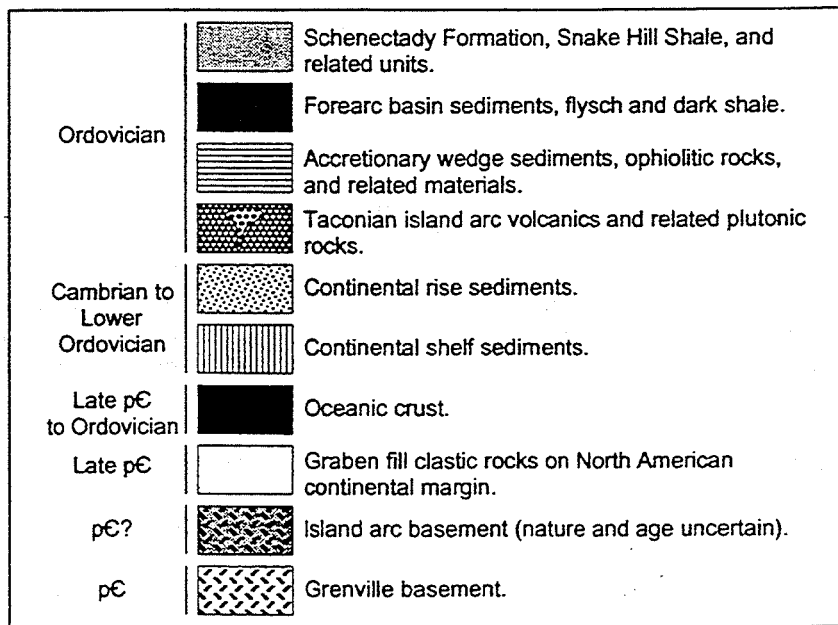
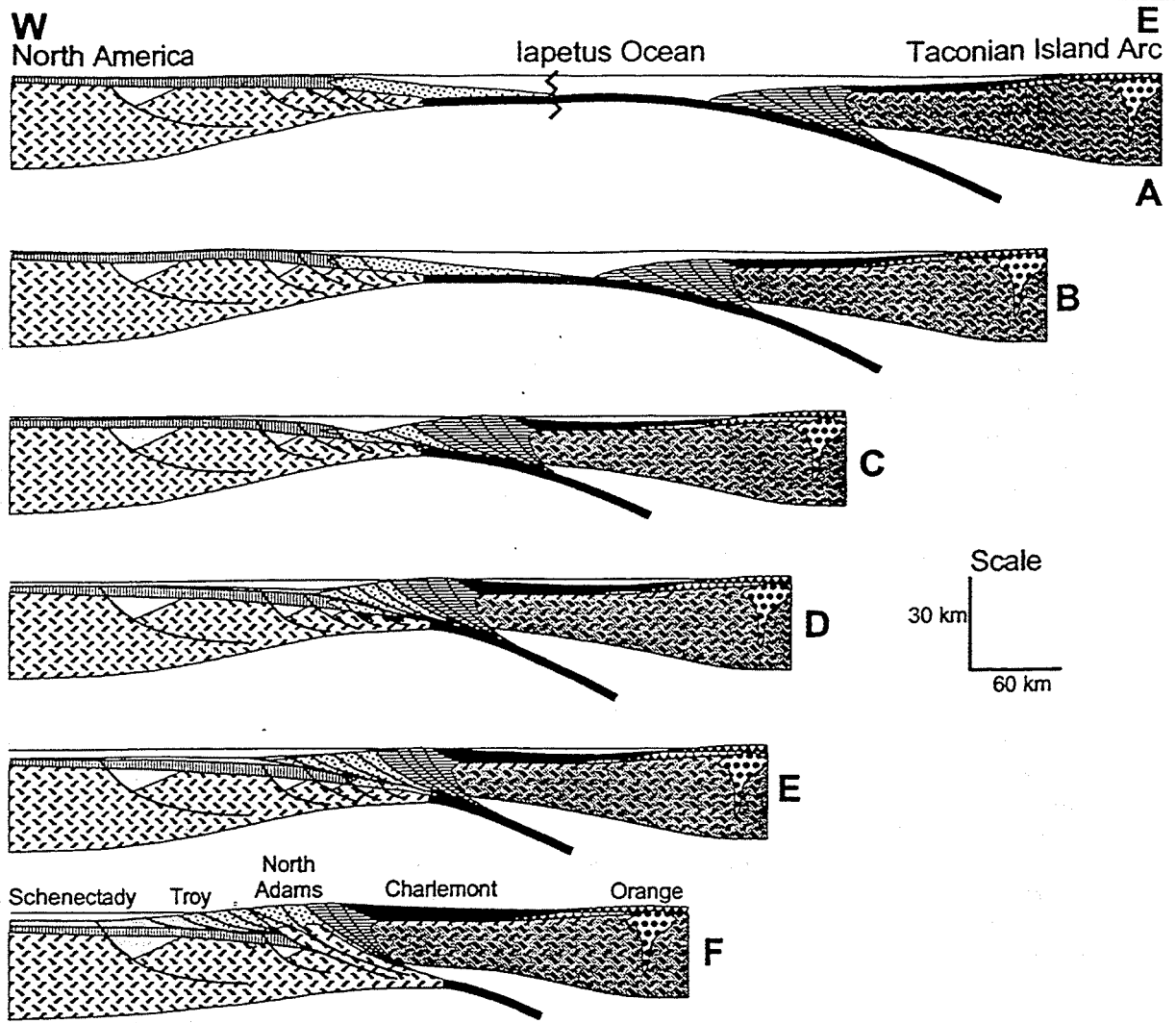


Figure 5. Schematic cross sections showing the tectonic development of the Taconic development of the Taconic Orogen from Early Middle Ordovician (A) to present (F) adapted from Rowley and Kidd (1981).

if not impossible to prove" (Merguerian and Sanders, 1994).

However, most well documented peridotite plutons are either emplaced as isolated, hypabyssal, hot-spot related diatremes such as the lherzolite of Kilberns Hole, New Mexico and the kimberlite mines of South Africa, or as integral portions of layered gabbroic plutons such as those associated with most worldwide chrome and platinum mining districts. In contrast the New York area serpentinites are chemically and tectonically unlike any known hot-spot related lherzolite or kimberlite and are missing all of the cumulate layering of oxides (particularly chromite) and sulfides that are characteristics of layered gabbroic plutons. If the New York bodies were tectonically removed from a layered gabbroic pluton, pods of chromite or sulfide cumulate might be expected.

Instead all evidence points to emplacement as an abducted layer-three portion of a Iapetus ocean floor ophiolite during the Taconic orogeny. Evidence includes:

1. The New York area serpentinites are associated with meta-sediments and meta-volcanic rocks of probable eugeosynclinal to deep-oceanic shale and interstratified arc volcanic affinity (the Hartland Formation). The associated Cambro-Ordovician schists may include layer one melange and/or flysch sedimentary wedges associated with Taconic subduction. The tectonic setting of the New York City area, in general, resembles the tectonic setting of western New England (Figure 5) as convincingly described by Rowley and Kidd (1981) as a Taconic subduction zone that includes abducted ophiolites. But as noted by Moores (1981) in his classic description of overthrust belts where deep-water or oceanic rocks are thrust over continental marginal sequences "Evidence of ophiolite complexes may be absent or only fragmentary. Examples of such occurrences include the the Antler sequence in the Cordillera, the Taconic system of the northern Appalachians, and the Ouachitas system." Moores (1981), however, describes a second type of overthrust where decollement-style fold and thrust belts of miogeosynclinal rocks are thrust over shelf deposits. He includes the Appalachian Valley and Ridge Province, extending from Alabama to New York as an example of this second type. As applied to New York City the Hartland/Manhattan-C suture (Cameron's Line) may be an example of the first type while the St Nicholas Thrust over Manhattan-A and Inwood Marble may be an example of the second type.
2. The lithology of the schists and amphibolites associated with the New York City area serpentinites is also very similar to the schists and amphibolites associated with the ophiolites of California. There is a growing consensus that California was gradually assembled by the accretion of exotic terrains that are bordered by suture zones characterized by serpentinite lenses (Coleman, 1977; Ehrenberg, 1975; and Saleeby, 1990). Virtually all of the serpentinite of California are generally interpreted as ophiolites; and to the extent that most of the serpentinites of eastern North America, including those of the New York City area, are petrologically and geochemically virtually identical to the Californian serpentinites (Table 1) it is quite likely that they are also ophiolites.
3. The ultramafic portion of all ophiolites consist of irregular pod shaped meta-dunite bodies contained within meta-harzburgite. Most of the Staten Island body is chemically equivalent to a meta-dunite although some rock chemically equivalent to meta-harzburgite is also present (Puffer and Germine, 1994).
4. Steiner (1995) has recently found what he interprets as ophiolite nodules in NYC Water Tunnel No. 3. through the Ravenswood Granodiorite. It has not yet been determined just how common these nodules are, but they may be significant.

Still another alternative interpretation has been offered by Germine (1990) who suggests that the Staten Island meta-peridotite cannot be an integral part of either the Manhattan schist or the Hartland Terrain because of the disparity in metamorphic grade. Germine (1990) interprets the Staten Island meta-peridotite as lower grade rock that was abducted between the two formations.

EXTENSIONAL STRUCTURAL ACTIVITY ?

The New York City area presently occupies a central position in the North American Plate with none of the structural activity typically associated with plate margins and no known source of extensional force (such as a hot-spot) that could generate active local motion. Hollick (1909), however, suggested that the eastern escarpment of the Staten Island serpentinite is fault controlled and that the development of serpentine-group minerals was related to shearing- and slippage along fault and shear surfaces. Merguerian and Sanders (1994) share this view. It is not clear if this fault scarp has been maintained by recent faulting that has raised the soft serpentinite through relatively hard schists that are presumably more resistant to erosion. The style of faulting, however, has been described as normal by Miller (1970), very unlike the compressional Taconic overthrusting that probably carried the Hartland terrain and the serpentinite over the schists of the Manhattan C.

The Staten Island serpentinite, therefore, is currently interpreted as a fault-bounded horst-block by Merguerian and Sanders, (1994) as originally suggested by Hollick (1909), Crosby (1914) and then by Miller, 1970. Behm (1954) has divided the Staten Island serpentinite into two zones: a highly sheared outer serpentinite characterized by an abundance of talc, anthophyllite, and magnetite, and a relatively massive, undeformed inner zone composed largely of partially serpentinized peridotite. Miller (1970) proposed that this inner zone is a horst displaced from the adjacent zones along NE trending normal faults. The western boundary of the inner zone is defined by the Silver Lake Fault and the eastern boundary by the Todt Hill fault.

If the Staten Island serpentinite and other New York area serpentinites have been uplifted along normal faults in an extensional setting, almost like salt diapirs, as suggested by an extrapolation of Miller's (1970) interpretation, than the age of the serpentinites would be older than the adjacent schists unless the source was younger rock located beneath allochthonous terrains. Depending on the reality or extent of such uplift, any interpretations pertaining to the Taconic activity (such as Figure 3) is subject to serious reexamination.

ENVIRONMENTAL CONSIDERATIONS

Despite the softness of most serpentinites, they tend to occur as topographic highs. This is presumably either because they are less susceptible to chemical weathering than adjacent rock or because they tend to transmit shearing because of their softness and get squeezed upward like viscous fluid. As transmitters of shearing the first environmental consideration for the New York City area would be the earthquake potential of serpentinite bodies.

Perhaps a more serious environmental consideration is the combination of both the topographic elevation of the serpentinite bodies and their asbestos content. Since most eastern North American and Californian serpentinites, including the serpentinites of the New York city area, are found as topographic highs or steep slopes, they are exposed to relatively high erosion rates. Although chrysotile tends to degrade during weathering to non-asbestiform alteration products, the constant downslope movement of freshly eroded serpentinite tends to spread chrysotile throughout the environment. This was found to be a particularly serious problem in the area near the asbestos (and mercury) bearing serpentinite of New Idria, California (Coleman, 1996). Some prudent caution may be also warranted around many of the large exposures and actively disturbed serpentinite excavations in the New York City area particularly at sites that are densely populated down wind or down stream.

The two major kinds of asbestos (as defined by Germine and Puffer, 1989) found in the serpentinites of the New York City area are chrysotile and to a lesser extent anthophyllite. Asbestos, however, is typically not easily recognized in samples of New York area serpentinite. In thin section, only lizardite was recognized in one Route 287 sample (Puffer and Germine, 1994), but using electron microscopic techniques, 50 percent chrysotile was measured as tubules with an outer diameter of 200-300 microns. Fiber lengths are typically only 0.5 to 6 microns which is beyond the resolution of polarizing light microscopy although some fibers are megascopic.

Two varieties of massive chrysotile asbestos were recognized in samples of serpentinite (Germine, 1981). One variety occurs in irregular masses and in veins ranging up to a centimeter in width. This type is composed of cross-fiber and randomly oriented fiber, and is often associated with olivine. The second variety has a pearly luster and platy to fine-grained meerschaum-like texture. This type of massive chrysotile occurs in veins, fracture fillings, and pore fillings. Electron microscopic examination indicates that it is composed of tubules with a diameter of 300 to 400 angstroms. Fiber lengths were generally less than one micron but up to 5 microns (Germine, 1981).

Asbestos with a megascopic fibrous appearance is much less common than massive varieties on Staten Island but occurs in veinlets typically less than 1 mm to 3 mm wide. The fibers are white to light green and silky. The veins readily fiberize and possess the flexibility that is a characteristic of asbestos (Germine and Puffer, 1989).

ACKNOWLEDGMENTS

I thank Alan Benimoff for his careful review of this manuscript and Mark Germine for several years of unsurpassable expert help and council with asbestos related issues.

REFERENCES

- Ageitos, D. M.; Buehler, S. C.; Eicher, J. C.; Rodda, T. D.; and Puffer, J. H., 1993, Serpentinites of Staten Island, New York and Castle Point, New Jersey: *Geochemistry: The Bulletin New Jersey Academy of Science*, v. 38, p. 17.
- Baskerville, C.A., 1982, The Foundation Geology of New York City, in Legget, R.F., ed., *Geology under cities: Geological Society of America Reviews in Engineering Geology*, v. 5, p. 95-117.

- Baskerville, C.A., 1987, Bedrock and engineering geologic maps of Bronx County and parts of New York: U.S., Geological Survey Open-File Report 87-360, scale 1:24,000, 3 sheets.
- Baskerville C.A., 1989, Geology and Engineering Geology of the New York Metropolitan Area: 28th International Geological Congress, Field Trip Guidebook T361, p. 39-48.
- Baskerville, C.A., 1989, New York City: Juxtaposition of Cambrian and Ordovician miogeoclinal-eugeoclinal rocks: in Baskerville, C.A., ed., Geology and Engineering geology of the New York Metropolitan Area: 28th International Geological Congress Field Trip Guidebook T361, p. 39-48.
- Behm J.J., 1954, The petrology of the serpentinite of Richmond County (Staten Island), N.Y., Proc. of the Staten Island Inst. of Arts and Sciences, v. 16, p. 1-39.
- Benimoff, A., Rice, S.B., Moore, P.B., and Sclar, C.; in prep., Picrolite from the Staten Island Serpentinite. submitted for review.
- Britton, N.L., 1881, On the geology of Richmond County, New York: New York Academy of Sciences, Annals, v. 2, p. 161-182.
- Cadmus, Denise; Hodgson, Richard; Gatto, Lisa M.; and Puffer, J. H., 1996, Geochemical Traverse Across Cameron's Line, Boro Hall Park, Bronx, New York, in Geology of Long Island and Metropolitan New York, Program with abstracts, Long Island Geologist, SUNY Stony Brook, p. 26-32.
- Coleman, R.G., 1996, New Idria Serpentinite: A Land Management Dilemma: Environmental & Engineering Geoscience, v. 2, p. 9-22.
- Cozzens, I., Jr., 1843, A geological history of Manhattan or New York island: New York, W.E. Dean, p. 11-39.
- Eicher, J. C., Ageitos, D. M., Seeber, F.C., Kaplan, C. H., Buehler, S. G., and Puffer, J. H., 1994, Geochemistry of the Amphibolites of Central Park, New York City: in Hanson, G.N., (editor), Geology of Long Island and Metropolitan New York, SUNY Stony Brook, p. 44.
- Germine, M., 1980, Determination of chrysotile content in serpentinites using X-ray diffraction (abstract): Bull. of the New Jersey Academy of Science, v. 25, p. 63-64.
- Germine, M., 1981, Asbestiform serpentine and amphibole group minerals in the northern New Jersey area: Masters Thesis, Geology Department, Rutgers University, Newark, New Jersey, 239 pp.
- Germine, M. and Puffer, J. H., 1989, Mineralogical definition of asbestos: Geological Society of America, Abstracts with Program, Northeastern Section, v. 21, p. 17-18.
- Germine, M., and Puffer, J. H., 1989, Origin and development of flexibility in asbestiform fibers: Mineralogical Magazine, v. 53, p. 327-335.
- Germine, M., and Puffer, J. H., 1990, Geochemistry of the New York Group Serpentinite. Empire State Geogram, abstract, v. 26, p. 16.
- Germine, M. Puffer, J. H., and Maresca, G. P., 1981, Water supply contamination from bedrock asbestos in the northern New Jersey area: Geological Society of America, Abstracts with Program, v. 13, No, 7. p. 458.
- Germine, M. and Puffer, J. H., 1989, Mineralogical definition of asbestos: Geological Society of America, Abstracts with Program, Northeastern Section, v. 21, p. 17-18.
- Gratacap, L. P., 1904, Geology of the City of New York, 2nd ed.: New York, N. Y., Henery Holt and Company, 119 p.
- Hall, L.M., 1968, Times and origin and deformation of bedrock in the Manhattan prong: in Zen, E-an, White, W.S., Hadley, J.B., and Thompson, J.B., eds., Studies of Appalachian geology: northern and maritime: Interscience Publishers, New York, p. 117-127.

- Hall, L.M., 1976, Preliminary correlation of rocks in southwestern Connecticut: in Page, L.R., ed., Contributions to the stratigraphy of New England: Geological Society of America Memoir 148, p. 337-349.
- Hess, H. H., 1955, Serpentines, orogeny, and epeirogeny, in Poldervaart, Arie, Ed., Crust of the Earth: Geological Society of America Special Paper 62, p. 391-407.
- Hollick, C. A., 1909, Notes in connection with specimens recently obtained from serpentines of Staten Island, N.Y.: New York Academy of Sciences, Annals, v. 19, p. 315-317.
- Imfeld, K. L.; Kaplan, C. H.; Kosinski, J. S.; Seeber, F. C.; and Puffer J. H., 1993, Serpentinities of Staten Island, New York and Castle Point, New Jersey: Petrology: The Bulletin New Jersey Academy of Science, v. 38, p. 17.
- Little, P.T., and Epstein, J.B., 1987, Geologic Map of the Newark 1 degree X 2 degree Quadrangle, New Jersey, Pennsylvania, and New York, Map 1-1715, U.S. Geological Survey.
- Maresca, G.P., Puffer, J.H., and Germine, M., 1983, Chrysotile asbestos content of Silver Lake Reservoir, Staten Island, New York: Geological Society of America Abstracts with Programs, v. 15, no. 3, p. 138.
- Maresca, G.P., Puffer, J.H., and Germine, M., 1984, Asbestos in lake and reservoir waters of Staten Island, New York: source, concentration, mineralogy, and size distribution: Environmental Geology and Water Science, v. 6, p. 201-210.
- Maresca, G. P., Puffer, J. H., and Germine, M. 1983, Chrysotile, asbestos content of Silver Lake Reservoir, Staten Island, New York: Geological Society of America, Abstracts with Program, Northeastern Section, v. 15, No. 3, p. 138.
- Merguerian, Charles, 1983, Tectonic significance of Cameron's Line in the vicinity of Hodges complex-- An imbricate model for western Connecticut: American Journal of Science, v. 283, p. 341-368.
- Merguerian, Charles, and Sanders, J.E., 1991, Geology of Cameron's Line and the Bronx Parks: Guidebook for On-The-Rocks 1990-91 Fieldtrip Series, Trip 21, Section of Geological Sciences, New York Academy of Sciences, 88 pp.
- Merguerian, Charles, and Sanders, J.E., 1994, Staten Island and Vicinity: Guidebook for On-The-Rocks 1990-91 Fieldtrip Series, Trip 33, Section of Geological Sciences, New York Academy of Sciences, 151 pp.
- Merrill, F.J.H., Darton, N. H. and others, 1902, Description of the New York City District: U.S., Geological Survey Geological Atlas, Folio 83, 19 p., 2 sheets.
- Miller, W., 1970, Structural geology and tectonism of the Staten Island Serpentinite: Brooklyn College of City University of New York, Department of Geology, Master's Thesis, 64 p.
- Moore, E.M., 1981, Ancient Suture Zones within Continents: Science, v. 213, p. 41-46.
- Newland, D.H., 1901, The serpentines of Manhattan Island and their accompanying minerals: School of Mines Quart., v. 22, p. 307-317, 399-401.
- Ohan, A.A., Kureshy, A.; and Kaarsberg, E., 1975, Geological aspects of Staten Island, New York: in Wolff, M.P., ed., Guidebook to Field Excursions: New York State Geological Association, 47 th Annual Meeting, Hofstra Univ, Hempstead, N.Y., Oct. 1975, Hempstead, New York, Hofstra Univ., 327 p.
- Okulewicz, S.C., 1979, Petrology of the Staten Island alpine ultramafic body: Masters Thesis, Brooklyn College, New York, 92 pp.
- Puffer, J. H., 1980, Toxic Minerals: The Mineralogical Record, v. 11, p. 5-11.
- Puffer, J. H., Germine, M., Hurtubise, D. O., Mrotek, K. A., and Bello, D. M., 1981, Asbestos distribution in the Central Serpentine District of Maryland and Pennsylvania: Environmental Research, v. 23, p. 233-246.

- Puffer, J. H. and Germiné, Mark, 1993, Distribution of asbestos in the serpentinite of Staten Island, New York and Castle Point, New Jersey: Geological Society of America, Northeastern Section, Boston, Mass. Abstracts with program v. 25, #6, p. A-350.
- Puffer, J. H.; Maresca, G.; and Germiné, M., 1983, Asbestos in water supplies of the northern New Jersey area: Division of Water Resources, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, 88 pp.
- Puffer, J. H., and Germiné, M., 1994, The Staten Island Meta-Peridotite: in Benimoff, A.I., (editor), Geology of Staten Island, New York, Field Guide and Proceedings, Geological Association of New Jersey, p. 1-25.
- Puffer, J. H., Ageitos, D. M., Buehler, S. C., Eicher, J. C., Kaplan, C. H., and Seeber, F.C., 1994 Geochemistry of the schists of Central Park, New York City: in Hanson, G.N., (editor), Geology of Long Island and Metropolitan New York, Long Island Geologists, SUNY Stony Brook, New York, p. 86-92.
- Rowley, D.B., and Kidd, W.S.F., 1981, Stratigraphic relationships and detrital composition of the medial Ordovician flysch of western New England: implications for the tectonic evolution of the Taconic orogeny: Journal of Geology, v. 89, p. 199-218.
- Steiner, J. C., and Chesman, S. C., 1996, Tonalitic gneisses and mafic to ultramafic associations in the Red Hook section of Brooklyn: Evidence for the tectonic emplacement of a dismembered ophiolite: Geological Society of America, Abstracts with Programs, Northeastern Section, v. 28 p.101.

**SERPENTINITES OF NEW YORK CITY AND VICINITY
ROAD LOG**

Miles From Start	Miles Between Points	
0.0	0.5	Start at the parking lot near the outcrop of Palisades diabase, proceed to the exit, and turn right onto Victory Blvd.
0.6	0.1	Continue on Victory Blvd. then turn right onto South Gannon Ave.
0.7	0.1	Continue on South Gannon then enter I-278 east.
3.4	2.7	Continue on I-278-East then exit at Clove Rd. and turn right onto Ocean Terrace.
3.6	0.2	Continue on Ocean Terrace and enter former campus of College of Staten Island.
4.0	0.4	Drive to parking lot near the west edge of the campus and park, then take path to Stop 1.

STOP 1. STATEN ISLAND SERPENTINITE

Caution!! At the outcrop, stay on the unused roadway, do not go near I-278; watch out for falling rocks and do not attempt to climb loose rock faces.

This is the most extensive exposure of serpentinite in the New York City area. The serpentinite here contains variable amounts of relic olivine and minor amounts of anthophyllite schist. Both the highly foliated and the massive types of serpentinite are exposed here. The serpentinite exposed within a few cm of any of the closely spaced astomosing shear planes visible on both walls of the road cut, tends to be green, highly foliated, and includes microscopically fibrous minerals. The rock furthest removed from the shear-planes is relatively dark-green to black and is massive.

An average mode based on 12 thin sections cut from the I-278 exposure is 88 % serpentine, (mostly lizardite and chrysotile), 3 % olivine, 2 % talc, 2 % anthophyllite, 3 % opaque oxide (mostly fine grained magnetite but also including coarse magnetite, chromite, and picotite.), and 2 % carbonate (including dolomite and magnesite). About 1/2 of the serpentine is lizardite with highly variable concentrations of chrysotile ranging from absent to 70 % but averaging about 50 %. Minor antigorite is also present including the fibrous variety (picrolite, Bemimoff and others, in prep) Olivine is commonly found in the massive, black rock typically as relic microislands surrounded by serpentine that has replaced most of the individual grains. Talc and anthophyllite are typically found together as a coarse fibrous schist or less commonly as individual grains disseminated within the rock or in veins. The opaque oxides consist largely of the kind of finely disseminated magnetite that is typically expelled from olivine during hydration to serpentine. Olivine can hold more iron than serpentine so the excess iron is typically left as an intergrowth of magnetite and serpentine.

Chrysotile is not readily recognizable in most hand specimens or thin-sections of samples from this exposure. In thin section, only lizardite was recognized in one sample, but using transmitting electron microscopic (TEM) techniques (Puffer and Germine, 1994) abundant chrysotile was found.

Ten samples collected on the south side of the I-278 outcrop, spaced approximately 50 feet apart, were ground in a rock grinder, mixed, split and prepared on an EM grid. TEM point count data indicate a total chrysotile content of approximately 54 volume percent. Germine and Puffer (1994) also performed selected area electron diffraction analyses (SAED) and energy dispersive x-ray spectroscopy (EDX) on several particles, confirming chrysotile as the major component and lizardite as comprising most of the remainder, with a minor talc component.

The same kind of analyses was conducted on another sample of serpentine from this roadcut (Sample 8p, Figure 4). It contains 38 percent chrysotile as confirmed by SAED and EDXS. The results were within the error range of the Puffer and Germine (1994) XRD estimate.

At least two varieties of massive chrysotile were recognized in samples of serpentine at the roadcut using TEM techniques (Germine, 1981). One variety is light to medium green and has a smooth fracture. It occurs in irregular masses and in veins ranging up to a centimeter in width. This type is composed of cross-fiber and randomly oriented fiber, and is often associated with abundant olivine. The second variety is a light green to white substance with pearly luster and platy to fine-grained meerscham-like texture. This type of massive chrysotile occurs in veins, fracture fillings, and pore fillings. TEM examination indicates that it is composed of tubules with a diameter of 300 to 400 angstroms. Fiber lengths are generally less than 1 micron but also occur up to 5 microns (Germine, 1981).

Chrysotile with a megascopic fibrous appearance is much less common than massive varieties at this outcrop but occurs in veinlets typically less than 1 mm to 3 mm wide. The fibers are white to light green and silky. The veins readily fiberize and poses the flexibility that is a characteristic of all asbestos (Germine and Puffer, 1989). Asbestiform anthophyllite from this roadcut consists of straw-colored aggregates on anthophyllite fiber in association with gray to yellow-brown talc. The anthophyllite fibers range up to 18 cm in length in silky and splintery aggregates that are fairly rigid.

Slip-fiber veins of picrolite from this outcrop measuring 1 to 3 mm thick are also described by Germine (1981) and Benimoff and others (in prep.).

- | | | |
|------|-----|---|
| 4.4 | 0.4 | Drive to the exit of CSI and turn right on Ocean Terrace. |
| 4.6 | 0.2 | Continue on Ocean Terrace and turn left onto Clove Road. |
| 4.8 | 0.2 | Cross I-278 and enter I-278-west. |
| 7.7 | 2.9 | Take I-278 to the exit onto 440 north. |
| 13.2 | 5.5 | Proceed on 440 north across Bayone Bridge (toll) and enter I-78-east (New Jersey Turnpike extension) at interchange 14A. |
| 18.2 | 5.0 | Proceed on I-78 east to the exit onto 12 th -street-east. |
| 18.7 | 0.5 | Take 12 th street to Henderson and turn left just before Holland Tunnel toll gate. |
| 19.5 | 0.8 | Proceed on Henderson across RR-tracks where Henderson becomes Jefferson then turn right onto 4 th street near the center of Hoboken. |
| 20.0 | 0.5 | Continue on 4 th street to River Road and turn left at the Hudson River. |
| 20.5 | 0.5 | Take River Road north and park across from the serpentinite exposures along the east edge of Stevens Institute of Technology. |

STOP 2. CASTLE POINT SERPENTINITE

This is probably the second most extensive exposure of serpentinite in the New York City area. The rock here is chemically (Table 2) and mineralogically indistinguishable from the I-278 exposure but is more highly foliated. Most rock surfaces are bright green. Close inspection reveals common grains of chromite. The network of thin white veins are composed largely of magnesite. Minor quantities of talc is visible on freshly broken rock surfaces.

Some of the bright green serpentinite has a glassy gem-like appearance that is a variety called Williamsite. The Williamsite is composed of very fine-grained chrysotile.

Chemical analysis of four typical bright green samples from this exposure are consistent with

meta-dunite although a two dark samples containing pseudomorphs of orthopyroxene are slightly richer in alumina and calcium and are interpreted as meta-harzburgite.

20.5 33.3 Return to CSI at the Victory Blvd. exit of I-278 by reversing the last 12.8 miles of the road-log.

ERRATA

in 1995 Field Trips for the 67th annual meeting of the New York State Geological Association, J.I. Garver, and J.A. Smith, Editors.

FLYSCH AND MOLASSE OF THE CLASSICAL TACONIC AND ACADIAN OROGENIES: MODELS FOR SUBSURFACE RESERVOIR SETTINGS

GERALD M. FRIEDMAN

Brooklyn College and Graduate School of the City University of New York, Brooklyn, New York 11210,
and

Northeastern Science Foundation affiliated with Brooklyn College of the City of New York,
P.O. Box 746 , Troy, New York, 12181-0746

In Figure 1b, page 110, note the position of the Rensselaer Conglomerate and the Rysedorph Hill Conglomerate within the Snake Hill Formation, here reprinted:

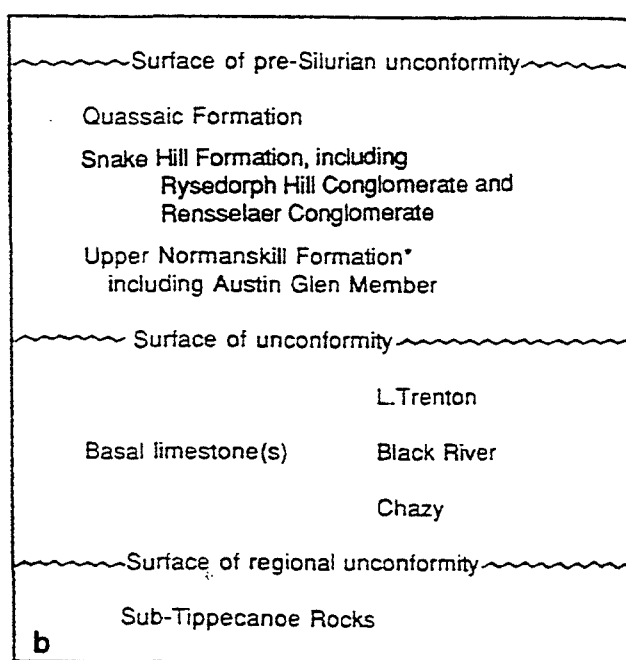


Figure 1b. Names of formations in Tiptecanoe Sequence, eastern New York (modified from Sanders, 1995).

On page 127 in the second paragraph for STOP 5 and in the caption to Figure 20 the Rensselaer Conglomerate has been mistakenly noted as part of the Hatch Hill Formation which should be corrected to read Snake Hill Formation, as in the above figure. On page 118 the Rysedorph Hill Conglomerate was labeled Rensselaer Conglomerate and once again its formation was given as Hatch Hill Formation instead of Snake Hill Formation.

Participants on the trip made these corrections in the field.

Note also Figure 1a (p. 110) : this table from Guo, Sanders, and Friedman (1990) is not intended to be a strict correlation chart between the shelf and basin strata.

REFERENCES

Friedman, G.M., 1995, Flysch and Molasse of the Classical Taconic and Acadian Orogenies: Models for Subsurface Reservoir Settings: *in* Garver, J.I., and Smith, J.A. (Editors). Field Trips for the 67th annual meeting of the New York State Geological Association, Union College, Schenectady, NY, p. 109-143.

Gou, B., Sanders, J.E. and Friedman, G.M., 1990, Columbia Gas Company No.1. Finnegan Boring, Washington County, New York: Microlithofacies and petroleum prospects in Lower Paleozoic platform strata beneath Taconic Allochthon: *Northeastern Geology*, v. 12, p. 238-265.

Sanders, J.E., 1995, Lower Paleozoic carbonate-clast diamictites: relationship to overthrusts that advanced across the floor of the Northern Ordovician foreland basin: *Northeastern Geology and Environmental Sciences*, v. 17, p. 23-45.