Geology of Staten Island, New York

Field Guide and Proceedings

Edited by
Alan I. Benimoff

Eleventh Annual Meeting
of the
Geological Association of New Jersey
October 14-15, 1994

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The Geology of Staten Island, New York

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Preface

"Southeastern Staten Island is a piece of Europe glued to an ophiolite from the northwest Iapetus floor"... John McPhee(1993) *Assembling California*, Farrar, Straus, and Giroux, New York, p. 208

In 1984, GANJ began with a field trip to the northern Newark Basin led by John Puffer. In 1988, Jonathan Husch and Mike Hozik organized a field trip to the central Newark Basin. Included in the trip this year is the eastern part of the Newark Basin in Staten Island. In addition, John Puffer will speak about the Staten Island Meta-Peridotite, Norma Itturino will speak about the Fresh Kills Landfill, Tim Pagano will speak on the geology of western Staten Island, north and south of the fall line, and John Sanders and Charles Merguerian will speak about the outcrops of plesistocene and cretaceous sediments. We will also observe the effects of beach erosion(if time permits) at Great Kills beach. This year's GANJ field trip should be an interesting one, and putting this field guide together has been an exciting experience. I hope you find this trip enjoyable and educational.

This trip would not be possible without the cooperation of John Sanders, Charles Merguerian, Tim Pagano, John H. Puffer, and Norma Itturino. I thank Douglas Mose, Dana Gumb and Edward Johnson for their contributions. In addition, I thank all the authors and field trip leaders for their cooperation and dedication.

Alan I. Benimoff
Editor

THE STATEN ISLAND META-PERIDOTITE

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Abstract

Serpentinite is exposed as a NE trending lens in the central and northern portion of Staten Island, New York along a broad hill. The serpentinite is composed largely of lizardite and chrysotile together with highly variable olivine, anthophyllite, talc, carbonates, magnetite and chromite. The chrysotile content, as determined using a combination of polarized light microscopy, transmission electron microscopy, and X-ray diffraction techniques averages about 23 volume percent.

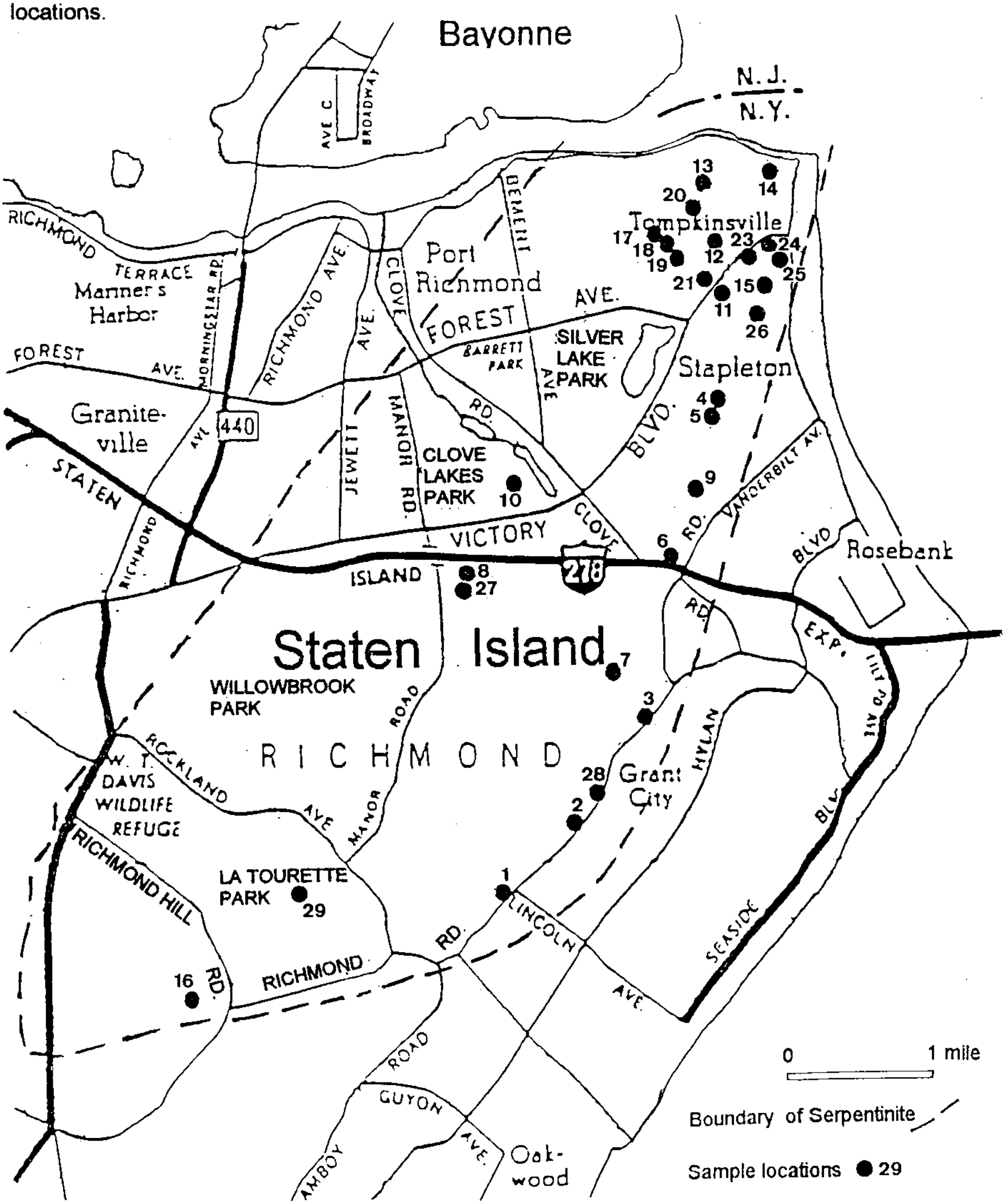
The chemical range of samples from 29 of the largest exposures is 35 to 45% SiO_2, 0.2 to 0.8% Al_2O_3, 6 to 8% FeO_t, 36 to 42% MgO, 0.03 to 3.0% CaO, 0.1 to 0.35% Cr, and 0.1 to 0.35% Ni. The chemical range is typical of metamorphosed harzburgite and dunite suites, although some unusually low CaO values may be due to hydrothermal leaching and re-precipitation as a network of amphibole and carbonate veins in shear zones.

The Staten Island peridotite is interpreted as the base of an ophiolite complex that was separated from the upper gabbroic and basaltic portions during Taconic abduction. It is located on Cameron's Line which separates Manhattan Schist to the west from the Hartland Formation to the east.

Geologic Setting

The Staten Island meta-peridotite is part of a discontinuous chain of ultramafic bodies that extends from Alabama to Quebec. The Staten Island body is the largest of four lenticular masses exposed in the New York City area that includes exposures at Hoboken, New Jersey, western Manhattan, and eastern Bronx. It is a wide lens shaped body (Figure 1) that trends NE-SW and is comprises the bedrock of northern Staten Island, although the western boundary is not exposed. The meta-peridotite is well exposed along a prominent ridge that extends from the northeastern shore of the island toward

Figure 1 Staten Island Serpentinite; approximate boundaries and sample locations.



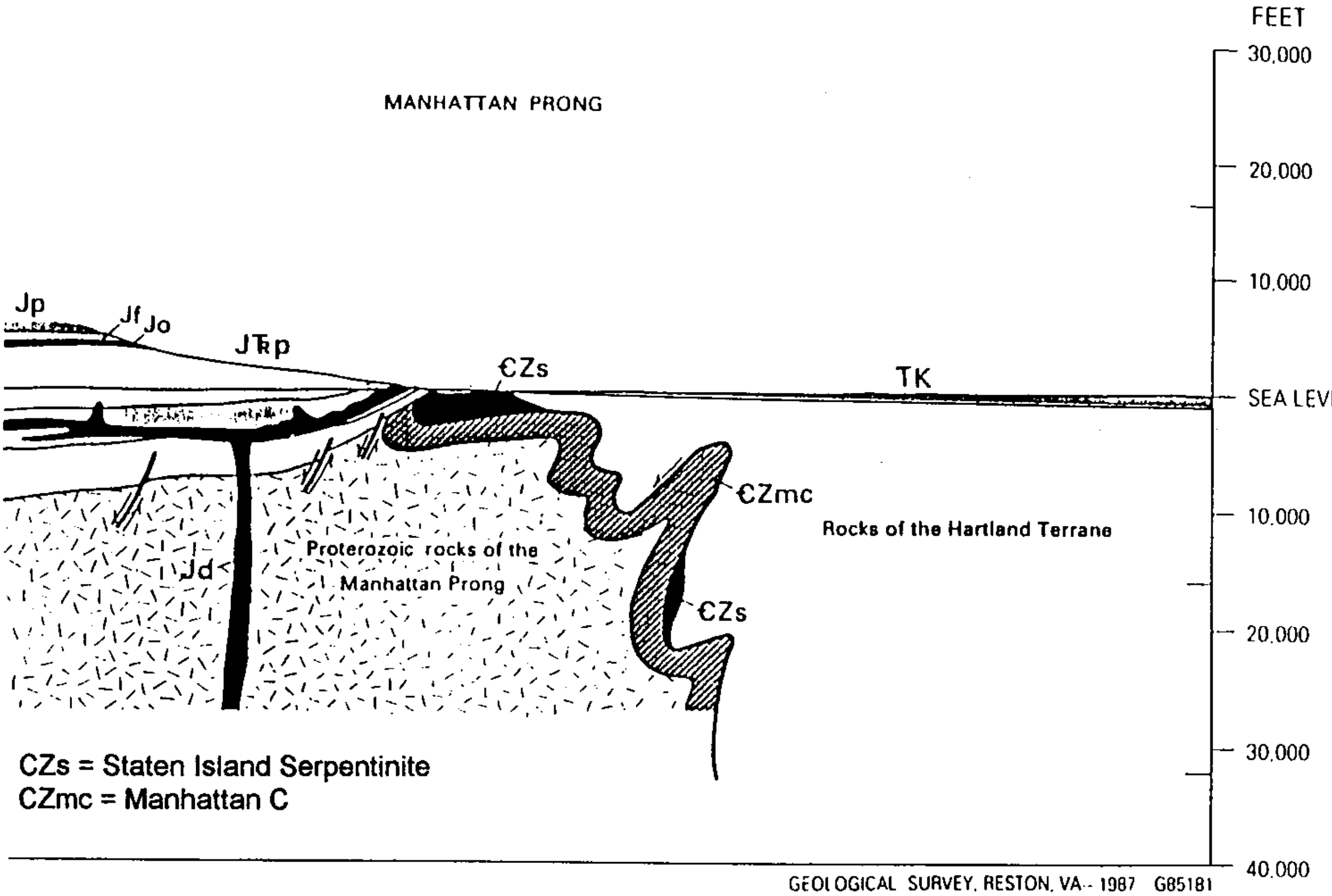


Figure 2 Cross-section through Staten Island Serpentinite (after Little and Epstein, l987).

the southwest. Beyond this ridge the meta-peridotite is covered by glacial drift, moraine, and beach sand (Behm, 1954).

There is general agreement that the Staten Island meta-peridotite is positioned on Cameron's Line which defines 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 metamorphosed shelf and transition-zone rocks to the west (Manhattan Schist) from eugeosynclinal rocks to the east (Hartland Terrain).

Little and Epstein (1987) stratigraphically place the Staten Island meta-peridotite and other related serpentinite bodies on Cameron's Line conformably above Member C of the Manhattan Schist but suggest that most of the peridotite lies east of Cameron's Line at the base of the Hartland terrain (Figure 2). 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. An 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.

To avoid confusing usage's of the term "Manhattan Schist" this paragraph will briefly review the development of current nomenclature. Merrill's (1890) original Manhattan Schist was subdivided by Hall (1968) into a Mid-Ordovician Manhattan A (a sillimanite-garnet-mmscovite-biotite schist) , Manhattan B (a discontinuous amphibolite), and Manhattan C (a garnet-muscovite-biotite schist). Hall (1976) later recognized that much of what was mapped as Manhattan Schist was older than Mid-Ordovician. These older eastern schists were overthrust above younger schists. The lowest but youngest unit is Manhattan A (an autochthonous miogeosynclinal basement cover rock) and the middle but oldest unit is Manhattan C and B (allochthonous transitional slope meta-sediments and discontinuous volcanics). The upper unit is described by Merguerian and Sanders (1991) as part of the Hartland Formation (meta-eugeosynclinal deep-oceanic shale and interstratified volcanics). The interpretation of the Hartland Terrain as deep-oceanic rock is based in part on it's association with the Staten Island meta-peridotite which is regarded as part of an ocean-floor ophiolite suite (Baskerville, 1989).

The Staten Island meta-peridotite has been divided 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 (Behm, 1954). Miller (1970) proposed that this inner zone is a horst that is 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.

Sampling and Analysis

The 29 largest exposures of meta-peridotite on Staten Island (Figure 1) were examined and sampled. In some cases a representative sample was easily selected, but at most locations wide variations in rock type required the collection of several samples. Individual samples were petrographically and geochemically analyzed using a combination of five techniques:

1. Hand specimen observations - were made at all exposures for megascopic features including veins or lenses of chrysotile, picrolite, or anthophyllite.

2. Polarized light microscopy (PLM) - was used to examine thin sections for mineral modes (Table 1) and texture (including ribbon texture, matte texture, and foliation) and structures (such as cross fiber veins). Ground samples were examined for fiber content.

3. Transmitting electron microscopy (TEM) - was used to examine ground rock samples dispersed in water then filtered through a 0.1 micrometer pore polycarbonate filter, and prepared for TEM analysis by the direct transfer method of Anderson and Long (1980). Mineral particles were also characterized structurally using selected area electron diffraction and energy dispersive x-ray spectroscopy (EDXS). Figure 3 is a typical EDXS spectrum of a chrysotile fiber filtered from Silver Lake reservoir water, Staten Island. Figure 4 is a TEM microphotograph of the same fiber.

4. X-ray fluorescence spectroscopy (XRF) - was used to chemically analyze whole rock samples (Table 2). A Rigaku wave-length dispersive XRF unit with a minimum detection limit of about 4 PPM was used for all samples. USGS standards

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

TABLE 2 Chemical compositions of Serpentinites and Anthophyllite Schist from Staten Island locations (Fig. 1), New York.

	Serpentinites						
Wt. %	4b	4e	7b	8b	8c	10	13c
SiO2	44.25	43.7	36.42	35.23	42.03	39.41	35
TiO2	0.01	0.01	0.01	0.01	0.009	0.01	0.01
Al2O3	0.63	0.48	0.38	0.53	0.62	0.5	0.29
FeOt	7.31	7.5	6.44	6.08	7.26	7.55	5.22
MgO	40.58	36.5	38.25	38.22	41.95	36	36.4
MnO	0.11	0.09	0.1	0.09	0.11	0.08	0.09
CaO	0.05	0.07	0.06	0.05	0.16	0.03	3.45
Na2O	0.006	0.01	0.25	0.28	0.005	0.01	0.27
K2O	0.005	0	0.06	0.07	0.004	0	0.06
P2O5	0.002	0	0	0	0.002	0	0
LOI	7.1	11.45	17.22	17.71	7.83	6.21	18.25
Total	100.053	99.81	99.19	98.27	99.98	99.8	99.04
PPM							
Co	103	96	112	110	108	98	96
Cr	2571	2100	544	686	2413	1780	510
Cu	11		1	1	11		2
Ni	2449	2460	1895	1810	2492	2630	1630
Sr	7		3	3	7		55
V	25		8	12	27		6
Zn	34	37	38	42	32	30	26
Zr	7	7			8	7	

	Serpentinites						
Wt. %	14c	15b	16c	19a	20b	22d	26b
SiO2	43.7	37.57	42.66	43.91	37	43.71	45.21
TiO2	0.01	0.01	0.012	0.009	0.01	0.011	0.045
Al2O3	0.16	0.5	0.81	0.14	0.1	0.21	0.5
FeOt	7	6.77	7.99	6.37	5.75	7.79	7.46
MgO	37	35.84	39.64	41.76	35	40.35	40.99
MnO	0.08	0.1	0.12	0.13	0.11	0.13	0.052
CaO	0.04	0.93	0.06	0.04	7.3	0.07	0.2
Na2O	0.01	0.27	0.006	0.005	0.01	0.005	0.006
K2O	0	0.06	0.007	0.004	0	0.007	0.006
P2O5	0	0.002	0.002	0.002	0	0.002	0.002
LOI	11.85	15.75	8.15	7.6	14.3	7.7	6.2
Total	99.85	97.802	99.457	99.97	99.58	99.985	100.671
PPM							
Co	100	116	115	102	64	115	107
Cr	1320	1250	2547	1031	1360	1322	1726
Cu		7	11	12		12	11
Ni	2740	1910	3603	2553	1780	2629	2456
Sr		15	7	6		7	7
V		14	25	22		24	24
Zn	33	42	35	30	31	31	32
Zr	8		7	8	9	7	7

Wt. %	Serpentinites 28a	28c	PCCI	Lizardite	Chrysotile	Harzburg	Dunite
SiO2	42.57	41.3	41.9	41.25	41.83	43.86	43.86
TiO2	0.009	0.01	0.015	0.02	0.02	0.02	0.011
Al2O3	0.12	0.27	0.74	0.54	0.3	0.77	0.36
FeOt	7.59	7.7	7.81	1.28	1.24	8.19	8.52
MgO	37.7	34.2	43.18	41.84	41.39	45.41	49.5
MnO	0.12	0.09	0.12	0.07	0.04	0.11	0.14
CaO	0.09	0.08	0.51	0.02	0	0.73	0.3
Na2O	0.005	0.01	0.006	0	0	0.11	0.03
K2O	0.009	0.01	0.004	0	0	0.02	0.05
P2O5	0.002	0	0.002	0	0	0	0
LOI	12.11	15.7	5.62	14.65	15.23	0	0
Total	100.325	99.37	99.907	99.67	100.05	100	100
PPM							
Co	115	108	112				
Cr	636	1240	2730			0.43	0.54
Cu	11		11				
Ni	2750	2525	2339			0.34	0.3
Sr	7		0.41			1	4
V	20		30				
Zn	31	42	36				
Zr	8	8	7				

Wt. %	Anthophyllite Schist 5b	11c	15c	25b	Anthoph
SiO2	53.02	54.22	55.32	51.82	58.48
TiO2	0.07	0.05	0.05	0.04	0.03
Al2O3	1.2	0.94	0.93	1.08	0.57
FeOt	8	7.25	6.66	8.65	8.37
MgO	29.5	32	30.29	26	29.25
MnO	0.11	0.11	0.19	0.11	0.27
CaO	0.35	0.26	0.26	0.83	0.14
Na2O	0.01	0.01	0.27	0.01	0.08
K2O	0	0	0.06	0.01	0.02
P2O5	0	0	0	0	0
LOI	7.5	4.65	5.83	9.78	2.9
Total	99.76	99.49	99.86	98.33	100.11
PPM					
Co	75	67	79	104	
Cr	2400	2620	1645	3750	
Cu			1		
Ni	360	480	361	605	
Sr			3		
V			27		
Zn	35	51	46	37	
Zr	7	7		6	

PCCI = USGS standard peridotite.

Lizardite and Chrysotile = Transvaal (Deer, W.A., Howie, R.A., and Zussman, J., 1962, Rock forming Minerals.

Harzburgite = average of 31 meta-harzburgites from ophiolites (Hyndman, 1989).

Dunite = average of 32 meta-dunites from ophiolites (Hyndman, 1989).

Anthophyllite = anthophyllite in a serpentinite, outer Hebrides (Guppy, E.M., 1956, Mem. Geol. Surv. Gt. Britain).

including PCC-1, BHV-01, GSP-1, AGV-1, JB1, and BCR-1 were used to prepare new calibration curves during each analytical session. USGS peridotite standard PCC-1 was in each case heavily weighted due to its close chemical correspondence to most Staten Island meta-peridotite samples.

5. X-ray diffraction (XRD) - was used to semiquantitatively determine the principal mineral content (lizardite, chrysotile, and anthophyllite) of 52 samples from 29 locations using a methods developed by Whittaker and Zussman, 1956, Chen, 1977, and Germine, 1980 (Table 3). The 32^{o} to 40^{o} 2Θ region was slowly scanned at high resolution and peak positions were used to identify mineral species using carefully selected standards including the Union Carbide chrysotile standard from Coalinga, California; Lizardite from Lizard, England; anthophyllite from Winchester, California and UICC standard anthophyllite. The standard chrysotile peak positions at 36.9^{o} 2Θ (Figure 5) and the chrysotile compared against the standard lizardite peak position at 36.0^{o} 2Θ (Figure 5) facilitated serpentine identifications while semiquantitative content determinations were made of the basis of relative peak heights.

Petrology of Staten Island meta-peridotite.

Although now largely a serpentinite the protolith was a peridotite that was serpentinized before or during Taconic tectonic emplacement. If the protolith was an ophiolite most hydration to serpentine was probably induced by heated deep marine water circulation near a spreading center. Most samples of peridotites dredged from the ocean floor are largely hydrated to serpentine and contain over 10 % H_2O^+.

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 is some of the massive serpentinite. These altered pyroxene phenocrysts make up about 15 % of some samples and indicate that such rock was a harzburgite. Most samples of massive serpentinite where primary igneous textures are preserved, however, do not contain evidence of pyroxene and are probably dunite.

Most of the original igneous olivine has been altered to serpentine but some samples contain as much as 50 % olivine. The average olivine content of the Staten Island meta-

TABLE 3

X-RAY DIFFRACTION ESTIMATES

Staten Island Project

SI-JM Series	SERPENTINE	CHRYSOTILE	LIZARDITE	TALC	ANTHOPHYLLITE
1-2		15-30	70-85*		
1-7		15-30	70-85*		
1-7 green		16-30	67-81*	3	
2-a		0-22	78-100		
2-b picrolite	92(antigorite)			8	
3-a		10-25	65-80	10	
3-c slip fiber	35			25	40
4-b		9-25	67-83	8	
5-a cross fiber	7			7	86
5-c cross fiber	12			21	67
5-E-1 foliated	24				76
5-J-1 cross fiber	5			13	82
5-J-2 cross fiber	50			50	
5-m		18-32	58-72	10	
5-m-1 green vein		42-54	48-56		
6-a foliated		29-35	24-30	41	
7-a		6-24	76-94		
8 a-j		28-42	58-72		
8-L-1 white		30-44	56-70		
8-m green		96-100	0-4		

	SERPENTINE	CHRYSOTILE	LIZARDITE	TALC	ANTHOPHYLLITE
8-p		28-42	58-72		
8-w		42-56	44-58		
9-c-1		18-34	66-82		
9-c-2		20-36	64-80		
10-a		0-16	79-95	5	
10-c white		100			
11-a mylonite	23			24	63
12-b		10-27	71-88	2	
13-b visible chrysotile		0-16	84-100		
14-b		8-24		12	
15-b		27-41	39-53	20	
15-c mother lode	18			8	73
16-a		26-39	61-74		
17-a mylonite		2-24	76-98		
18-a mylonite		0-18	82-100		
19-b		14-29	71-86		
20-a visible chrysotile		8-24	76-92		
21-b		12-24	76-88		
22-d		48-56	41-49	3	
23-a		9-20	47-58	33	
24-c		4-22	78-96		
25-a mylonite	25				75
26-a		10-27	73-90		
27-b		15-30	70-85		
28-c		10-26	74-90		
29-a		18-33	67-82		

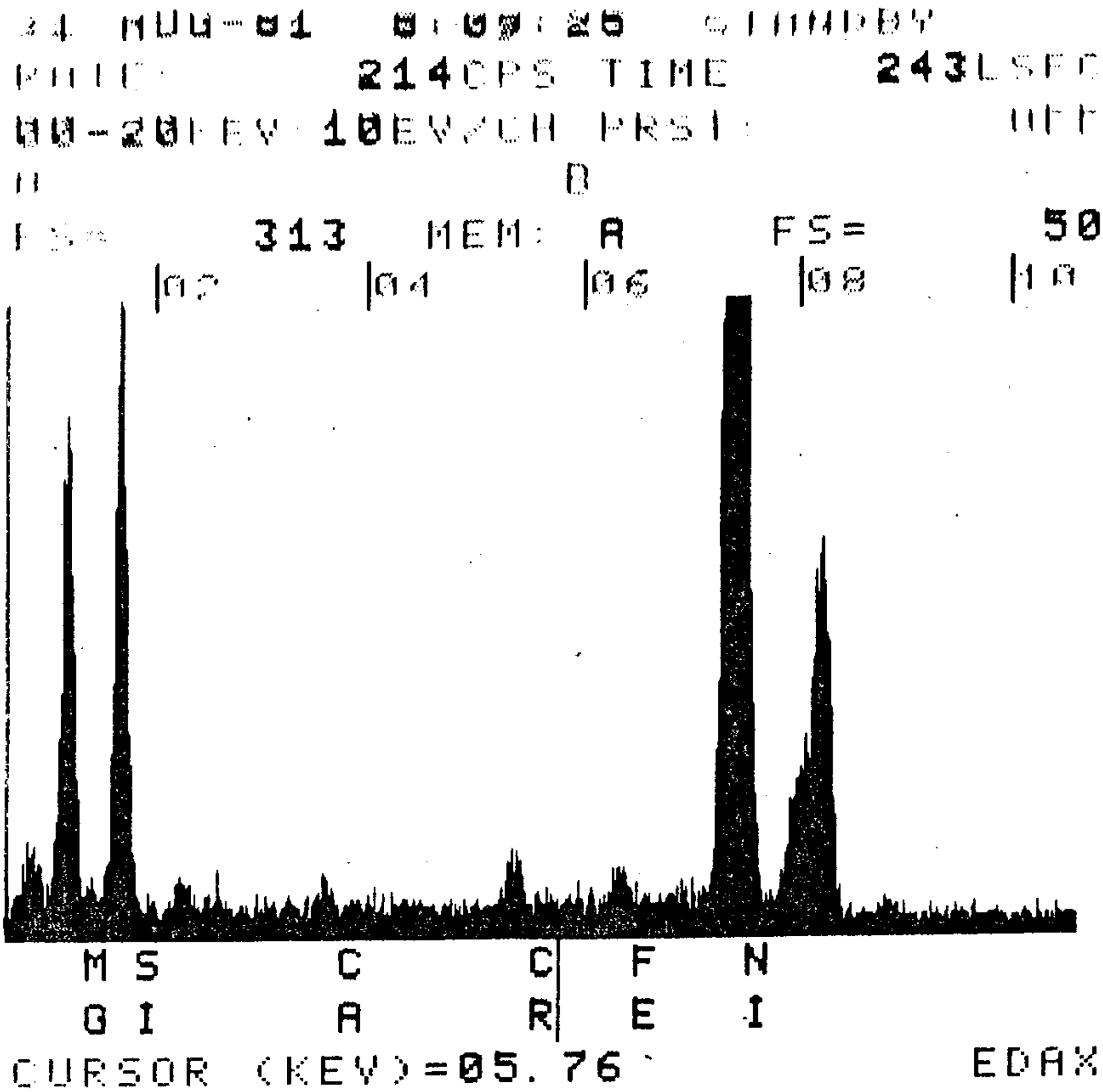


Figure 3 EDXS spectrum of a chrysotile fiber from a Silver Lake water sample. Elements are labelled below and slightly to the right of their major peaks. Nickle peaks are caused by excitation of the electron microscope grid.

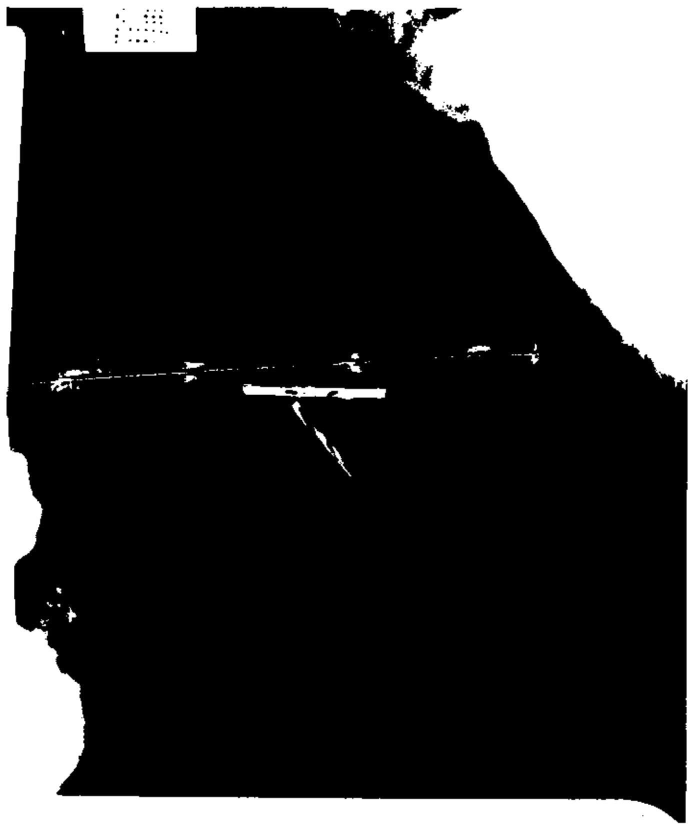


Figure 4 TEM photomicrograph of analyzed (Fig. 3) chrysotile **fiber**.

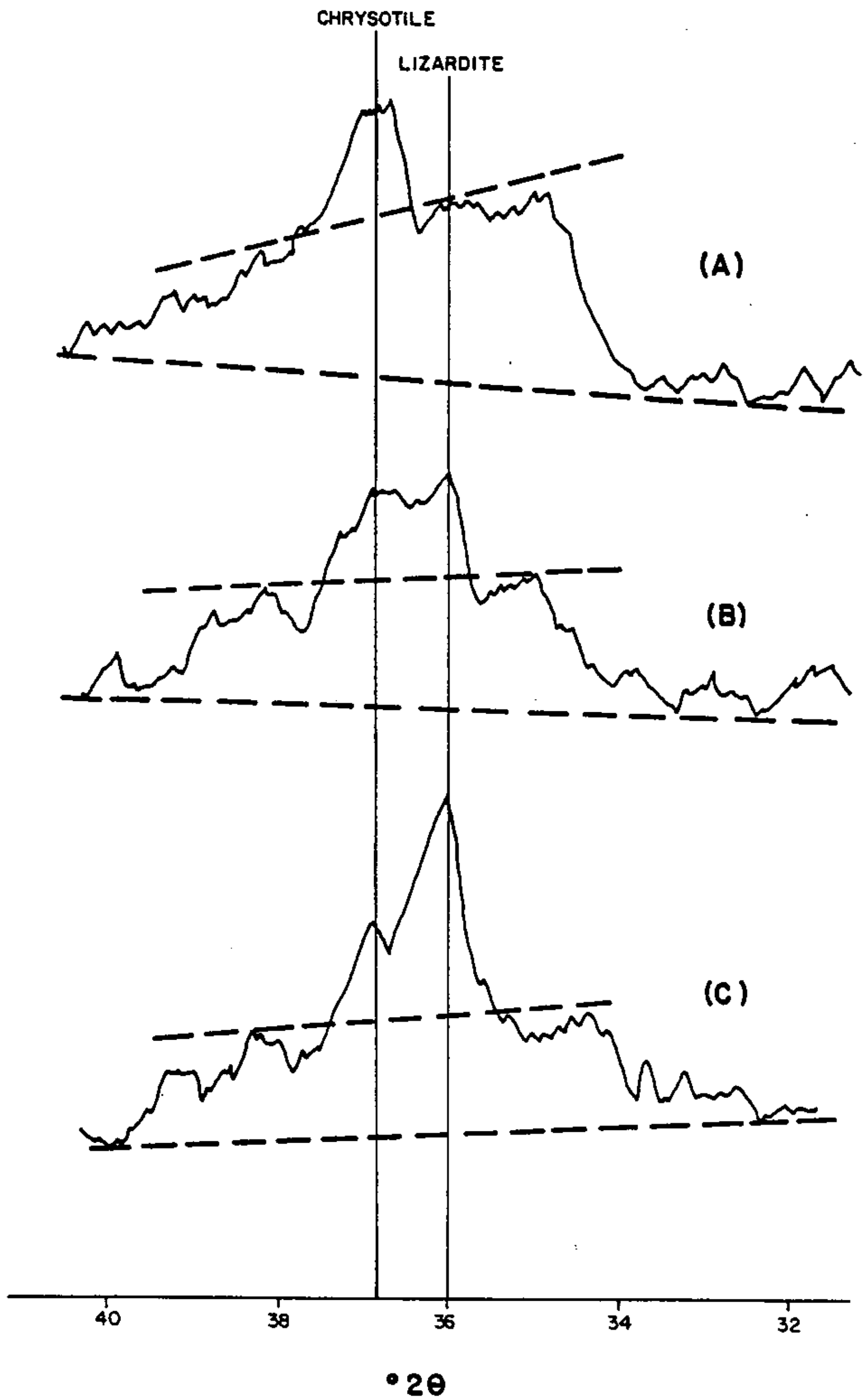


Figure 5. X-ray diffraction data for serpentine standards: A. chrysotile standard; B. mixture of chrysotile and lizardite; C. 20 weight % chrysotile, 80 weight % lizardite. Dashed lines show the lower limit of background and the upper limit of the broad band for chrysotile. Measurements of the relative intensity of this band before and after the solution treatment of Faust and Nagy (l967) in the unknown and dilution standards can be used to arrive at a determination of chrysotile content (Germine, l980).

peridotite is about 5 percent 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.

Although olivine content is accurately determined by means of PLM, serpentine minerals are optically ambiguous. Unless chrysotile fibers are long enough to be optically resolvable at the level of PLM examination the fibers are lost in a matrix of lizardite or antigorite. XRD techniques, however, are able to determine serpentines at submicroscopic grain sizes. The XRD data (Table 3) shows that of the 52 representative samples of Staten Island meta-peridotite from 29 locations, 8 samples are anthophyllite schist, and 44 samples are serpentinite.

Serpentinite -

The serpentine content of 36 serpentinite samples from 27 locations (Figure 1, Table 3) averages 66 percent lizardite and 27 percent chrysotile using the mid-points of each XRD range as for the average. Minor olivine, chromite, and magnetite makes up the remaining 7 %. TEM analysis of ten samples from the I-278 outcrop (sample 8), however, indicates a chrysotile content of 54 volume percent although it is absent at a few locations. In sample 1 some evidence of minor antigorite was found but since our XRD standards were calibrated to chrysotile and lizardite ratios we were unable to accurately estimate antigorite content. Fibrous antigorite (picrolite) was also found at site 2 (sample 2-b) and is common at the 287 roadcut. Picrolite from the Staten Island meta-peridotite has been recently described by Benimoff and others (in prep).

Chrysotile is typically not readily recognizable in hand specimens or thin-sections of Staten Island serpentinite. In thin section, only lizardite was recognized in one Route 287 sample, but using TEM 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.

At least two varieties of massive chrysotile were recognized in samples of serpentinite 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 meerschaum-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 were generally less than one. micron but up to 5 microns (Germine, 1981).

Chrysotile 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 posses the flexibility that is a characteristic of asbestos (Germine and Puffer, 1989).

Anthophylite schist -

The mineral content of the 8 anthophyllite schist samples (Table 3) averages 15 percent talc, 20 percent serpentine and 65 percent anthophyllite. Thin section evidence suggests that most of the serpentine content of the anthophyllite schist is lizardite although XRD evidence is ambiguous. Carbonates are also present in accessory amounts in most samples of anthopyllite schist. Asbestiform anthophyllite from the Route 287 roadcut consists of straw-colored aggregates on anthophyllite fiber in association with gray to yellowish-brown talc. The anthophyllite fibers range up to 18 cm in length in silky and splintery aggregates and are fairly rigid.

At location 15 (represented by sample 15c, Figure 1) there is a zone of anthophyllite asbestos about 2 meters wide, exposed near the hill top, at a location very close to the location given for the original Johns mine. We confirmed the presence of anthophyllite with a UICC anthophyllite standard in both XRD and TEM analyses. We took 13 photos of a ground split sample and found anthophyllite asbestos with fibers of aspect ratio greater than 100 to 1 and clearly flexible fibers comprising about 80 percent of the sample. We photographed and measured SAED patterns on 8 of these fibers, and found one pure anthophyllite, and the rest of them to be intergrowths of anthophyllite and talc. In all cases anthophyllite was lying on {100} and talc on {001}. We measured d{001} = 5.2A and d{010} = 17.7A consistently for anthophyllite, and d{100} = 5.2A and d{010} = 8.9A for talc, consistent with standards and published values. In all cases {hkl} odd was absent in talc, forming a pseudohexagonal net, and all intergrowths were of anthophyllite on {100} and talc on {001} which were precisely superimposed so that talc shared the same spots as anthophyllite, with anthophyllite spots between. With these and all other SAED measurements we calibrated d spacing against a gold standard. We used the {111} line for gold with d{hkl} = 0.2355A. Intergrowths of talc were longitudinal to fiber length, and fibers were observed to be broken off of aggregates along talc/anthophyllite interfaces. These aggregates had showed formation of thinner fibers from thicker fibers of "talcbole". Some curly ribbons of pure talc were also observed splitting from the aggregates, but these were a minor component of the total sample.

A TEM analysis of an anthophyllite mylonite sample (sample 5a, Figure 1) confirmed that it was predominantly anthophyllite, with minor lizardite and talc. We estimated a anthophyllite asbestos content of 3 to 5 percent using our (Germine and Puffer, 1989) criteria of aspect ratio greater than 10 to 1, and observed intergrowth with talc in some of these fibers. Most of the rock consists of non-fibrous anthophyllite fragments without talc, lizardite, talc plates, and about 1-2 percent chrysotile. We separated out a thin)1 mm) vein of cross fiber anthophyllite and found it to be nearly pure anthophyllite asbestos with some talc intergrowth as described above.

Germine did the same kind of analyses on the highly carcinogenic samples of anthophyllite form Korea and reported similar results regarding tremolite/talc intergrowths. These results were important because under the current OSHA regulations an asbestos fiber has to be formed as a separate crystal, so none of these anthophyllite fibers are asbestos under the current OSHA definition of asbestos.

Geochemistry

The chemical compositions of typical samples of Staten Island rocks are within the overlapping range of some common meta-peridotite types particularly metamorphosed dunite and harzburgite from ophiolite suites (Table 2). Most samples contain about 7.5 % less combined SiO_2, MgO, and loss on ignition (LOI, principally $H2O^+$) than pure chrysotile or lizardite (Table 2) due to the presence of about 7.5 % FeO_t that is contained within the olivine, magnetite, and chromite of the Staten Island serpentinite. The 7.5 % FeO_t content is fairly consistent and does not correlate with either magnetite or olivine content. As olivine is hydrated to form serpentine plus magnetite there is no net change in the iron content.

The highly variable olivine content of the Staten Island serpentinite correlates inversely with LOI content. The LOI content ranges from about 6 % in olivine rich rock to about 15 % which is the LOI content of pure serpentine (Table 2). A few samples contain slightly more than 15 % LOI due to the presence of minor clay, brucite, and 1 to 4 % $H2O^-$.

The highly variable CaO content (Table 2) is interpreted as due to hydrothermal leaching of CaO during serpentinization or metamorphism and its localized reprecipitation as dolomite veins that are particularly common within the anthophyllite schist. Some CaO contents approach values corresponding to pure serpentine (Table 2) whereas others are more typical of harzburgite.

The Al2O3 content of the serpentinite (Table 2) averages 0.45 % after normalizing to anhydrous compositions. To the extent that Al2O3 is relatively insoluble, it is less influenced by hydration and metasomatic changes than most elements. It may, therefore, be meaningful that the 0.45 % average is more typical of anhydrous meta-dunite (averaging 0.36 %) than anhydrous meta-harzburgite (averaging 0.77 %, Table 2). Some samples, however, such as 4b, 8c, and 16c, are close to the meta-harzburgite average. A harzburgite protolith for such samples is also supported by common chlorite pseudomorphs after pyroxene and rare pyroxene-chlorite intergrowths as seen in samples 4b and 16c.

Interpretation

The interpretation of the Hartland Terrain as deep-oceanic rock is based in part on it's association with the Staten Island peridotite which is interpreted as part of an abducted ophiolite suite associated with metamorphosed deep water marine shales (Little and Epstein, 1987; Merguerian and Sanders, 1991; Baskerville, 1989). Alternatively, the Staten Island meta-peridotite may be a metamorphosed olivine cumulate zone formed as part of a layered gabbroic magma chamber such as some interpretations of the serpentinites of the Pennsylvania piedmont (including Gates, 1988), although the evidence is somewhat ambiguous. Evidence of any clear association with either the fractionated gabbroic rocks of a mafic intrusion or any of the upper portions of ophiolites (sheeted dikes or pillow basalts) is absent from Staten Island. In addition,

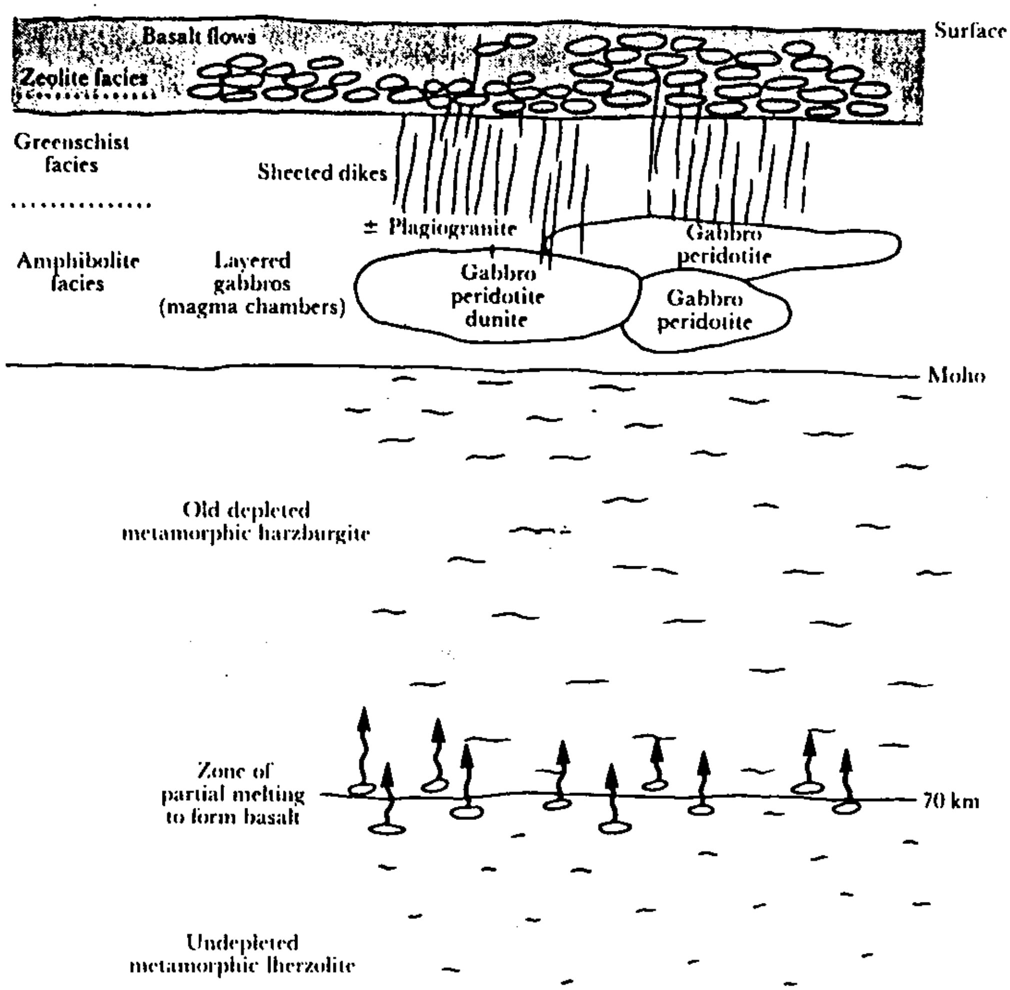


Figure 6. Formation of an ophiolite sequence during partial melting near a spreading center. (after Hyndman, 1985).

evidence of thermal metamorphism at serpentinite contacts or xenoliths within the serpentinite is also absent.

If, however, the serpentinite body was formed at the base of a gabbroic intrusion before it was tectonically displaced, some evidence of fractionation or layering might be expected. The absence of any clear fractionation trend (Table 2) or any clear layering, such as the cryptic and rhythmic layering of the Bushveld, argues against such a mode of origin.

The Staten Island meta-peridotite, however, is chemically and mineralogically the same as most meta-peridotite bodies such as those of California that are generally regarded as abducted ophiolites occupying terrain sutures (Coleman, 1977; Ehrenberg, 1975; and Saleeby, 1990). The ability of soft, hydrated, serpentine to absorb ductile shearing is well known. The close association of the Staten Island serpentinite with schist that posses several of the characteristics of metamorphosed deep water shales (Merguerian and Sanders, 1991) also agrees with an ophiolitic origin. Ophiolites are typically composed of large irregular pod shaped dunite bodies contained within harzburgite (Figure 6). Most of the Staten Island body is chemically equivalent to a meta-dunite although some rock chemically equivalent to meta-harzburgite is also present.

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The Mesozoic Igneous Rocks of Staten Island, New York

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Introduction

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), and Hozik (1992). 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 2. Outcrops of diabase occur at the Graniteville Quarry, the toll plaza of the Bayonne Bridge, the Travis Quarry, and the Teleport as shown in Figure 2. 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(This Field Guide) show that Lockatong argillite overlies and underlies that Palisades intrusion in this area.

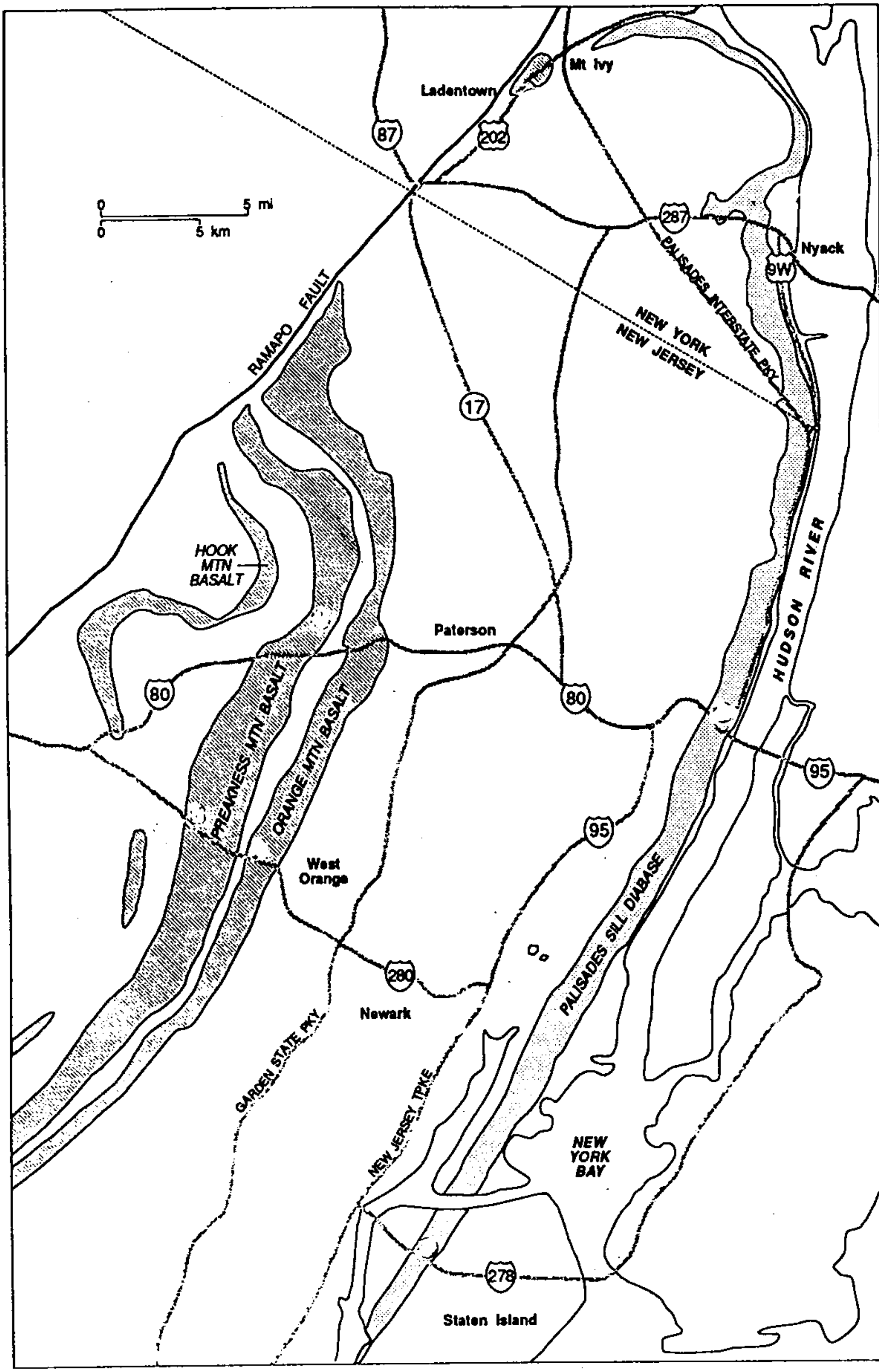

Figure 1. Map of the northern Newark Basin(From Puffer et al. 1992)

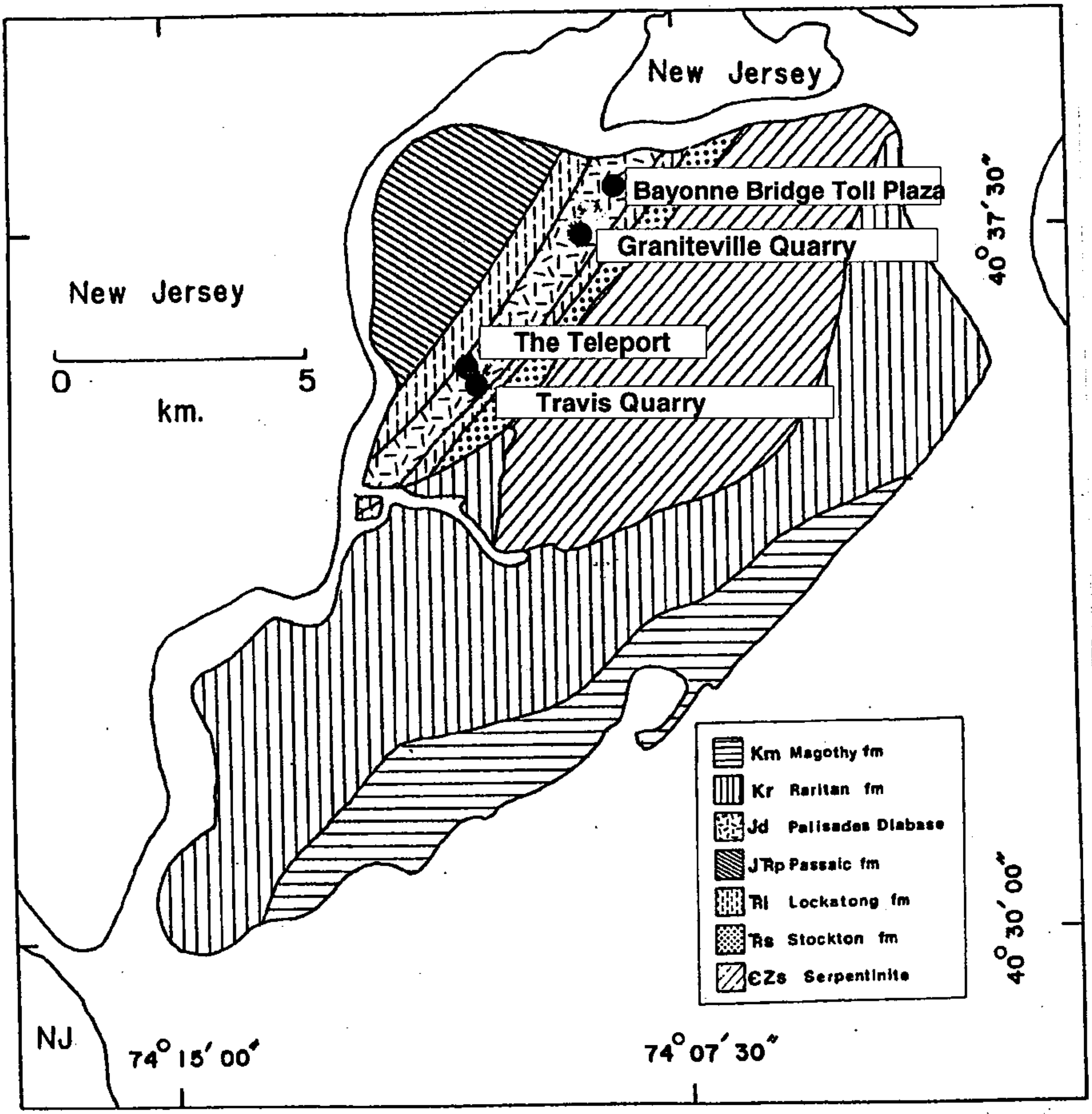

Figure 2. Geologic map of Staten Island showing locations of outcrops of Palisades diabase on Staten Island(from Lyttle and Epstein, 1987)

PART I: Coexisting silicic and mafic melts resulting from marginal fusion of a xenolith of Lockatong Argillite in the Palisades Sill, Graniteville,

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 1 on this field trip) where marginal fusion of a xenolith of sodium-rich Lockatong 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, 1980, 1984, 1988, 1992, and Sclar and Benimoff(1993), and a summary of these studies is presented below.

The occurrence of a coarse-grained igneous rock in direct contact with its protolith is rare. Much of the uncertainty regarding the origin of coexisting silicic and basic igneous rocks arises either because of the absence of contiguous parental material or because we cannot identify unequivocally the parental material through either geochemical and/or petrographic study.

Yoder (1973) in his investigation of contemporaneous basaltic and rhyolitic magmas, cited the field evidence of various workers, and noted that, in many cases, two magmas of greatly contrasting composition coexisted at the same locality and erupted from the same vent or were intruded into the same dike at the same time. He also showed that two magmas of highly contrasting composition may be generated successively from the same parental material by the mechanism of fractional melting. Other investigators (Roedder and Weiblen, 1970, 1971; De, 1974; Philpotts, 1976, 1978) described the occurrence of pairs of chemically diverse glasses intergrown as globules of one in the other which constitute the mesostasis of certain basalts, and suggested that silicate liquid immiscibility may be a viable process for producing certain coexisting silicic and basic liquids. McBirney (1975) has shown experimentally that liquid immiscibility could have been responsible for the late-stage granophyres of the Skaergaard intrusion. Liquid Immiscibility in certain chemically restricted natural silicate systems is supported experimentally by the work of Roedder, 1951, 1978; Koster Van Groos and Wyllie, 1966; Rutherford et al., 1974; Irvine, 1976; Watson, 1976; Naslund, 1976; Cygan and Koster Van Groos, 1978; Visser and Koster Van Groos, 1978, 1979.

Vogel and Wilband (1978) discussed the geochemistry of composite acidic and basic dikes near Winnsboro, South Carolina. They favor the mechanism of silicate liquid immiscibility, based on partitioning of rare-earth elements, to explain the origin of coexisting lamprophyre and granophyre. McSween et al. (1979) argue that these dikes represent the co-mingling of two unrelated magmas. Coexisting granitic and basaltic rocks at Mt. Desert Island, Maine, appear to represent two miscible liquids of divergent composition that co-mingled and failed to mix due to large differences in viscosity and rapid crystallization (Taylor et al., 1979).

In rare occurrences, thermal metamorphism in the sanidinite facies may result in partial melting of hornfels (Spry, 1969). Holgate (1954, 1956) cited the field evidence of various investigators (Wright, 1911;Campbell et al., 1932; Holmes, 1936; Kennedy and Read, 1936; and Reynolds, 1938;) and noted that siliceous xenoliths reacted with basic magmas such that a melt zone of quartzo-feldspathic material surrounded by a rim of prismatic pyroxenes was produced at the interface between the basic magma and each siliceous xenolith. Holgate concluded that basic magma and the quartzo-feldspathic melt were immiscible. Roedder (1956) presented evidence that the coexisting basic and silicic melts described by Holgate are not necessarily in an immiscible relationship. Instead, he concluded that there was simultaneous diffusion of alkaluminous and cafemic ions in a strong concentration gradient.

Geological setting of the Xenolith in the Graniteville Quarry

A xenolith of Lockatong 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. Based on the measured density of 2.60 g/cc and 2.95 g/cc for the xenolith and the enclosing diabase, respectively, we conclude that the xenolith was derived from the Lockatong 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. We have categorized the coarse-grained rock of the interface zone as a melanocratic pyroxene trondhjemite[1]

The diabase-trondhjemite interface and the trondhjemite-hornfels interface are sharp and irregular . Pyroxene and plagioclase in the diabase within 5 mm of the diabase-trondhjemite interface show the effects of hydrothermal alteration. In the pyroxene, this is manifested by the development of hornblende and actinolite; in the plagioclase, sericite was formed.

[1] We note that, in the classification of Streckeisen et al. (1973), this rock would be classified as albite granite. However, we consider the term albite granite a contradiction in terms inasmuch as a granite by definition is a K-feldspar-bearing phanerite and K-feldspar is absent in this phanerite. We prefer the classification of O'Connor (1965) in which a quartz-bearing phanerite containing plagioclase of composition Ab_{99} as the dominant feldspar is classified as a trondhjemite.

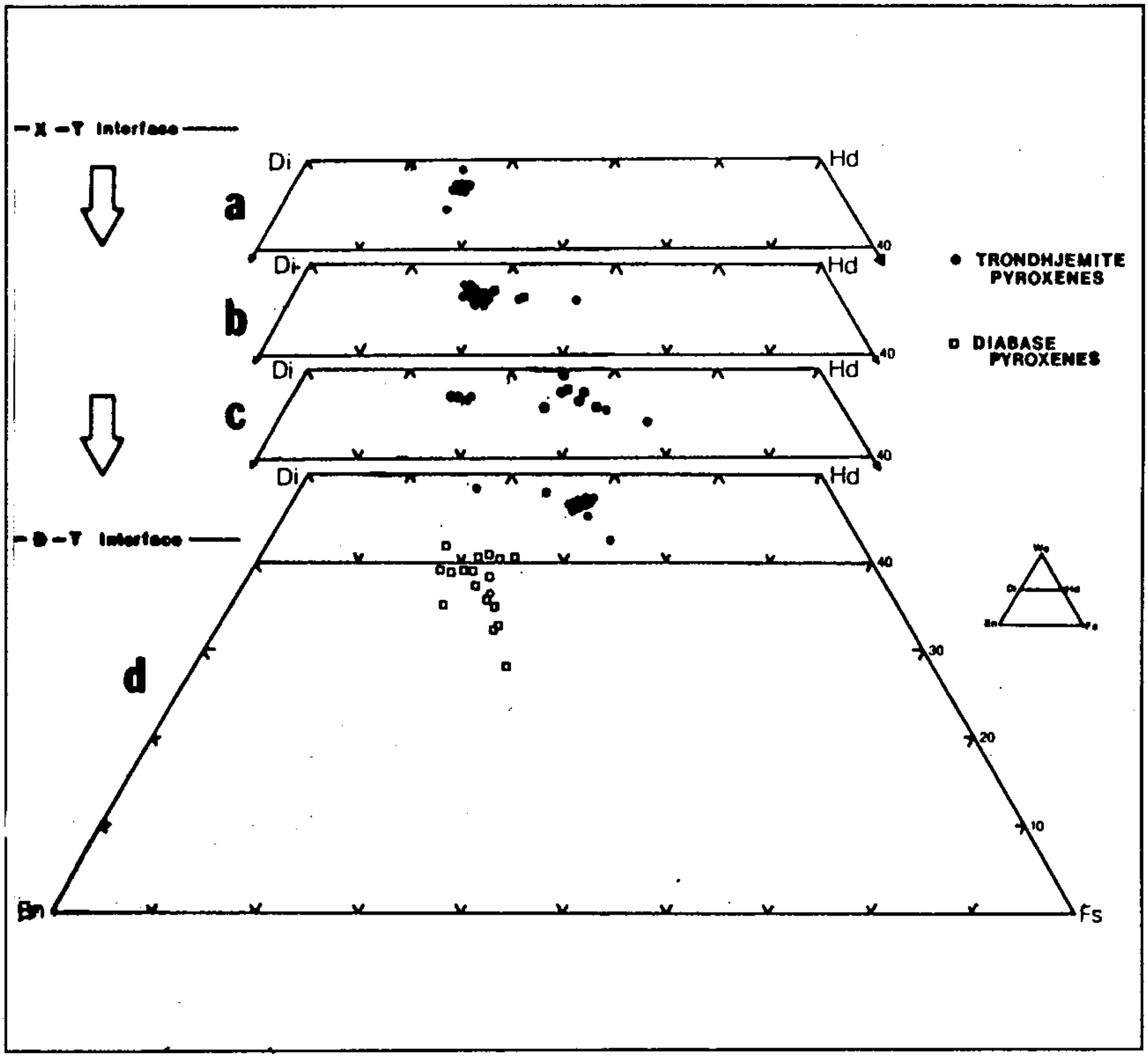

Figure 3. Composition of pyroxenes in trondhjemite and in adjacent diabase. (a) 30-35 mm from the diabase- trondhjemite interface; (b) 19-20mm from the diabase- trondhjemite interface; (c) 14-16 mm from the diabase- trondhjemite interface; (d) 3-12 mm from the diabase-trondhjemite interface

The diabase

The diabase at Graniteville is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34-44}Fs_{17-31}Wo_{35-42}$) 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. In view of the occurrence of oxidation lamellae of ilmenite in the titanomagnetite, no attempt was made to use the Buddington and Lindsley (1964) relationship to obtain an fo_2 and temperature of crystallization. However, an independent approach to determining the temperature of the diabase magma will be discussed below.

The trondhjemite

The trondhjemite is composed dominantly of quartz-albite granophyre in which are enclosed large discrete crystals of albite and Ca-rich clinopyroxene . 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.

Chemical variation in the pyroxenes is illustrated in Figure 3 . There is a complete gradation from Fe-rich compositions close to the diabase-trondhjemite interface to Mg-rich compositions close to the trondhjemite-hornfels interface. Pyroxenes adjacent to the trondhjemite-hornfels interface are large euhedral crystals 5 to 30 mm in length.; Cores of some of these clinopyroxenes are enriched in Mg; Mg/Fe (atomic) ranges from 2.7 in the cores to 2.2 in the rims. Within a distance of 16 mm from the diabase-trondhjemite interface, a few augite crystals occur which are similar to the augite of the diabase inasmuch as they contain lamellae of pigeonite parallel to (001). These crystals are enclosed in the trondhjemite and are probably xenocrysts derived from the diabase. Near the diabase-trondhjemite contact, high-Ca clinopyroxene related to the trondhjemite occurs as overgrowths in optical continuity with cores of pigeonite-augite intergrowths derived from the diabase. The pigeonite-augite intergrowths apparently served as nucleation sites.

Some of the high-Ca clinopyroxene crystals in the trondhjemite were altered hydrothermally by post-magmatic fluids to the assemblage: actinolite + titanite + calcite.

The dominant petrographic component of the trondhjemite is an albite-quartz granophyric intergrowth. Albite ($Ab_{99}An_{0.52}Or_{0.44}$) occurs as both early-formed discrete euhedral crystals and also as a major component of the granophyric intergrowth with quartz. The early albite crystals are localized at the diabase-trondhjemite interface. Some of these large crystals of albite exhibit Carlsbad twinning.

Minor Minerals

Zinc sulfide occurs as euhedral crystals(30-70 μm in diameter) embedded selectively in the albite of the granophyre. As seen in thin section , dark well-defined cores contains 13-16 mole% FeS, whereas pale yellow-brown rims contain between 0.2 and 2.0 mole percent FeS. Electron microprobe data (Figure 4) show that there is a sharp compositional discontinuity between the core and the rim. In reflected light the core-rim relationship is resolvable because of the higher reflectivity of the core, and in transmitted polarized light between crossed polarizers, the rim appears illuminated because of internal reflections.

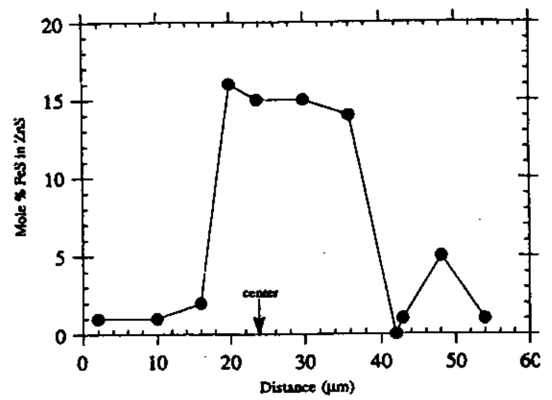

Figure 4. Typical zoning profile of the magmatic ZnS crystals, showing the distribution of iron as determined by electron-microprobe analysis.From Sclar and Benimoff,(1993)

The euhedral grains of zinc sulfide typically have the shape of an equilateral triangle, the corners of which are truncated . This results in a six-sided form with alternating long and short sides that resembles most closely the crystallographic form of an isometric positive tetrahedron modified by a negative tetrahedron. This morphology is characteristic of sphalerite. Nevertheless, such a morphology is not incompatible with the hexagonal symmetry of wurtzite if the grains are considered to be basal (0001) sections or near-basal sections. However, the absence of anisotropic longitudinal *c*-axis sections suggests that the crystals that nucleated in the trondhjemite magma were sphalerite and not wurtzite. Some of the euhedral crystals show deep embayments that may be indicative of magmatic resorption.

The carbonate phase in the trondhjemite is calcite which occurs as single-crystal interstitial fillings between the silicate minerals. There is no evidence, such as colliform or crustiform structures, which would indicate that this calcite is a product of cavity filling. The calcite, therefore, appears to be a late igneous mineral.

Aggregates of ilmenite are locally surrounded by euhedral to subhedral crystals of titanite. Titanite is also present as discrete euhedral crystals which appear to be part of the early magmatic suite. Optically homogeneous euhedral grains of titianomagnetite occur as inclusions in the high-Ca clinopyroxene. Nickel- and cobalt-bearing pyrrhotite is present as microscopic grains. Euhedral apatite crystals occur in the granophyre and as inclusions in the high-Ca clinopyroxene.

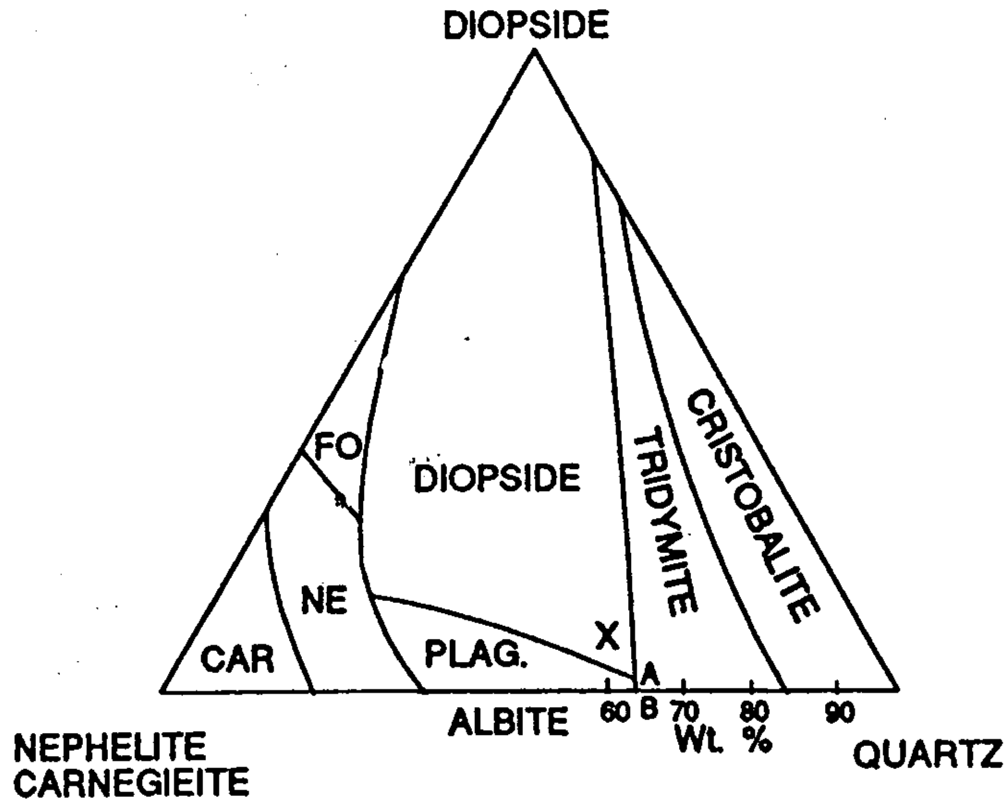

Figure 5 The system diopside-nepheline-silica (Shairer and Yoder 1960). The deduced composition of trondhjemite magma is shown by x which lies at a temperature of approximately 1150°C. The crystallization sequence of major phases is: diopside, followed by diopside and albite, and lastly by quartz-albite granophyre. A is at 1073°C. B represents the dry minimum melting temperature (1062°C) in the quartz-albite system. The composition at B, is 68.5 albite and 31.5 quartz (in wt.%).(from Benimoff and Sclar, 1984)

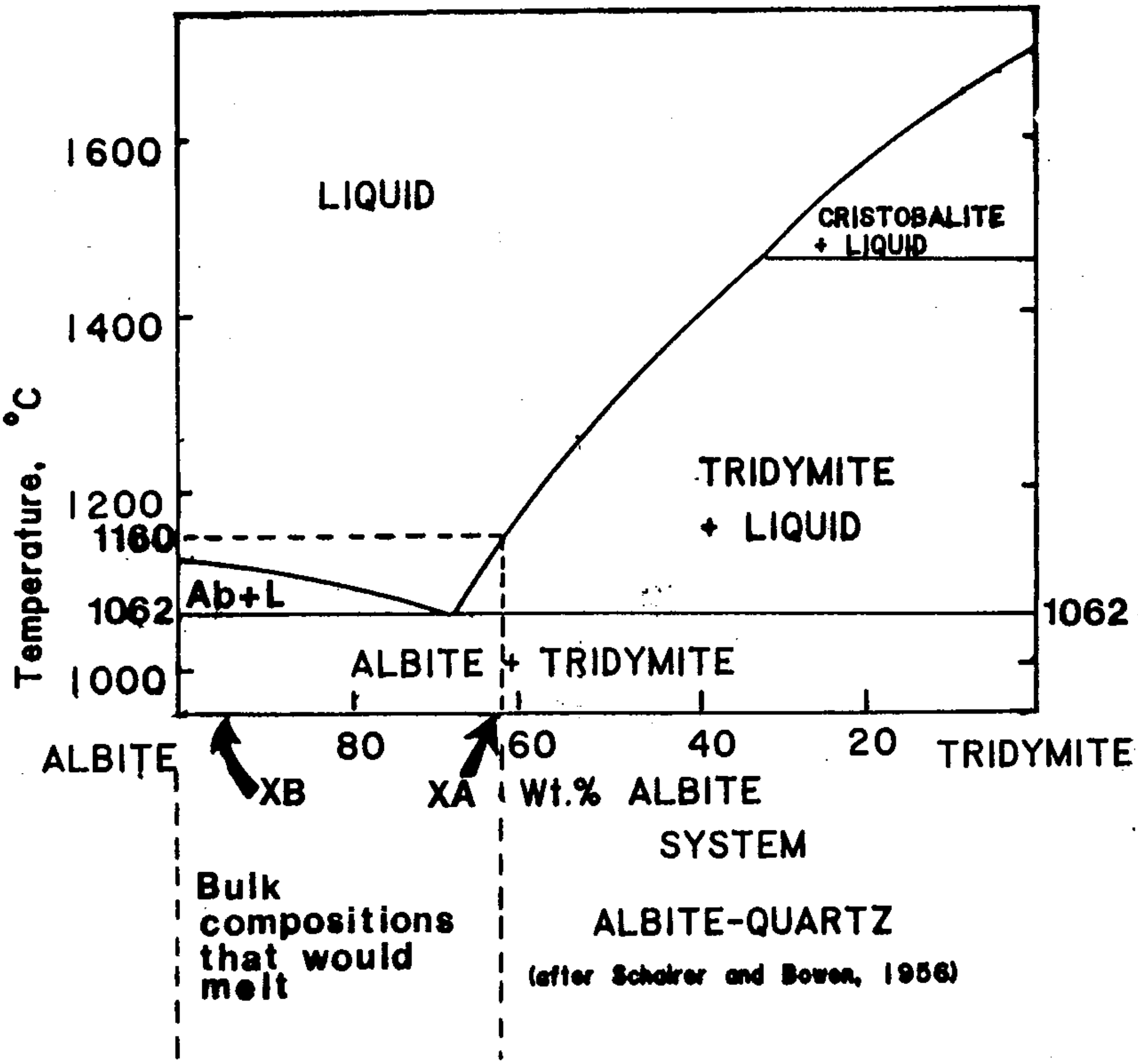

Figure 6 The dry one atmosphere albite-quartz system(Schairer and Bowen, 1956) From Benimoff and Sclar, (1988)

Crystallization sequence

The sequence of magmatic crystallization in the trondhjemite, as shown by petrographic relationships is apatite, titanomagnetite, ilmenite, high-Ca clinopyroxene, discrete crystals of albite, titanite, zinc sulfide, albite-quartz granophyre, and interstitial calcite. The crystallization sequence of the major phases (albite, quartz, and pyroxene) is in accord with the most pertinent ternary phase diagram of this system (diopside-nepheline-silica) as determined by Schairer and Yoder (1960) (see Figure 5). If crystallization commenced at x, which is close to 1160° C, the temperature of crystallization of the trondhjemite deduced in subsequent discussion (see below), diopsidic clinopyroxene would be the first major phase to crystallize. When the diopside-plagioclase boundary was reached on cooling, albite and diopside crystallized. When the temperature reached 1073 °C, an albite-quartz would granophyre crystallize until the albite-quartz eutectic is reached at 1062 °C, which is the dry minimum melting temperature in the quartz-albite system (Figure 6) at one atmosphere (Schairer and Bowen, 1956). The composition of this eutectic is 31.5 quartz-68.5 albite which is close to the normative quartz and albite content of part of the parental hornfels of the trondhjemite.

The xenolith

Petrographic examination 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, as shown in Table 1, 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.%.

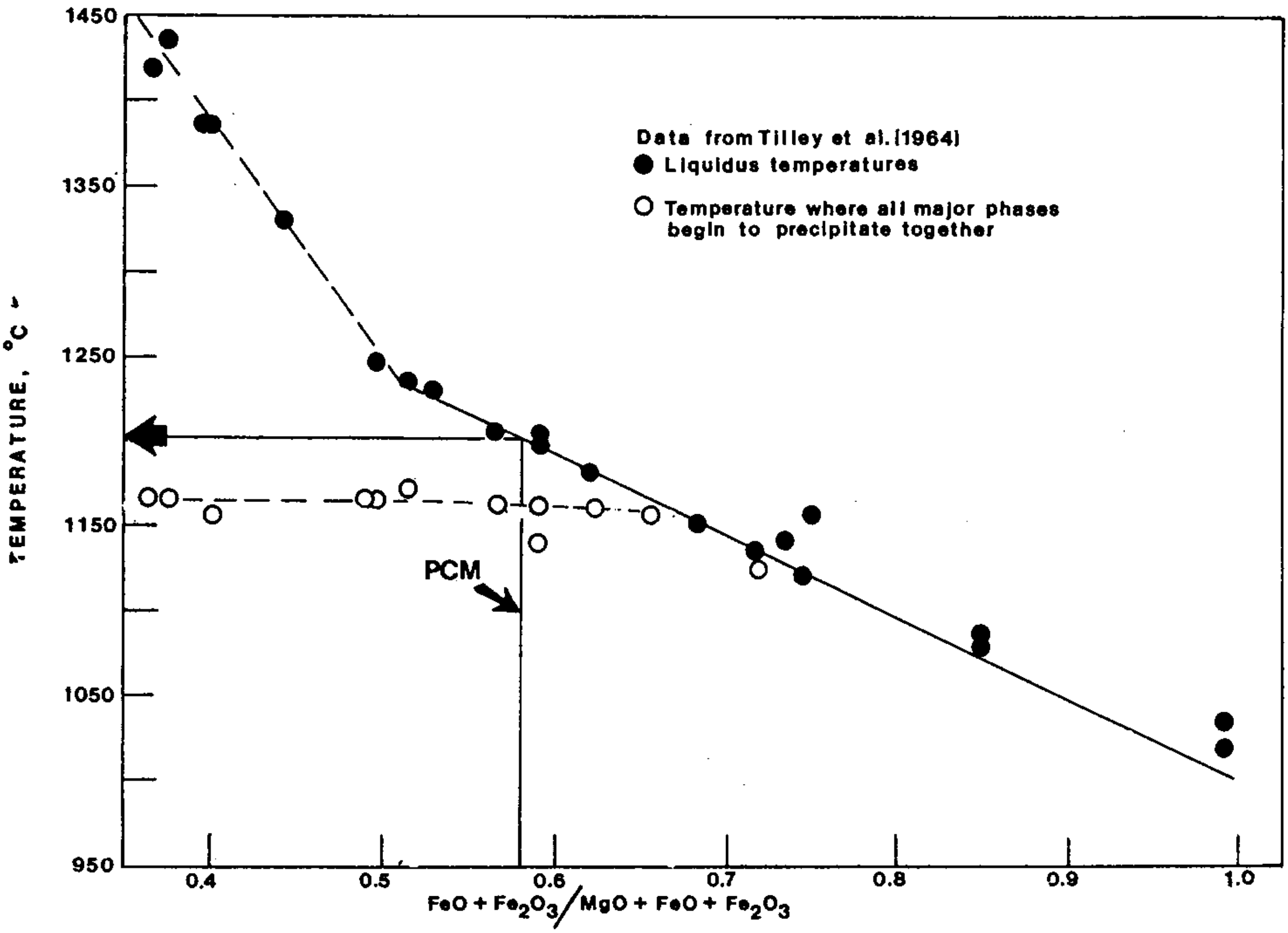

Figure 7 Plot of temperature vs. iron enrichment(after Tilley et al. 1964) showing that Graniteville Quarry sample D-2 correlates with a liquidus temperature of 1160° C and that the Palisades chill margin(PCM;Walker 1969 correlates with a liquidus temperature of 1220° C. From Benimoff and Sclar, (1988).

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

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_2O_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_2O_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_2O	6.67	9.48	3.76	3.81	3.22	2.58
K_2O	0.07	0.12	0.12	0.14	1.4	0.76
P_2O_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_20					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 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.

Discussion

It is apparent from spatial relationships and petrochemical data that the margins of the xenolith of Lockatong argillite fused as a result of being immersed in the diabase magma. Based on the dry albite-quartz equilibrium diagram(Figure 6) of Schairer and Bowen (1956), the temperature of the diabase magma surrounding the hornfelsed xenolith must have been about 1160°C in order to have effected melting of a xenolith of the bulk composition shown in Table 1. Hess (1956) concluded that dolerites crystallize at a temperature of about 1100°C. Later, Tilley et al. (1964) correlated experimental determinations of liquidus temperatures with an iron-enrichment index [(FeO + Fe_2O_3)/(MgO + FeO + Fe_2O_3)] in natural rocks. The iron-enrichment index of the chilled-zone of the Palisades diabase (Walker, 1969a) is 0.58 which correlates with a liquidus temperature of 1220°C. The iron-enrichment index of specimen D-2(see Table 1) is 0.67 which correlated with a liquidus temperature of approximately 1160°C(figure 7). We have examined hornfelsed xenoliths of Lockatong argillite at the base of the Palisades Sill in New Jersey, but these xenoliths do not show any evidence of fusion. Sosman and Merwin (1913) found that arkosic xenoliths in the Palisades Sill in New Jersey did not show evidence of fusion, although this material was shown experimentally to be partly fused at a temperature of 1150°C dry. It appears that in some instances hornfelsed xenoliths which should have fused at the temperature to which they were subjected did not fuse, perhaps because of the relatively high rate of cooling which might be expected to prevail near the basal contact of the sill.

In the case presented in this study, the presence of pyroxene suggests that the xenolith of Lockatong argillite was dry at the time of fusion. In addition, the position of the xenolith in the middle of the sill suggests that any original water in the sedimentary rock would have been expelled long before it reached this position.

Several lines of evidence suggest that the location of this xenolith is approximately 525±50 feet above the base of the sill. Normalizing the diabase surrounding the xenolith to the Englewood Cliff section of Walker (1969a) shows that: (1) modal analysis of D-1 (Table 2) lies between W-N-60 and W-R-60 of Walker, thus placing upper and lower constraints of 560 feet and 365 feet above the base of the sill for the xenolith; (2) the composition of augite and plagioclase in D-1 is in accord with the above constraints and indicates the middle differentiation series of Walker; (3) the mafic fractionation indices [(Fe) + Fe_2O_3)(100%)/(MgO +Fe_2O_3)] of W-N-60 and D-2 are respectively 66.55 and 66.92 (Figure 8), and (4) D-2 plots directly on the differentiation trend for the Palisades Sill (Figure 9). D-2 plots closer to W-N-60 than any of the Englewood Cliff specimens of Walker (1969a).

Table 2. Modal Analyses (in Volume%) Of Palisades Diabase, Englewood Cliffs (from Walker 1969a)

Specimen	Height*, ft	Plagioclase	Pyroxenes	Opaques	Micropegmatite
W-889LC-60	1	39	1.5	5	
W-865-60	30	46	54	2.5	1.5
W-824-60	70	30	38	2	
W-804-60	90	43	51	1.5	2.5
W-U-60	215	49	47	1.3	1.4
W-R-60	365	59	33	2	3.0
W-N-60	560	66	24.5	3	3.8
W-J-60	685	47	34.3	5	10.0
W-E-60	805	35	23	6.2	23.0
W-F-60	790	40	tr.	3	24.5

Micrometric analysis Of Diabase, Graniteville Quarry, Staten Island, N.Y., From Benimoff and Sclar, (1984).

D-1	500± 50	60.7	32.6	4.2	2.5

* above the base of the sill

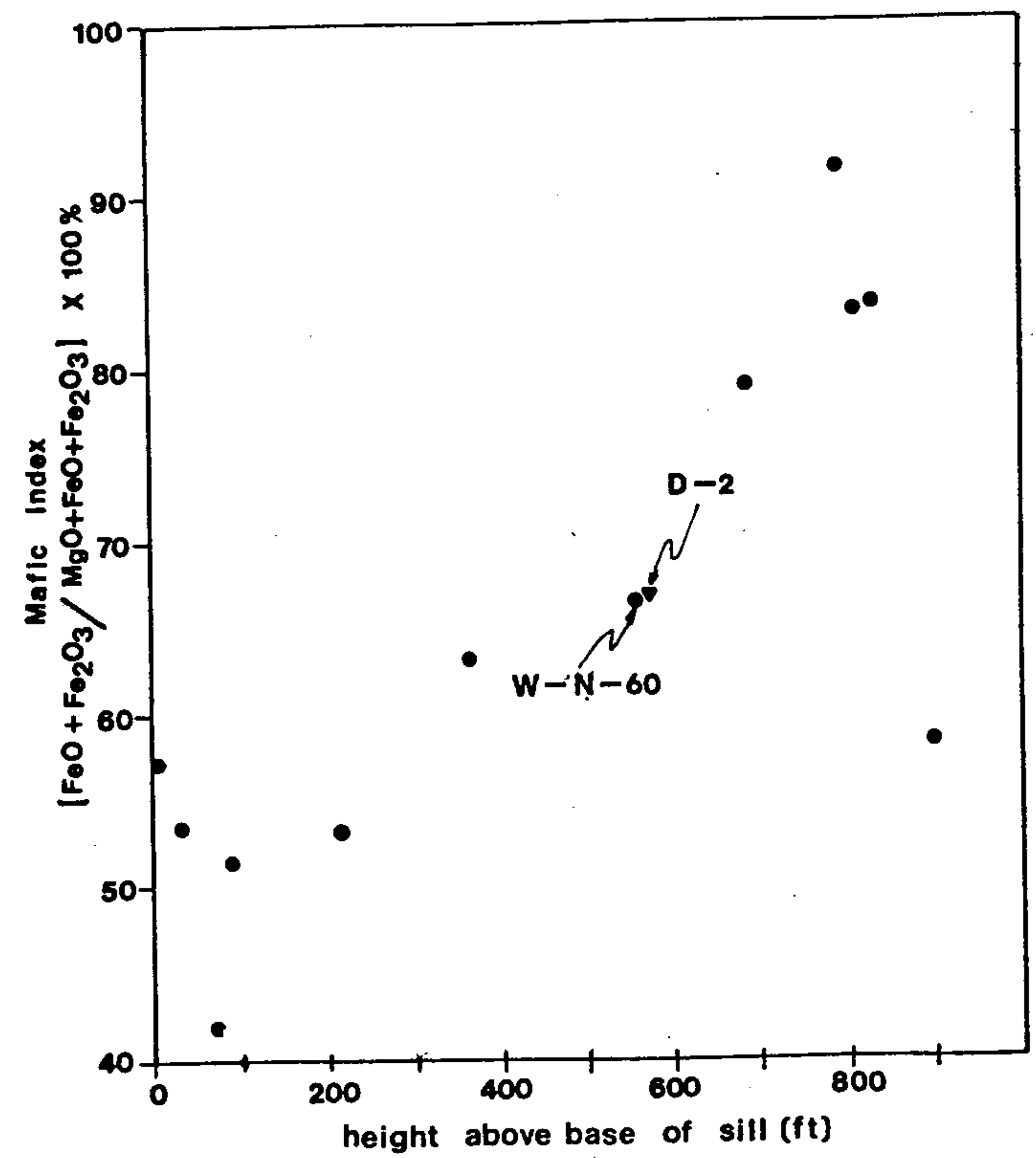

Figure 8. Plot of mafic index of Palisades diabase against height above the base of the sill. Note that Graniteville sample D-2 coincides with Palisades Sill sample W-N-60(Walker, 1969) From Benimoff and Sclar(1988)

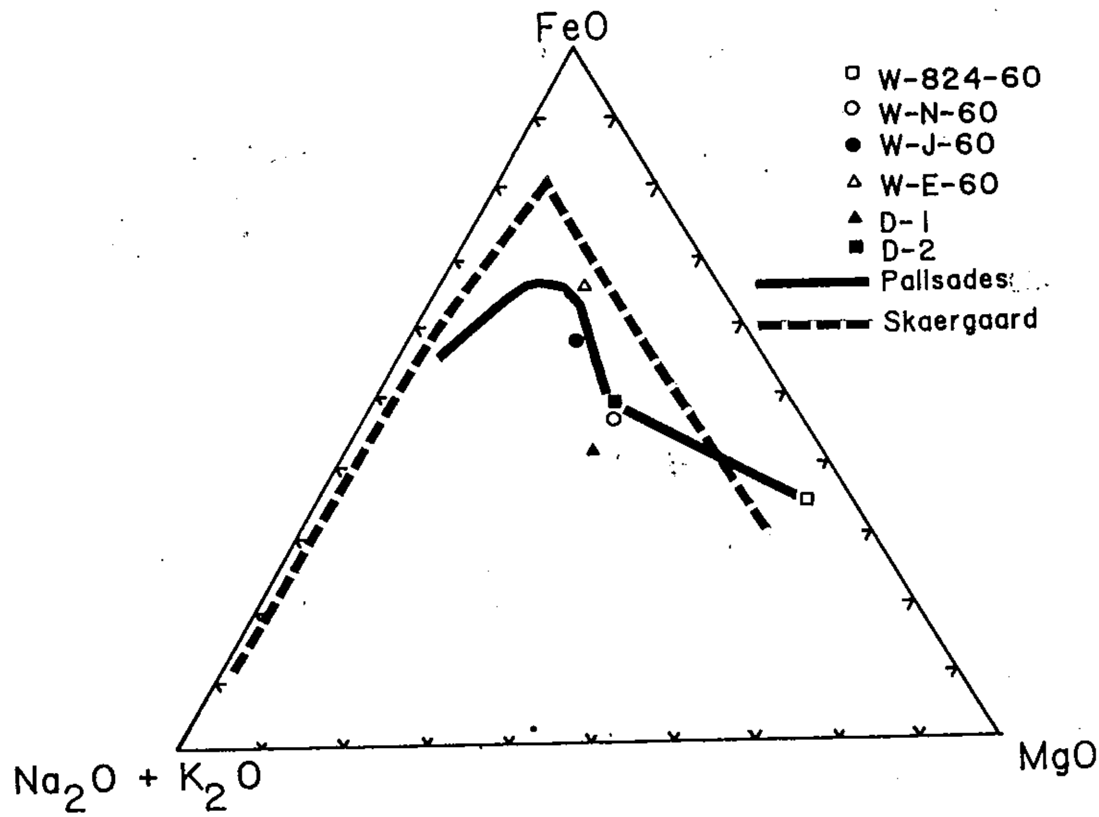

Figure 9. ($Na_2O + K_2O$)-FeO-MgO) diagram which shows the composition of Palisades diabase specimens D-1 and D-2 from this study and the diabase from the Englewood Cliffs section of Walker (1969a). D-2 falls directly on the Palisades diabase differentiation trend of Walker (1969a). D-1 shows Fe-depletion and alkali enrichment. FeO represents total Fe expressed as FeO. From Benimoff and Sclar, (1984;1988)

A thickness of 900 feet is assumed for the Palisades Sill at Graniteville, Staten Island in accord with a subsurface intersection of the sill revealed in drill-core at Sewaren, N.J. (Van Houten, 1969). At 525 feet above the base of the sill, a xenolith of Lockatong argillite might easily have fused.

There are differences between the bulk chemical composition of the trondhjemite and that of the Lockatong hornfels (see Table 1), which are due to the paucity of the ferromagnesian component in the Lockatong hornfels. This suggests that Fe^{2+},Mg^{2+}, and some Ca^{2+} diffused from the diabase magma into the fusion zone of the xenolith and were incorporated into the high-Ca clinopyroxene now present in the trondhjemite. This gave rise to a more complex bulk chemistry for the trondhjemite than would have been obtained solely by fusion of the xenolith. As shown in figure 9, D-1 and D-2 differ in that D-1 is relatively enriched in sodium and relatively depleted in iron. This indicates that Na^+ ions diffused out of the trondhjemite magma and into the diabase magma, whereas Fe^{2+} ions diffused from the diabase magma into the trondhjemite liquid.

The identity of two contiguous magmas of diverse composition may be maintained for a limited amount of time (Yoder, 1973). The coexisting melts described in this study did not mix, although there appears to have been simultaneous diffusion of ions across the liquid-liquid interface. The coarse grain size of the trondhjemite (especially the large euhedral clinopyroxene crystals) and the evidence for chemical diffusion strongly indicate that these two melts coexisted for some time.

Yoder (1973) suggests that the failure of two contrasting magmatic liquids to mix might be due to (1) immiscibility, (2) short time of contact, or (3) high viscosity occasioned by volatile loss.

Silicate liquid immiscibility involves the splitting of a homogeneous magma into two immiscible fractions upon cooling (Roedder, 1978). This occurs when $\Delta\overline{H}_{mix}$ (enthalpy of mixing), is greater than the entropy of mixing term $T\Delta\overline{S}_{mix}$ so that $\Delta\overline{G}_{mix}$ in equation (1) is positive

$$\Delta\overline{G}_{mix} = \Delta\overline{H}_{mix} - T\Delta\overline{S}_{mix} \qquad (1)$$

(Ryerson and Hess, 1978). An upward convexity in the G-X surface of the liquid is produced such that the ΔG of the system is minimized by the liquid-liquid separation (Hess, 1977; Ryerson and Hess, 1978). This is not the case in the study presented in this paper, inasmuch as the spatial relationship of the trondhjemite to the xenolith and the diabase, and the petrochemical data reveal that the trondhjemite is a fusion product of the xenolith.

In order to determine whether or not the diabase magma and the trondhjemite magma were in an immiscible relationship, their respective positions on an FeO-(Al_2O_3 + K_2O)-SiO_2 diagram (Watson, 1976) were plotted(Figure 10). This showed that the diabase and trondhjemite compositions plot outside of the liquid-immiscible field. Also it was noted that any attempt to draw conjugate tie lines between respective diabase and trondhjemite compositions resulted in lines which were perpendicular to the conjugate tie lines within the field of liquid immiscibility.

We also plotted the diabase, trondhjemite, and xenolith compositions, respectively, on the hypothetical pseudoternary phase diagram, [SiO_2] - [Na_2O-K_2O-Al_2O_3] - [FeO + TiO_2 + MnO + MgO + P_2O_5] (see Grieg, 1927; Weiblen and Roedder, 1973; McBirney, 1975, Philpotts, 1979), but conjugate tie lines drawn between diabase and trondhjemite compositions are still perpendicular to the tie lines shown in the field of liquid immiscibility (Figure 11). Therefore, the diabase and the trondhjemite do not appear to be in an immiscible relationship.

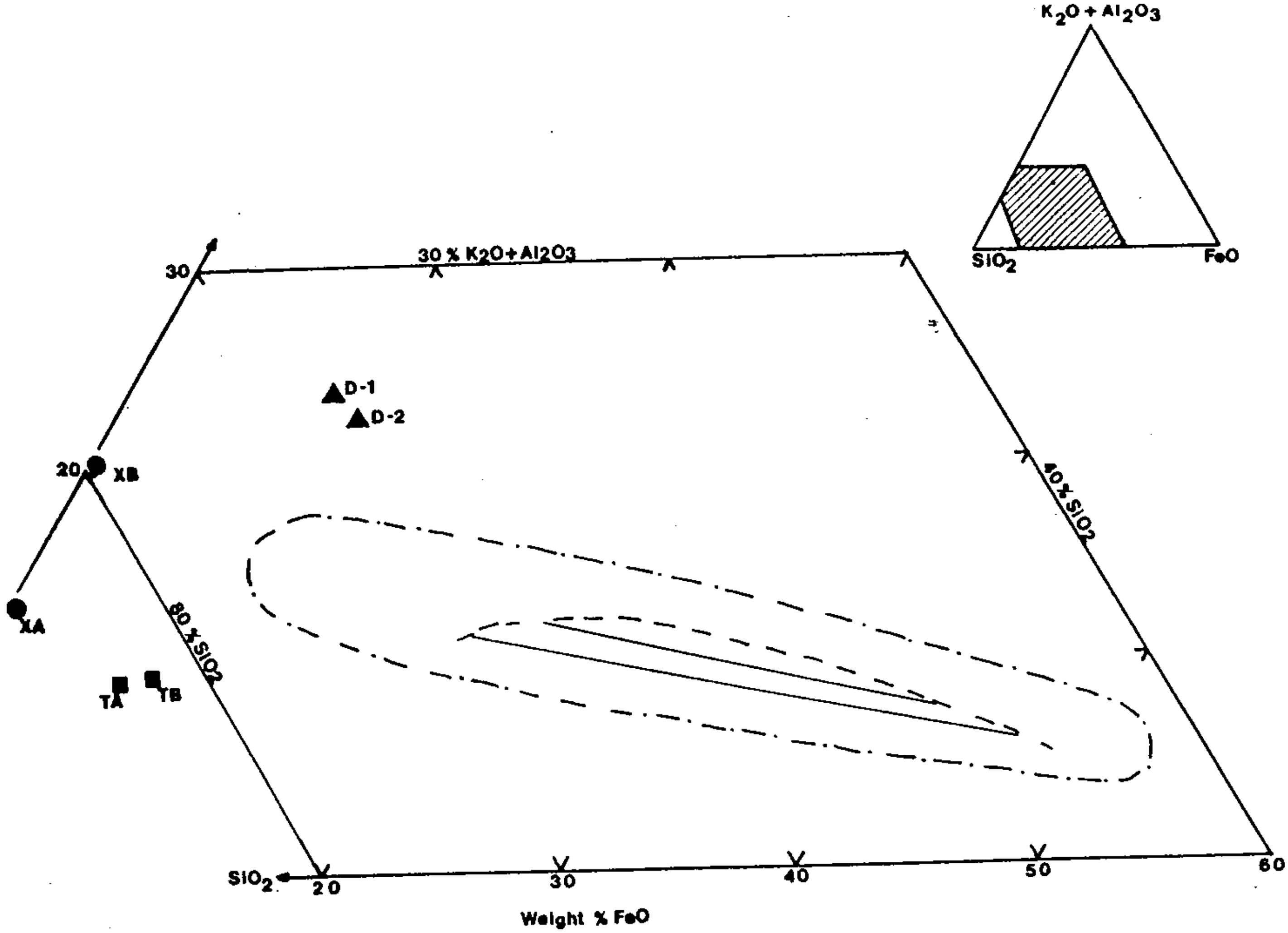

Figure 10. Diabase, xenolith, and trondhjemite compositions plotted in the system FeO-(Al_2O_3 + K_2O)-SiO_2 diagram (Watson, 1976) showing that the diabase and trondhjemite are not in an immiscible relationship. The high-temperature and low-temperature immiscibilty fields are marked by the dashed and dot-dashed curves, respectively. From Puffer et al. (1992)

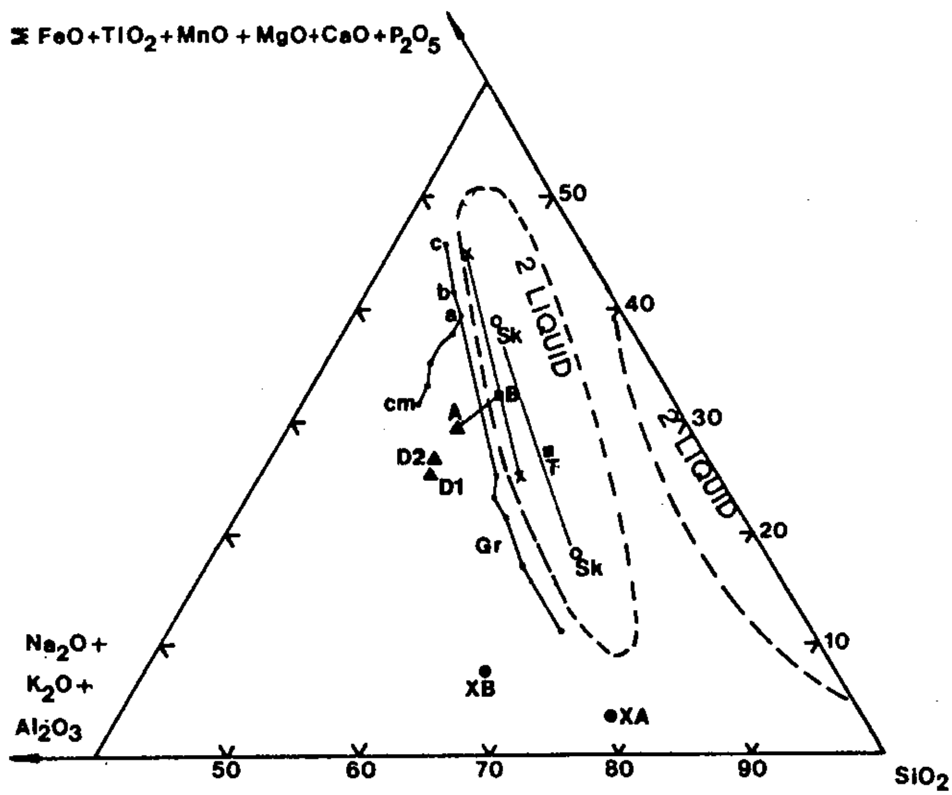

Figure 11. Diabase, trondhjemite, and xenolith compositions plotted on the pseudoternary diagram (SiO_2)-(K_2O + Na_2O + Al_2O_3)-(FeO + TiO_2 + MnO + MgO + CaO + P_2O_5). The high temperature and low-temperature immiscibility fields are marked by dashed lines (system fayalite-leucite-silica after Roedder, 1951). Also plotted are the compositions of (1) Rattlesnake Basalt (A) and its mesostasis (B) (Philpotts, 1979); and (2) a pair of conjugate liquids (SK) produced experimentally from mixtures of late-stage Skaergaard rocks (McBirney, 1975). The calculated Skaergaard differentiation trend is shown for comparison (cm = chilled margin; a, b, and c represent the upper zone, Gr = melanocratic granophyres). Inasmuch as both TA and TB coincide, their compositions are represented as T. As expected, Walker's (1969a) W-N-60 coincides with D2. The x's represent immiscible liquids in the Rattlesnake Hill Basalt (Philpotts, 1979). From Benimoff and Sclar (1984, 1988)

It seems highly improbable, in view of the geological setting in which these contrasting liquids occur, that lack of mixing was due to the short time of contact. It also seems highly unlikely that lack of mixing was due to high viscosity occasioned by volatile loss inasmuch as the xenolith would probably have been devolatilized before melting of its margins occurred. The relatively high viscosity of the relatively silicic trondhjemitic liquid appears to be the factor responsible for the lack of mixing.

Origin of the Sphalerite

Sphalerite is a remarkably refractory sulfide, with a melting point at one atmosphere of pressure in excess of 1800°C (Kullerud 1966). Nevertheless, all known economic deposits of sphalerite are of hydrothermal origin, and occurrences of magmatic sphalerite are rare (Ramdohr 1980, p. 519). However, a few occurrences of magmatic sphalerite have been reported. Desborough (1963) reported the occurrence in Missouri of sphalerite of apparently magmatic origin; it occurs as disseminated grains in unaltered intrusive tabular bodies of olivine diabase, coarse ophitic gabbro, and layered gabbro. He indicated that, because of its lack of distinctive optical properties, sphalerite may easily be overlooked or mistaken for ilmenite in microscopic examination of thin and polished sections. He also reported that sphalerite may be a rare constituent of magmatic droplets of iron, nickel, and copper sulfides in mafic igneous rocks. Wilson (1953) stated that some zinc may enter the magmatic Cu-Ni-Fe sulfides, although zinc typically reaches its maximum concentration in a mafic magma at a much later stage than the formation of the magmatic sulfides. Naldrett (1989) pointed out that zinc is conspicuously absent in magmatic sulfide ore, although some of the magmatic sulfide ores of Sudbury average 100-200 ppm of zinc, and some copper-rich stringers contain up to 3700 ppm of zinc. According to Naldrett (1989, p. 52), the sulfide melt - silicate melt partition coefficient of zinc is about 1, and, consequently, zinc does not concentrate in sulfide melts. We report evidence here for the direct crystallization of magmatic sphalerite from a felsic silicate melt.

Petrographic relationships indicate that the sphalerite is part of the magmatic suite and that is probably crystallized from the silicate melt at temperatures between 1062° and 1073°C (before the albite of the quartz-albite granophyre and after the augite phenocrysts and early discrete crystals of albite). Based on the geological setting, pressure at the time of crystallization was probably less than 2 kilobars. A possible source of the zinc and sulfur was the sedimentary xenolith (now a hornfels), which contains 20-54 ppm of zinc. Another possible source of the zinc and sulfur is the surrounding uncontaminated diabase, which contains 50 ppm of zinc. Zinc and sulfide ions could have diffused from the basaltic magma across the liquid-liquid boundary between the coexisting basaltic and trondhjemite magmas.

The equilibrium boundary between sphalerite (low-temperature polymorph) and wurtzite (high-temperature polymorph) in pure ZnS occurs at 1020°C at 1 atmosphere (Kullerud 1966); the pressure-dependence of the inversion is not known. The inversion temperature is lowered at about 960°C with 15 mole % of FeS in solid solution (Kullerud 1966). These phase relationships in the ZnS-FeS system suggest that wurtzite should have nucleated as the equilibrium phase in the temperature interval 1062-1073°C and then inverted to sphalerite on cooling below the solidus, but the morphology of the ZnS crystals suggests, at first, that sphalerite was the magmatic phase.

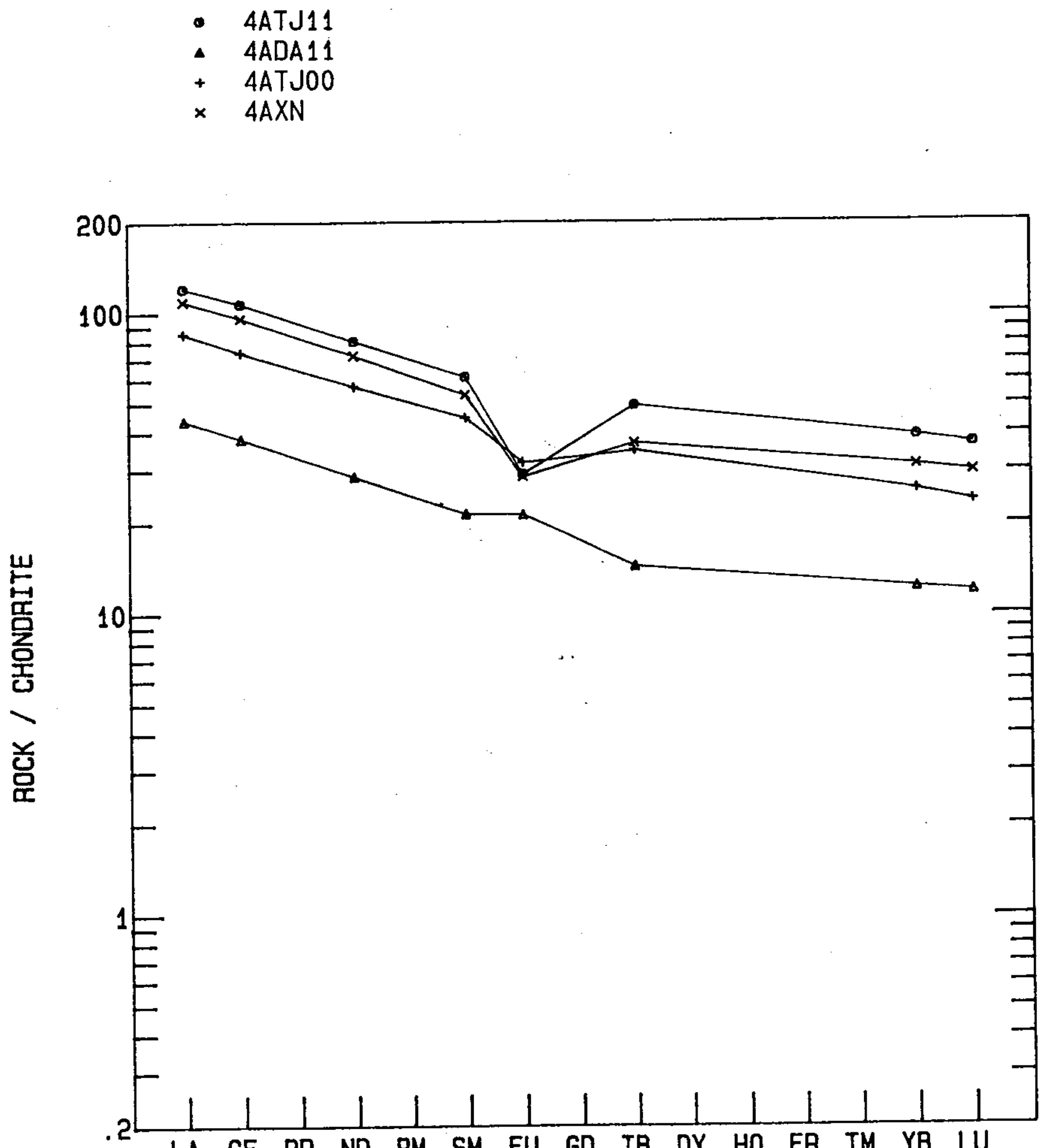

Figure 12. Chondrite Normalized plot (composite of 9 chondrites, Haskin, et. al 1968)of trondhjemite specimens 4ATJ11, 4ATJ00; Diabase 4ADA11, and xenolith 4AXN. Note the LREE enrichment and negative Eu anomaly in trondhjemite and xenolith specimens, and the positive Eu anomaly in the diabase specimen.

However, it is important to note that several of the polytypes of wurtzite (3R, 9R, 12R, 15R, 21R) have symmetry *R3m* (Kostov & Minševa-Stefanova 1982). It is possible, therefore, that the magmatic ZnS crystals developed as thin tabular forms of wurtzite parallel to (0001). They would display trigonal outlines like basal sections of tourmaline and appear optically isotropic regardless of whether they inverted to sphalerite. Such an occurrence of wurtzite would be compatible with the estimated temperature of crystallization and the equilibrium relationships between wurtzite and sphalerite.

Toulmin *et al.* (1991) have recently reviewed the binary system (ZnS-FeS) with specific reference to the FeS content of sphalerite in association with pyrite and pyrrhotite as a function of temperature and pressure. However, the absence of pyrite and pyrrhotite in direct association with Graniteville sphalerite precludes the application of their conclusions to this occurrence.

REE Studies

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. This setting provides an opportunity to test whether REE signatures reflect the source of an igneous rock. Chondrite-normalized RE plots(Figure 12) of the xenolith, the trondhjemite, and the contiguous Palisades diabase were prepared from RE 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 chrondites, 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. It is concluded that the REE signature of an igneous rock does indeed reflect that of the source rock.

Conclusions

Petrographical, mineralogical, and chemical data, plus field evidence indicate that coexisting silicic and mafic melts resulted when the margins of a xenolith of Lockatong argillite enclosed within the Palisades sill fused. There must have been diffusional interchange of ions to account for the more complex bulk chemistry of the trondhjemite as compared with the argillite protolith. This study suggests that Fe^{2+}, Mg^{2+}, and Ca^{2+} diffused from the diabasic magma into the fusion zone of the xenolith, and that Na^{+} diffused from the fusion zone of the xenolith into the diabasic magma. Evidently, these two chemically divergent magmas did not physically mix.

A dry magma of the composition of the trondhjemite would have a very high viscosity compared with the diabase magma. This high viscosity apparently prevented disruption of the liquid-liquid interface and thereby minimized physical mixing of the diabase and trondhjemite magmas. We are currently studying the chemical gradients in the three contiguous rocks with particular reference to what is interpreted as the liquid-liquid boundary. Slices, cut $\perp$ to the long axis of a core containing the three contiguous rocks, were chemically analyzed for major, minor, and trace elements including REE's. We hope to determine the relative diffusivities of the corresponding ions in the coexisting melts.

PART II: Leucocratic Dikes at the Travis Quarry and Bayonne Bridge Toll Plaza

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 (1cm) . 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 3.

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 et al. (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 3.

Interpretation of the albitite dikes

Based on the chemical and mineralogical characteristics of the leucocratic dikes in the Palisades Sill, it is 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-kspar with a relatively high Na_2O/K_2O 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 in Part I. The Lockatong argillite is a chemically unusual sedimentary rock with an exceptionally high Na_2O/K_2O 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).

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 13) 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.).

PART III: 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 Table 3) 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.

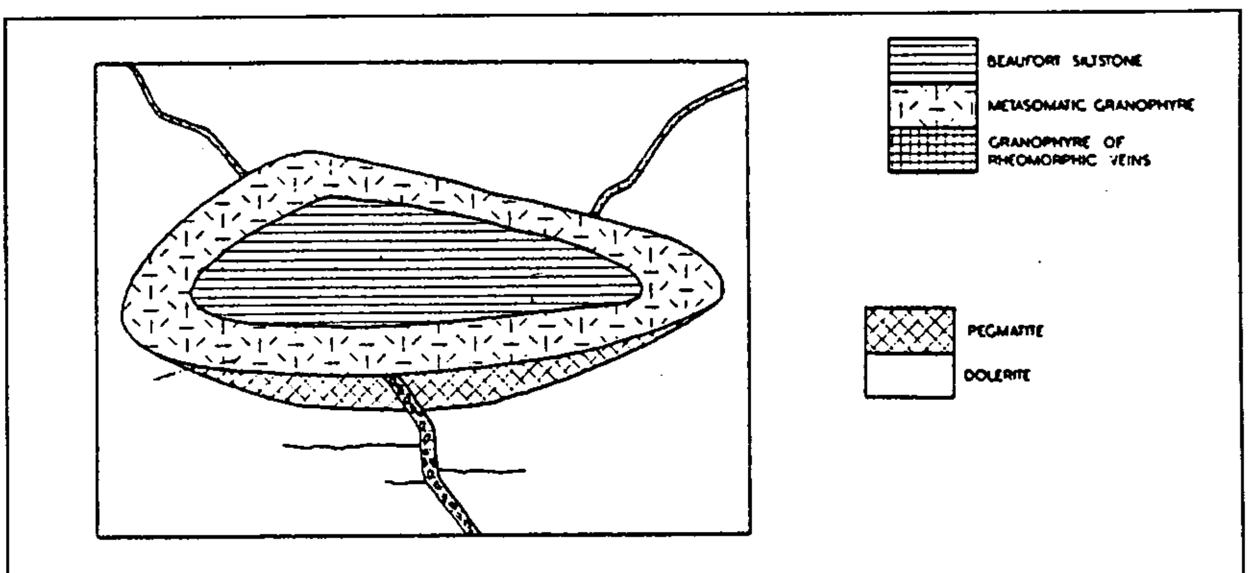

Figure 13. Sketch of the xenolith and pegmatite enclosed in the Karroo Dolerite (from Walker and Poldervaart 1949)

Table 3.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

Chemical Analyses, weight % oxides

	TV01	TV02	BBAL	BBDB	TL01	CSI03
SiO_2	62.7	52.3	60.1	52.5	51.88	53.29
Al_2O_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_2O_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_2O	8.79	0.18	9.39	2.48	2.65	3.2
K_2O	0.48	0.91	0.36	0.84	0.86	1.83
P_2O_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

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IMPLICATIONS OF THE GRANITEVILLE XENOLITH FOR FLOW DIRECTIONS OF THE PALISADES MAGMA.

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Examination of the orientation and marginal relationships of xenoliths in the Palisades intrusive sheet of New York and New Jersey suggests that one of the feeder areas for the intrusive sheet was in the vicinity of Graniteville, Staten Island. Geological relationships in Fort Lee, New Jersey, indicate that internal flow of the magma was directed northward, perhaps away from the Graniteville feeder area.

The Palisades Sill, a world-renowned mafic intrusive sheet, is continuously exposed from west of Haverstraw, New York southwestward to Staten Island, NYC. Many investigators have postulated that the Palisades magma flowed outward from fractures paralleling the NE-SW-trending Ramapo fault. To reach Fort Lee, magma from such fractures would have to flow from NW to SE. Beneath the George Washington Bridge, in Fort Lee, NJ, many large Lockatong xenoliths and screens containing contact-metamorphosed, deformed, highly laminated cyclic lacustrine sediments, are exposed. At the S end of the xenolith, hypocrystalline basalt is adjacent to metamorphosed Lockatong. Microscopic vesicles in the basalt may have been caused by fluidized pore water from the bounding sediments. Near the contact, the sandy sediments are chaotic and have "intruded" the igneous rock to form crude "sedimentary apophyses" and clastic dikes up to 20 cm long.

The microscope shows altered, contact-metamorphosed remnant clastic textures within the "clastic dikes" with subrounded feldspars, quartz, basalt, and other lithic fragments. Locally, the clastic grains are aligned parallel to the clastic-dike margins. In the same contact zone, a 40-cm-thick basaltic offshoot intrudes a Lockatong xenolith. Furthermore, the basal contact of the Palisades sheet cuts across the bedding in a ramp-like fashion toward the north. In the contact zone, tight, chevron folds with vertical, E-W-trending axial surfaces indicate differential flow from S to N not from NW to SE. Similar relationships occur at an exposure of the Palisades at Kings Bluff. Such flow to the N is consistent with evidence from the Graniteville quarry, Staten Island, where a partially fused, Lockatong xenolith is vertical and surrounded by annular fractures. All other xenoliths in the New York City area are oriented parallel to the contact of the Palisades intrusive sheet. This unique vertical xenolith implies upward flow of the magma and thus proximity to the feeder channel. If this is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from SSW to NNE. South of Staten Island, we predict NNE- to SSW-directed lateral paleoflow.

Our field data suggest that in the vicinity of New York City burial of the Palisades magma was not deep enough to allow dewatering and total compaction of the Lockatong sediments (~ 2 km?). As such, we envision wet and wild conditions at the base of the Palisades intrusive sheet during intrusion of the Palisades magma.

THE GEOLOGY OF WESTERN STATEN ISLAND, NEW YORK NORTH AND SOUTH OF THE FALL LINE

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INTRODUCTION

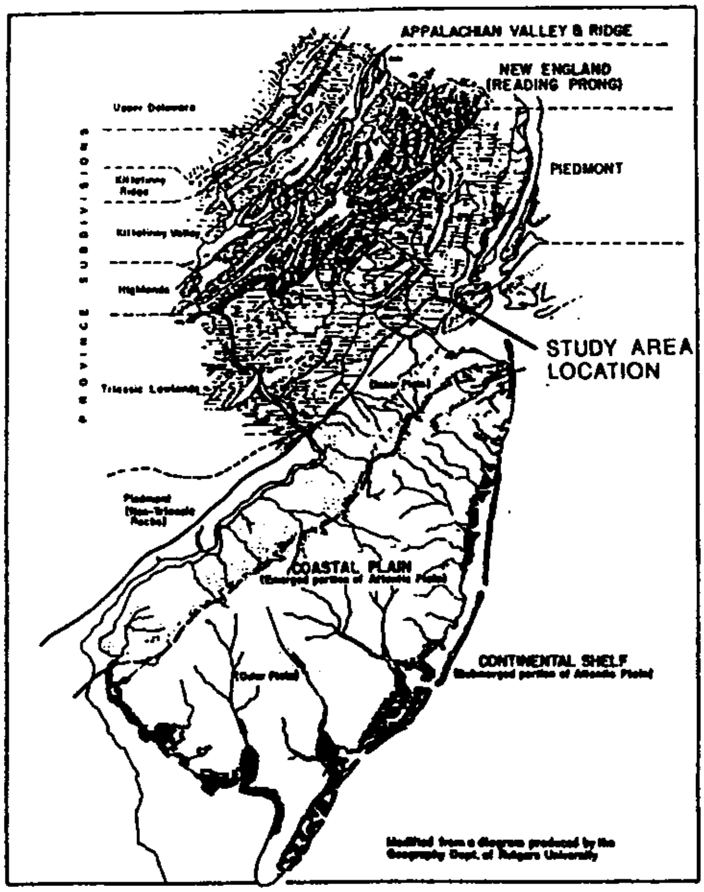
Most of the information for this paper was obtained from work conducted for the Hydrogeologic Investigation for the Fresh Kills Landfill Leachate Mitigation System Project (IT Corporation and Wehran EnviroTech, 1993). One of the purposes of the Hydrogeologic Investigation was to evaluate and interpret the geologic and hydrogeologic data obtained from previous studies and from the Mitigation System Project itself. The results of these analyses in regard to the geology of the Fresh Kills Landfill site and surrounding area are summarized below.

STUDY AREA LOCATION

The Fresh Kills Landfill and surrounding area are located along the western border of Staten Island, New York (Figure 1). The landfill site itself occurs in the area where Richmond and Main Creeks join to form the Fresh Kills (Figure 2). The Arthur Kill is a major feature, bordering Staten Island to the west. Geologic data was obtained from the landfill site and surrounding areas. The total area investigated extends northward, eastward, and southward into Staten Island, and westward across the Arthur Kill into New Jersey (Figure 2).

SCOPE OF INVESTIGATION

The main investigative tool used in determining the stratigraphy of the study area was conventional test borings. Soil and sediment samples were taken using split-spoon samplers. Bedrock was sampled by coring using either NX or HX size core barrels. Test boring logs from other investigations on the landfill site and in the surrounding area were also evaluated. In all, several hundred test borings were used in the interpretation (Figure 2).



MODIFIED FROM WIDMER, 1964

FIGURE 1

LOCATION OF STUDY AREA

Over 200 piezo-electric cone penetration test borings were conducted on the landfill site. The lithologic data obtained from this investigation was used to supplement the lithologic data obtained from the conventional test boring program.

Selected deep (drilled into bedrock) boreholes were also analyzed by borehole geophysics. A total of 59 boreholes were analyzed by several different geophysical logs and compared and contrasted with the results of the conventional test boring interpretations.

In addition, over 180 soil samples were selected for microfossil analysis. Holocene, Pleistocene, Cretaceous, and residual clay sediment samples were analyzed by palynologists to check the classifications and provide more detailed stratigraphic control.

A major portion of the analysis was done by creating plan view maps of each geologic unit which included top of unit, bottom of unit, and thickness of unit. Over 20 cross-sections were developed across the study area to provide a vertical perspective of the stratigraphy.

PHYSIOGRAPHY

The Fresh Kills Landfill region is located within two physiographic provinces, the Coastal Plain and Piedmont (Figure 1). The Coastal Plain is characterized by relatively flat, to slightly undulating topography. The Piedmont is slightly more undulatory, with higher relief and elevations.

The Fresh Kills Landfill site itself is located almost entirely within a former tidal marsh environment of low relief (Figures 2 and 3). Numerous channels drain the remaining tidal marsh. Most surface drainage eventually makes its way to the Arthur Kill/Fresh Kill/ Main Creek/Richmond Creek drainage network. Two remnant glacial topographic features (kames) existed prior to the placement of fill; rising as hills out of the tidal marsh (see "A" and "B" in Figure 3). The ground surface rises to the north, south, and east from the former tidal marsh area along the Fresh Kills (Figure 3).

FIGURE 2

CONVENTIONAL TEST
BORING LOCATIONS

STRATIGRAPHIC COLUMN

Figure 4 presents the stratigraphic column for the Fresh Kills Landfill and much of the surrounding area. Four major geologic subdivisions occur; Holocene (Recent) sediments, Pleistocene (glacial) sediments, Cretaceous sediments, and bedrock (includes residual clay). Each major subdivision is divided into geologic units based on textural analysis. More detail will be given on the geologic units below. Figures 5, 6, and 7 are generalized cross-sections through a portion of the study area in a north-south direction, and in east-west directions north and south of the "Fall Line," showing the distribution of the major geologic subdivision strata.

Recent Deposits

Four types of Recent deposits have been identified. They consist of Refuse/Fill, Peat, Recent silt and clay, and Recent sand.

Since the late 1940s, fill consisting of refuse and clean fill has been placed in primarily the tidal marsh portions of the study area. In addition to the Fresh Kills Landfill site, other major fill areas include the Fresh Kills Ash/Residue Landfill north of the Fresh Kills Creek between the Fresh Kills Landfill Section 3/4 and PASNY site and the Brookfield Avenue Landfill along Richmond Creek.

Peat occurs in the former tidal marsh areas throughout the study area. It is composed mainly of brown and black vegetative matter. Silt, clay, and sand occur as minor constituents in the peat. The thickness of the peat deposits are usually on the order of a few feet. The peat tends to occur near the top of the Recent sequence. It is sporadically distributed. However, the unit has been correlated over portions of the former tidal marsh areas.

Recent silt and clay occurs throughout most of the tidal marsh areas. It is composed of light gray to black clayey silt to silty clay. Small amounts of sand may be included. The thickness of the unit is usually a few feet, but sequences over 10 feet thick have been encountered. Peat and sand often occur interbedded with the silt and clay. The Recent silt and clay is interpreted as originating mostly from deposition of fine-grained sediment in the lower energy marsh areas.

The Recent sands are limited to the former tidal marsh environments or along existing drainage ways. The sand was usually fine to medium grained and light gray to black in color. Silt and clay often occur in minor amounts. Thicknesses average a few feet; however, sequences over 10 feet have also been found. The Recent sands are interpreted as originating from tidal channel processes either from deposition in the channel itself or as overbank deposits.

VERMEULE AND BEIN, 1890

MILES

FEET

METRES

LEGEND.

Tide Marsh

Fence Lines

Fresh Marsh

Low Water Mark

Woods

WehranEnviroTech

FIGURE 3

1890 TOPOGRAPHIC MAP

Pleistocene Deposits

Three types of glacial deposits have been identified. They are glaciolacustrine silt and clay, glacial sand, and glacial till/diamict.

Glaciolacustrine silt and clay occurs over much of the lower lying portions of the study area (Figure 8). In general, it corresponds somewhat closely in horizontal extent to the existing and former tidal marsh environments (Figure 3). The sediment is composed of red brown silty clay to clayey silt. Minor amounts of sand are often present. Occasionally gravel-sized fragments are encountered. The thickness of the unit ranges from a few feet to over 40 feet.

The glaciolacustrine deposits in this area are believed to have been deposited in glacial Lake Bayonne (Stanford and Harper, 1991). At maximum extent, glacial Lake Bayonne is believed to have extended from the terminal moraine to the Bayonne, New Jersey area (Figure 9).

Most of the glacial sand encountered in this area is composed of ice contact stratified drift. Glacial sand is found in areas throughout the glacial sequence. It is composed of red brown sand with minor amounts of silt, clay, and gravel. Thicknesses are quite variable and range from less than 1 foot to tens of feet. The most prominent deposits of glacial sand/ice contact stratified drift are two kame features that occur at the Fresh Kills Landfill site (Figure 3, "A" and "B"). The kames are composed of interbedded deposits of glacial sand and diamict. The kame sediments interfinger with the glaciolacustrine deposits, suggesting deposition in the glacial lake environment as kame deltas. The kame deposits may be traced to the east and west for a distance, implying an ice marginal configuration at each kame location. Other glacial sand deposits have been attributed to streams flowing into the glacial lake creating small delta deposits and/or isolated sand lenses within the lodgement till.

Glacial till/diamict is found throughout most of the study area. The glacial till/diamict is composed of two separate units: lodgement till and non-lodgement till diamict. Lodgement till occurs as a unit at the base of the glacial sequence (Figure 10). It is usually composed of red brown silt and clay, with varied amounts of sand and gravel. In some cases, the lodgement till has a high sand content. It is postulated that the sand was obtained from glacial erosion of sandy facies of the Stockton Formation in this area, or incorporation of sandy sediment from pre-Wisconsin surface water channels. Lodgement till thickness ranges from a few feet to tens of feet.

Non-lodgement till/diamict is found within the glacial sequence as melt-out till, flow till, water-laid till, and turbidities. Texturally, these deposits resemble the lodgement till, but quite often are sandier and usually occur within the glacial sequence, instead of at the base. The kame features are composed of a fairly large amount of diamict that is interbedded with glacial sand. Diamict also occurs within portions of the glaciolacustrine sequence as deposits such as water-laid till or turbidities.

PERIOD OR EPOCH	GEOLOGIC UNIT	GENERALIZED TEXTURAL DESCRIPTION OF THE FORMATION
RECENT	FILL (REFUSE) FILL (CLEAN)	REFUSE (HOUSEHOLD & CONSTRUCTION DEBRIS) STRUCTURAL FILL - RANGING FROM SILTY CLAY TO C-F SAND, LITTLE SILT
	NON-CONFORMITY	
RECENT	PEAT	BLACK PEAT, TRACE TO LITTLE SILT AND CLAY, TRACE FINE SAND
	RECENT SILT & CLAY	LIGHT GRAY TO BLACK CLAY AND SILT, TRACE FINE SAND TO DARK GRAY ORGANIC SILT, TRACE FINE SAND
	RECENT SANDS	LIGHT GRAY TO BLACK SAND, TRACE TO LITTLE SILT AND CLAY
	NON-CONFORMITY	
PLEISTOCENE	GLACIOLACUSTRINE CLAY & SILT	MODERATE RED BROWN SILT AND CLAY, TRACE TO LITTLE SAND, TRACE TO LITTLE FINE GRAVEL
	GLACIAL SANDS	MODERATE RED BROWN SAND, TRACE TO LITTLE SILT AND CLAY, TRACE TO AND GRAVEL
	GLACIAL TILL	MODERATE RED BROWN SILT AND CLAY, LITTLE TO AND SAND, LITTLE TO AND GRAVEL
	NON-CONFORMITY	
PLEISTOCENE OR TERTIARY	COLUMBIA GROUP?	YELLOW TO ORANGE BROWN SAND, LITTLE TO AND SILT AND CLAY YELLOW SILT AND CLAY, LITTLE TO SOME SAND

FIGURE 4A

STRATIGRAPHIC COLUMN

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PERIOD OR EPOCH	GEOLOGIC UNIT	GENERALIZED TEXTURAL DESCRIPTION OF THE FORMATION
CRETACEOUS	CRETACEOUS CLAY	LIGHT GRAY TO BLACK OR MODERATE RED BROWN AND LIGHT GRAY CLAY AND SILT, TRACE FINE SAND
	CRETACEOUS SAND	LIGHT GRAY TO DARK GRAY SAND, TRACE TO LITTLE SILT AND CLAY
POST TRIASSIC	RESIDUAL CLAY LOCKATONG FORMATION	LIGHT GRAY TO MODERATE GRAY, OR BLUE, OR GREEN CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
	RESIDUAL CLAY STOCKTON FORMATION	RED BROWN TO RED PURPLE CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
POST ORDOVICIAN	RESIDUAL CLAY SERPENTINITE	DARK GREEN AND YELLOW GREEN CLAY AND SILT, TRACE FINE SAND, TRACE GRAVEL
TRIASSIC	FRACTURED AND WEATHERED BEDROCK LOCKATONG FORMATION	LIGHT GRAY TO BLACK, WEATHERED AND FRACTURED SHALE, FRIABLE WITH FREQUENTLY LESS WEATHERED ZONES
	FRACTURED AND WEATHERED BEDROCK STOCKTON FORMATION	RED-BROWN, FRACTURED WEATHERED SHALE, FRIABLE WITH FREQUENTLY LESS WEATHERED ZONES
ORDOVICIAN	FRACTURED AND WEATHERED BEDROCK SERPENTINITE	DARK GREEN TO YELLOW GREEN FRACTURED AND WEATHERED SERPENTINITE, OFTEN WEATHERS TO A SANDY TEXTURE
JURASSIC, TRIASSIC ORDIVICIAN, OR CAMBRIAN	"COMPETENT" BEDROCK	PALISADE DIABASE-INTRUSIVE SILL GRAY, WHITE, BLACK, FINE GRAINED, DENSE, DIABASE, PREDOMINANTLY PLAGIOCLASE FELSPAR AND AUGITE, MINOR AMOUNTS QUARTZ LOCKATONG FORMATION - LIGHT GRAY TO BLACK SHALE, FISSILE, FREQUENTLY BEDDED STOCKTON FORMATION - MODERATE RED-BROWN OR RED-PURPLE SHALES, SILTSTONE AND ARKOSIC SANDSTONE STATEN ISLAND SERPENTINITE-GREENISH CRYSTALINE SERPENTINITE, ULTRABASIC, OFTEN PORPHORITIC SCHIST-TALC SCHIST, CHLORITE SCHIST, MANHATTAN SCHIST

FIGURE 4B

STRATIGRAPHIC COLUMN

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As the investigation at the Fresh Kills Landfill site proceeded, a pattern emerged in regard to the occurrence of the lodgement till and glaciolacustrine silt and clay. In certain portions of the site, both these deposits were absent, with no reasonable explanation from a depositional perspective. Upon studying the available data, it was concluded that the lodgement till and glaciolacustrine silt and clay were deposited in these areas but subsequently eroded during deglaciation, or removed by human activity.

A specific area where the absence of these deposits was noted was in the western portion of the landfill site along the Arthur Kill (see Figures 8 and 10). Stanford and Harper (1991) proposed a deglaciation scenario for this area that helps to explain the absence of the lodgement till and glaciolacustrine silt and clay. They believe that as the glacier receded northward, an outlet for the glacial lakes was established over the terminal moraine where it crosses the Arthur Kill. After the glacier receded past where the Palisades diabase crosses the Arthur Kill near Tremley Point, the meltwater traveling down the Arthur Kill eroded the ground surface down to the diabase. Once this occurred, a stable spillway was created because of the diabase's resistance to erosion. The creation of this spillway signaled the end of glacial Lake Bayonne and the beginning of glacial Lake Hackensack. Using this scenario, it is postulated that the turbulent meltwater was able to erode most of the previously deposited glacial sediment from this area along the Arthur Kill. This concept is further supported by information supplied by Stanford and Harper (1991) on an uplift curve diagram used to show the various glacial lake stages in this area (Figure 11). They identified the base of the Recent deposits at the Outerbridge Crossing at approximately -60 feet in elevation. This elevation matches quite closely with the elevation of the base of the Recent deposits in the western portion of the landfill site.

Another area where lodgement till and glaciolacustrine silt and clay were often missing was in the area of the kames. It is believed that the meltwater that deposited the kame sediment was also able to erode some of the lodgement till from those areas.

Some of the areas where lodgement till and glaciolacustrine silt and clay were absent did not correspond with either of the above locations. However, when the existing ground surface beneath the refuse was compared to the ground surface on the pre-landfill topographic maps, it was noted that the existing ground surface was lower in elevation than it was prior to landfilling. It is believed that at these locations the sediments were removed for use as cover or other landfill-oriented activities.

South of Fresh Kills Creek, a few sediment samples were obtained above the Cretaceous sediments that consisted of a thin layer of yellowish sand or silt/clay. It is believed that these samples might be of the Columbia Group, possibly Pensauken Formation sediment. However, because of the small amount of sample, limited extent, and unresolved origin of such sediment, the interpretation is

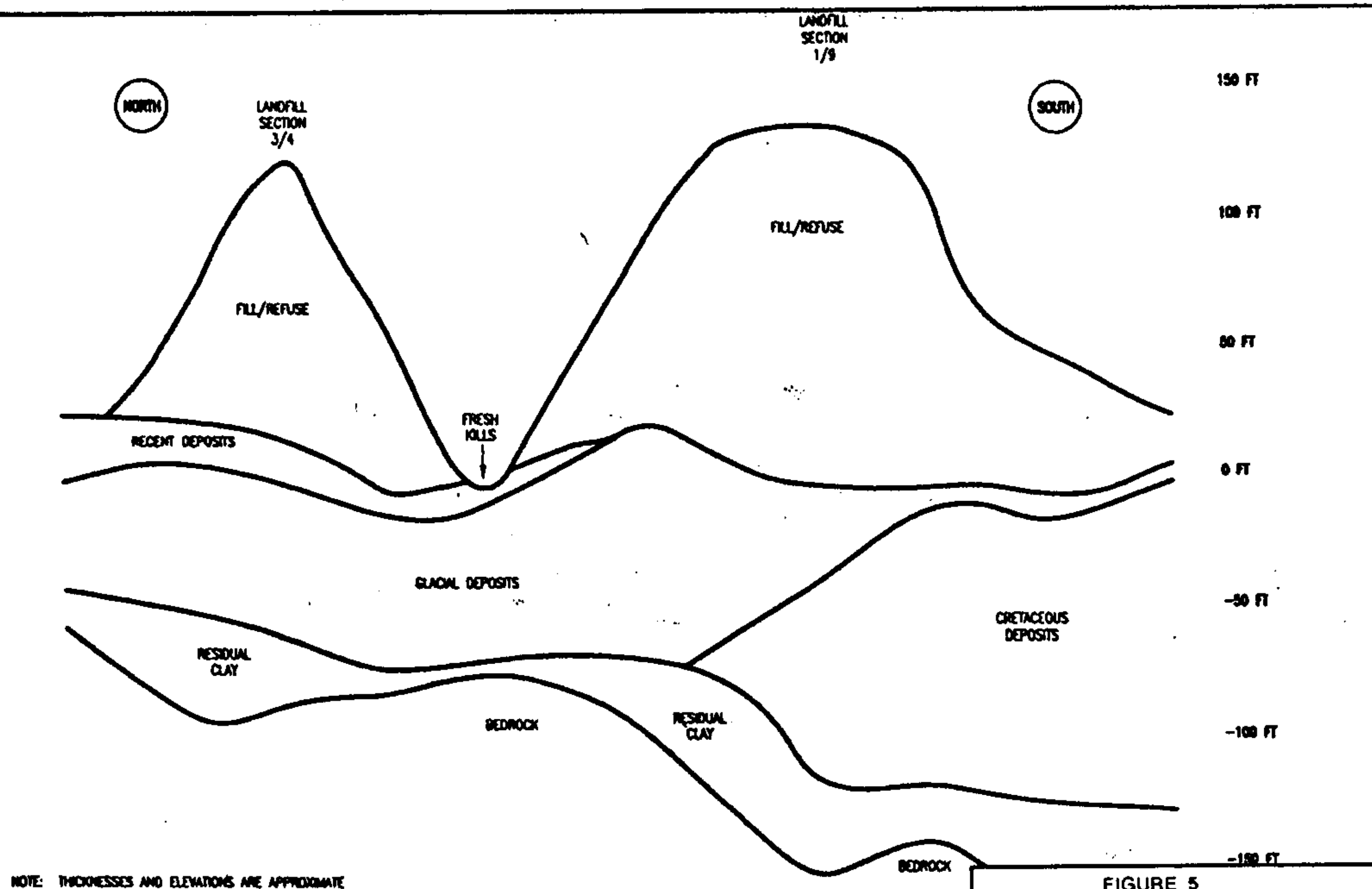

FIGURE 5

NORTH-SOUTH SCHEMATIC PROFILE ACROSS FALL LINE

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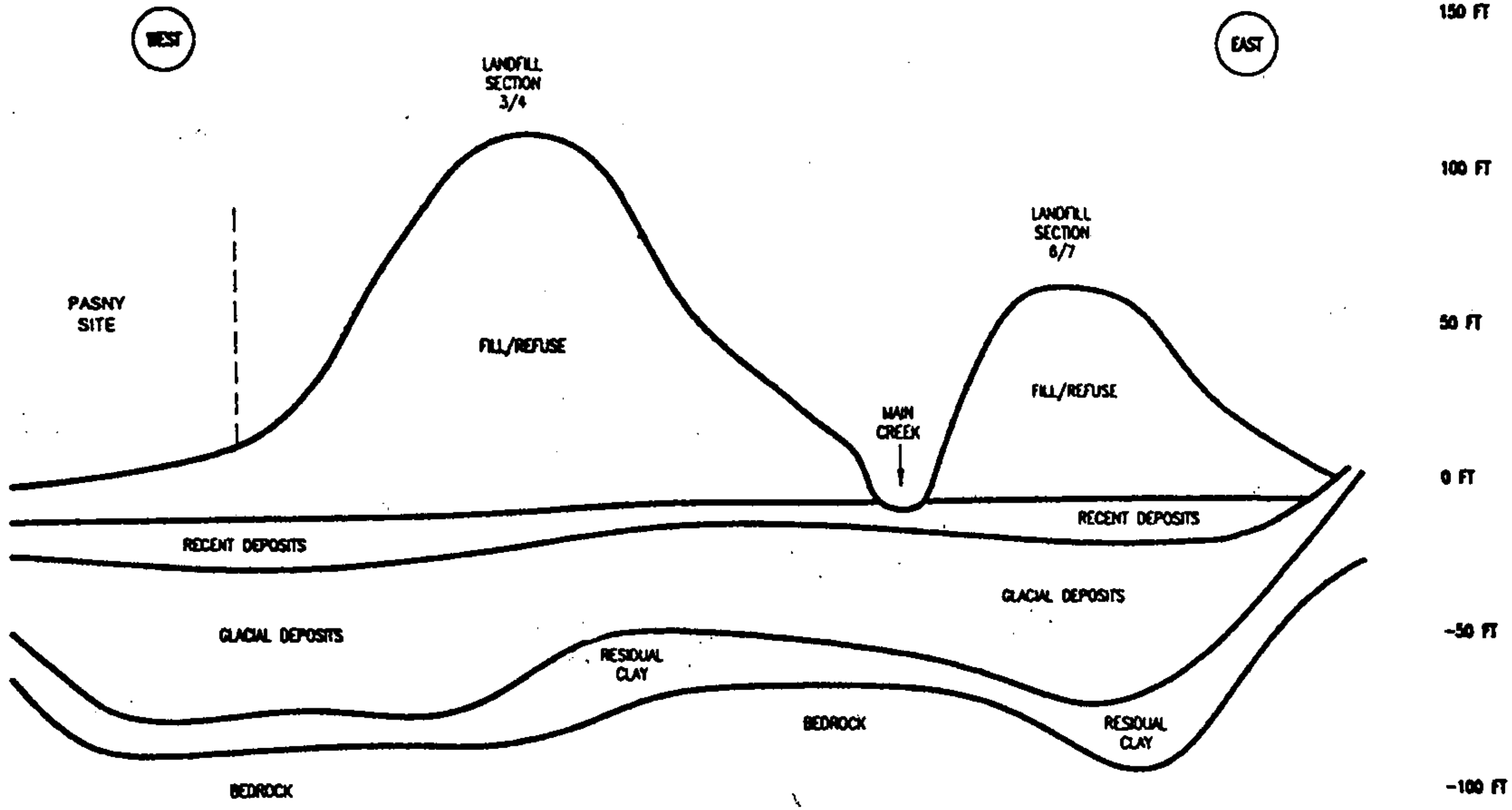

NOTE: THICKNESSES AND ELEVATIONS ARE APPROXIMATE

WehranEnviroTech

FIGURE 6

WEST-EAST SCHEMATIC PROFILE NORTH OF FALL LINE tentative. Examination of the samples does not rule out the possibility that the samples may be oxidized Cretaceous sediment or fill.

Cretaceous Deposits

Two types of Cretaceous deposits were identified: Cretaceous sand and Cretaceous silt and clay. The Cretaceous sediments occur south of Fresh Kills Creek (Figure 12). The Cretaceous sediments are complexly stratified deposits that are difficult to map using conventional methods. The sediments represent a time-transgressive depositional sequence. However, some generalities can be made. Sand generally dominates the lower one-quarter to one-third of the sequence, while clay dominates the upper two-thirds to three-quarters of the unit. However, clay and silt units occur within the basal sand and sand units occur within the silt and clay unit above.

The Cretaceous sand is composed of light gray to dark gray sand, with minor amounts of silt and clay. Thicknesses are quite variable and range from less than 1 foot to close to 100 feet.

The basal sand unit has been correlated across a large portion of the area. It thickens to the south, and thins somewhat to the east. The sand units above the basal sand are more difficult to correlate; however, correlations have been made in these upper units across portions of the area. Cretaceous sands occur at the top of the Cretaceous sequence in several locations due to the interbedding with the clay, combined with the erosion of the surface by glacial processes.

The Cretaceous silt and clay is composed of light gray to black, or red brown and light gray, silty clay to clayey silt. Minor amounts of fine sand are encountered. Like the Cretaceous sand unit, thicknesses vary from less than 1 foot to close to 100 feet.

Silt and clay is the principal material of the upper portion of the Cretaceous sequence, but as stated above, sand is interbedded throughout. The silt and clay unit shows an overall thickening to the south. East to west, it is fairly uniform in thickness.

As mentioned above, microfossil analysis was conducted to serve as a check for the geologic classifications and to assist with correlations. Two palynologists independently examined a specific set of Cretaceous sediment samples. Some disagreement was noted from this analysis, especially regarding the presence or absence of Zone II (Lower Cretaceous) age sediment. However, what can be concluded from both analyses is that the Cretaceous sediment below the study area is at least Zone III (Lower Cretaceous/Upper Cretaceous transition zone) to IV (Upper Cretaceous) in age. This age determination suggests the potential for correlation of at least a portion of the Cretaceous sediment beneath the study area to the Cretaceous sediments in adjacent areas of New Jersey.

Residual Clay

The residual clay is formed from the in situ weathering of bedrock to a clay unit. It is composed of silty clay to clayey silt of various colors, depending on the color of the parent bedrock. Occasional chunks of weathered rock are found in the residual clay due to differential weathering. Thicknesses range from less than 1 foot to over 70 feet. The residual clay tends to form thick sequences over the Newark Supergroup bedrock (Stockton and Lockatong Formations), while it is usually absent or thin over the serpentinite, schist, and diabase.

Bedrock

Weathered bedrock occurs across almost the entire extent of the study area. It is fractured, weathered, broken rock above the "competent" bedrock surface (competent, in this context, meaning not weathered, few fractures). The contact between the weathered bedrock and "competent" bedrock was delineated by calculating bedrock Rock Quality Designation (RQD).

Five major bedrock types occur in the study area.

The Palisades Diabase occurs in a belt that stretches northeast to southwest in the northwest portion of the study area (Figure 13). It is a gray, white, and black dense rock composed mostly of plagioclase feldspar, augite, and quartz, and exhibits very little weathering and fracturing.

The Lockatong Formation occurs in a wider belt that has the same orientation as the diabase occurring adjacent and to the south (Figure 13). It was found to be a light gray, grayish black, or grayish green shale.

The Stockton Formation covers a large portion of the study area (Figure 13). Most commonly, it is a red brown shale or siltstone. However, in some locations near the contact with the Lockatong it was found to be more purplish, grayish, or greenish. In some locations near the contact with the Serpentinite it was darker in color, with quartz and/or chloride veins. Vugs were also noted in some of these locations (Figure 13). In many locations, a sandy facies was present (Figure 13). Grain-size ranged from fine to coarse, with some arkosic samples.

Serpentinite occurs in the east central portion of the study area (Figure 13). Samples examined ranged from fine-grained dark green serpentinite, to the classic "snake skin" serpentinite, with a porphyritic texture, to the serpentinite group mineral lizardite. Much of the rock was porphyritic. Talc was present with many of the lizardite samples. Magnetite and pyrite were noted in some samples.

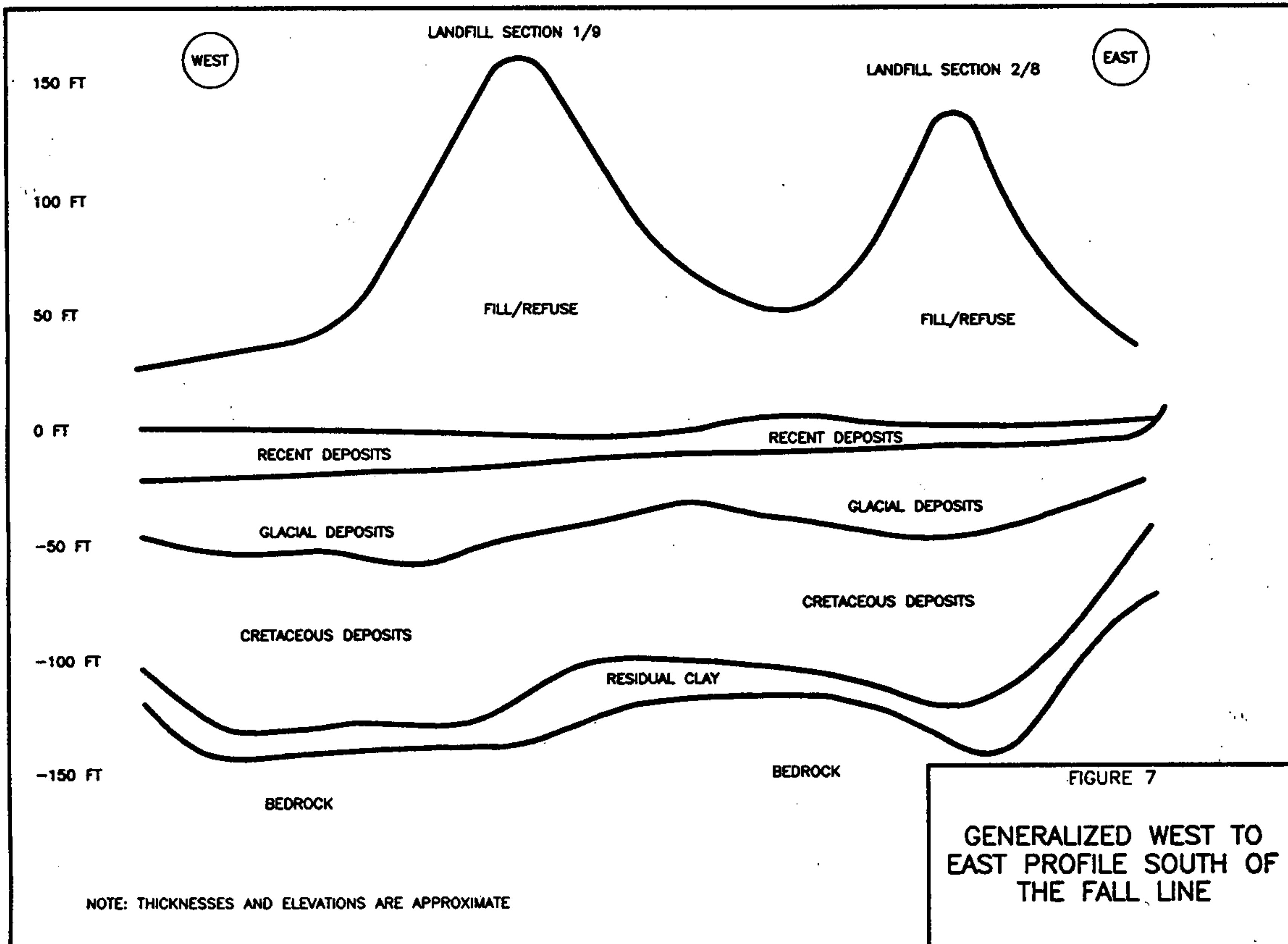

FIGURE 7

GENERALIZED WEST TO EAST PROFILE SOUTH OF THE FALL LINE

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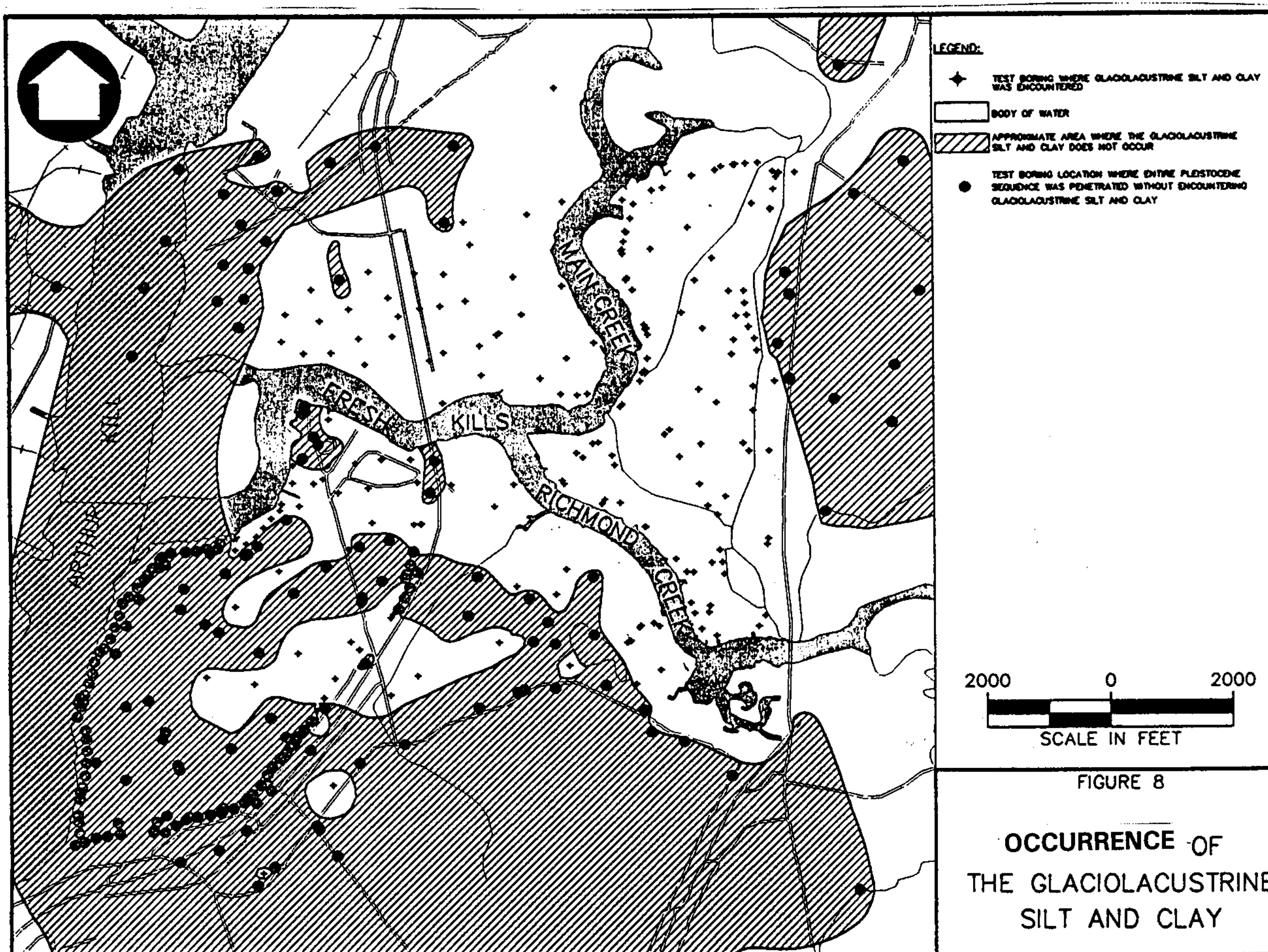

FIGURE 8

OCCURRENCE OF THE GLACIOLACUSTRINE SILT AND CLAY

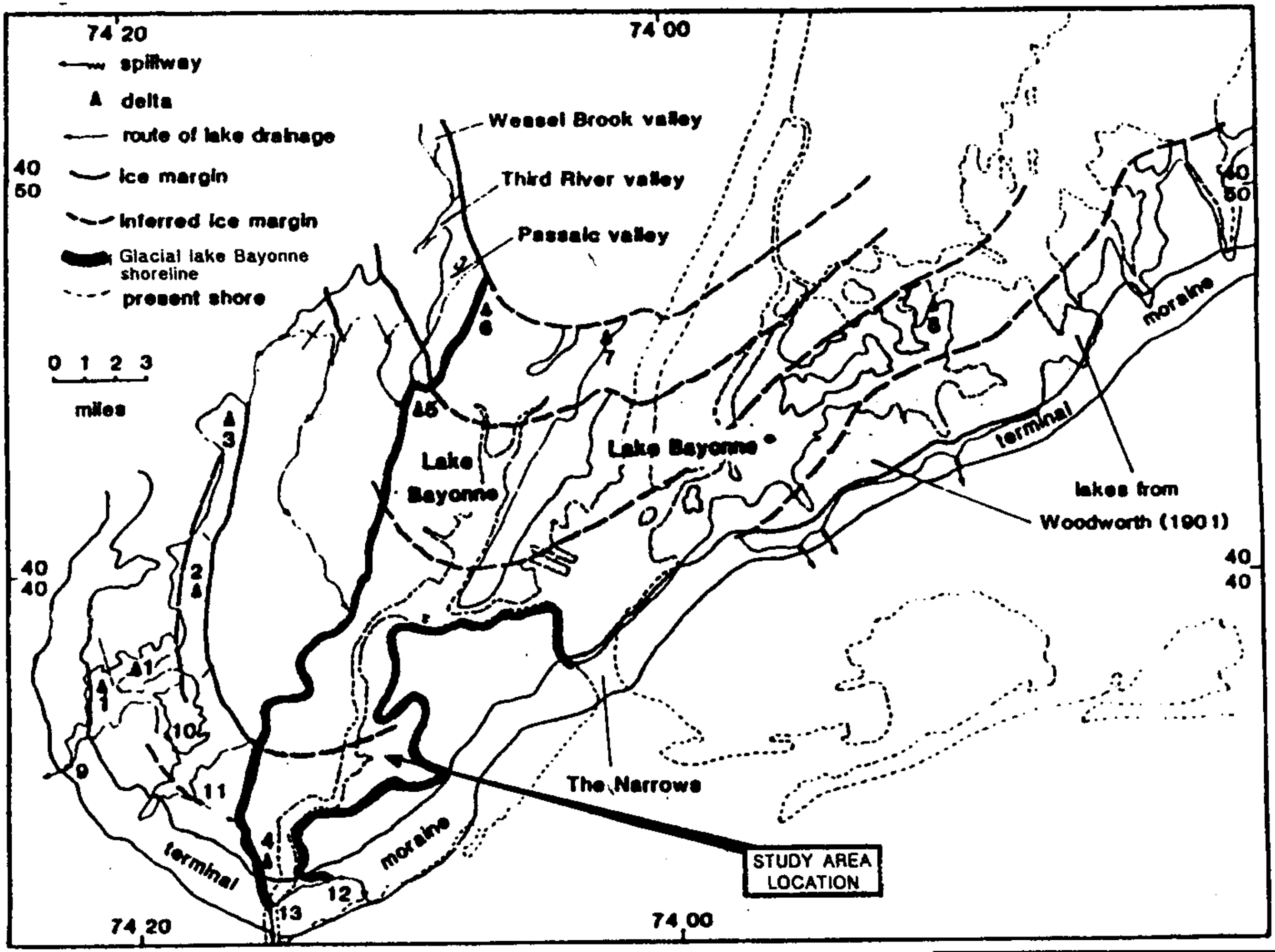

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FIGURE 9

EXTENT OF GLACIAL BAYONNE IN THE STUDY AREA REGION

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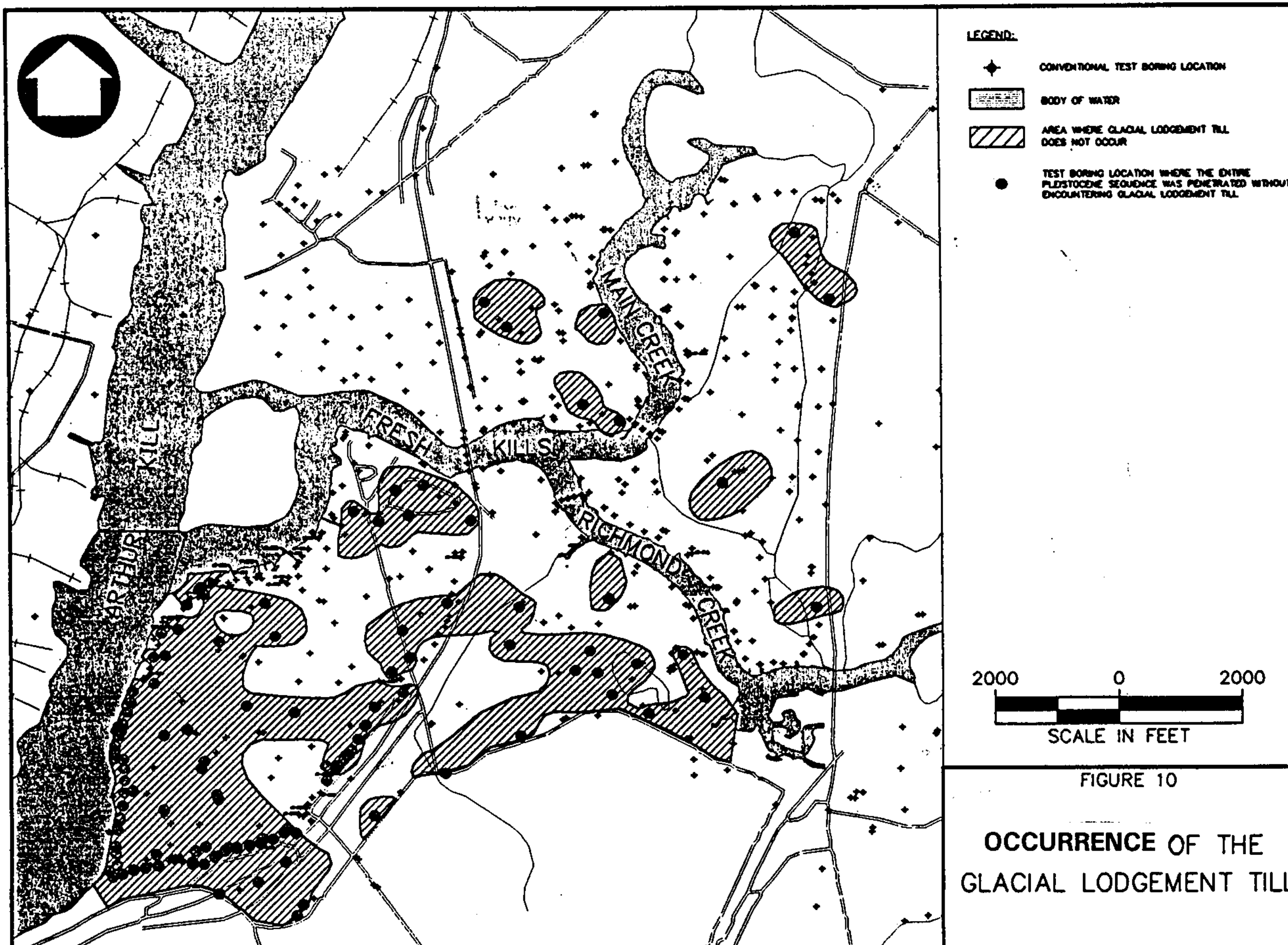

FIGURE 10

OCCURRENCE OF THE GLACIAL LODGEMENT TILL

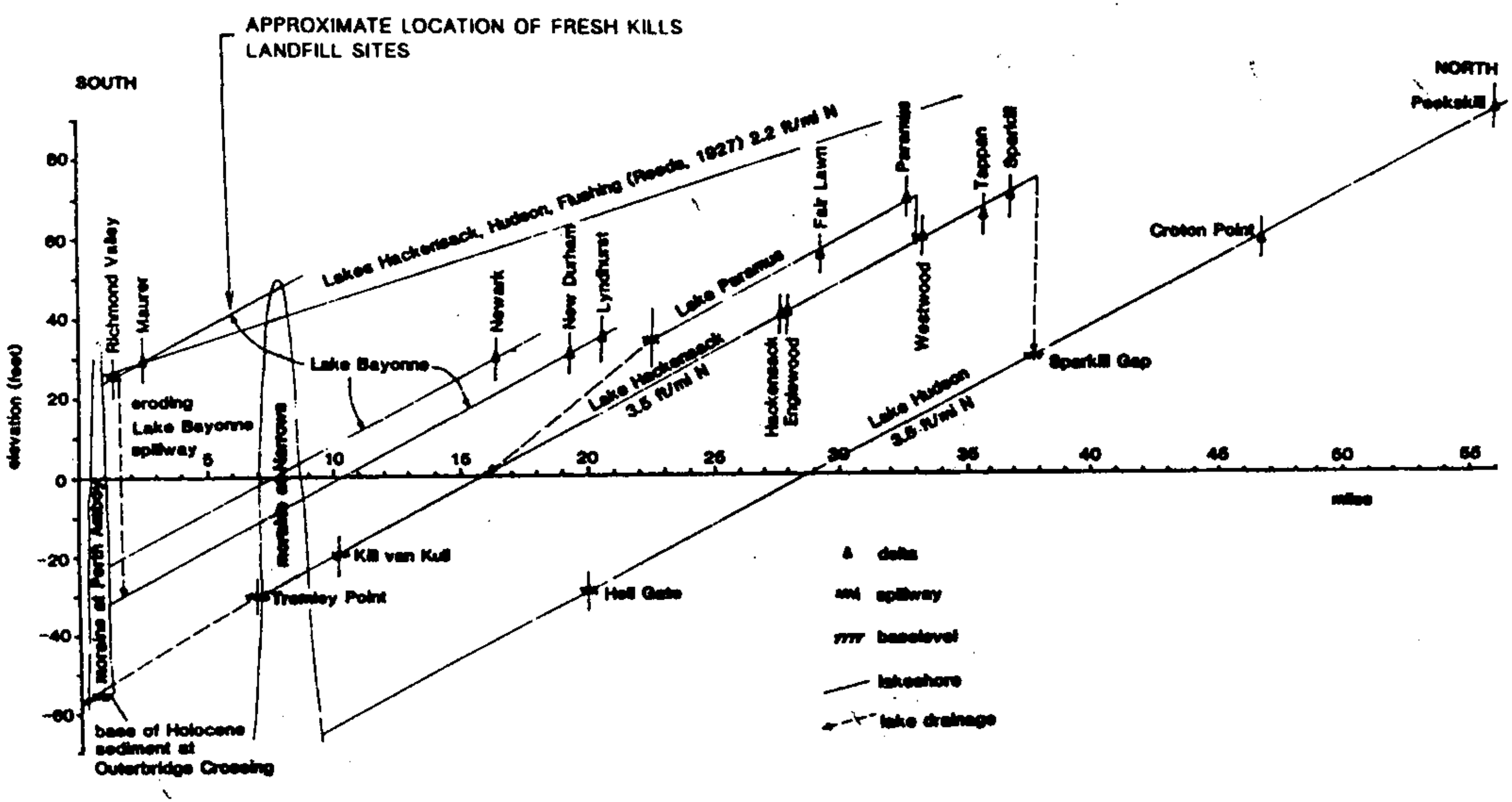

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FIGURE 11

UPLIFT CURVES FOR VARIOUS GLACIAL LAKES IN THE STUDY AREA REGION

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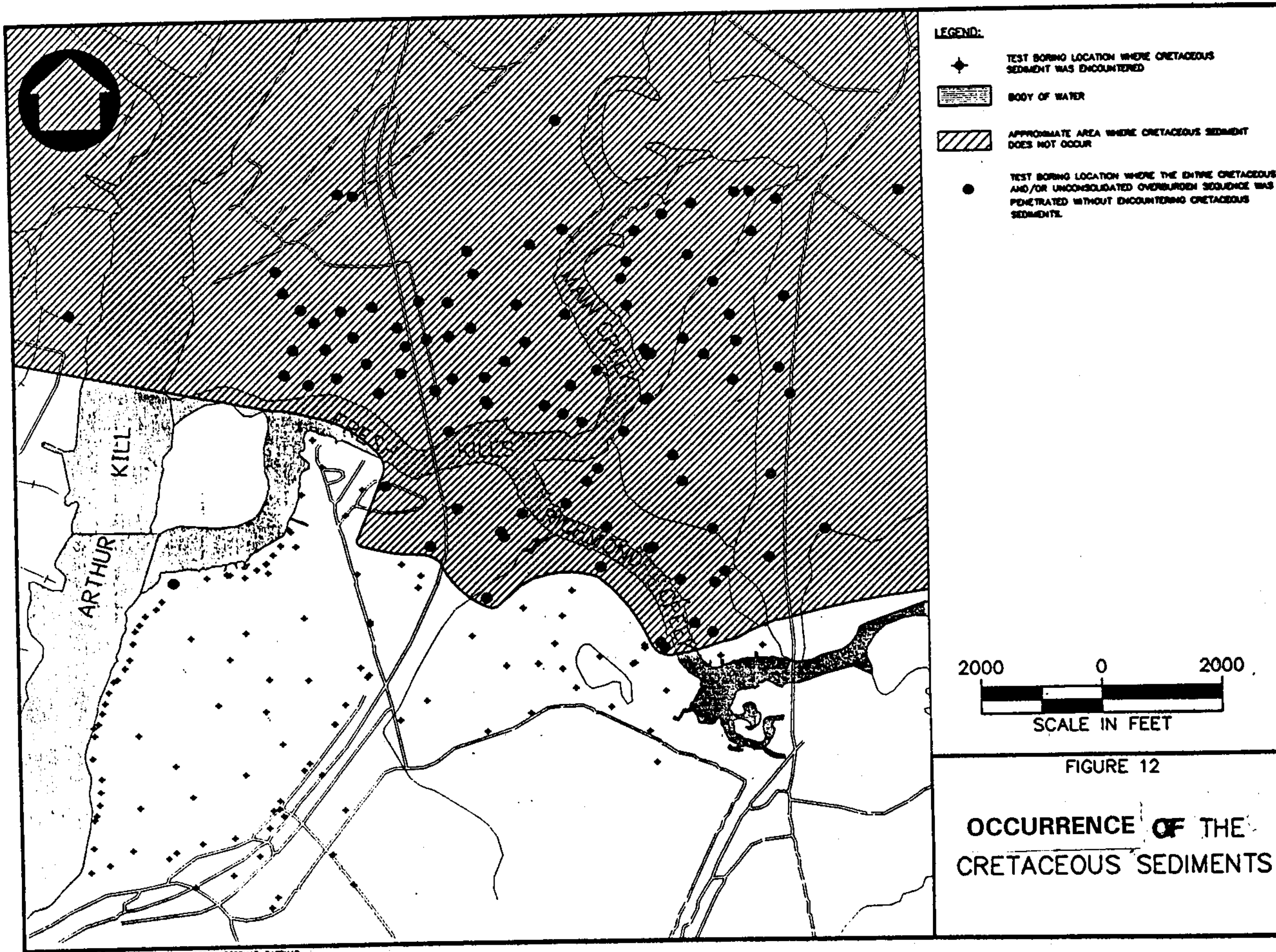

FIGURE 12

OCCURRENCE OF THE CRETACEOUS SEDIMENTS

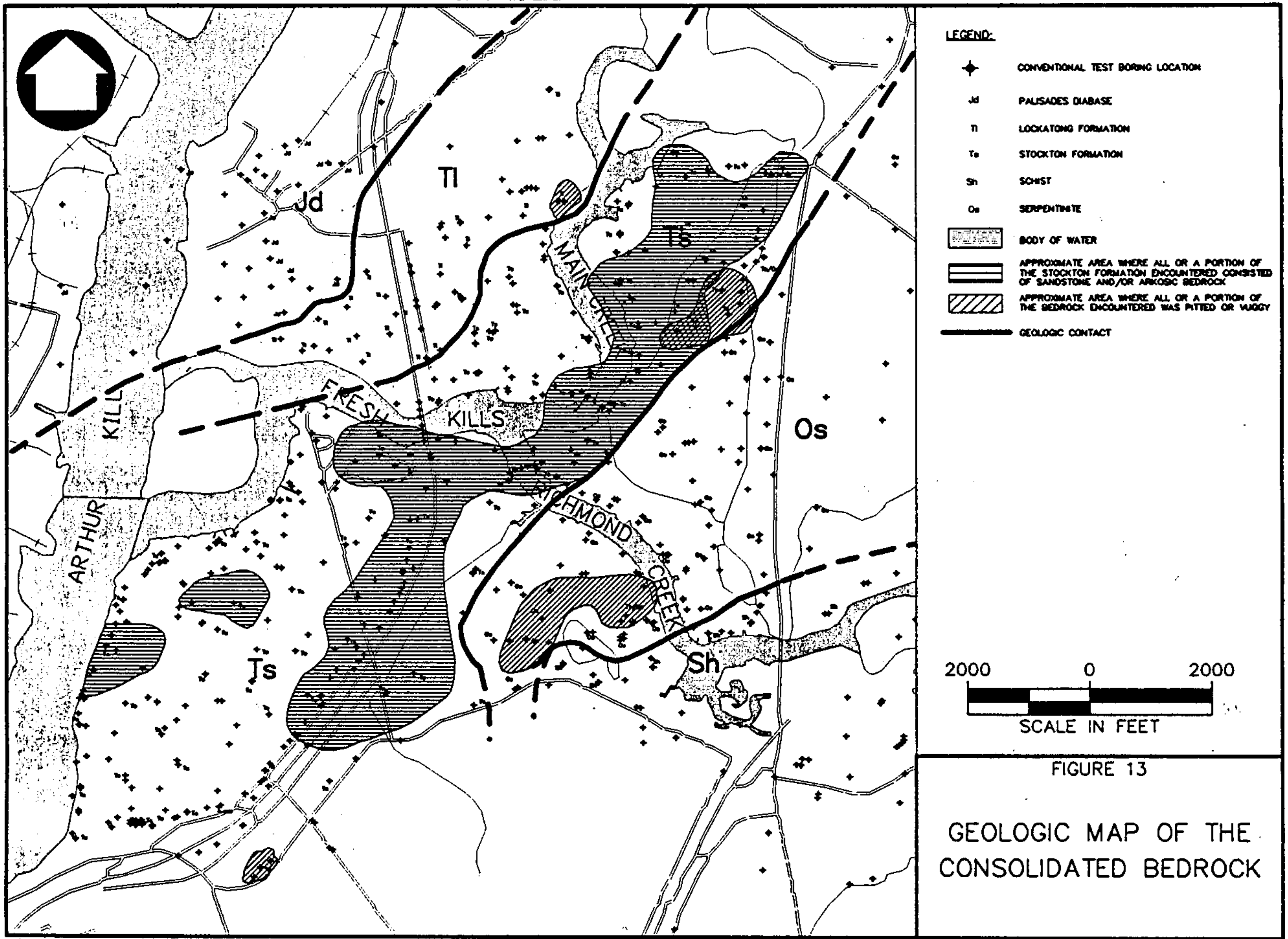

FIGURE 13

GEOLOGIC MAP OF THE CONSOLIDATED BEDROCK

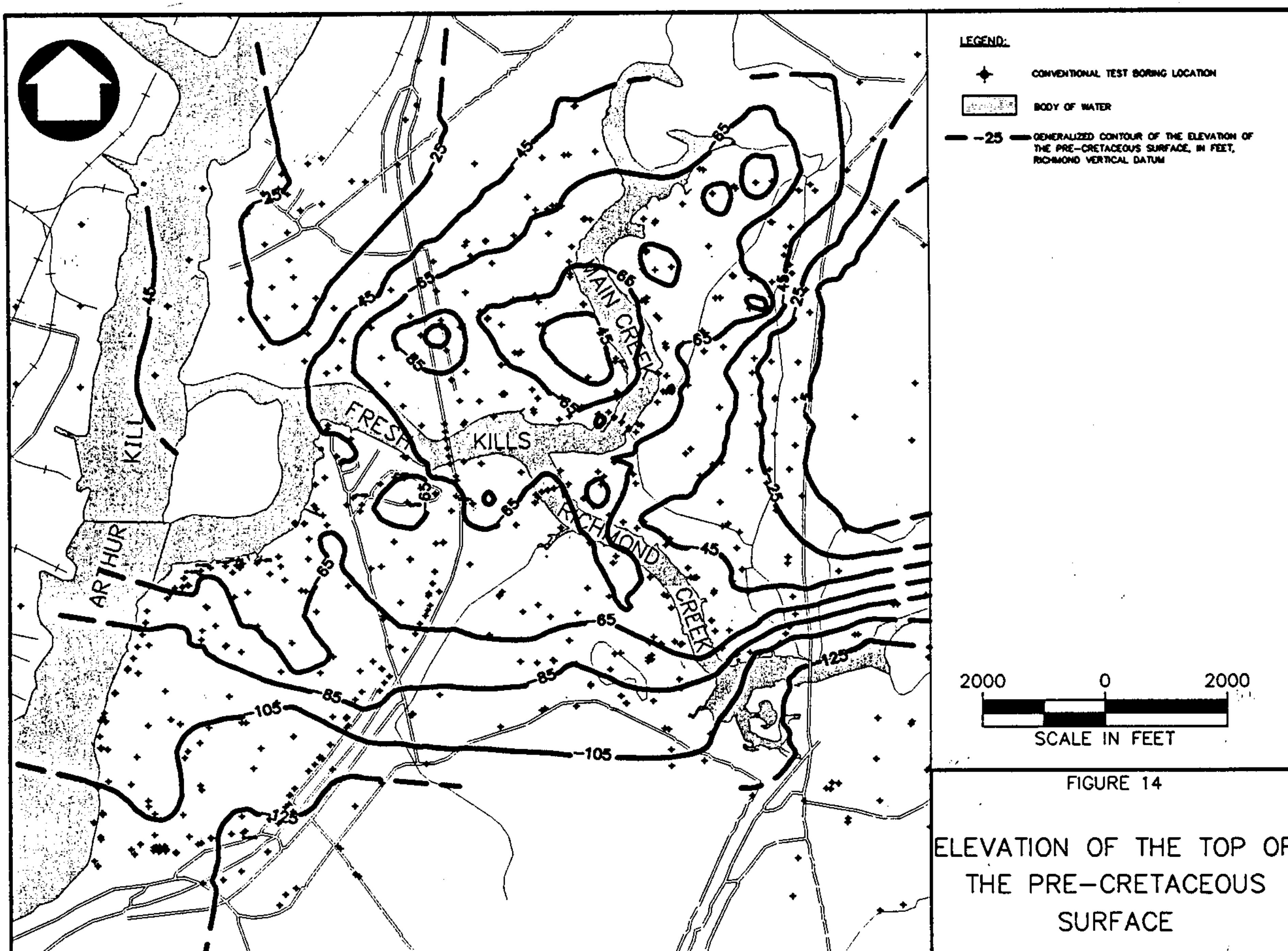

FIGURE 14

ELEVATION OF THE TOP OF THE PRE-CRETACEOUS SURFACE

Occasional quartz or calcite veins were present in many samples and vugs were noted in a few samples near the contact with the Stockton Formation (Figure 13).

Chlorite schist and talc schist were identified from bedrock cores from the southeastern portions of the study area. The rock is believed to have formed as alteration products of the serpentinite body. The occurrence of what appears to be Manhattan Schist in one test boring in the southeastern portion of the study area is consistent with the type of basement rock expected beneath the coastal plain in this area based on the literature.

The bedrock surface shows a general slope to the south below the study area. A bedrock low or "trough" occurs beneath the Main Creek area. This low may be an extension of the buried channel cut into bedrock to the north of the site, as described by Lovegreen (1974).

Figure 14 is a contour map of the residual clay/bedrock surface which allows evaluation of the "pre-Cretaceous" surface that exists beneath the study area. This was done to obtain a configuration for the "Fall Line." Examination of the figure indicates that there is a definite southeastward or seaward slope to the surface. A sudden break or steep slope is not observed. This, however, is consistent with the definition of the Fall Line by early workers. They define the Fall Line as a zone of appreciable width sloping to the east that is relatively minor in terms of its physiographic expression (Renner, 1927a, 1927b). If the occurrence of the Cretaceous sediments mark the Piedmont/Coastal Plain boundary, and if the Piedmont/Coastal Plain boundary, by definition, occurs at the Fall Line, then Figure 14 represents the configuration of the Fall Line in this area.

Acknowledgements

Many people who participated in the Fresh Kills Landfill Leachate Mitigation System Project deserve credit for the results presented in this paper and participation in the other activities related to this meeting. Phillip Gleason of the New York City Department of Sanitation approved the production of this paper, participation in the symposium, and field trip visit to the Fresh Kills Landfill site. New York City Department of Sanitation Project Geologist Norma Iturrino oversaw the hydrogeologic investigation, provided review of this paper, and coordinated the logistics of the field trip stop at the landfill site. Project team members Robert Miller of Wehran EMCON Northeast and Edward Wysocki and Steven Posten of the IT Corporation worked closely with the author to assure the successful completion of the project. Les Sirken and Gilbert Brenner served as palynologists for the project. Steven Okulewitz provided valuable assistance in interpretation of the bedrock samples. James Owens of the U.S. Geological Survey and Peter Sugarman of the New Jersey Geological Survey provided assistance with interpretation of the Cretaceous sediments. Scott Stanford of the New Jersey Geological Survey provided helpful information on the glacial processes and deposits in this region. Daniel Walsh and Raphael Ketani of the New York State Department of Environmental Conservation provided review and comment during the project. Wehran EMCON Northeast graciously supported the production of this paper and the attendance of the author at the symposium and field trip.

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The Staten Island Bluebelt Project: Preserving Wetlands for Storm Water Management

By Dana Gumb
Project Director
New York City Department of Environmental Protection

The Staten Island Bluebelt project is an effort by the New York City Department of Environmental Protection (NYCDEP) to provide storm water management for the last large unsewered area of the city which makes sense from both an environmental point of view and from the perspective of dollars and cents.

In a city where the conventional method of handling storm water is to put everything in a pipe, the NYCDEP is pioneering a different approach which preserves streams, ponds and other wetland areas in order to allow these systems to perform their natural functions to convey, store and filter storm water.

This approach is proving to allow not only for the preservation of scarce and valuable urban wetlands but is also saving equally scarce capital construction dollars. The NYCDEP has found that wetland preservation saves millions of dollars in infrastructure costs when compared to the conventional storm sewer system. This analysis is a model of how natural area preservation can have important long-term cost-saving implications.

Even though NYCDEP's specific mandate is the provision of drainage services, this project is truly multi-objective. The wetland preservation, underway and proposed, not only preserves natural drainage patterns for flood control purposes, but also provides for the filtering of storm water run-off, utilizing the natural cleansing functions of wetlands. In addition, the wetland and riparian corridors called Bluebelts provide important community open space amenities and diverse wildlife habitats.

Background

South Richmond, Staten Island, the most southerly part of New York City and State, is the last area of the City with a significant amount of vacant land. South Richmond is bounded by the Arthur Kill, Raritan Bay and the mid-Island area from Fresh Kills Landfill to Great Kills Harbor. Historically, land development in this area has been concentrated in villages which grew up around the stations of the Staten Island Rapid Transit System (SIRTS).

Since the opening of the Verrazano Narrows Bridge in November 1964 and the construction of the ancillary highway network, land development in South Richmond has been in a more scattered pattern of low density settlement. Since the area is virtually without sewers, that development has employed on-site waste disposal systems like septic tanks and package treatment plants and on-site storm water management measures like dry-wells and retention basins.

For the past 30 years, the idea of using the area's freshwater wetlands for storm water management purposes has percolated through City government. In the late 1960's during the Lindsay era, an effort to create a system of "fenways" in South Richmond was advocated by some city planners.

Not until the mid-1970's did the City act to preserve some of the stream systems on the southern end of the Island. In 1975 the City enacted the Special South Richmond Development District (SSRDD), a special purpose zoning district for the same southern end of the Island. A primary goal of the district was the preservation of the area's low density open character. One step taken to accomplish that goal was the creation of the Open Space Network (OSN), a system of about 700 acres which are to remain in their natural state. The purpose of the zoning designation is to preserve important natural features such as ponds and streams.

Following the creation of the OSN, the New York State Department of Environmental Conservation began regulating development in an extensive system of freshwater and tidal wetlands in South Richmond. During the 1980's, the State issued a series of maps for the freshwater wetlands on the Island which include the streams and ponds of importance for storm water management. The on-going regulatory program has resulted in the preservation of some wetland areas with significance for the overall drainage system.

Finally, capping off the activity of the 1970's and '80's, the Department of City Planning issued a report in October 1989 entitled the "South Richmond's Open Space Network An Agenda for Action: Storm Water and Open Space Management" which advocated using the OSN as a storm water management system. This effort propelled the NYCDEP into the latest phase of the project.

Bluebelt Land Acquisition

In the last three years, NYCDEP has undertaken a major effort to acquire wetland properties in order to complete the continuity of the stream corridors and other wetland systems in the OSN. Eight applications for site selection and acquisition of Bluebelt parcels have been fully approved under the City's Uniform Land Use Review Procedure (ULURP). Those eight are West Poillon Woods in the Arbutus Creek watershed, the Page Avenue Wetlands in the Mill Creek watershed, Sweet Brook, Richmond Creek, Arbutus Creek, Wolfe's Pond, Lemon Creek/Sandy Brook and Wood Duck Pond. ULURP applications for two other Bluebelt stream systems -- Jack's Pond and Mill Creek -- have been filed and are making their way through the approval process.

When combined with wetlands already owned by the City and mapped but unbuilt streets which will be incorporated into the system, the acquisition projects will protect the following numbers of acres: West Poillon Woods (40 acres), Page Avenue Wetlands (15 acres), Sweet Brook (31 acres), Richmond Creek (18 acres), Arbutus Creek (51 acres), Wolfe's Pond (3.7 acres), Lemon Creek/Sandy Brook (40 acres), Wood Duck Pond (9.5 acres), Jack's Pond (5.5 acres), and Mill Creek (40 acres).

The land acquisition program is a major step toward preserving the wetland resource for storm water management purposes. NYCDEP has found that the wetland acquisition will save some $50 million in construction costs for the fully conventional storm sewer system envisioned for the area in the drainage plan that was done in the early 1960's. The land acquisition will help to complete the Bluebelt corridors by building upon existing parks, other city owned properties and private land zoned as open space along the streams and other wetland systems.

Drainage Plan Revision

In addition to the acquisition program, the other major initiative of NYCDEP has been the effort to re-do the official drainage plans for South Richmond. The Bluebelt concept of making use of the wetland systems is to be applied by redoing the old official drainage plans for the last large unsewered part of New York City.

The total area of South Richmond for which new drainage plans are required amounts to about 10,000 acres. The seven watersheds in South Richmond where wetlands are to be incorporated into the overall storm water management system cover about 6,000 acres of that total.

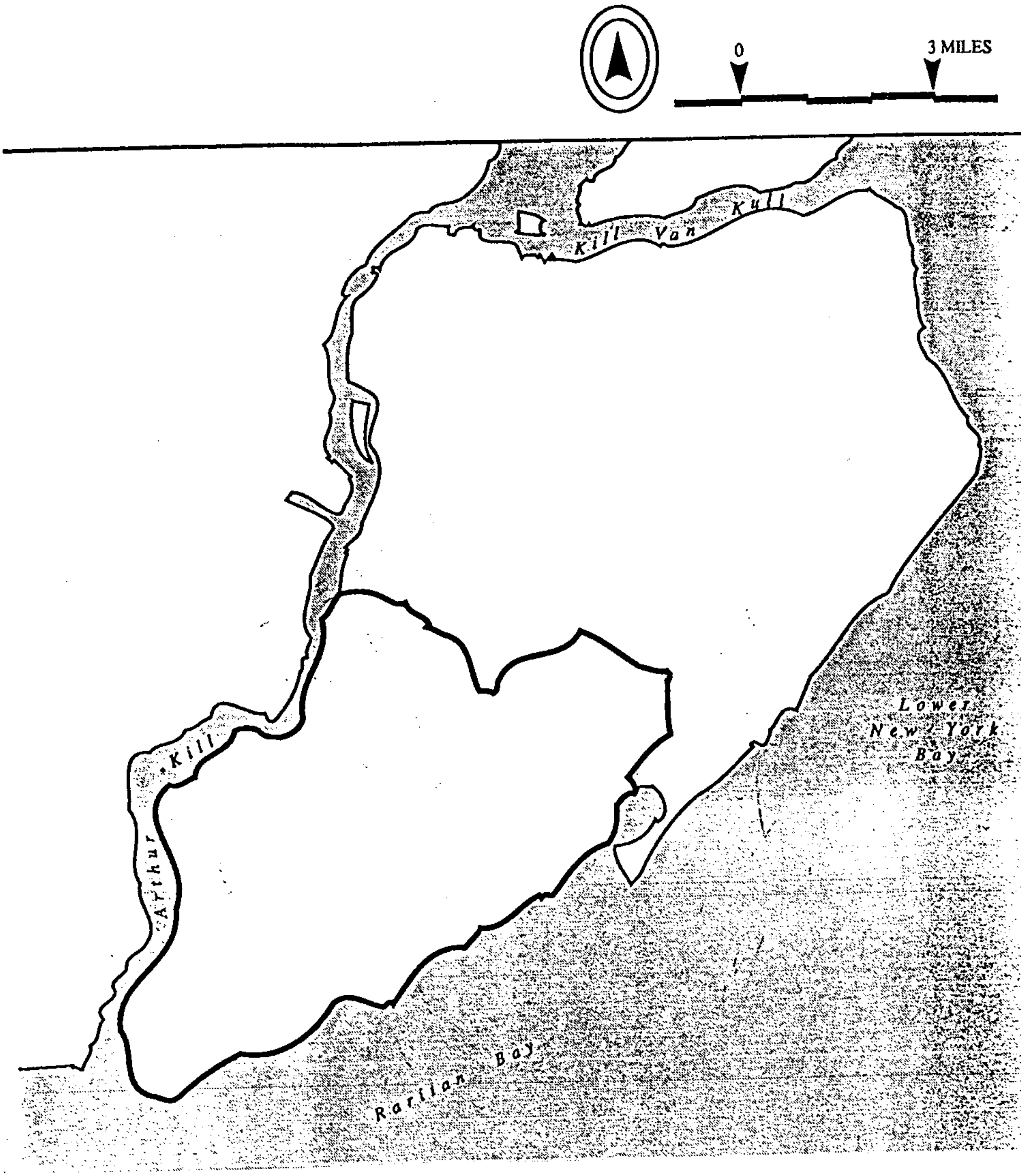
The old plans done 30 years ago assume complete obliteration of the riparian and wetland systems and full storm sewering like that in the urban settings of the other four boroughs. The mapped street network which generated this drainage plan assumes a grid pattern of streets, laid over the landscape without regard for any natural features. Following the logic of these preliminary designs for the sewer system, streets mapped on ponds, streams or other wetlands are not at all inappropriate since those water features would have been eliminated anyway by the adopted storm water sewerage system.

The old plans are obviously not usable any more. NYCDEP is now in the process of selecting a consultant for a major $6 million study to prepare new drainage plans that would incorporate the preserved wetland systems into the overall storm water management network.

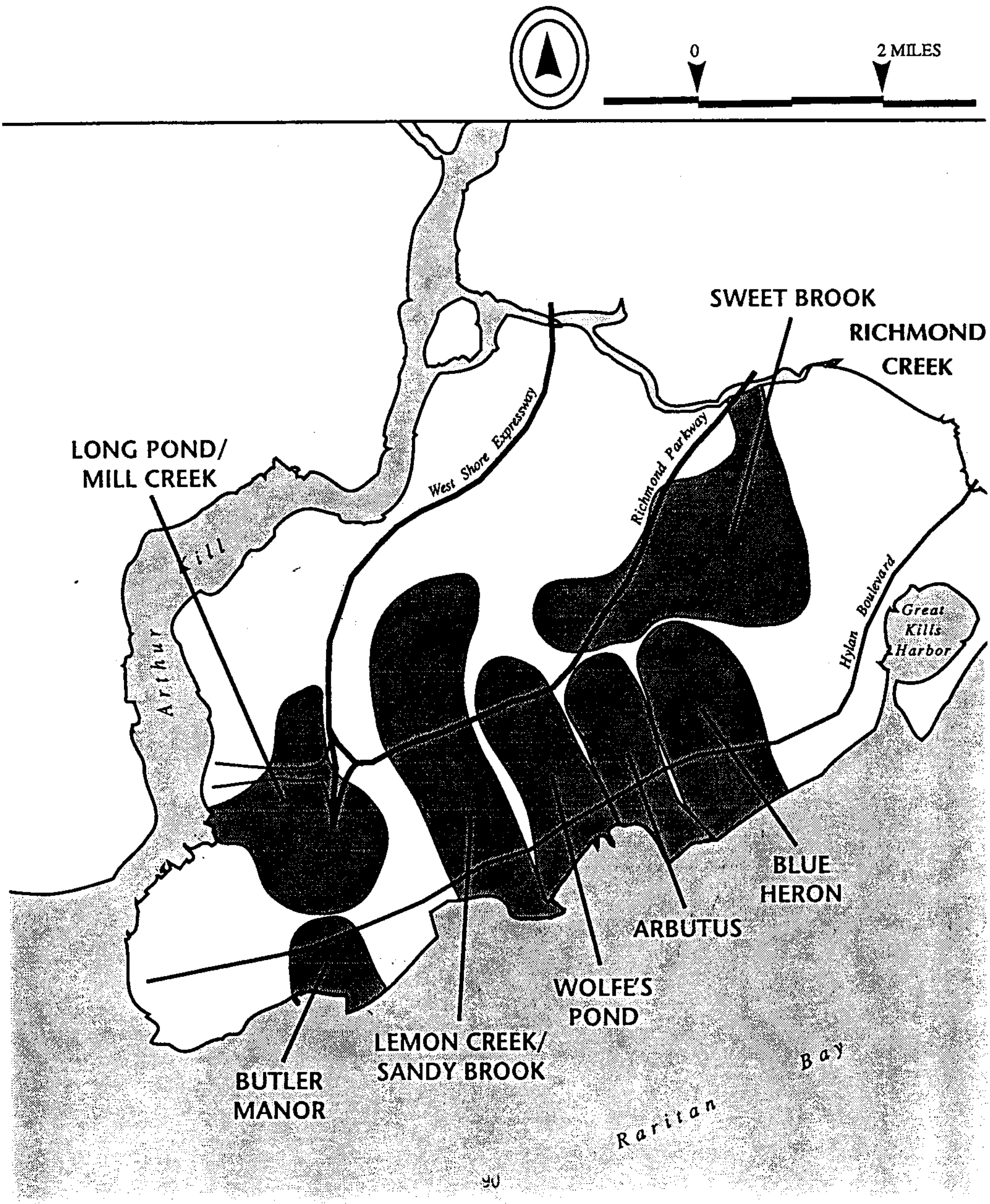
An important consideration in the preparation of the drainage plan will be the issue of the water quality of the urban storm water runoff running into the preserved wetland systems. NYCDEP will employ innovative designs for best management practices to reduce pollutant loadings. How to design retention basins for quality control of urban storm water, in addition to their more conventional quantity control functions, will be an important issue in the study. What can be done at the storm sewer/wetland interface to reduce the impact of the discharge into the wetlands is a related issue. Constructed wetlands for the treatment of storm water may be one approach for the Bluebelt system.

The new plan will guide the agency in its on-going capital construction program in southern Staten Island. The resulting combination of natural systems with some necessary constructed sewer networks will be a model of how urban wetlands can be incorporated into a drainage scheme for a fast developing area.

SOUTH RICHMOND, STATEN ISLAND



BLUEBELT WATERSHEDS



HYDROGEOLOGICAL INVESTIGATION AT THE FRESH KILLS LANDFILL, STATEN ISLAND, NEW YORK

Norma Iturrino, New York City Department of Sanitation, 44 Beaver Street, New York, NY 10004

The largest scale hydrogeological investigation of a municipal solid waste facility was undertaken at the Fresh Kills Landfill from January 1991 through October 1992. Its purpose was to determine the location, quantity, composition and movement of leachate at the site and to analyze its impact on the surrounding environment.

An extensive historical literature review was performed. Methods used in the investigation included geophysical techniques, micropalaeontological analyses, stratigraphic/sedimentological studies and geochemical analyses.

The study found that the majority of leachate movement proceeded horizontally and was primarily contained in the refuse layer of the landfill. Vertical movement is limited due to the presence of large deposits of fine grained materials.

GLACIAL GEOLOGY OF NEW YORK CITY AND VICINITY

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ABSTRACT

The fundamental question pertaining to the Pleistocene features of the New York City region is: "Did one glacier do it all? or was more than one glacier involved?" Prior to Fuller's (1914) monographic study of Long Island's glacial stratigraphy, the one-glacier viewpoint of T. C. Chamberlin and R. D. Salisbury predominated. In Fuller's classification scheme, he included products of 4 glacial advances. In 1936, MacClintock and Richards rejected two of Fuller's key age assignments, and made a great leap backward to the one-glacier interpretation. Subsequently, most geologists have accepted the MacClintock-Richards view and have ignored Fuller's work; during the past half century, the one-glacial concept has become a virtual stampede. What is more, most previous workers have classified Long Island's two terminal-moraine ridges as products of the latest Pleistocene glaciation (i. e., *Woodfordian*; we shall italicize Pleistocene time terms). Fuller's age assignment was Early *Wisconsinan*. A few exceptions to the one-glacier viewpoint have been published. In southern CT, Flint (1961) found two tills: an upper Hamden Till with flow indicators oriented NNE-SSW, and a lower Lake Chamberlain Till with flow indicators oriented NNW-SSE, the same two directions of "diluvial currents" shown by Percival (1842). In Boston, MA, and vicinity, C. A. Kaye (1982) found many tills having these same two inferred flow directions.

We here summarize our reasons for re-establishing Fuller's 4-glaciation classification and for rejecting a latest-Pleistocene age of Long Island's terminal-moraine ridges. Our analysis is based on our integrated regional studies of features glaciers eroded on bedrock, on the provenance implications of erratics and of indicator stones, on superposition of tills, and on the principle of "one glacier, one flow direction."

We accept as *Woodfordian* only the youngest till deposited by a glacier that flowed from NNE to SSW, **down** the Hudson Valley (the same direction as Flint's Hamden Till in CT). In the New York City region, such a till is gray to light brown in color, contains poikilitic mafic indicator stones from the Cortlandt Complex near Peekskill (which many may have confused with "trap rock" from the Palisades Sill) and erratics of Inwood Marble and other rocks from Westchester County, and totally lacks any erratics derived from the Newark Basin, which is situated on the W side of the Hudson. In our classification, we label the *Woodfordian* till and associated outwash by Roman numeral IV.

Till IV is present in Queens and on Staten Island, but is not present on much of Long Island; the terminal moraine of glacier IV lies along the S coast of CT (Flint and Gebert, 1974, 1976).

The next-older till, our III, was deposited by a glacier that flowed over the New York City region following a rectilinear course from NW to SE, **across** the Hudson Valley (the same direction as reported by Flint from the Lake Chamberlain Till in CT). In New York City, southern Westchester County, and western Long Island, Till III is a distinctive reddish-brown color from its content of pulverized Newark sedimentary rocks. Diagnostic indicator stones from outcrop belts NW of the Newark Basin include Lower Silurian Green Pond Metaconglomerate and Pennsylvanian anthracite coal (Sanders, 1974; Friedman and Sanders, 1978). In Long Island City (Queens), Woodworth (1901) found glaciated bedrock gneiss with striae and grooves oriented N25°W-S25°E overlain by reddish-brown materials forming the Harbor Hill Moraine. At Corona, Woodworth found reddish-brown sand underlying a gray till containing erratics of what he called "trap-rock." (We have not seen these but suspect that they may **not** be dolerite from the Palisades as one might suppose from his use of the term "trap rock." Other possibilities are indicator stones from the Cortlandt Complex, or Paleozoic amphibolites and or -mafic igneous rocks from SE New York and/or western CT. In any case, we classify this gray till as our IV, the *Woodfordian*).

Farther E on Long Island, in localities that lie outside the downflow path from the Newark Basin, Till III undergoes a dramatic lateral lithologic facies change. In localities that lie downflow from a "crystalline corridor" of bedrock exposed between the NE end of the Newark Basin and the SW end of the Hartford Basin in south-central CT, our Till III is **not reddish brown**, contains no Newark- or other erratics derived from NW of the Newark outcrop belt, but contains indicator stones of Inwood Marble and the Cortlandt Complex, as at Target Rock, for example. Still-farther E, the color of Till III becomes reddish brown once again as it contains erratics from the Hartford Basin of central CT and MA (for example on Gardiners Island). Reddish-brown till (our No. III?) occupies valleys eroded into the sandy S-dipping Gilbert-type deltaic foreset sediments that underlie the eroding cliffs at Sands Point and elsewhere on Long Island's north shore (Sanders, Merguerian and Mills, 1993; Sanders and Merguerian, 1994). At Caumsett State Park, these deltaic sediments contain abundant gravel including partly decomposed stones. We assign these to Fuller's Manhasset Formation and think the newly exposed relationships demonstrate that Fuller's pre-*Wisconsinan* age assignment was correct. Accordingly, we reject the *Wisconsinan* ages proposed by W. L. S. Fleming (1925) and by MacClintock and Richards (1936) for the Manhasset.

In the subsurface at Jones Beach, on the S shore of LI, the inferred nonmarine upper outwash (of Rampino, 1978 ms.; the Bellmore Formation of Rampino and Sanders, 1981) has been correlated with the Harbor Hill Moraine. We accept this correlation and assign both the upper outwash (Bellmore Formation) and Till III to the Early *Wisconsinan*.

The next-older glacial advance, our No. II, which also crossed the New York City following rectilinear flow paths from NW to SE, deposited tills having the same color-distribution pattern as deposits of glacier No. III. We think glacier No. II deposited the Ronkonkama terminal-moraine ridge. In the Jones Beach subsurface, the lower inferred outwash (of Rampino, 1978 ms.; the Merrick Formation of Rampino and Sanders, 1981) is separated from the upper inferred outwash (the Bellmore Formation) by the marginal-marine sediments of the Wantagh Formation (of Rampino and Sanders, 1981; the "20-foot clay" of Perlmutter, Geraghty, and Upson, 1959, Table 1, p. 420, p 422; Doriski and Wilde-Katz, 1983; and others of the U. S. Geological Survey). If the correlations of the two subsurface units of inferred outwash with the Harbor Hill- and Ronkonkama moraines are correct, then they imply that these two moraines were **not** deposited by the fluctuating margin of the same glacier (whatever its age), but by two different glaciers, as originally visualized by Upham (1879). The Wantagh Formation implies that these two outwash-connected glaciers were separated in time by an interval sufficiently long and with a climate sufficiently "nonglacial" so as to enable the sea to rise to close to its present level to deposit sea-marginal sediments. The age of the Wantagh Formation is not certain. Initially, Rampino and Sanders (1976) assigned it the mid-*Wisconsinan* and thought it is correlative with the *Portwashingtonian* warm interval of Sirkin and Stuckenrath (1980). In light of Wehmiller's amino-acid racemization results (reported in Ricketts, 1986), however, we now think the Wantagh is pre-*Wisconsinan*, possibly *Sangamonian*. If that is correct, then the next-older slot for the Ronkonkama Moraine and Till II is *Illinoian*.

We regard the newly exposed Gilbert-type delta foresets in Fuller's Manhasset Formation as deposits of proglacial **Lake Long Island**. The relationships at Montauk Point imply that this lake was there dammed on the S by the now-eroded Ronkonkama terminal-moraine ridge (Sanders and Merguerian, 1994). If this is correct, it implies that the age of these extensive proglacial-lake deposits is the same as that of the Ronkonkama Moraine, which we place in the *Illinoian*, the same age Fuller assigned. The extent of decomposition shown by the stones in the gravels at Caumsett State Park on the N shore of Long Island, however, suggests that the Manhasset Formation could be the product of a still-older glaciation, namely *Kansan*. If so, then the Long Island Lake must have been dammed on the S in part by a now-vanished terminal-moraine ridge that is older than the Ronkonkama.

Glacier III (and/or II; we cannot as yet distinguish between their erosive effects) sculpted the bedrock with prominent grooves trending NW-SE as found in Manhattan by Dr. L. D. Gale in 1828-29 (published in Mather, 1843), in Central Park by Hanley and Graff (1976) and in many parts of the New York City region by us (Merguerian and Sanders, 1988; 1991a, e; 1993a, c; 1994a; Sanders and Merguerian, 1991a, 1992). We ascribe the numerous effects of glacial flow oriented NW-SE, as reported from the erratics in the Brooklyn Botanical Garden (Gager, 1932) as shown on the Glacial Map of North America (Flint, 1945) and also as found by C. A. Kaye (1982) in Boston, MA, and vicinity to glacier(s) II and/or III.

Tills II and III, separated by a few meters of reddish-brown outwash of the kind deposited in a proglacial lake, are exposed in eroding bluffs along the E shore of the Hudson River at Croton Point Park, Westchester Co. At Enoch's Nose, they underlie yellowish-brown till IV that has been shaped into a drumlin whose long axis trends N-S; at Squaw Cove, they are overlain by gray varved clay containing scattered dropstones (assigned to the meltdown phase of glacial-episode IV); and at Teller's Point, they are underlain by a grayish-brown till (our Till No. I) containing indicator stones from the Cortlandt Complex and granitic rocks in which the feldspars have been totally decomposed to clay. Reddish-brown tills II/III underlie the terminal-moraine ridge being eroded in southern Staten Island; a prominent paleosol caps the upper reddish-brown till. The youngest unit in the coastal cliffs is a brownish loess (the "surficial loam"? of R. D. Salisbury (*in* New York City Folio of the U. S. Geological Survey).

The earliest glacier to leave its mark in New York City and vicinity (from our Episode I) flowed from the NNE to the SSW. It eroded the prominent rock drumlin at Fort Tryon Park, Manhattan, and many elongate rounded features eroded on the bedrock that constitute the smoothed, upglacier parts of typical roches moutonnées but lack the diagnostic steep, quarried-and-plucked down-ice sides. We have been using the term "roche-moutonnée structures" for these partial- or modified roches moutonnées. Examples are known from Bear Mountain, Orange County; from FDR Veterans Hospital, Westchester County; and in various parks in New York City.

Glacier No. I deposited the gray-brown till that underlies red-brown till (No. II?) at Teller's Point, Westchester Co. and the gray-brown till at Target Rock, L.I., which contains "greenstone" indicator stones from the Maltby Lakes metavolcanics SW of New Haven [misidentified by Sirkin and Mills (1975) as Palisades Dolerite and thus assigned by them to a till that was deposited by a glacier that flowed NW-SE; the upper till here, deposited by a glacier that **did** flow from NW to SE, is gray and contains no Newark erratics but rather indicator stones, such as Inwood Marble and the Cortlandt Complex, derived from what we have called the "crystalline corridor" of southeastern NY and western CT].

At least two pre-*Woodfordian* glaciations are implied by the relationships at three localities on Staten Island: (1) Till, exposed in coastal cliffs eroded into a terminal-moraine ridge in southern Staten Island, containing but-minor quantities of decayed pebbles (only the "greenstones") and capped by a well-developed paleosol, yields provenance data which prove that at least one glacier flowed regionally across Staten Island from NW to SE (**across** the Hudson Valley, thus our Till II and/or III) not NNE to SSW, (**down** the Hudson Valley) with local diversions to the SE, the pattern inferred for the *Woodfordian* ice by R. D. Salisbury (1902) and accepted by many one-glacier advocates. (2) At the AKR Excavating Corp., much-decayed stones in outwash gravels that underlie comparatively fresh red-brown till and overlie Cretaceous sands imply a pre-*Wisconsinan* age (possibly a product of our Episode I). (3) Superposed glacial striae and -crescentic marks on the dolerite exposed at the Graniteville quarry are inferred products of two ice-flow directions: an older NW to SE (our II and/or III) cut by a younger NNE to SSW (our No. IV).

We infer that on Staten Island are products of at least 3, possibly 4, glacial advances. We regard their ages as: *Kansan* (?) or even *Nebraskan* (?) for the much-decomposed outwash at AKR; Early *Wisconsinan +/- Illinoian* (?) for the coastal exposures of "terminal-moraine" materials derived from the NNW (capped by a well-developed paleosol and including a giant "erratic" slab of displaced Cretaceous sediments); and *Wisconsinan (Woodfordian)* for the till overlying the striae trending NNE-SSW at Graniteville. We do not know the location on Staten Island of any *Woodfordian* terminal-moraine ridge. Elsewhere, this ridge follows the south coast of Connecticut.

We have not yet turned up any absolute-age data that would settle the age assignments of our multiple-glacier interpretation and that would totally destroy the one-glacier-did-it-all view which we think is not correct. However, we think the case we have made for the pre-*Woodfordian* age for the Harbor Hill Moraine is very compelling. If we have correctly interpreted the subsurface relationships Rampino (1978 ms.) established at Jones Beach, then Long Island's two world-famous terminal moraines were not only **not** made by the fluctuating margin of the *Woodfordian* glacier, as has been universally believed for many years, but were made by **two different glaciers** whose appearance on Long Island was separated by an interglacial episode when the glacier retreated back into Canada and the sea rose nearly to its present level.

At present, the best hope for settling our chronological impasse is amino-acid-racemization analysis of shells from the Wantagh Formation. Our inference is that the Wantagh is *Sangamonian*, but as noted above, it could be mid-*Wisconsinan* or even *Yarmouthian*.

INTRODUCTION

This article has been written to provide regional geologic background about the Pleistocene sediments in the New York City region (Figure GG-1) against which what will be seen at four of the stops on the New Jersey Geological Association's Staten Island field trip can be evaluated. In writing it, we have been mindful that geological field guides are unique vehicles for disseminating field data that tend not be be accepted for publication elseswhere. Herein we present many such results from our continuing field investigations that have spanned twenty-five years.

In this article we: (1) briefly summarize selected items from the large geologic literature about local Pleistocene stratigraphy and -glacial history; (2) present our credentials and background and reasons for studying New York City's glacial history and offer a new stratigraphic classification; (3) summarize our field results under the headings of (a) inferred directions of glacial flow based on eroded bedrock in the New York City region, (b) directions of glacial flow inferred from sediments (erratics and indicator stones and long axes of drumlins), (c) discussion of the ice-flow evidence, and (d) stratigraphic superposition of tills and Pleistocene sediments; and (4) a summary of the glacial geology of Staten Island with respect to our proposed stratigraphic classification.

SUMMARY OF SELECTED GEOLOGIC LITERATURE ABOUT LOCAL PLEISTOCENE STRATIGRAPHY AND -GEOLOGIC HISTORY

In our review of previous work, we make no attempt at complete coverage. Moreover, in this section we include only major articles about the stratigraphic relationships with emphasis on the number of glaciations and the glacial history particularly with respect to the ages of the terminal-moraine ridges. We defer our attempts to evaluate these previous results until after we have presented our own results. We include some previous results on orientations of striae and on indicator stones alongside our own work.

Work Done Prior to 1914: Concept of One Glacial Episode is Born

In this category we include published work by L. D. Gale (1828-29, published *in* Mather, 1843), by James Gates Percival (1842) in Connecticut; by Mather (1843), by Warren Upham (1879), by T. C. Chamberlin (1883); by R. D. Salisbury (Salisbury, 1902, 1908; Salisbury and others, 1902; Salisbury and Peet, 1894; Peet, 1904); and by J. B. Woodworth (1901). Because of the difficulty in locating many of these old references, we quote from some of them at length. (Fuller, 1914, p. 4-19 summarizes **all** of the pre-1914 literature on Long Island Pleistocene sediments.)

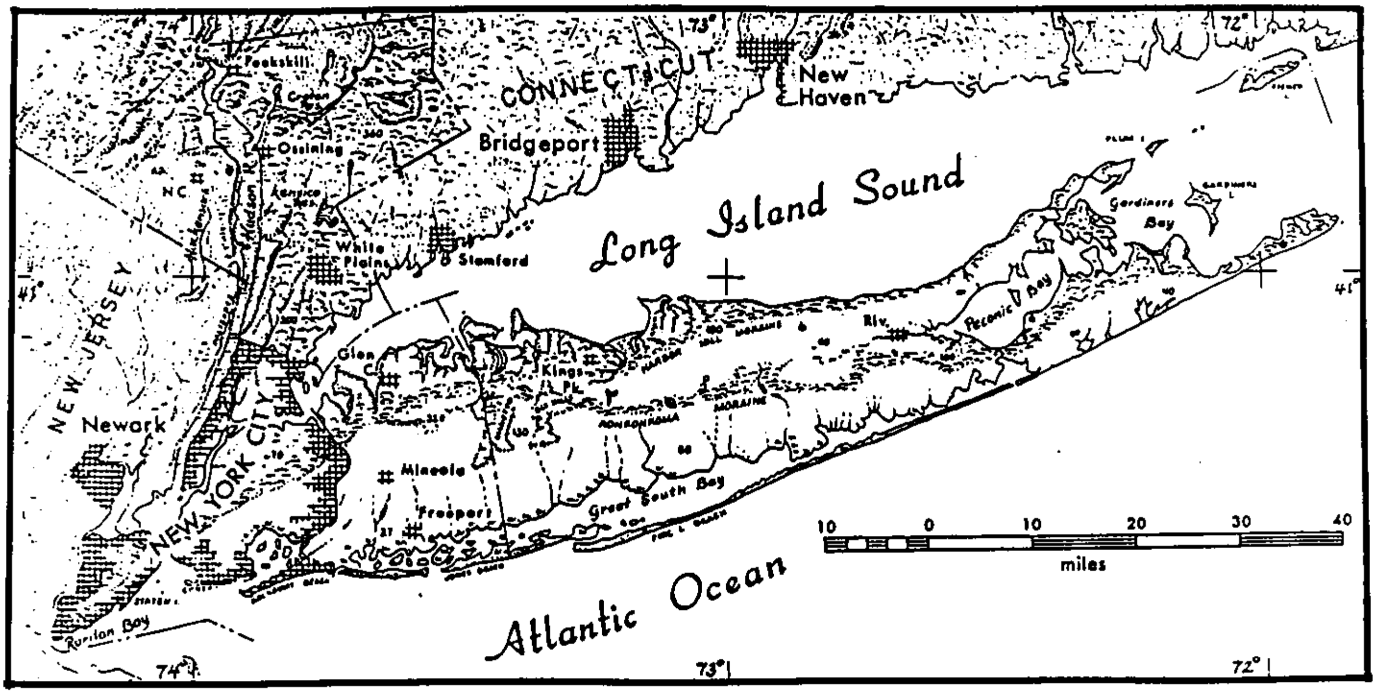


Figure GG-1. Physiographic sketch map of Long Island and vicinity showing the locations of localities mentioned in text. (J. A. Bier, 1964.)

The first systematic attempt to record directions of striae and grooves on the bedrock in New York City, was carried out in 1828-29 by Dr. L. D. Gale. Modern geologists would ascribe these to the effects of now-vanished glaciers. But in the early 19th century, these were considered to be products of the great flood of Noah; they were named "diluvial scratches and furrows".

Back then, most of the present-day streets had been laid out, but only a few buildings existed north of what is now known as Lower Manhattan. Therefore, Gale was able to study Manhattan Island in a more-or-less natural condition. Gale's street references can be taken directly; few buildings were present, and probably the ones to which he does refer have been long removed.

As was common in his day, Gale supposed that the grooves and scratches had been made by water currents, perhaps assisted by icebergs. The presumed significance of water is implied in his use of the term "diluvial." L. D. Gale (1839, Geological Report of New-York; New-York island; published *in* Mather, 1843, p. 209-210):

> "Diluvial grooves and scratches have been found in every section of the island, from Sixteenth-street on the south, to 200th-street on the north, (or to the southern termination of the limestone;) and from the banks of the Hudson on the west, to Harlem

river on the east. The furrows generally are most distinct where the rock has been recently uncovered, and least where it has been long exposed to the action of the elements. They have been found on the highest rocks, and at the lowest tide-water marks, being a difference of more than one hundred feet perpendicular height. The furrows are always most strongly marked on the northwestern slopes of the hills, and least so on the southeastern. In many instances they are very distinct on the western and northwestern slopes, extending to the highest point of the rock; but no traces are to be seen on the eastern and southeastern slopes, although both slopes are equally exposed.

"Direction of the furrows. Observations of the diluvial furrows were made in between sixty and seventy different places on the island. Taking together the whole series of observations, the general course of the current was from northwest to southeast, or north forty-five degrees west, but varied in the extremes from north twenty-five degrees west to north forty-eight west, making a difference of twenty-three degrees. Of the whole series of observations, thirty-nine were north forty-five degrees west, twelve varied from north forty-five degrees west (seven being north thirty-five degrees west), two were north forty-eight degrees west, and a few scattering ones varying from north thirty-five degrees west to north forty-five degrees west.

"Abundance of the furrows. The furrows occur most abundantly in the middle portions of the island, between the city and the Harlem and Manhattanville valley, somewhat less in the western, and least of all in the eastern.

"Direction of the furrows in particular neighborhoods. Half of all the places where the furrows were noticed were in the middle portion of the island, in the line of the Eighth avenue from Sixtieth-street to 105th-street, where without exception the direction is north forty-five degrees west. About one fourth of all are on the west side, and vary but little from north thirty-five degrees west; and about one-eighth on the eastern side, where the direction varies from north twenty-five degrees west to north thirty-five degrees west. In connection with this subject, I have examined the surface of the greenstone on the neighboring shores of New-Jersey (*sic*), and find their grooves and scratches abundant, and their general direc-/ (p. 210): tion is north forty-five degrees west. Hence it appears, that the diluvial current which once swept over this island from northwest to southeast, on reaching the western shore, was deflected southward, as by the action of some force at a right or some other angle to its course; and that the same current, before it reached the middle of the island, again assumed a southeasterly direction, but was again diverted southerly on approaching the eastern shore. That some portion of the current was diverted southerly on reaching the western shore of the island, is evident, not only from the diluvial furrows, but from the boulders of anthophyllite found in large numbers in the lower part of the Eighth avenue near Fifteenth-street, a distance of two miles in a south-southwest direction from the only locality whence they could have proceeded. Again, the white limestone of Kingsbridge has been distributed along the eastern shore of the island, in a direction almost due south of the only locality in the vicinity where it is found in place; whereas had they been carried in the general direction of the current, they would have been deposited eastward in Westchester county, as before stated.

"Magnitude of the furrows. The size of the furrows varies in the same and different localities. Sometimes they are the finest scratches, not more than a line in diameter horizontally, and of the smallest appreciable depth; from this they increase to grooves four inches deep and eighteen inches in horizontal diameter. In a few cases, they are furrows, or rather troughs, more than two feet wide and six or eight inches deep. A case of the latter kind occurs on Eighth avenue, between Seventy-ninth and Eight-first-streets; and one of the former on the west side of the island, on the very banks of the Hudson, five hundred yards north of Mr. John H. Howland's country seat (near Ninety-seventh-street).

"Convenient places for examining the diluvial furrows. The nearest places to the city for examining the furrows are at the junction of Twenty-second-street and First avenue, south of the Almshouse yard; and again about half a mile northward at Kip's bay, at the junction of First avenue and Thirty-fifth-street. Both of these localities will soon be destroyed by grading the streets. Some of the most interesting localities have been made known by cutting through Eighth avenue, from Bloomingdale road, at or near Sixtieth-street, to Harlem and Manhattanville valley at 105th-street; these locations are on both sides of the avenue, and very conspicuous. Another, equally interesting in many respects, is on the banks of the Hudson west of the Bloomingdale road, about six miles from the city, and about six hundred yards northwest of Burnham's hotel. The interest excited by this locality arises from the fact, that the furrows ascend from beneath the lowest tide water, up to an elevation of seventy feet in three hundred or four hundred feet distance."

Gale's observations clearly suggest the effects of two contrasting flow directions, (a) nearly all the "diluvial scratches and furrows" indicating flow from the NW to the SE and (b) the displacement of indicator erratics (the anthophyllite-bearing rock and the white limestone) showing transport from the NNE to the SSW. Yet his interpretation of his data was that of a single event, which he expressed as "the diluvial current." Gale tried to show how the changes in flow of a single such current could account for both the regional trends of the scratches and furrows on the smoothed bedrock and the displaced indicator erratics. In this regard, Gale began a pattern that would be followed by most subsequent students of the "diluvial" deposits: trying to account for all the disparate observations: trying to force fit all data into a single transport event. But Gale's single transport event differed significantly from the one favored by later investigators. Gale concluded that his single "diluvial current" had flowed from NW to SE and he sought aberrations in this flow direction to account for the displacement from NNE to SSW of indicator erratics.

Independently of and nearly simultaneously with Gale's survey of Manhattan, that great genius of Connecticut geology, James Gates Percival, was mapping the geology of the state of Connecticut. Percival was well acquainted with both the bedrock and what we would now refer to as the Pleistocene deposits. As did Gale, Percival classified these as "Diluvium," or the "unstratified (*sic*) materials," and contrasted them with the *Alluvium*, "those arranged in strata." Percival (1842, p. 453-456) cited many examples of distinctive kinds of rocks that had been displaced from NW to SE:

> "The greater part of the Diluvium was apparently deposited by a general current, traversing the surface from N. N. W. to S. S. E. This is satisfactorily indicated both by the bowlders, scattered over the surface, or imbedded in the diluvial earth, and by the smaller fragments included in the latter, as well as by its general character (*sic*)." (Percival, 1842, p. 453).

Percival emphasized that knowledge of the composition of the bedrock was absolutely essential for reconstructing the directions of the "diluvial currents:"

> "In order to determine the direction of the diluvial currents, a particular knowledge of the local character (*sic*) of the rocks, as indicated in the account already given of the different local

> formations, is indispensable. Several of these local formations are so peculiar in the character (*sic*) of their rocks, that the latter cannot be mistaken, to whatever distance they may have been transported. These, by the distribution of their bowlders and fragments, furnish conclusive evidence that the more general (*sic*) direction of the diluvial current was S. S. E." (Percival, 1842, p. 454).

Despite the numerous examples he cited that demonstrate transport from NW to SE, Percival reported that some rocks had been moved from NNE to SSW. As did Gale in Manhattan, Percival supposed that this transport to the SSW had resulted from local deflections of the general SSE-flowing diluvial current:

> "Although the general direction of the diluvial current was apparently S. S. E., yet in some instances, from local obstructions, its course was deflected to a S. S. W. direction. This is most distinctly obvious along the Western border of the larger Secondary formation, where blocks and fragments of the Trap and Sandstone of that formation are accumulated, sometimes quite abundantly, in such a direction from their apparent source." (Percival, 1842, p. 457).

In contrast to both Gale and Percival, the single flow event most later workers invoked was from the NNE to the SSW. They called upon aberrations from this "main-flow" direction to explain the scratches and furrows that trend NW-SE.

Mather (1843) described the geology of Long Island emphasizing strata exposed in the north-shore cliffs (Figure GG-2). At Lloyd's Neck, a storm exposed dipping strata that had been truncated and are overlain by horizontal strata. Mather was not able to interpret these strata as any modern geologist would do. After all, Mather's date of publication preceded general acceptance of the concept of Pleistocene continental glaciation and was 42 years before G. K. Gilbert (1885) presented his analysis of the topographic features of lake shores in which he proposed the terms *topset*, *foreset*, and *bottomset* as the three kinds of lacustrine deltaic strata formed along the shores of ancient Lake Bonneville, Utah (and 47 years before Gilbert's Lake Bonneville monograph appeared in 1890).

Mather used the name "Long Island Formation" informally for the sediments that he thought underlie most of the island; he assigned this formation to the Tertiary. Mather's term has been abandoned, but we are considering the feasibility of reviving it for the extensive suite of pre-*Wisconsinan* sediments deposited in a lake the occupied much of what is now Long Island. (We refer to it as **Long Island Lake** and discuss it in a following section.) Mather mentioned the two prominent curvilinear ridges now known to be terminal moraines, but he did not realize they were of glacial origin.

Warren Upham (1879) mapped and discussed Long Island's two terminal-moraine ridges and associated outwash plains (Figure GG-3). He inferred that each had been built at the margin of a separate glacier. (Upham recognized two tills throughout southern New England and on Long Island.) He noted that on Long Island, till is abundant W of Roslyn and generally absent to the E.

T. C. Chamberlin (1883; 1885; 1895a, b) laid the foundation for the stratigraphic classification of North American Pleistocene deposits. He described the conditions at the margin of the continental glacier in terms of lobes and inferred that the main axis of concentrated flow in eastern New York state had been down the Hudson Valley (1883, map following p. 346). He reviewed the previous work on the Long Island terminal moraines and outwash plains but differed with Upham's assignment of these to two separate glaciers. Based on the lack of differential erosion and dissection of the associated outwash plains, Chamberlin argued that both the terminal-moraine ridges and associated outwash plains were products of the latest glacial episode. Chamberlin's argument has been nearly universally accepted.

R. D. Salisbury and associates mapped the glacial geology of New Jersey and reported ice-flow indicators oriented not only NNE-SSW, as they expected, but also NW-SE, which they did not expect. Early in the studies of the glacial deposits, Salisbury concentrated on the flow indicators on the Palisades ridge. The position of the Palisades ridge was critical with respect to Chamberlin's view that a main axis of accelerated ice flow had been down the Hudson Valley. Chamberlin supposed that within the margins of an ice sheet are localized zones within which the ice flows faster than it does in adjacent areas. At such places of localized faster flow, he imagined that the ice-flow "stream-lines" would be crowded close together. On either side of such supposed zones of concentrated flow, the ice tends to spread out toward each side. Chamberlin had illustrated this concept by sketching a map of ice-flow indicators in the region surrounding Lake Michigan (Figure GG-4).

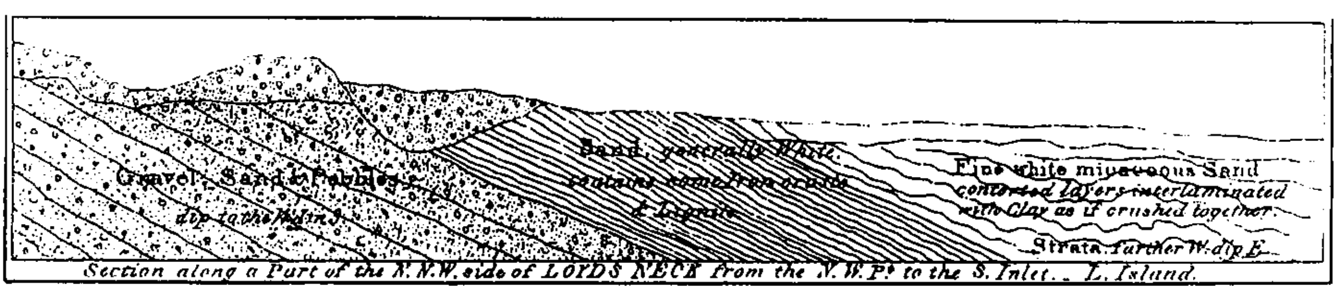


Figure GG-2. Mather's profile-sections, Lloyd's Neck, North shore cliffs, Long Island. (Mather, 1843, Plate 4, fig. 16.)

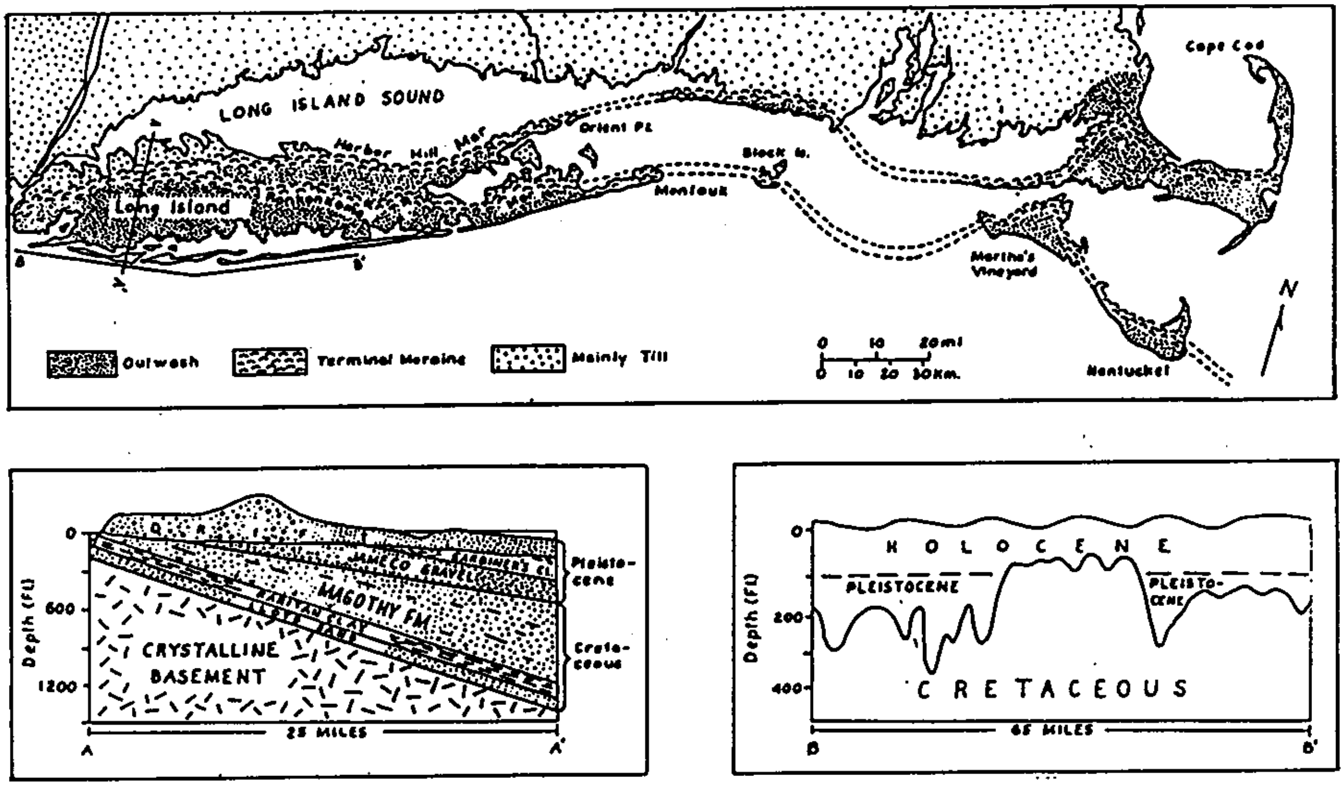


Figure GG-3. Map of Long Island and vicinity showing the locations of the two terminal moraines and profile sections showing subsurface relationships. (Wolff, Sichko, and Leibling, 1987, fig. 3, p. 24.)

Salisbury accepted Chamberlin's flow model. But if the zone of fast ice flow had followed the Hudson Valley, as Chamberlin had supposed, then divergent flow across the Palisades ridge should have been **from NE to SW**. Salisbury and Peet went to considerable trouble to study the glacial geology of the Palisades ridge. After they found virtually all the ridge-crest striae indicating glacial flow from **from NW to SE** and none from the predicted NE to SW, Salisbury reconciled the situation by shifting the axis of the presumed accelerated flow westward and placing it in the Hackensack Valley. From this inferred zone of concentrated flow down the Hackensack Valley, Salisbury and assistants (1902) thought that the ice had flowed toward the SSE over the Palisades ridge and Manhattan, and toward the SSW over the crests of the Watchung Ridges in New Jersey (Figure GG-5). This was consistent with their findings that glacial-flow indicators over the Watchung ridges had been predominantly from the NNE to the SSW, the predicted flow direction for the Palisades ridge for a fast-flow axis located either in the Hudson Valley or the Hackensack Valley.

Salisbury admitted that the regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from northwestern New Jersey and the divergent orientations of the glacial grooves and -scratches constituted anomalies to this explanation of marginal-flow divergence within a single glacier. Salisbury acknowledged that another succession of events which could explain the distribution of erratics of Green Pond Conglomerate involved two glaciations, but he merely mentioned the possibility of two contrasting glaciers.

> "No single Green Pond mountain conglomerate bowlder has been found on the ridge. West of Hackensack, such bowlders are found in abundance, and this in spite of (*sic*) the fact that in New Jersey the movement of the ice along the Green Pond mountain range was to the southwest, approximately

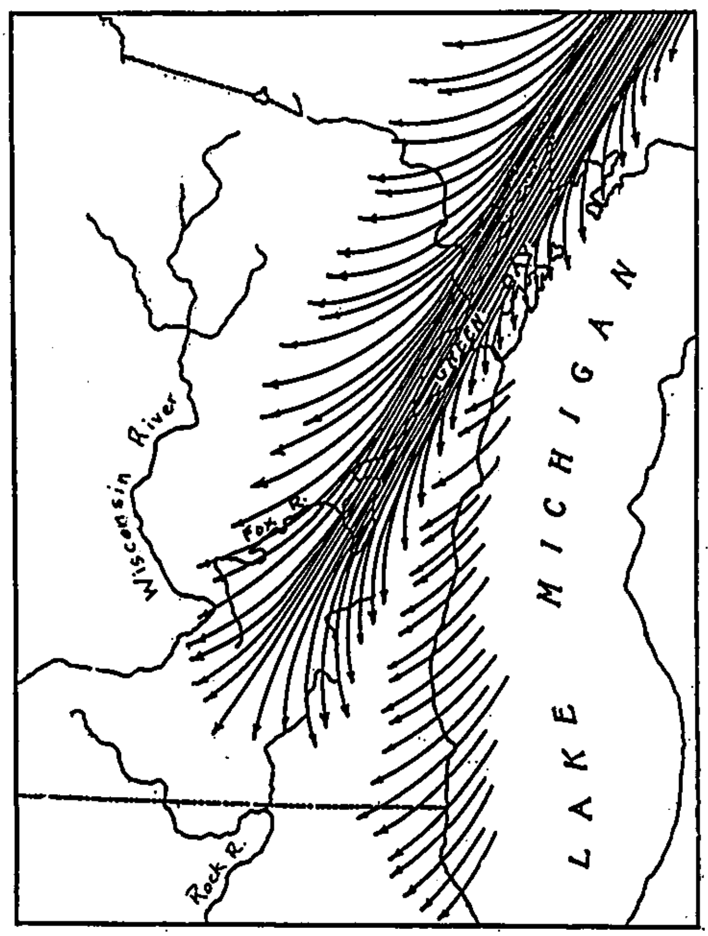


Figure GG-4. Sketch map of area west of Lake Michigan (mostly in Wisconsin, but including parts of Michigan and Illinois), showing concept of divergent flow from a narrow zone (centered above Green Bay, Wisconsin) of rapid flow within an ice sheet. (R. D. Salisbury, 1902, fig. 31.)

parallel to the range itself. Glacial movement in this direction could not have carried bowlders from the New Jersey part of the the Green Pond mountain formation to the Hackensack valley. It would seem that the conglomerate ledges which furnished the Hackensack valley bowlders must have lain somewhere north of New Jersey, in the axis of the ice lobe, or perhaps a little to the west of it, and that the bowlders derived from this ledge were carried southward in the direction of ice movement, and finally out of the valley onto the highlands to the west by the westerly-diverging currents, but that they were not brought within the influence of easterly diverging currents, and therefore were not carried eastward upon the Palisades ridge. Another hypothesis which would equally well explain the distribution of the Green Pond mountain conglomerate bowlders, but for which there is no demonstrative evidence at hand, is that these bowlders were carried southeastward from their parent ledges by an earlier ice movement, the movement in the last epoch being to the southwest over or along the Green Pond mountain formation. A good deal may be said for this suggestion. The distribution

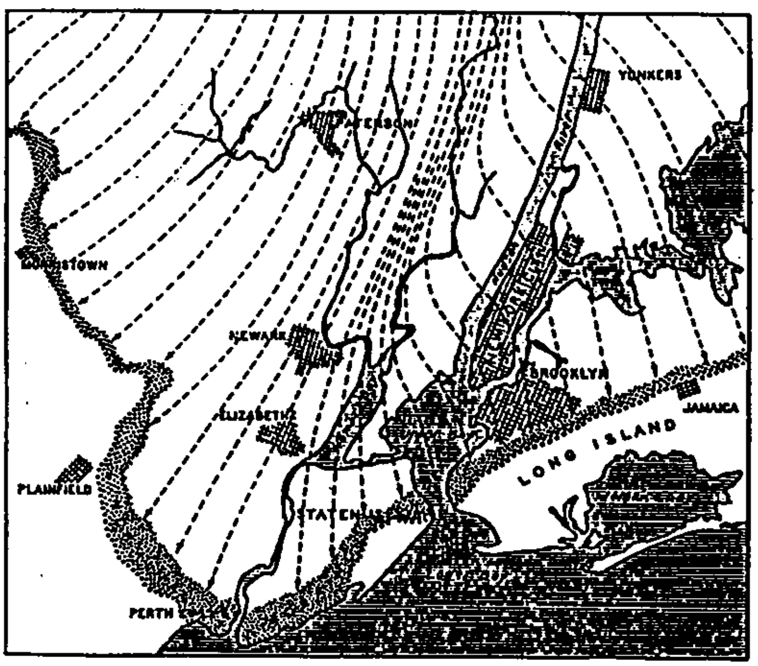


Figure GG-5. Map of northeastern New Jersey and southeastern New York showing inferred flow lines within the latest (and supposedly the only) Pleistocene glacier that reached the New York City region. Further explanation in text. (R. D. Salisbury, *in* Merrill and others, 1902, fig. 12, p. 13; also 1908, fig. 11; also, H. B. Kümmel, 1933, fig. 13, p. 66.)

of these bowlders has not been studied beyond the State of New Jersey" (Salisbury, 1894, p. 180).

All of Salisbury's work on the glacial deposits of New Jersey was based on the flow pattern shown in Figure GG-5. He published it repeatedly in various folios that the U. S. Geological Survey published in the region (New York City, Passaic, Franklin Furnace).

Woodworth (1901) reported on the Pleistocene geology of Queens County. About inferred directions of flow of the glacier(s), he wrote:

"Frontal moraines mark the position of the ice front. The motion of the ice, at least near its margin, will tend to be toward that front; hence, since (*sic*) the moraine in this part of the island trends to the south of west, forming a lobate line across this region and that adjacent in New Jersey, glacial striae in this part of the island should run to the east of south. A number of ledges of gneiss in Long Island City meet (*sic*) this requirement."

"The southeastward movement of the ice on this side of the Hudson valley is further attested by the drift. The moraine from Brooklyn as far east as Oyster Bay contains trap boulders, the nearest known site of which rocks is in the Palisade trap ridge on the west bank of the Hudson river.

"Stratified red sands, also undoubtedly derived from the area of Triassic red sandstones now found only on the west bank of the Hudson, occur in a section by the roadside from Corona to Astoria, being there overlain by 8 or 9 feet of gray till... " (Woodworth, 1901, p. 652),

With respect to divergent flow directions, Woodworth wrote:

"This fanning of the ice sheet to the eastward on the east side of the lower Hudson and to the westward on the west side is consistent with the form of the moraine across the mouth of the river. The axis of the lobe thus indicated has been fixed by Salisbury on the west side of the Palisade trap ridge. (ftn. 1)

Ftn. 1: "Salisbury, R. D. N. J. geol. sur. An. rep't state geol. for 1893. 1894, p. 161." (Woodworth, 1901, p. 653).

Woodworth discussed ancient glacial lakes that lay between the high parts of Long Island and/or a terminal-moraine ridge on the S and the glacier itself on the N and sandy/gravelly delta deposits built into such lakes. He included, as Plate 8, a photograph by Heinrich Ries of Gilbert-type delta foresets and

-topsets taken in the large Port Washington sand pit during the early days of its active phase. In Figure GG-6 we have modified Woodworth's figure 9 (p. 658) to show a gap between the ice front and a terminal moraine on the S which could serve as a dam to hold in the water of a proglacial lake. Woodward's map and text clearly indicate that is what he had in mind even though in his figure 9, he showed other relationships.

Woodworth also discussed examples of older gravels assigned to the Columbia Formation (p. 624-637) that include an interstratified thin unit of boulder-bearing till (his "boulder clay bed" of p. 627). He described it as follows:

> "*The boulder clay bed.* In many of the coastal sections on the north shore an unstratified (*sic*) mixture of pebbles, sand and clay in a bed varying from 3 to 10 feet in thickness may be seen in a position to indicated that it is interstratified with these older gravels; but it is only in the sand pits on Hempstead bay that a bed of this character (*sic*) is fully revealed. About half way up the bluff, or about 100 feet above the bay, there is a bed of boulder clay from 2 to 3 feet thick, traceable in all the pits open in 1900 south of Bar beach. The matrix of this bed is an unctuous dark blue (*sic*) clay locally sandy or gravelly. Scattered through it and sometimes in close contact with each other (*sic*) are glaciated boulders ofter over (*sic*) 1 foot in diameter and numerous pebbles attesting the glacial origin of the deposit. Several large boulders examined in 1901 by Dr. F. J. H. Merrill and the writer were recognized by the first named as having been transported in all probability from the Adirondacks. Other small boulders carrying Silurian fossils indicated their origin in the Hudson Valley north of the Highlands. The longest journey made by these materials appears to exceed 200 miles."

In summary, it is clear that by early in the twentieth century, T. C. Chamberlin and R. D. Salisbury had stamped on the glacial geology of the New York City their one-glacier view with flow deviation at the margin based on the behavior of inferred ice lobes. Lost in the shuffle were J. B. Woodworth's important contributions, especially that his older series of gravels and interbedded till form a foundation upon which the Harbor Hill moraine was deposited and with respect to his proof that the direction of flow of the glacier which had deposited the Harbor Hill Moraine had been from **NNW to SSE** and to his clear evidence for multiple glaciation based on the older unit of interstratifed till and gravels as seen in sand pits and north-shore coastal cliffs.

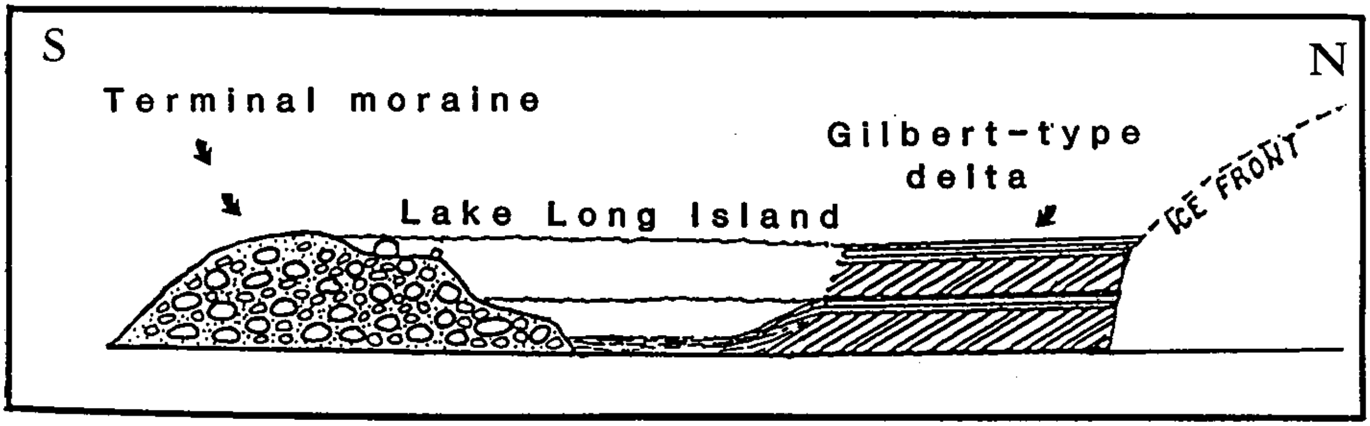


Figure GG-6. Schematic profile-section showing Gilbert-type deltas on N side of Lake Long Island, which formed in the lowland beteen the ice front on the N and the terminal-moraine ridge on the S. Two levels are shown: the lower at +40 feet and the upper at +80 feet (referenced to modern sea level). Highlands of Long Island, underlain by Cretaceous strata, could also serve as a dam for the lake on the S side. (Sanders and Merguerian, 1994, fig. 1, p. 103; adapted from Woodworth, 1901, fig. 9, p. 658.)

A note about language: Salisbury and Woodworth always used the term **striae** as the plural for glacial scratches, whereas T. C. Chamberlin adopted the plural of the attribute word "striation" and wrote "striations." In the interests of being gramatically correct, we accept Salisbury and Woodworth and reject the "striations" of T. C. Chamberlin and his legion of followers.

Fuller's (1914) Monographic Results: Four Glacial Episodes

The fundamental study of the stratigraphy of the glacial deposits in the New York metropolitan region is Fuller's (1914) monumental treatise on the geology of Long Island. Fuller found deposits that he interpreted as products of 4 glacial advances; between some of the glacial sediments, he found nonglacial strata. Table GG-1 shows the names- and stratigraphic relationships of Fuller's units. Notice his assignment of the Harbor Hill Moraine and the Ronkonkoma Moraine to the post-*Illinoian* (Early *Wisconsinan*); he inferred they are both younger than the Vineyard unconformity but assigned them to the Early *Wisconsinan*. (Later workers changed Fuller's age assignment from Early *Wisconsinan* to latest *Wisconsinan*, or *Woodfordian*).

Fuller inferred that during the Vineyard erosion interval, which he assigned to the *Sangamonian*, streams had eroded the deep north-facing valleys. Although Fuller did not discuss the relationship between glaciation and low sea level as contrasted with interglacial conditions and high sea level, he did realize that the extensive valley erosion he assigned to this interval required that base level be relatively low with respect to Long Island. He attributed the low base level to uplift of Long Island.

Early Wisconsinan G	Harbor Hill Terminal Moraine Ronkonkama Terminal Moraine	
Sangamonian I	Vineyard Fm. (marine deposits and peat); surface of erosional unconformity with relief of ca. 300 ft.	
Illinoian G	Manhasset Formation	Hempstead Gravel Mbr. "Ice-erosion" unconformity Montauk Till Mbr. "Ice-erosion" unconformity Herod Gravel Mbr.
	Jacob Sand	
Yarmouthian I	Gardiners Clay	
Kansan G	Jameco Gravel	
Aftonian I	Unconformity surface of great erosion	
Pre-*Kansan* G	Mannetto Gravel	

Table GG-1. Fuller's stratigraphic classification of the Pleistocene deposits of Long Island. G, glacial; I, interglacial. (Fuller, 1914, p. 20.)

Fuller applied the name Manhasset formation (with upper Hempstead gravel member, middle Montauk till member, and lower Herod gravel member) to the "Columbia formation" of Woodworth. Because, as mentioned, Fuller inferred that the extensive network of north-flowing valleys had been cut into the Manhasset Formation, he classified this formation as being older than the Vineyard erosion interval. Fuller assigned the Manhasset to the *Illinoian*. Fuller drew many sketches of strata exposed in coastal cliffs. Among these, he illustrated examples of Manhasset Formation showing one-directional dips (Figures GG-7 and GG-8). We discuss these further in a following section.

The next-older unit in Fuller's classification is the Jacob Sand. Fuller took the name from Jacob Hill, "a high point on the north shore of Long Island, 8 miles northeast of Riverhead, near which the formation is well exposed" (Fuller, 1914, p. 107).

The Gardiners Clay grades upward into Jacob Sand which Fuller described as:

> "In its most characteristic (*sic*) form the Jacob sand consists of exceedingly fine sands, mainly quartz flour, but with many grains of white mica and some of dark-colored minerals. In color the sands commonly range from a very light gray to yellowish (*sic*) and buff tints, but where laminae of true clay are present they may be stained reddish externally. They are everywhere clearly stratified, although individual beds several feet thick and appearing structureless to the eye are encountered. When wet most of them are somewhat plastic but lack the toughness of true clay; all are decidedly gritty to the teeth and most of them to the touch. Interbedded with the fine varieties of the Jacob deposits are some more distinctly (*sic*) sandy beds, usually buff or yellowish, and several feet thick, in which particles of fairly fresh granitic minerals can be recognized" (Fuller, 1914, p. 107).

Fuller (1914, p. 113) assigned the Jacob Sand to the Illinoian, but considered it to be transitional between the interglacial *Yarmouthian* Gardiners Clay below and overlying *Illionian* glacial materials of the Manhasset Formation.

> "There is reason to believe that the change in deposition, as was pointed out in the discussion of the source of the material (p. 107), was caused by the advent of glacial silts brought down from the north during the advance of the Montauk ice, but long before it invaded the region under discussion" Fuller (1914, p. 113).

Fuller (1914, p. 92) gave the name Gardiners clay from "Gardiners Island, situated between the North and South flukes at the east end of Long Island, on which several clay beds with included sands are well exposed at a number of points."

> "On western Long Island, where the formation reaches its maximum development, the Gardiners clay consists of irregular dark-colored beds alternating with layers (*sic*) or lenses of sand and fine gravel and attaining near Brooklyn an aggregate thickness of 150 feet. In this region the clays, unlike those in the localities farther east, grade downward through glauconitic (*sic*) and locally fossiliferous sand into the Jameco gravel, representing in fact transitional deposits. The clays themselves consist of a very fine

silt, dark from the contained organic matter and carrying more or less lignitized wood. The included sandy layers are commonly from 5 to 10 feet thick and at some places have yielded fossil remains (Fuller, 1914, p. 93).

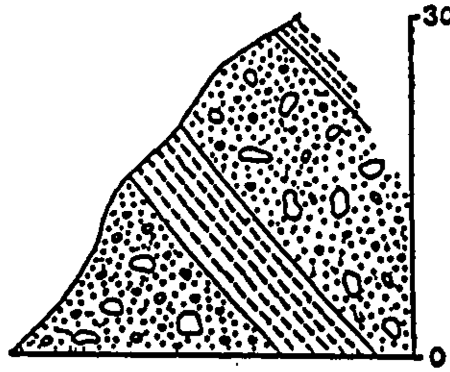


Figure GG-7. Fuller's sketch of exposure 1 mile west of Rocky Point, Montauk showing dipping diamictons and intercalated well-bedded strata. Based on what is exposed at Caumsett State Park, we infer that all these dipping layers are deltaic strata, the diamictons being products of subaqueous debris flows, not tills. (M. L. Fuller, 1914, fig. 156, p. 143.)

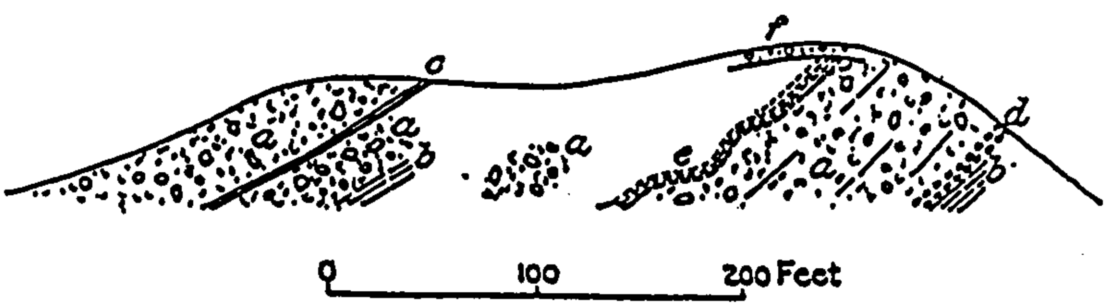


Figure GG-8. Fuller's sketch of exposure 0.5 mi S of Cullodan Point, Montauk, showing a dipping succession of diamictons and well-bedded strata and overlain by a horizontal till (f, at top; "Wisconsin till" in Fuller's caption. Other letter notations, after Fuller, are: a, "Montauk till member"; b, clayey sand; c, clay; d, gravel, and e, sand. (M. L. Fuller, 1914, fig. 157, p. 143.)

"The great body of the Gardiners clay rests upon the Jameco gravel, but along the borders of the Jameco next to the Cretaceous land mass, especially along the edges of the great depression in the vicinity of Jamaica Bay, the clay laps up on the eroded surfaces of the Cretaceous and Mannetto (fig. 57) or even upon the metamorphic rocks (fig. 62), with sharp erosion (*sic*) and overlap unconformities (*sic*) (Fuller, 1914, p. 94).

In all of the localities where the Gardiners Clay is visible at the surface, evidence of ice-thrust deformation is unmistakeable (Fuller, 1914, p. 96-102, figs. 65-86).

Fuller's two oldest units, the Jameco Gravel and Mannetto Gravel, are known mostly from wells. They form valley fills. The oldest valleys on Long Island, the pre-Mannetto valleys, were completely filled in by the Mannetto Gravel (Fuller, 1914, p. 44). The Jameco Valley cuts the Mannetto Gravel; it in turn has been filled in by the Jameco Gravel, which filled the valley and obliterated it as a landscape feature.

Fuller took the name Jameco Gravel "from the Jameco pumping station, near Jamaica South, 3 miles south of Jamaica, in western Long Island," where Veatch first recognized and named these deposits from deep wells.

> "The Jameco gravel, although it has not been definitely recognized at the surface at any point on Long Island, has been encountered in a considerable number of wells. In its type locality, in the area extending from Jamaica Bay northward toward Whitestone, it occupies a broad //(p.86) depression in the underlying rocks (either Cretaceous or Mannetto). It is easily recognized in the wells in this locality because of its striking dissimilarity to all other Pleistocene beds (except the Montauk till member of the Manhasset formation) and to the Cretaceous formations. The difference between the Jameco gravel and the Mannetto gravel is especially marked. Although the older beds are prevailingly light-colored (*sic*) and composed principally of quartz, the Jameco is generally a very coarse dark-colored gravel containing a predominance of granitic pebbles with a few streaks of black (*sic*) or other dark sands or finer silts..."
>
> "Where lithologic characteristics are not determinative, the formation is recognized by its position beneath the fossiliferous Gardiners clay" (Fuller, 1914, p. 85-86).

"The Mannetto gravel was named from the Mannetto Hills (West Hills), on the crest of which just west of Melville some of the best exposures of this gravel on the island were found" (Fuller, 1914, p. 80).

Fuller described the Mannetto as follows:

> It "consists of stratified (*sic*) and in some places cross-bedded gravels composed mainly

> of well-rounded pebbles of quartz from half an inch to an inch in diameter mixed with coarse yellowish quartz sand, but carrying everywhere a few deeply weathered granitic pebbles and scattered large bowlders of crystalline rock, also deeply weathered or disintegrated. It includes a few thin intercalated beds of yellowish clay. The granitic fragments can usually be crushed by the finger or by a slight blow of a hammer, and even the quartz is far more friable than fresh fragments. The quartzose (*sic*) and stained character (*sic*) of the gravels, the deep weathering of the pebbles, and the complex flow and plunge (*sic*) structure are the distinguishing features of the formation " (Fuller, 1914, p.80).

We note a distinctive anomaly in the relationships Fuller described for the Jameco and contrasted with the Mannetto gravels. Both are prominent subsurface units in western Long Island where the upper unit, the Jameco, fills a major depression eroded in the Mannetto and is therefore the younger unit. Fuller reported that the Jameco is not known at the surface on Long Island. By contrast, the type locality of the Mannetto is on the surface in the Mannetto Hills.

The key feature that Fuller used to identify the Mannetto is the decayed granitic pebbles. Such decayed pebbles can originate in two ways. (1) They can be distinctive erratics, indicator stones, for example, of a region of pre-glacial decayed bedrock, such as is found in the northernmost 500 feet of the Garrison tunnel of New York City's Catksill aqueduct (Berkey and Rice, 1921, p. 101-103; Berkey and Fluhr, 1948); or (2) they can be the result of intensive *in-situ* chemical weathering after deposition and thus indicate great age.

Two indices of the first alternative are that (a) the pre-glacial (probably even pre-Late Cretaceous; Blank, 1978) decomposition of the feldspars was accompanied by the dissolution of quartz; and (b) other stones do not show comparably advanced states of decomposition.

The key feature of the second alternative is that **all** stones display the effects of advanced stages of decomposition. We have not checked the surface exposures that Fuller assigned to the Mannetto Gravel for dissolution of quartz, but have noticed a contrast in states of decomposition: only in the granitic rocks has the feldspar turned into clay. In other kinds of pebbles, only the effects of incipient decomposition are visible. Therefore, the decay of the feldspars should not be considered a badge of extremely ancient age (as we have previously supposed).

Given the validity of the first alternative, we raise the possibility that the Mannetto Gravel of the surface exposures may not be correlative with the subsurface unit Fuller assigned to the Mannetto Gravel in wells from western Long Island. This possibility would be highly likely if the degree of decomposition of the pebbles in the subsurface units assigned to the Mannetto is more or less uniform throughout in contrast to decay of granitic pebbles only in the surface exposures. Whatever is the outcome of this discussion about the Mannetto, the message is clear: decayed feldspars by themselves do not necessarily prove an early Pleistocene age.

Work Done After 1914: Most Return to the Single-glacier Hypothesis, But Multiple Glaciers Do Rear Their Ugly Heads Again

In the mid-1930's, W. L. S. Fleming (1935) and MacClintock and Richards (1936) published their analysis of the Pleistocene record. Both rejected several key age assignments in Fuller's stratigraphic classification. Fleming argued that the age of the Manhasset Formation is *Wisconsinan*; he invoked several *Wisconsinan* glacial advances to account for the Montauk Till and changed the age assignment of Long Island's famous terminal moraines from Early *Wisconsinan* (Fuller's interpretation) to Late *Wisconsinan*. MacClintock and Richards led the multitude back to the one-glacier view that Fuller had thought he had buried. Not only did they move Fuller's Manhasset Formation up into the *Wisconsinan* but also they shifted the Gardiners Clay from the *Yarmouthian* interglacial, where Fuller had placed it, into the *Sangamonian* (but MacClintock and Richards weaseled by allowing as how the age of this clay might be partly *Sangamonian* and partly *Yarmouthian*).

According to Sirkin:

> "...the Gardiners Clay, was believed to represent an Early Pleistocene interglacial (Fuller, 1914) and was subsequently placed in the Sangamonian Interglacial Stage (MacClintock and Richards, 1936). In historical usage, a variety of fine-grained sediments of both fresh water (*sic*) and marine orgin have been called the Gardiners Clay. These strata, which have been observed in surface exposures and well sections, can vary considerably from the original fossiliferous marine sediments of the type section (Upson, 1968; Sirkin and Mills, 1975). Gustavson (1976) has shown that certain so-called Gardiners Clay units contain fossil faunas quite unlike the fauna from the type section, while (*sic*) Sirkin and Stuckenrath (1980) indicate that some strata identified as Gardiners Clay could be of Portwashingtonian age, particularly in the absence of radiometric ages for either the original or the presumably correlative units.

> "The inclusion of such strata in the Woodfordian moraines only show that they predate (*sic*) the Woodfordian advance. As a surface deposit, the Manetto Gravel, although well weathered, is probably Woodfordian outwash (Sirkin, 1971), derived from deeply weathered granite and granite gneiss in Connecticut. The Jameco Gravel and the Gardiners Clay as recognized in well section are undoubtedly post-Cretaceous and probably represent Late Pleistocene deposits that are older than the overlying glacial deposits" (Sirkin, 1982, p. 38).

MacClintock and Richards experienced difficulty in recognizing Fuller's Montauk Till Member of the Manhasset Formation and did not accept Fuller's stream-dissection hypothesis for the origin of the north-facing valleys. According to Fuller, streams of post-Manhasset age eroded valleys into the Manhasset Formation. Because Fuller thought this interval of erosion correlated with the *Sangamonian* interglacial age, he assigned the pre-erosion Manhasset Formation to the *Illinoian*. By contrast, MacClintock and Richards argued that the valleys had not been stream eroded, but were left as depressions (somewhat analogous to giant kettles) because they had been occupied by tongues of glacial ice. While the ice tongue remained in what is now the valleys, thick bodies of outwash sand were aggraded in between. After the ice had melted, valleys appeared. Valleys having such an origin are not younger than the adjoining sands, but of the same age. We prefer Fuller's interpretation.

The theoretical background in support of the concept that one and the same continental ice sheet could display multiple flow directions was proposed at the time when the modern version of the Laurentide Ice Sheet was advocated (Flint, 1943). According to Flint, the Laurentide Ice Sheet began as one or more snowfields in the highlands of northeastern Canada. With continued additions of snow, an ice cap appeared and it began to spread southward and westward. The azimuth from the northeastern Canadian highlands to New York City is 195° or along a line from N15°E to S15°W. After this ice cap had become a full-fledged ice sheet and had attained something close to its full thickness, it is presumed to have itself become a factor in localizing where further snow would fall. Flint inferred that the ice sheet could divert the flow of moisture-bearing winds from the Gulf of Mexico and thus would have acted as a self-generating orographic source of precipitation. In other words, the ice sheet forced the air to rise and to be cooled and thus to drop its moisture. Enough snow is therefore thought to have been heaped up at various localities near the outer margin of the ice sheet and thus to have formed ice domes whose relief altered the direction of flow. Thus, the initial direction of regional rectilinear flow toward the SSW as a result of snow supply from northeastern Canada, could change locally to centers of quasi-radial flow under of the influence of the ice domes each of which could display divergent flow patterns, including zones of flow from NNW to SSE. During retreat, the above-described situation would be reversed. The factors responsible for radial ice-dome flow, including sectors from NNW toward the SSE, would cease to operate and those causing rectilinear flow toward the SSW to resume their former pre-eminence. The predicted pattern of flow for each advance of such an ice sheet, therefore, would involve three phases in the following order: (1) rectilinear flow from the NNE toward the SSW; (2) quasi-radial flow from the glacier-marginal ice domes, but locally from the NNW toward the SSE; and (3) rectilinear from the NNE toward the SSW.

Because he was convinced that if two glaciers had flowed over an area and both had extended their influence deep enough to polish and scratch the bedrock, then the younger glacier would tend to obliterate all traces of the older one, Flint opposed the multiple-glacier hypothesis. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one.

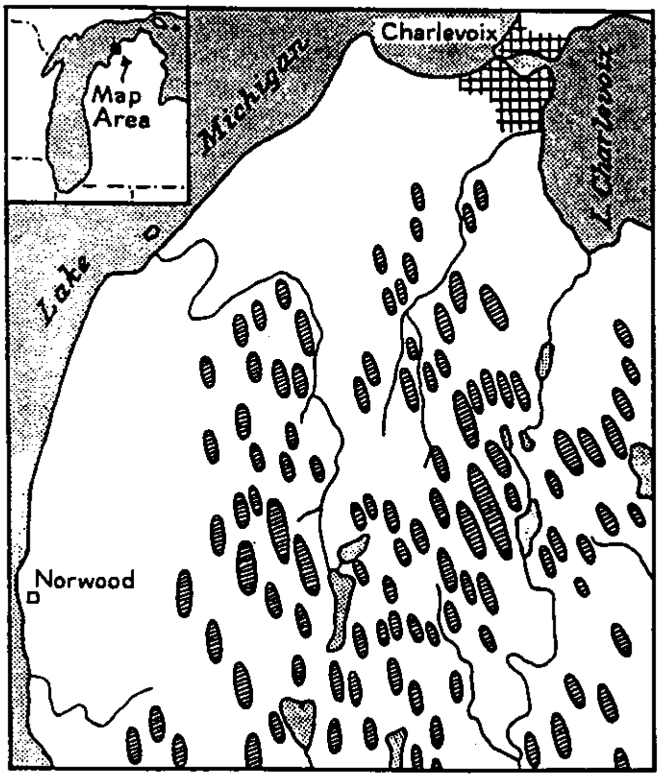
On the Glacial Geologic Map of North America, Flint (1945) mapped the two contrasting flow directions, one from the NNE to the SSW and the other from NW to SE. Figure GG-9 show examples from the upper midwest and from SE New England that demonstrate glacial flow from the NW to the SE.

The first post-Fuller challenge to the one-glacier-did-it-all school of thought came from one of the staunchest one-glacier partisans, Richard Foster Flint (1961). In south-central Connecticut, Flint found two tills in direct superposition. He gave the name Hamden Till to the upper till, whose flow indicators imply glacier movement from NNE to SSW. He proposed the name Lake Chamberlain Till for the lower till, whose flow indicators showed glacier movement from NNW to SSE.

Despite Flint's results, Sirkin (1968, 1971, 1977, 1982) has attached to his noteworthy paleobotanical contributions a strong adherence to the one-glacier interpretation. Because he disagreed with some of Fuller's correlations, Sirkin swept aside all Fuller's work. Because we think Wehmiller (*in* Ricketts, 1986) has destroyed one of the keystones of Sirkin's interpretation, namely the supposedly mid-*Wisconsinan* Portwashingtonian warm interval (the amino-acid-racemization results suggest an age of 200,000 yr for the shells that gave a radiocarbon age of about 40,000 yr BP), we accord Sirkin the same treatment that he applied to Fuller (1914) and for the same reasons. [For further discussion of the problem of contrasting ages between these two dating methods in specimens from Port Washington, Long Island, see Muller and Calkin (1993, p. 1841), and for the Pleistocene deposits at Sankaty Head, Nantucket Island, MA, see Oldale and others (1982).]

We think that Sirkin's Roslyn Till probably is the same till that Upham (1879) noticed in extreme western Long Island and also the "trap-rock"-bearing gray till at Corona mentioned by Woodworth (1901). Like Sirkin, we assign the Roslyn Till to the

Woodfordian (our Till IV); unlike Sirkin, we interpret the Roslyn Till as being **younger** than the Harbor Hill Moraine (which we assign to our Till III and place in the Early *Wisconsinan*).



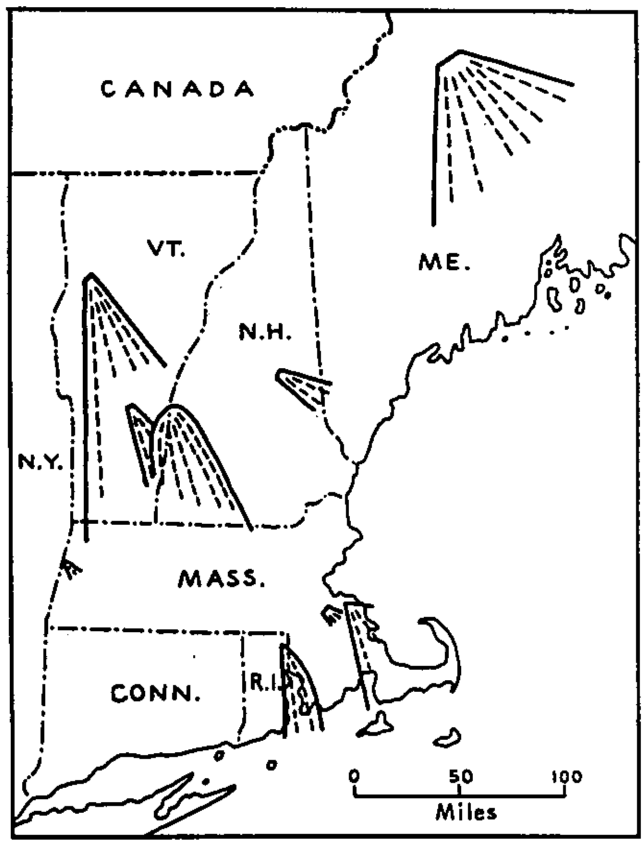


Figure GG-9. Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, MI. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, all products of regional glacier flow from NW to SE. (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p. 190.)

In his study of the Quaternary sediments in the Boston area, Kaye (1982) found deposits that he ascribed to several *Wisconsinan* glaciers. Kaye's inferred flow directions of these

Boston glaciers are virtually identical to those that we infer for the ancient glaciers in the New York City region. To quote from Kaye's paper:

> "The direction of ice flow in the Boston Basin and adjoining uplands was studied by means of the orientation of striations (*sic*) and grooves on the bedrock surface, the orientation (*sic*) of the long axes of drumlins, the direction of transport of erratics in till, and the direction of thrusting and overturning of bedding in glacially deformed drift. These data range through 360 degrees in azimuth. Analysis of this confusing message shows the existence not of an ever-shifting ice current but of at least four separate and distinct ice currents of different ages. Three of these flowed fairly rectilinearly, but one (the last) was multicomponent and marked by strong lobation" (1982, p. 31).

Kaye numbered these tills from I (oldest) to IV (youngest). Tills I, II, and III flowed from the NW to the SE, with means as follows:

Till	**Mean flow direction**
III	S31°E, +/- 02°
II	S64°E, +/- 18°
I	S23°E, +/- 01°

Recently, Sirkin has moderated his one-glacier viewpoint. In an open-pit mine at Sanford Hill, in the central Adirondacks, Muller, Sirkin, and Craft (1993) described two tills separated by 3.6 m of brown Tahawus lake- or pond clay containing wood fragments older than 55,000 radiocarbon years B. P. that were exposed in 1963 in the National Lead Company's (now NL Industries) open-pit mine. They assigned the Tahawus Clay to the *Sangamonian*; according to them, it contains "an interglacial pollen record, the first one identified in northeastern New York" Muller, Sirkin, and Craft, 1993, p. 163).

In their summary of the glacial events in New York State, Muller and Calkin (1993) did not recognize any pre-*Wisconsinan* tills in the New York City region. They wrote: "The pre-Wisconsinan record involves saprolith and till in the Adirondack Mountains, marine clay on Long Island, multiple tills at Fernbank, Otto, and Gowanda, and major drainage derangement of the Allegheny River" (Muller and Calkin, 1993, p. 1829).

After summarizing the amino-acid-racemization results, they continued:

"...it is difficult to escape the conclusion that two temporally distinct stratigraphic units are involved. Indeed, Stone and Borns (1986) propose that the name Gardiners Clay be reserved for brown marine clay and silt (*sic*) with interbedded sand and gravel of probable Sangamonian to Eowisconsinan age (Table 3). This action clarifies the age of the Gardiners Clay, and implicitly acknowledges the probability that marine clays of both Sangamonian and pre-Sangamonian age are present" (Muller and Calkin, 1993, p. 1830).

OUR WORK

We subdivide this section into two parts: (1) a narrative of our background and credentials for investigating the glacial deposits in the New York City region, and (2) a summary of our interpretation of the stratigraphic framework of the Pleistocene deposits in the New York City reigon.

Background and Credentials of Investigators

In 1949-50 Sanders (hereafter abbreviated JES) took the late Professor Richard Foster Flint's graduate course in Geomorphology and Glacial Geology and for 10 years (1954-1964) was a faculty colleague of Flint's at Yale University. In the late 1950's and early 1960's, JES mapped the bedrock geology of several 7.5-minute quadrangles in and around New Haven at the same time as Flint was mapping the surficial deposits. They undertook several joint field conferences during which Flint interested JES in looking for and recording the orientations of features on bedrock surfaces that are valuable in determining the direction of flow of a glacier. JES found this a logical extension of his interest in the features made in sediments that enable directions of paleocurrents to be inferred, a topic he began to study during 1954 while a postdoctoral fellow working in Europe with the late Professor Ph. H. Kuenen, of the University of Groningen, The Netherlands (Kuenen and Sanders, 1956).

In 1964 JES moved to New York. He continued to work closely with Flint as a co-author of the Longwell, Flint, and Sanders Physical Geology textbook published in 1968. In 1968, JES began teaching the introductory geology course in the Department of Geology at Barnard College, Columbia University. Guided by Ina Alterman, a City College graduate then a graduate teaching assistant in the Department of Geology, Columbia University, JES started to examine local features at Fort Tryon Park (Figure GG-10) and the Palisades, places where many generations of geology students had been taken on required half-day field trips. One of the first things that JES noticed was the prominent evidence at both localities of striae and grooves made by a glacier that had flowed from about N15°W to S15°E. In search of what the experts on Pleistocene geology had made of such evidence, JES read into the geologic literature on the Pleistocene geology of the New York City region. In the writings of H. B. Kümmel (1933) and of R. D. Salisbury (1902, 1908; Salisbury and others, 1902), JES

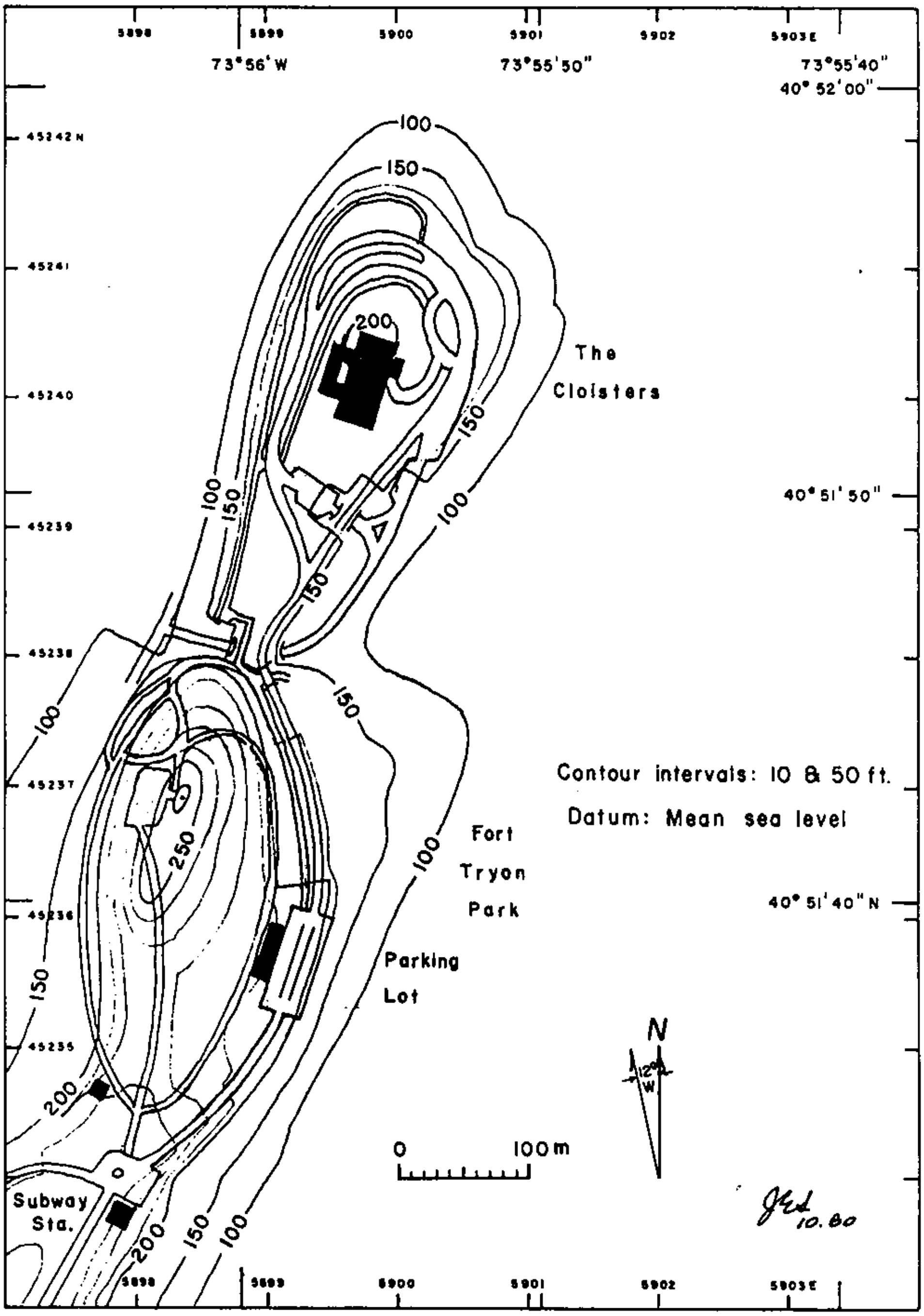


Figure GG-10. Enlarged topographic map of the Cloister area, Fort TRyon Park showing the two rock drumlins oriented NNE-SSW. Enlarged from USGS Central Park 7.5-minute quadrangle by JES.)

found how Salisbury, one of America's foremost specialists on Pleistocene geology, had explained this evidence of glacial flow from NW to SE. (See Figures GG-4 and GG-5.) JES thought Salisbury's explanation, which had been accepted by Kümmel and many other geologists, was somewhat unusual, but initially found no reason to challenge it.

Three other developments caused JES to change his position with respect to the Salisbury explanation. (1) In the summer of 1969, JES and son Thomas accompanied John Burger and his son David on a two-week canoe trip in the International Boundary Waterways Wilderness Area in northern Minnesota. One rainy day, they paddled past a splendid example of a roche moutonnée comparable to the one shown in Figure GG-11. JES vividly recollected Richard Foster Flint's efforts to find an outstanding photograph of a roche moutonnée for use in the Physical Geology textbook and how Flint had finally settled on the one shown. Accordingly, JES kept on the lookout for other examples of roches moutonnées that he could photograph on a fair-weather day. To his surprise, he found no other examples as typical as the one passed during the rain. A few nights later, we camped on a bedrock knoll whose surface had been glaciated. Next morning when we studied it closely, we found that it had been shaped by glacial-ice flow from two directions nearly at a right angle. The typical jagged, quarried-and-plucked downglacier side created by earlier ice flow from the NE to the SW had been destroyed by later ice flow from NW to SE. Being mindful of the standard version of the North American ice sheets during the Pleistocene (Figure GG-12), JES asked John Burger if local Pleistocene geologists had noticed what we had seen and if so, how they explained it. Burger was puzzled. When we returned to Beloit, Burger took JES to visit a local limestone quarry, where the stripped surface of the bedrock near the quarry faces displayed crossed sets of striae, one oriented NE-SW and the other, NW-SE, the same directions of flow that had sculpted the bedrock knolls we had seen on the canoe trip. Both of us left the quarry in a puzzled state of mind.

(2) In 1970, based on material in Schuberth's (1968) book, JES worked up a one-day Palisades/Staten Island field trip to be included as part of a new course on the Natural History of the New York City region offered in alternate years jointly with faculty colleagues in the Department of Biology, including the late Donald R. Ritchie, Chairman, who had kept up a life-long interest in geology. One of the localities included on our trips was Princess Bay (Stop 6 on today's trip). On the beach we found examples of many kinds of rocks that had been washed out of the reddish-brown till exposed in the eroding bluff; before us lay the materials for virtually a complete course in petrology. Among the washed-out erratics were two varieties that qualify as indicator stones: (A) the Lower Silurian Green Pond Conglomerate from the Appalachian fold-thrust belt in NW New Jersey. (One particularly distinctive kind, featuring small, white, rounded, uniformly sized quartz pebbles about 4 mm in diameter set in a

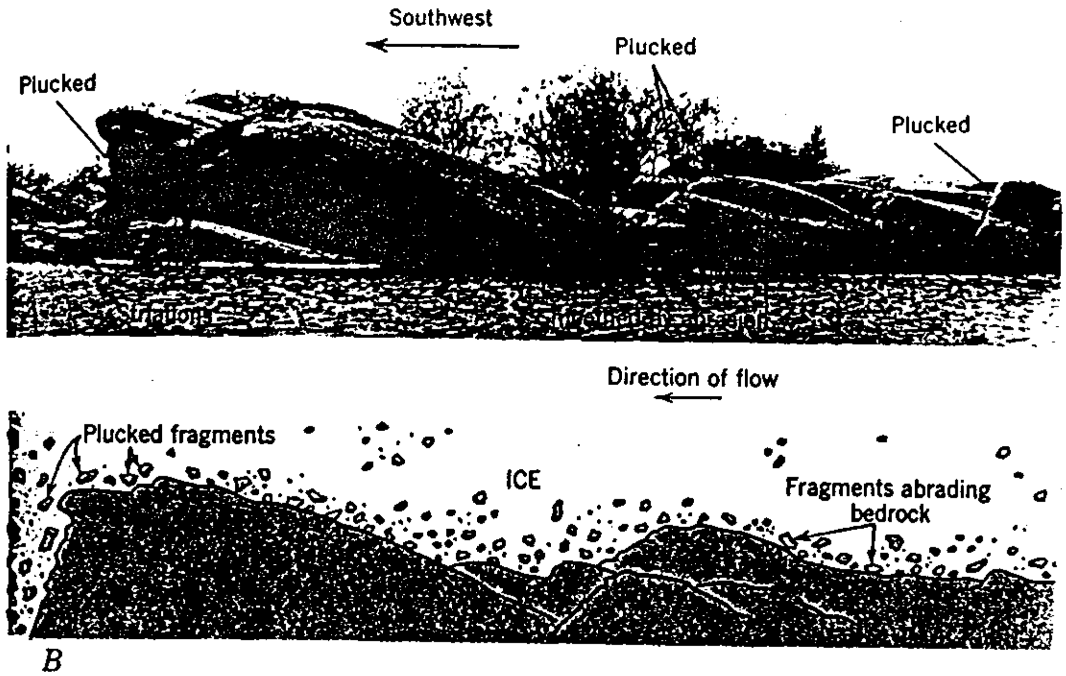


Figure GG-11. Roches moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roches moutonnées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roches moutonnées beneath a glacier.

dark-reddish brown hematitic matrix, prompted Professor Ritchie to name it the "braunschweiger-sausage" rock). (B) Small angular erratics of anthracite, which we found by studying the eroding face at close range. Both these kinds of indicator stones demonstrate that glacial flow from NW to SE had been **not local and curved** (as implied by the flow lines in Figure GG-5) but **regional and rectilinear** (Figure GG-13). JES subsequently interested Joanne Bourgeois in studying the erratics here for her Senior Thesis (Bourgeois, 1972 ms.)

(3) Alexandra Gardiner Tufo (now Goelet) enrolled in the course on the Natural History of New York City and as one of the trips, invited the class to visit her family home on Gardiners Island. The eroding cliffs on the E side of Gardiners Island display reddish-brown till featuring abundant erratics from the Newark-age rocks of the Connecticut valley belt in central Connecticut and -Massachusetts (now designated as the Hartford basin). A Pleistocene glacier could have transported these erratics to Gardiners Island only if it had flowed regionally from NW to SE.

Figure GG-12. Map of North America showing a reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

JES began to think about the Pleistocene history of New York City in terms of two glaciers, possibly the same two that Flint (1961) had described in southern Connecticut: an older glacier that had flowed from NW to SE and a younger one that had flowed from NNE to SSW and that Long Island's prominent terminal-moraine ridges had **not been deposited by ice flowing from NNE to SSW, the direction assigned to the latest glacier, but rather by a glacier that had flowed from NW to SE** (Sanders, 1974).

The thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other strike valleys that trend NE-SW disclosed evidence for only a single glaciation. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and -silts) that is overlain by estuarine deposits (Berkey, 1933, 1948; Berkey and Healy, 1912; Berkey and Fluhr, 1948; Lovegreen, 1974 ms.).

Rampino (1978) examined the numerous vibracores collected along the routes of the outfall pipes from the sewage-treatment plants being built for Nassau County and for Suffolk County in the vicinity of Jones Beach on the S shore of Long Island (Figure GG-14). These cores provided the basis for recognizing three new formations (Figure GG-15). A lower nonmarine sand unit, interpreted as outwash, was named the Merrick Formation. It was separated by coastal marine (intertidal- and bay) deposits, the Wantagh Formation, from an upper sandy nonmarine unit of inferred outwash, the Bellmore Formation (Rampino and Sanders, 1981). They correlated the inferred upper outwash (the Bellmore Formation) with the Harbor Hill Moraine and the lower inferred outwash (the Merrick Formation) with the Ronkonkama Moraine.

JES and Rampino (1978) presented a paper at the Northeastern Section of the Geological Society of America on proposed revisions is the Pleistocene stratigraphy of the New York City region. The response from the reigning "experts" on Pleistocene geology was a massive yawn.

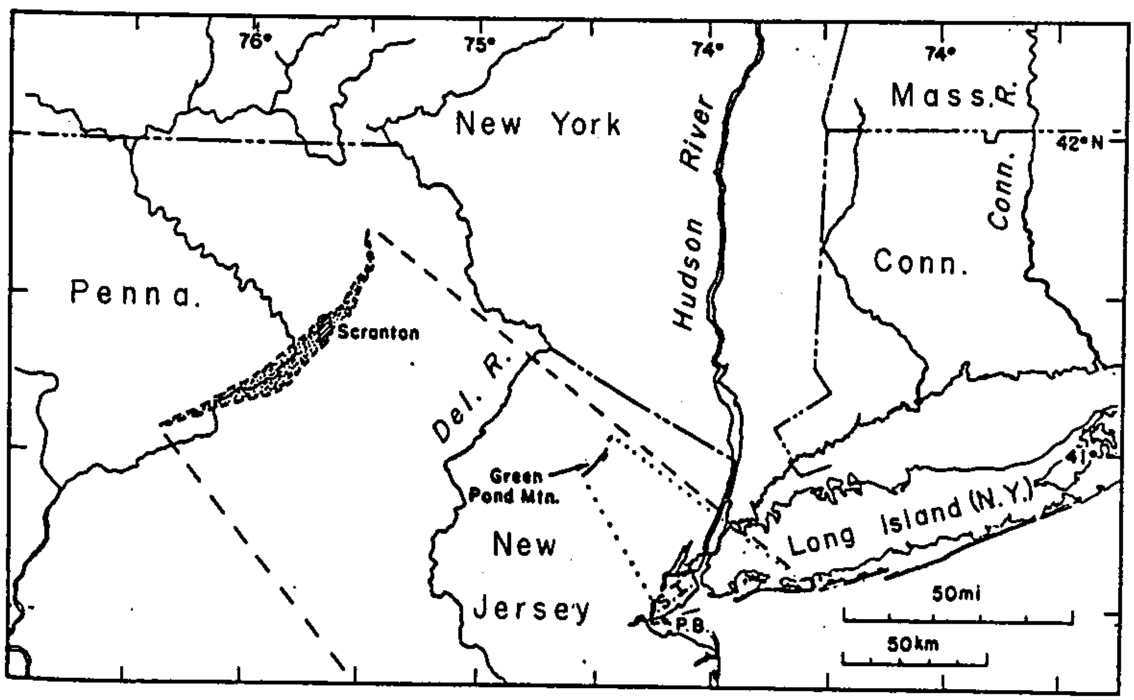


Figure GG-13. Distinctive indicator stones found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (Friedman and Sanders, 1978, fig. 2-1, p. 27; Friedman, Sanders, and Kopaska-Merkel, 1992, Box 2.2 fig. 1, p. 48.)

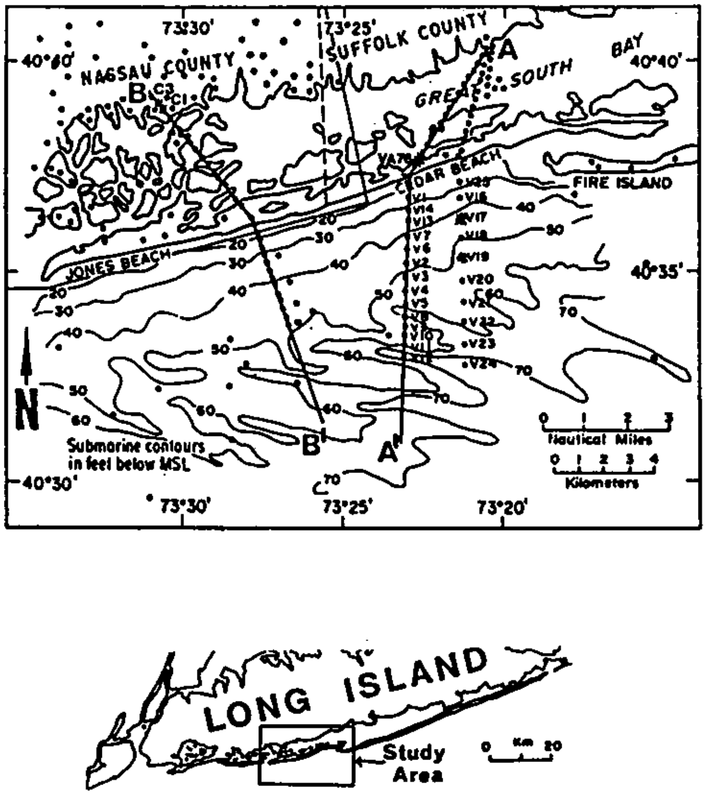


Figure GG-14. Index map, location of Jones Beach profile-sections. (Rampino and Sanders, 1981, fig. 3, p. 118.)

Merguerian's (hereafter abbreviated CM) experience in mapping metamorphic- and igneous rocks in the southern part of the New England Appalachians and in the foothills metamorphic belt of the Sierra Nevada of California and adjacent regions has spanned more than twenty-five years. As an extension of his work on Cameron's Line and the bounding units in western Connecticut (Merguerian 1983a, 1985, 1987), CM has mapped all of the bedrock exposures in Manhattan (under the auspices of the U. S. Geological Survey branch of Engineering Geology during 1981-83) and has continued his research to the present (Merguerian, 1983b; 1986a, b; 1994; Merguerian and Baskerville, 1987; Merguerian, Baskerville, and Okulewicz, 1982). CM has led hundreds of geological field trips to Central Park and other sites in Manhattan and vicinity.

As a dyed-in-the-wool hard-rock geologist, CM would have never imagined working on the non-lithified "cover" that masks our more-interesting crystalline tectonostratigraphic terranes. His first nudge away from this hard-rock attitude was delivered during a graduate course in Pleistocene Geology at Columbia University taught by Professor Rhodes W. Fairbridge.

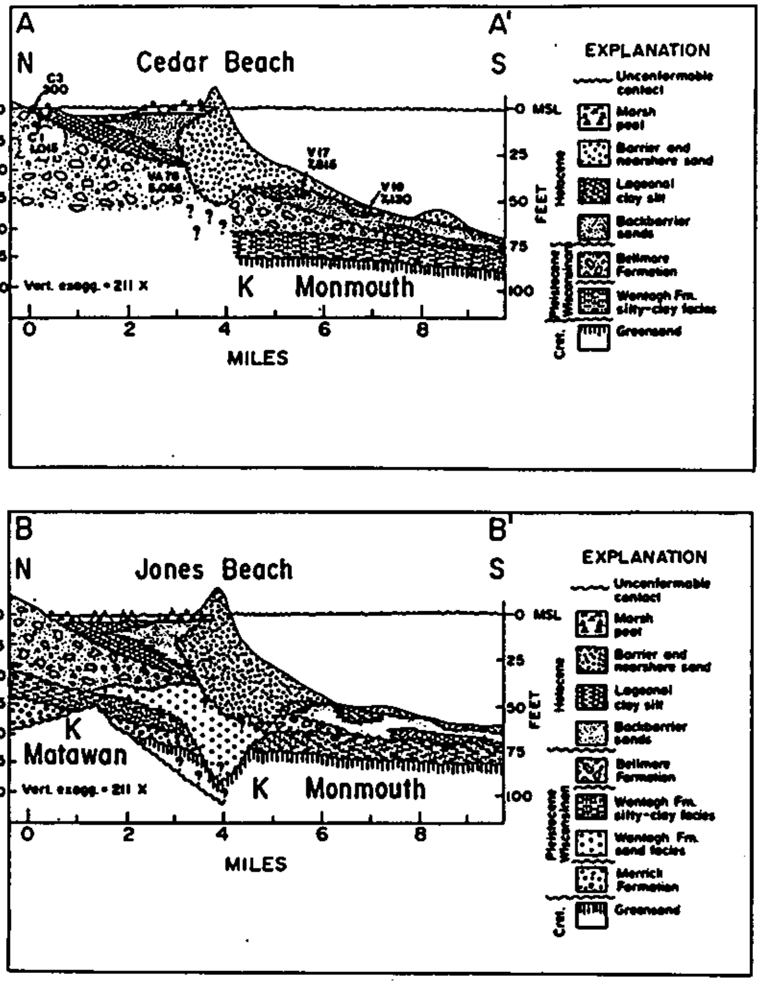


Figure GG-15. Profile-section subsurface of Jones Beach. (Rampino and Sanders, 1981, fig. 4, p. 119.)

Since 1987, our collaboration has given CM a new perspective and appreciation for soft-rock geology (as such, CM now feels that only mild heating to 600°C under 5 Kb pressure is needed to correct their *soft* character!). CM's main contribution to this project has been the identification of far-travelled erratics and indicator stones excavated and brought down from areas of his bedrock familiarity, the field measurement of superposed features of glacial erosion, and keeping JES on schedule for publication deadlines.

Our joint studies have been made starting in 1987 and are continuing in connection with preparations of guidebooks and the carrying out of many of our On-The-Rocks field trips for the Section on Geological Sciences of the New York Academy of Sciences (Merguerian and Sanders, 1988; 1989a, b, c, d, e, f; 1990a, b, c, d, d, e, f; 1991a, b, c, d, e, f; 1992b, c, d, e;

1993 a, b, c, d; 1994 a, b) and a special trip on the glacial geology of the north shore of Long Island for the Long Island Geologists (Sanders and Merguerian, 1991b). We have published abstracts of papers presented at meetings related to our joint research on the glacial history of the New York metropolitan area (Sanders and Merguerian 1991a; 1992; 1994; Sanders, Merguerian, and Mills, 1993).

We are now at work on the manuscript of a book on the geology of New York City and vicinity, a book on the Roadside Geology of New Jersey, and an introductory-level Geology lab manual based on materials that we have presented in the On-The-Rocks field-trip guidebooks.

Together we have focused on three aspects of the glacial geology: (1) features made by glaciers flowing over the bedrock (not an altogether new topic; geologists have been studying the orientations of small-scale glacial striae and -grooves in the New York City region for 166 years; we have concentrated on glacial features at all scales not only on the small-scale ones); (2) glacially displaced indicator stones [another topic on which many previous workers have expended first-class efforts locally; any edge we claim for ourselves falls in this department--between the two of us we are very familiar with the bedrock in the region over which the glaciers flowed, posssibly more so than many of the geologists who have specialized in study of the Pleistocene sediments on Long Island, for example. In this connection, we think our most-important contributions have been in our ability to distinguish between a common kind of mafic erratic (Palisades dolerite/diabase) from four potential look-alike rocks, (a) mafic- and ultramafic rocks from the Cortlandt complex near Peekskill; (b) Paleozoic dark-colored amphibolites from southeastern New York and western Connecticut; (c) Paleozoic mafic igneous rocks from western Connecticut; and (d) the Paleozoic metavolcanic rocks from southwest of New Haven, CT.; and (3) exposures of stratigraphic relationships [in this topic we have lucked into some "treasures" exposed in new excavations and in coastal cliffs that were severely eroded during storms, but then several of our predecessors, namely Mather (1843) and Fuller (1914) likewise studied storm-eroded coastal cliffs on Long Island; more importantly perhaps, we have been resolute diggers with trenching tools and routinely clear up the slope wash to see what is really under there--some of our contemporaries have been less inclined to use trenching tools and thus, we think, have made some serious mistakes in their interpretation of the slope wash). Our view parallels the U. S. Supreme Court's voting-rights decision: "one person, one vote." With respect to New York's glacial record, we paraphrase that Supreme Court ruling with "One glacier, one flow direction."

Our View of New York City's Pleistocene Stratigraphy

Table GG-2 shows our interpretation of the Pleistocene stratigraphic units in the New York City region. Although for the sake of completeness, we have included in Table GG-2 all of Fuller's units, we emphasize that our work has concentrated on tills and their directions of flow and has not dealt at all, for example, with the Gardiners Clay or with such important subsurface units as the Jameco Gravel and subsurface Mannetto Gravel. We have included the Gardiners Clay not because we have studied it but because we accept the Ricketts-Wehmiller result that the age of the Gardiners Clay is *Yarmouthian*, where Fuller

Age	Unit No.	Ice-flow Direction	Description; remarks
Late *Wisconsinan* (*Woodfordian*)	IV	NNE to SSW	Gray-brown till in W. Queens, Westchester Co., Staten Is.; gray lake sediments at Croton Pt. Park
Early Wisconsinan (?)	III	NW to SE	Harbor Hill Terminal Moraine and associated outwash; Bellmore Fm. in Jones Beach subsurface
Sangamonian (?)			Wantagh Fm. of Jones Beach subsurface
Illinoian (?)	II	NW to SE	Ronkonkama Terminal Moraine and associated outwash (=Merrick Fm. of Jones Beach subsurface)
Yarmouthian			Gardiners Clay
Kansan (?)	I	NNE to SSW	Manhasset Fm. of Fuller (including debris flows) deposited in Lake Long Island dammed on S in part by pre-Ronkonkama terminal-moraine ridge; Gray till at Teller's Pt., Croton Pt. Park
Aftonian			Not known to be present
Nebraskan (?)			Decayed-stone outwash at AKR Excavating Co., SI

Table GG-2. Our stratigraphic classification of the Pleistocene deposits of New York City and vicinity.

(1914) assigned it and **not** *Sangamonian*, where the multitude following MacClintock and Richards (1936) has placed it and where Stone and Bornes (1986) would officially redefine it (a proposal that we totally reject).

The key to the changes we have made comes from our results from directions of flow. We argue that the youngest glacier (the *Woodfordian*; our No. IV) flowed along a direction that is parallel to the Hudson Valley (from about N10°E to S10°W). In the New York City area, the color of this till is gray or yellowish brown. The next-older till (our No. III) was deposited by a glacier that we think flowed from a direction that is *across* the lower Hudson Valley (direction from N25°W to S25°E). As mentioned previously, in his study of the Pleistocene deposits of Queens, J. B. Woodworth (1901) showed that the Harbor Hill moraine is associated with reddish-brown materials that rest on striated bedrock with striae oriented N25°W-S25°E. In our scheme of things, we think this means that the Harbor Hill moraine cannot possibly be of *Late Wisconsinan* age (i. e., *Woodfordian*, as most workers except Fuller believe), but must be **at least one glacier older.**

We are confident in our relative arrangements, but readily admit that we have assigned ages by the method of "counting down from the top" that is subject to change at the first whiff of solid chronostratigraphic data, of which we offer absolutely none. We still lack the definitive interglacial stratigraphic evidence necessary to destroy forever the one-glacier-did-it-all viewpoint that we think is erroneous.

In the following sections, we present the basis for our multiple-glaciers interpretation.

Our discussion features evidence of effects of glacial erosion on bedrock from localities (only one being on Staten Island, at the Graniteville quarry) where we think the *n* value for Pleistocene glaciers must be >1. To this, we add local- and regional data from glacial sediments (provenance and long axes of drumlins) that support multiple-flow directions. Then follows a discussion of superposition of tills exposed at localities in Westchester County, in northern New Jersey, on Long Island, and on Staten Island. We close with a brief summary of the glacial geology of Staten Island interpreted using our proposed stratigarphic framework.

DIRECTIONS OF GLACIAL FLOW BASED ON ERODED BEDROCK IN THE NEW YORK CITY REGION

We begin our presentation by summarizing the kinds of features glaciers erode on bedrock that can be used for inferring ice-flow direction(s). Then follows a presentation of results from study of local examples.

Kinds of Features Glaciers Erode on Bedrock That Can be Used For Inferring Ice-Flow Direction(s)

Features that a glacier erodes on the bedrock that can be used to infer ice-flow direction include striae and grooves, crescentic marks, long axes of roches moutonnées and "roche-moutonnée structures" and long axes of rock drumlins. We describe each of these and show their value in reconstructing ancient flow directions.

Striae and grooves

Glaciers are one of the few geologic agents known to create scratches and even large grooves on solid bedrock (Figure GG-16). The ice flowed along the trend of the linear elongate features.

In a study of glacial striae cut into the bedrock by the Saskatchewan Glacier in Alberta, Iverson (1991) illustrated examples of three categories: (a) groove widening in a down-flow direction and ending abruptly in a deepened part against a slope that dips steeply in an up-flow direction; (b) groove symmetrical and ending at sharp points at both ends with deepest excavation at midpoint; and (c) groove widest at up-flow end [a near-mirror image of those of group (a)]; long profile asymmetric, beginning at a steep slope, dipping in a down-flow direction, and dying out at the pointed down-flow end. He also carried out experiments in which blocks of carbonate rock were forced against a fixed striator point having various shapes.

Crescentic marks

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable. Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure GG-17).

Orientations of long axes of roches moutonnées and "roche-moutonnée" structures

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as *roches moutonnées*. (See Figure GG-11.) These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow); but jagged, irregular, and steep on the side toward which the ice flowed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction].

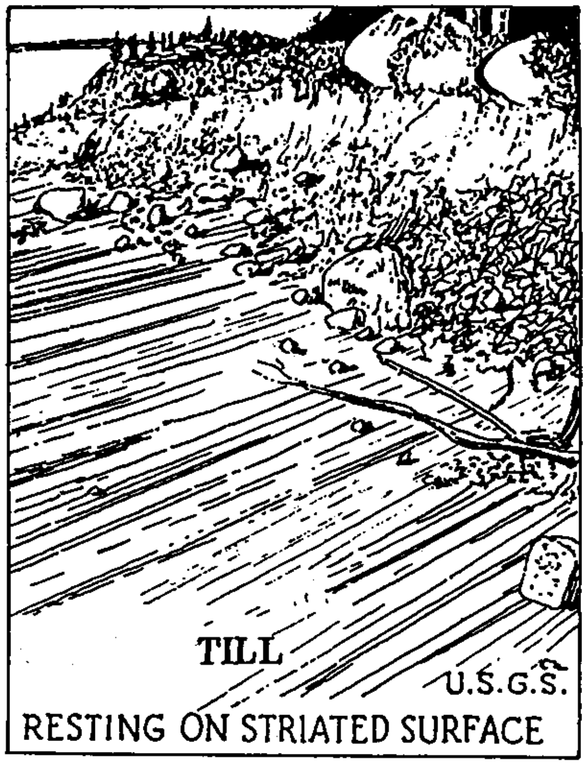


Figure GG-16. Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

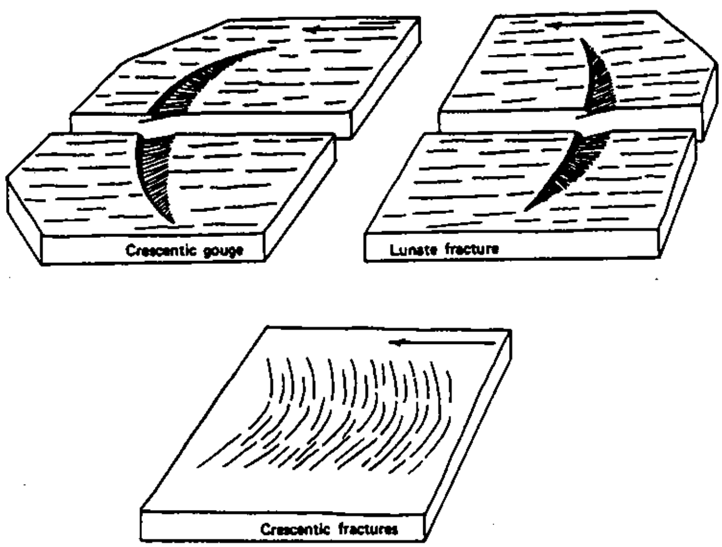


Figure GG-17. Sketches: glacial crescentic marks. (Flint, 1971.)

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, we have found many features displaying only part of the morphologic expression of a classic roche moutonnée. The rounded, gently dipping part is present, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by one glacier has been modified by flow across and over it of a glacier flowing from a direction that differs by about 45° from the direction of the first glacier.

In our studies of ice-flow directions we have made use of the orientation of the median axis of the elongate, rounded up-ice side of a classic roche moutonnée (Figure GG-18). We have been using the informal term "roche-moutonnée structure" for these.

Orientations of long axes of rock drumlins

Drumlins are elongate streamlined hills shaped by the flow of a glacier; the long axis of a drumlin is parallel to the flow direction of the ice and the steeper side is toward the direction from which the ice came. Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consistins of both till and of bedrock. Rock drumlins consist only of bedrock. (See Figure GG-10.) Because most drumlins consist of till, we discuss them in a following section devoted to glacial sediments. In this section, we include only rock drumlins. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.)

Examples from Manhattan

Many examples of features eroded on bedrock by a glacier, notably striae and grooves, are known from nearly all parts of Manhattan where bedrock is exposed. Many are found in Central Park, in Riverside Park, in Fort Tryon Park, and in Inwood Hill Park. We present our results from all four of the parks mentioned. All of these parks are situated on the Central Park 7.5-minute topographic quadrangle map of the U. S. Geological Survey (Figure GG-19); the northern end of Inwood Hill Park lies on the southern edge of the Yonkers quadrangle.

Central Park

In Central Park, glacial grooves trending NW-SE are present on virtually every rock knoll (Figure GG-20). Evidence for SE-directed glacial flow is obvious in the glacially sculpted exposure SE of the Zoo shed (UTM: 586.72E - 4513.18N). Large- and small grooves at the south end of the exposure are oriented N30°-35°W to S30°-35°E; on top of the knoll, they trend N40°W to S40°E. The steep, jagged slope on the E side of the exposure must be registered as a "fake" roche moutonnée; the drill holes reveal it is the product of drilling and blasting during park construction.

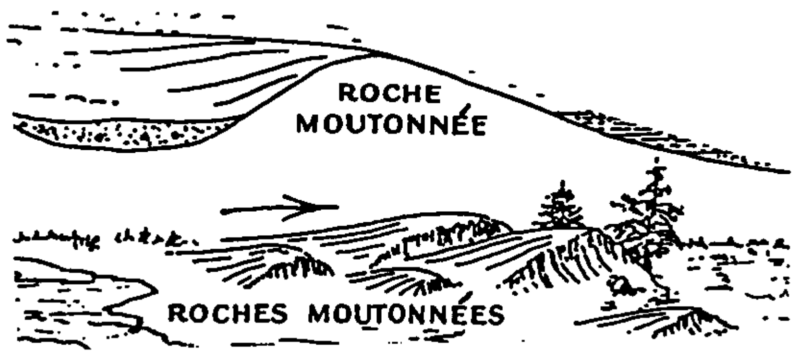


Figure GG-18. Sketch showing roche-moutonnée structure (above) and three-dimensional views of roche-moutonnées (below). Arrow indicates direction of ice movement. (Lobeck, 1939, part of figure on p. 298.)

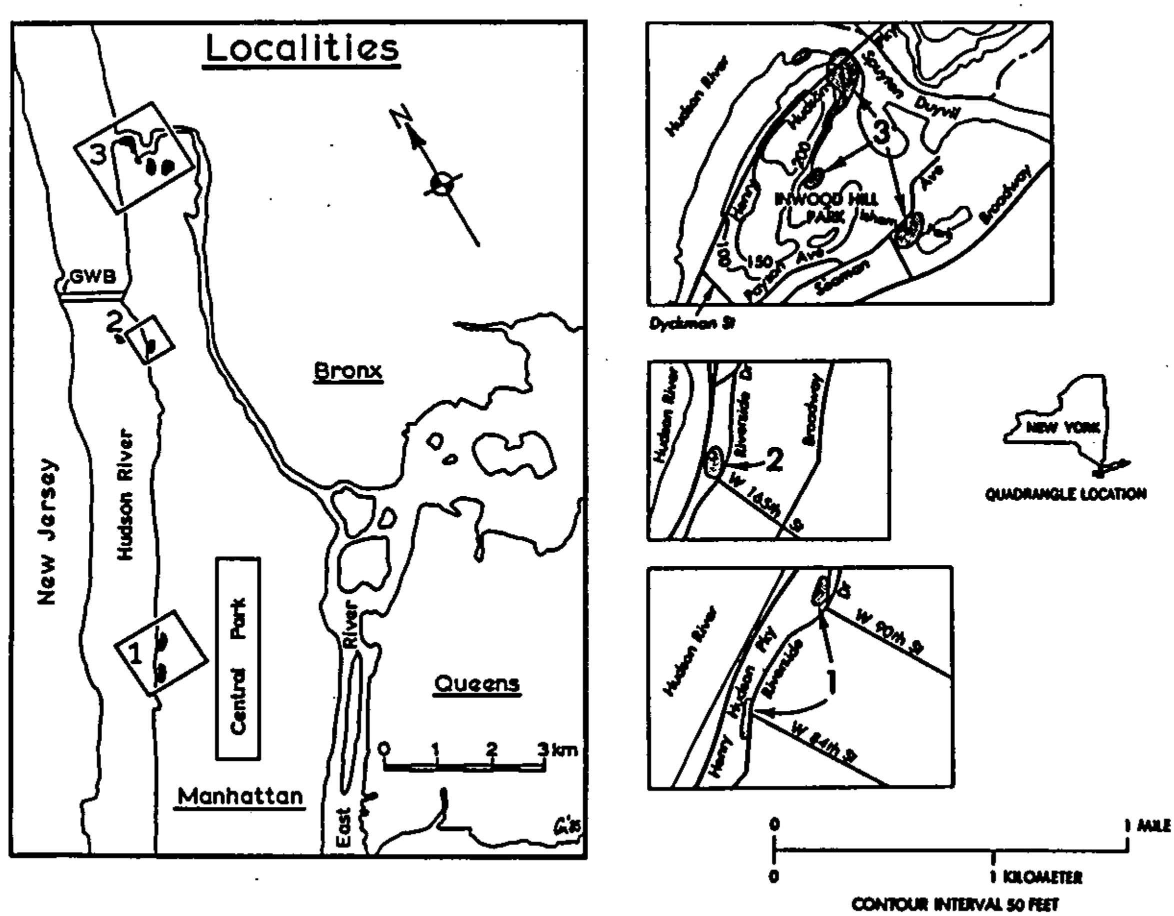


Figure GG-19. Index maps of three Manhattan park localities mentioned in text. 1) southern Riverside Park; 2) northern Riverside Park; 3) Inwood Hill Park. (Drawn by C. Merguerian.)

All of the scattered outcrops E of the walkway just N of the 65th Street Transverse Road (UTM: 586.82E - 4513.42N) show the effects of glacial rounding and polish. Glacial grooves are oriented N47°W to S47°E; they resulted from ice flowing to the SE (Figure GG-20).

On the surface of the bedrock exposed E of the walkway where the walkways make an X pattern S of "The Dene" (UTM: 586.85E - 4513.49N), glacial grooves are oriented N25°W to N32°W; they are products of a glacier that flowed SE.

On the bedrock knoll W of "The Dene," (UTM: 586.7E - 4513.50N) numerous glacial grooves are oriented N35°W-S35°E, they indicate glacial flow toward the SE. At the NE end of the exposure, a subdued-roche moutonnée structure with long axis oriented N37°E-S37°W has been cut by glacial grooves that trend N36°W-S36°E.

By "The Platform," the N end of the knoll E of "The Dene" and N of the playground (UTM: 586.90E - 4513.57N) has been shaped into broad roche-moutonnée structure whose long axis trends N10°E-S10°S. Glacial grooves and -troughs nearby are oriented N32°W-S32°E, but we have not observed crosscutting relationships between the grooves and the roche-moutonnée structure. We infer that the NW-SE-trending grooves are younger than the roche-moutonnée structure.

At the U. S. Geological Survey benchmark S of The Pond (UTM: 586.92E - 4513.50N), glacial grooves oriented N32°W-S32°E indicate that glacial ice flowed over the Hartland Formation here in a SE direction.

The knoll W of The Pond, opposite the access to Central Park from the Avenue of the Americas (UTM: 586.35E - 4513.08N), prominent glacial grooves are oriented N28°W-S28°E. The long axis of a subdued roche moutonnée structure is oriented N40°E-S40°W. As at "The Platform," we have not able to establish any cross-cutting relationships between the grooves and the roche-moutonnée structure.

On the northward-sloping surface of the roche-moutonnée structure at the knoll W of The Pond, opposite the access to Central Park from the Avenue of the Americas are SSW-oriented "chattermarks" (crescentic marks; products of Glacier IV?).

On the S side of West Drive, near the SW boundary of Central Park (UTM: 586.28E - 4513.10N), the effects of glacial rounding and -smoothing of the bedrock surface underlain by the Hartland Formation are conspicuous. The trend of the glacial grooves is N38°W-S38°E.

Umpire Rock (UTM: 586.25E - 4513.38N) is the most-spectacular natural exposure in the south part of Central Park (Figure GG-21). Here, rocks of the Hartland Formation show the

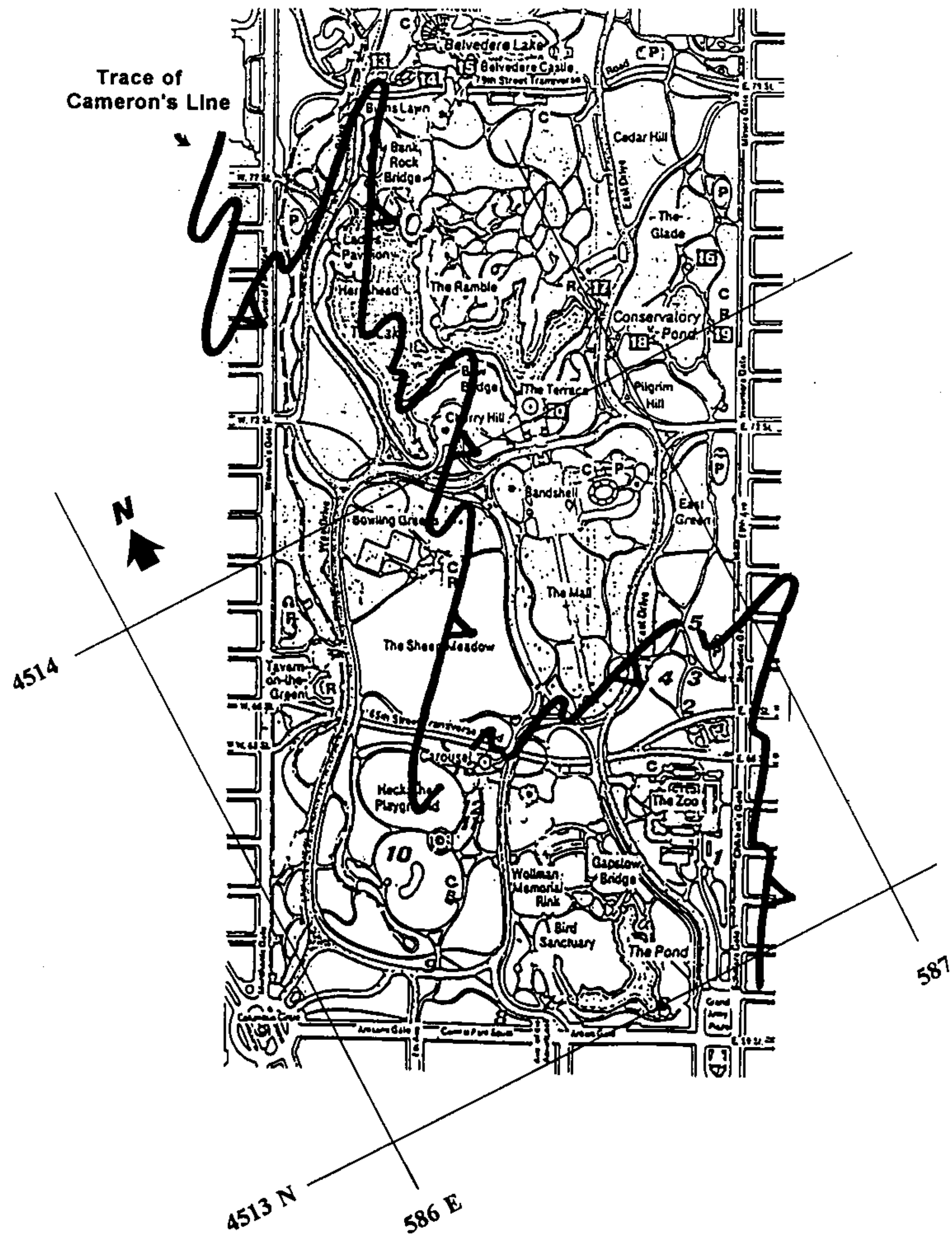


Figure GG-20. Index map of localities in southern Central Park. Arabic numerals show stop numbers from Merguerian and Sanders, 1993c, fig. 41, p. 143 with UTM grid from USGS 7.5-minute Central Park quadrangle added by JES.

effects of superposed folds, abundant syn- and post-tectonic pegmatite intrusives, brittle faults, and numerous glacial features. See Merguerian and Sanders (1993c) for details.

Perhaps the most-obvious geologic features here are of glacial origin. At the NW edge of the exposure, glacial meltwaters have modified spectacular glacial troughs oriented N28°W-S28°E parallel to the overall SE-directed roche-moutonnée shape of the exposure that drops off settply toward the playground. Many glacial erratics can be found here. We have identified Palisades diabase and hornfelsic Lockatong Formation (from the Newark basin W of the Hudson River), Hartland Formation, granite, and diorite. Evidence of the youngest (*Woodfordian*) glacier that flowed from NNE to SSW is shown by a block of Hartland Formation that has been tipped upside down and now lies immediately south of its former "home" defined by steep joint faces. The fact the SE-flowing groove-making glacier did not displace this block of the Hartland Formation proves that the block was moved later on; therefore, the *Woodfordian* (i. e., youngest, our No. IV) glacier must have moved and tipped this block.

Around the steep, north-facing wall of the exposure, the glacial grooves are oriented N46°W-S46°E. On the eroded outcrops immediately north of the north-facing wall, groove orientation is N35°W-S35°E.

On the E side of the walk E of the Heckscher Playground (UTM: 586.38E - 4513.42N), a coarse pegmatite erratic, about 2 m high, displays megacrysts of K-feldspar. This erratic rests on rocks of the Hartland Formation that have been scored by glacial grooves trending N38°W-S38°E.

Farther N, near the 79th Street entrance to Central Park, opposite the main entrance of the American Museum of Natural History, a low bedrock knoll near the low wall separating the park from the sidewalk on Central Park West (UTM: 586.70E - 4514.75N) a low, rounded bedrock surface displays striae oriented NNE-SSW (more or less parallel to the wall, cut by our Glacier IV) that are younger than the larger, more-obvious grooves and striae trending NNW-SSE (products of our Glacier III and/or II). This is one locality in Central Park where the effects of Glacier IV and one or more of the earlier glaciers can be seen together.

Riverside Park

In Riverside Park from West 116 St. southward to West 75 St., bedrock knolls are numerous. Described here are exposures of the Hartland Formation near West 90-91 Streets. and exposures from West 82-85 Streets. (See Figure GG-19, No. 1.) The northernmost outcrops (UTM: 586.10E - 4515.96N) consist of gray-weathering, well-layered and slabby- to laminated, lustrous muscovitic schist containing interlayers of quartz-muscovite biotite granofels. Locally in the schist, 1-cm-thick glassy

Figure GG-21. Photgraph of NW-SE-trending glacial grooves on glacially polished NW-facing slope of Umpire Rock. (Photo credit, C. Merguerian.)

quartzose layers and elliptical pods of recrystallized dark quartz are present.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roche-moutonnée structures. Not only have the rock surfaces been glacially rounded and -smoothed on a large scale, but glacier-cut 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 such a flow direction is the reddish-brown color of the till and the kinds of erratics present (including dolerite from the Palisades Sill and anthracite coal from northeastern Pennsylvania). (See Figure GG-13.)

The large knoll W of the intersection of Riverside Drive and West 165th St. (See Figure GG-19, No. 2; UTM: 589.1E - 4521.4N) displays evidence of both glacial erosion and -deposition. The overall shape of the surface of the knoll defines several roches moutonnées. Many years ago, this particular knoll probably was a splendid exmple of a "natural" roche moutonnée, it 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, as at the knoll SE of the Zoo shed in Central Park, has been blasted away to make way for the street and the sidewalk.

Not only has the rock surface been glacially rounded and -smoothed on a large scale, but glacial grooves and -striae are present as well. The trends of these show that the ice flowed from NW to SE, across the Hudson River. The reddish-brown color of the till and erratics of dolerite from the Palisades Sill and of Newark-age sandstone plus indicator "stones" of anthracite coal from northeastern Pennsylvania further demonstrate glacial flow from NNW to SSE.

Fort Tryon Park

At Fort Tryon Park (See Figure GG-10.), effects of glacial erosion are conspicuous. Only minor products of glacial deposition are present.

The enlarged contour map of Figure GG-10 shows that the whole park is situated on two aligned rock drumlins trending NNE-SSW. Along the sidewalk S of the deep cut for the access road from/to the northbound lanes of the Henry Hudson Parkway (UTM: 589.75E - 4523.75N) glacially rounded bedrock knolls and glacially-cut grooves trend N15°W-S15°E. Here is a well-defined example of a feature eroded by an older glacier (the more-southwesterly of the two aligned rock drumlins; we infer that it is a product of our Glacier I that flowed from NNE to SSW) which has been cut across by features eroded by a younger glacier (either our Glacier III or II that flowed from NNW to SSE).

Along the sidewalk at the SW corner of the Cloisters (UTM: 589.92E - 4524.00N), on the more-northeasterly and larger of the two aligned rock drumlins, prominent glacial striae trending N15°W-S15°E are present on a bedrock surface that was cleared during construction.

Inwood Hill Park

The area of Manhattan north of Dyckman Street, in the extreme northwest corner of Manhattan Island, is known as the Inwood section. Except for the "hill" in Inwood Hill Park, the region is underlain by a marble that Merrill (1890) named the Inwood Limestone. The "hill" is a synformal overthrust of allocthonous "Manhattan" Formation (Merguerian and Baskerville, 1987). Inwood Hill Park, is bordered by Dyckman Street on the S, by the Hudson River on the W, by Spuyten Duyvil (Harlem Ship Canal) on the N, and by Payson and Seaman Avenues on the E. (See Figure GG-19.)

On the crest of the bedrock knoll at the NE end of Inwood Hill Park (UTM: 594.2E - 4525.9N) a broadly rounded roche-moutonnée structure trending NNE-SSW, has been cut by grooves trending NNW-SSE, as at Fort Tryon Park.

Examples from The Bronx

Many bedrock knolls displaying the effects of glaciation are present in The Bronx. We describe those from only two localities: the New York Botanical Garden and Pelham Bay Park.

New York Botanical Garden

Published geological results of studies made in the New York Botanical Garden include origin of the Bronx River gorge (Kemp, 1897), discussion- and illustration of obvious glacial features such as erratics and prominent grooves, but with no measurements of groove orientations (Hollick, 1926), and investigations of the geologic structure (Langer, 1966; Bowes and Langer, 1969). Merguerian and Baskerville (1987) and Baskerville (1992) have independently mapped the rocks here as belonging predominantly to the Hartland Formation.

Glacial features noted in the Botanical Gardens include polished bedrock surfaces, roche-moutonnée structure, and glacial grooves, indicating at least three major glacial episodes: (1) earliest movement from NNE to SSW (our Glacier I); (2) movement from the NNW to SSE (our Glaciers II and/or III), and (3) movement from NNE to SSW (our Glacier IV). These are in keeping with our results from studies of glaciation elsewhere in the region.

We have plotted localities in the New York Botanical Gardens on a trail- and garden map issued by the Botanical Gardens (Figure GG-22).

Along the road near the Rockefeller Rose Garden (UTM 594.87E - 4523.58N, a rounded bedrock knoll has been sculpted into a classic roche-moutonnée structure with a gentle up-glacier side and a steep down-glacier side. As such, this asymmetrical erosional indicator indicates glacial flow from N15°E toward S15°W (Our Glacier I or IV in Table GG-2). The development of the steep, down-glacier side of the roche moutonnée was undoubtedly facilitated by the subvertical A-C joints which formed perpendicular to the local F_3 fold axes in the Hartland.

The evidence for glaciation here (UTM: 594.60E - 4523.62N) is in the form of a huge glacial erratic of the Fordham Gneiss perched upon the glacially polished outcrop surface of the

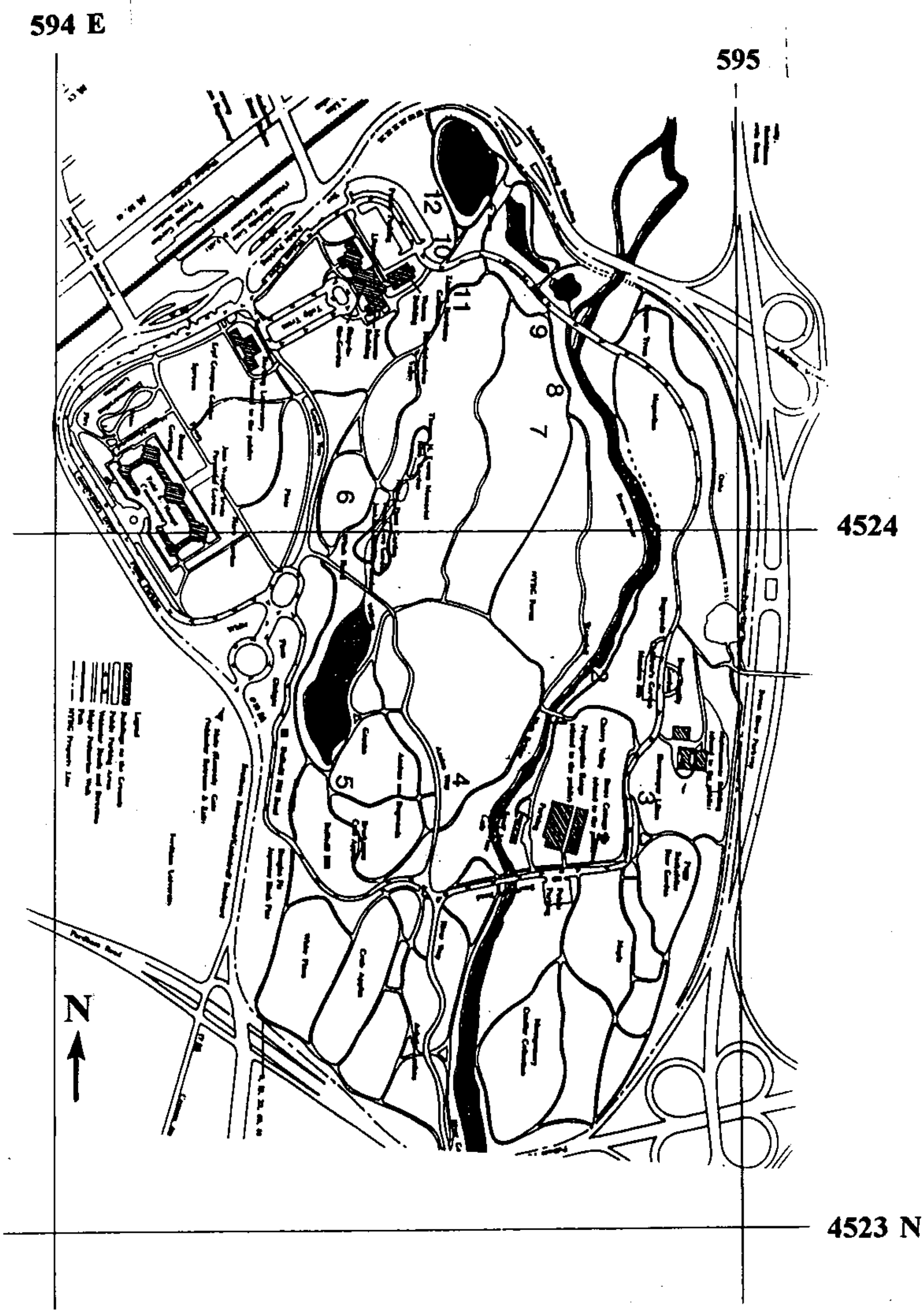


Figure GG-22. Trail map of the New York Botanical Gardens showing the locations of striae localities. (NY Botanical Gardens; JES added the UTM metric grid from the Central Park- and Flushing 7.5-minute quadrangle maps of the U. S. Geological Survey.)

Hartland Formation. Etched into the surface are prominent glacial grooves oriented from N26°W to S26°E (our Glacier II or III in Table GG-2). They are parallel to the overall asymmetry of the outcrop with smoothed, gentle NW slopes and jagged, steep SE ledges. The gentle, polished NE-facing slopes suggest that the outcrop may also have been sculpted in a direction parallel to the strike of the foliation (N21°E). The associated jagged SW edge of this suspected roche moutonnée may have been strongly modified by the more-obvious effects of the younger, SE-directed glaciation.

The overall shape of this glacially sculpted, low-relief outcrop (UTM: 594.42E - 4523.61N) displays the erosional effects of two glaciations from different directions. The prominent N22°W to S22°E glacial grooves (Glacier II or III) here cut across an older roche-moutonnée structure (Glacier I) oriented from N26°E to S26°W. Thus, when combined with evidence from localities previously discussed, further indicates glacial flow from two contrasting directions.

The most-obvious glacial feature at Elephant Rock (UTM: 594.43E - 4524.05N) is the enormous, split erratic boulder of Yonkers Gneiss on the NE part of the exposure near the entrance to the Rock Garden. The presence of the Yonkers here constrains ice-flow direction in that exposures of the Yonkers are limited to areas directly north and east of us. Accordingly, this boulder was **NOT** transported by ice flow from the NW; it **must have been** deposited by our Glacier IV from the NNE. (See Table GG-2.) Because subsequent glaciers tend not to leave pre-existing erratics in place, the mere presence of this Yonkers Gneiss boulder mandates the Glacier-IV interpretation.

Evidence of glacial flow from the NW (Glacier II and/or III) in the form of roche-moutonnée structure and a plethora of photogenic glacial striae oriented N23°W to S23°E is abundant. If one walks toward the western part of the outcrop, one encounters hard evidence for the older, SSW-directed glaciation (Glacier I). Here, roche-moutonnée structure, crescentic-, as well as lunate gouges together indicate glacial flow from N22°E to S22°W. These older glacial features are clearly crosscut by striae oriented NW to SE and roche moutonnée features described above. As described below, the development of crescentic- and lunate gouges was undoubtedly the result of emphatic structural control of the subhorizontal S_2 foliation in the Hartland Formation.

The orientation of the S_2 foliation in the Hartland is here subhorizontal; it is similar to its orientation at our previous stop. Because of differential weathering susceptibility of the minerals aligned in the foliation an inherent weakness is established in the bedrock. Thus the early foliation in the Hartland, delineated by a penetrative foliation, subparallel granofels interlayers and quartzose segregations, evidently exerted a controlling influence on the local development of glacial gouges. We suspect that such favorable structural settings "stubbed the toe" of the advancing glacier and promoted frost-generated mechanical plucking. Of structural interest, shallow south-plunging F_3 Z-folds deform the older S_2 foliation and related subparallel features. The axial surfaces of the F_3 folds are oriented N15°E, 90°, consistent with measurements made elsewhere in the Gardens.

Lincoln Rock (UTM: 594.71E - 4524.14N) is the highest natural point in the New York Botanical Gardens and consists of highly glaciated rocks of the Hartland Formation in the form of a steep-walled rock drumlin. The older glacial feature (made by Glacier I) is the overall NNE- to SSW-oriented roche-moutonnée structure of this large roche moutonnée with its steep, well-polished NNE side and jagged, glacially plucked SSW side. Glacial striae eroded by Glacier I are oriented N13°E to S13°W. Superimposed on these features are glacial grooves oriented N32°W-S32°E, a divergence of 6° to 10° from our earlier measurements of the SE-directed flow of Glaciers II and/or III. This could be the result of a local westward divergence caused by the unusually steep-walled outcrop. Or, it may represent the basic difference in flow direction between Glaciers III and II.

In summary, glacial-erosion features on display in the New York Botanical Garden were cut by our Glacier I (flow from NNE to SSW), by our Glaciers II and/or III that flowed from NNW to SSE), and by our Glacier IV. Not many depositional features other than erratics (discussed in a following section) are present.

Pelham Bay Park

In this large park, we concentrate on the bedrock knolls at South Twin Island, near Orchard Beach (UTM: 602.4E - 4525.0N, Flushing 7.5-minute quadrangle).

The glacial features of South Twin Island are remarkable and take the form of glacial striae oriented N32°W-S32°E, glacial polish, and roche-moutonnée structure (these features related to our Glacier II and/or III in Table GG-2). Two boulders of distinctive poikilitic ultramafic rock from the Cortlandt Complex in Peekskill, New York can be found at the southern end of the South Twin Island exposure near Orchard Beach. This discovery mandates glacial advance from the NNE (Glacier IV in Table GG-2). In addition to these features, a thin red-brown till, consisting of rounded boulders set in a reddish-brown matrix of poorly sorted sand, -silt, and -clay, was extensively exposed as a byproduct of the erosion of a wave-cut scarp during the higher-than-normal spring tides accompanying the perigee-syzygy Full Moon of Passover (06 April 1993). We do not know the exact date of the erosion, but can bracket it as being between 01 April when CM visited here with his class and 17 April when the Hofstra beginning-geology class trip stopped here. Judging from the newly visible features in the bedrock, we estimate that during the storm, the scarp retreated from 3 to 5 m.

Before the scarp was cut, a sod-covered slope extended down to the bedrock pavement. Beneath the red-brown till are clear NW-SE-trending glacial grooves on the bedrock surface. (Compare with Figure GG-16.) Here, then, is a second example of red-brown till resting on striated bedrock, as in the Queens localities described by Woodworth (1901). We have seen many examples of red-brown till and many other examples of striae oriented NW-SE, but this is the first example we have seen of these two features together.

At the extreme north end of South Twin Island, glacial erosion by two different glaciers has produced what we suggest is a double roche moutonnée. Here, the bedrock shows evidence of being been sculpted by ice that flowed initially from NNE to SSW (Glacier I) and subsequently from the NW to the SE (Glacier II and/or III). Similarly, just E of the jetty, a roche moutonnée with long axis oriented NNE-SSW has been cut across by grooves trending NW-SE.

Example from Long Island City, Queens

As previously mentioned, Woodworth (1901) recorded that in Long Island City (Queens), the red-brown materials forming the Harbor Hill moraine rest on striated bedrock with grooves oriented N25°W to S25°E. In his words:

> "One of the largest exposures of bed rock occupies a vacant lot adjoining the Queens county courthouse on the west. The ledge is heavily glaciated, forming a long low roche moutonnée. The striae range in direction from 29° to 30° west (magnetic). A few striae run from n 15 w, and one set of scratches lies in a northwest direction. The strike of the foliation of the gneiss is n 25 e magnetic. Other outcrops occur to the northeast with striae running from the north northwest. A series of shallow oval depressions extends in a northwest and southeast direction across one outcrop..." (Woodworth, 1901, p. 652).

This is the same result we have described from Pelham Bay Park, but with the huge difference that the red-brown till at Pelham Bay Park is not part of a terminal moraine.

As we have mentioned in a preceding section, we interpret Woodworth's evidence on the relationship between flow directions and the reddish-brown color of the materials forming the Harbor HIll moraine to mean that the age of the Harbor Hill Moraine must be pre-*Woodfordian*. We assign the Harbor Hill Moraine to our Till III (*Early Wisconsinan*?). We regard as *Woodfordian* only the the 8 or 9 feet of gray till with "trap" boulders that overlies reddish-brown sands (outwash associated with our Till III?) that Woodworth described along the road from Corona to Astoria.

Examples from Staten Island

On the New Jersey Geological Association's Staten Island field trip, at Stop 1 we shall examine striae, grooves, and cresentic marks eroded on the Palisades Dolerite by our Glaciers III and/or II (indicating flow from NNW to SSE) and by No. IV (flow from NNE to SSW). For further particulars, consult the Stop descriptions.

Another example showing striae trending N15°W to S15°E ie present where the glacier eroded the Palisades Dolerite now exposed in the yard of PS 21, just SE of the tollgate plaza for the Bayonne Bridge (UTM: 572.40E - 4498.03N, Elizabeth, NJ-NY 7.5-minute quadrangle).

Examples from Bear Mountain and Stony Point, New York

Atop Bear Mountain at Perkins Observatory (UTM: 583.15E - 4573.5N, Popolopen Lake quadrangle), Proterozoic Y granitic gneiss exhibits crescentic glacial gouges. Here rounded knolls of Proterozoic gneiss have been sculpted by glaciers that flowed across the Hudson Highlands. The usual two directions are indicated: from NNE to SSW (Glacier I) and from NW to SE (Glacier II or III). The older glacier flowed from the NNE to SSW and shaped rock drumlins and roches moutonnées. The younger glacier came from the NW and flowed SE. This glacier formed the many crescentic marks and smoothed any jagged southern ends of roches moutonnées made by the earlier glacier.

Both glaciers flowed across the Highlands as if they were not a serious obstacle. This implies that these glaciers were very thick (perhaps, 8 to 10 km). By contrast, the most-recent *Wisconsinan* glacier *(Woodfordian)* did not leave many traces up here. For other reasons, we can infer that the thickness of the *Woodfordian* ice was much less than that of the earlier glaciers.

Within the grounds of the Stony Point Battlefield (UTM: 585.62E/4565.8N, Haverstraw quadrangle), intrusives forming the west edge of Cortlandt Complex crop out in glaciated knolls of diorite that show many cross-cutting fine-textured dike rocks. Here, glacial striae and roche moutonnée are oriented N03°W.

We turn now to the features of glacial sediments from which glacial-flow direction can be inferred.

DIRECTIONS OF GLACIAL FLOW IN THE NEW YORK CITY REGION BASED ON GLACIAL SEDIMENTS: DIRECTIONS OF DISPLACEMENT OF ERRATICS AND INDICATOR STONES AND ORIENTATIONS OF LONG AXES OF DRUMLINS

The abundant evidence that glaciers eroded on the bedrock of New York City and vicinity does not provide much of any indication of age. As mentioned, in some cases, relative ages for three episodes of glacial erosion can be demonstrated. Other evidence comes from the glacial sediments. In this section, we include erratics and indicator stones and drumlins. In the following section, we take up stratigraphic aspects.

Definitions

An indicator stone is defined as an erratic whose parent area in the bedrock is known. Accordingly, a line between the indicator stone and its "home base" gives the direction of transport. As mentioned, a drumlin is an elongate but asymmetric streamlined hill shaped by the flow of a glacier (Figure GG-23). The long axis of a drumlin is parallel to the flow direction of the ice. The steeper side is toward the direction from which the ice came. The term used by itself usually implies a feature composed of till. A rock-cored drumlin is one that consists of both till and of bedrock. A rock drumlin consists only of bedrock.

Directions of Displacement of Indicator Stones

A prerequisite to understanding the significance of the indicator stones that were transported glacially during the Pleistocene is knowledge of the bedrock over which the glacier(s) flowed. In order to provide some background on the local bedrock, we include a brief summary of the geologic features in the bedrock of southeastern New York and vicinity.

Geologic features of the bedrock in southeastern NY and vicinity

In the following paragraphs, we review the distinctive features of the bedrock in southeastern New York and the state of Connecticut. Our objective is to help "soft-rockers" pinpoint distinctive kinds of bedrock so that certain erratics found in the till or along local bouldery beaches can serve as indicator stones.

The Newark and Hartford Basins. Extending southwestward from Stony Point, Rockland County, NY, on the Hudson River valley and into New Jersey, are Mesozoic igneous- and sedimentary rocks of the Newark basin (Figure GG-24). Distinctive in their reddish-brown color, the west-dipping sedimentary strata range in age from Late Triassic to Early Jurassic and are time- and lithostratigraphic equivalents of rocks of the Hartford basin of central Connecticut. The west-dipping Palisades intrusive sheet, which forms a prominent ridge on the west side of the Hudson River valley from the New York Bight to the vicinity of Stony Point, New York, is a medium- to coarse-textured diabase (dolerite) that was intruded into the Lockatong Formation to form a sill. Farther westward at at higher stratigraphic positions, sheets of extrusive basaltic rock underlying the Watchung mountains are intercalated within red-brown Jurassic sedimentary

Figure GG-23. Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

rocks. These constitute the fill of the Newark Basin, that extends SW from Rockland County, NY across central New Jersey and into Pennsylvania and beyond.

Near the Ramapo fault, the basin-marginal fault at the NW edge of the Newark Basin, distinctive clast-supported basin-marginal rudites are present that bear Paleozoic boulders eroded from above the Hudson-Reading Prong and from areas to the north- and northwest of the highlands, set in a red-brown matrix.

The Mesozoic sedimentary- and igneous rocks rocks filling the Hartford Basin underlie a north-south-trending lowland in the central part of Connecticut. This central lowland is one of three major geologic terranes in Connecticut. The central terrane intervenes between the western terrane and the eastern terrane (to be discussed in a following section). The central-Connecticut lowland continues northward into Massachusetts (Longwell, 1922, 1928, 1933, 1937). To the west, the basin-filling rocks adjoin the Paleozoic metamorphic rocks of the western crystalline terrane. In at least two localities, the unconformable contact between the younger Mesozoic sedimentary rocks and older Paleozoic metamorphic is visible. In most places, however, the boundary between the Mesozoic rocks and the Paleozoic rocks is a normal fault of probable Mid-Jurassic (or younger) age that has dropped the Mesozoic rocks. On the east, the basin-filling rocks end abruptly at the basin-marginal fault (Merguerian and Sanders, 1991e, 1994d). East of this fault are the rocks of the eastern crystalline terrane of Connecticut and Rhode Island. [In this discussion, we include the Mesozoic rocks found in an isolated half-graben known as the Pomeraug Basin within the western terrane. (See Figure GG-24.)]

Lithologically distinct, the strata filling the Mesozoic basins consist predominantly of east-dipping, red-colored sedimentary rocks and intercalated sheets of extrusive basalts with local intrusive mafic rocks (for example, the Buttress and West Rock dolerites). Correlative with the Upper Triassic to Lower Jurassic Newark Supergroup of New Jersey (Merguerian and Sanders, 1989b, 1991g, 1993c, 1993e), the rocks of the Hartford and Pomeraug Basins include the New Haven, Shuttle Meadow, East Berlin, and Portland formations consisting of red- to maroon-colored micaceous arkose and quartzose sandstone and -siltstone, shale, and local conglomerate and fanglomerate, together with subordinate black shale and local dolostone, and intercalated dark-colored mafic volcanic rocks of the Talcott, Holyoke, and Hampden basalts.

The strata filling both basins have been internally cut by a myriad of faults and, as discussed below, trend southward and project into Mesozoic grabens in the subsurface of Long Island and the New York Bight that have been identified by samples from drill holes and data from geophysical surveys (Klitgord and Hutchinson, 1985; Hutchinson, Klitgord, and Detrick, 1986; Hutchinson and Klitgord, 1988). The distinctive color- and

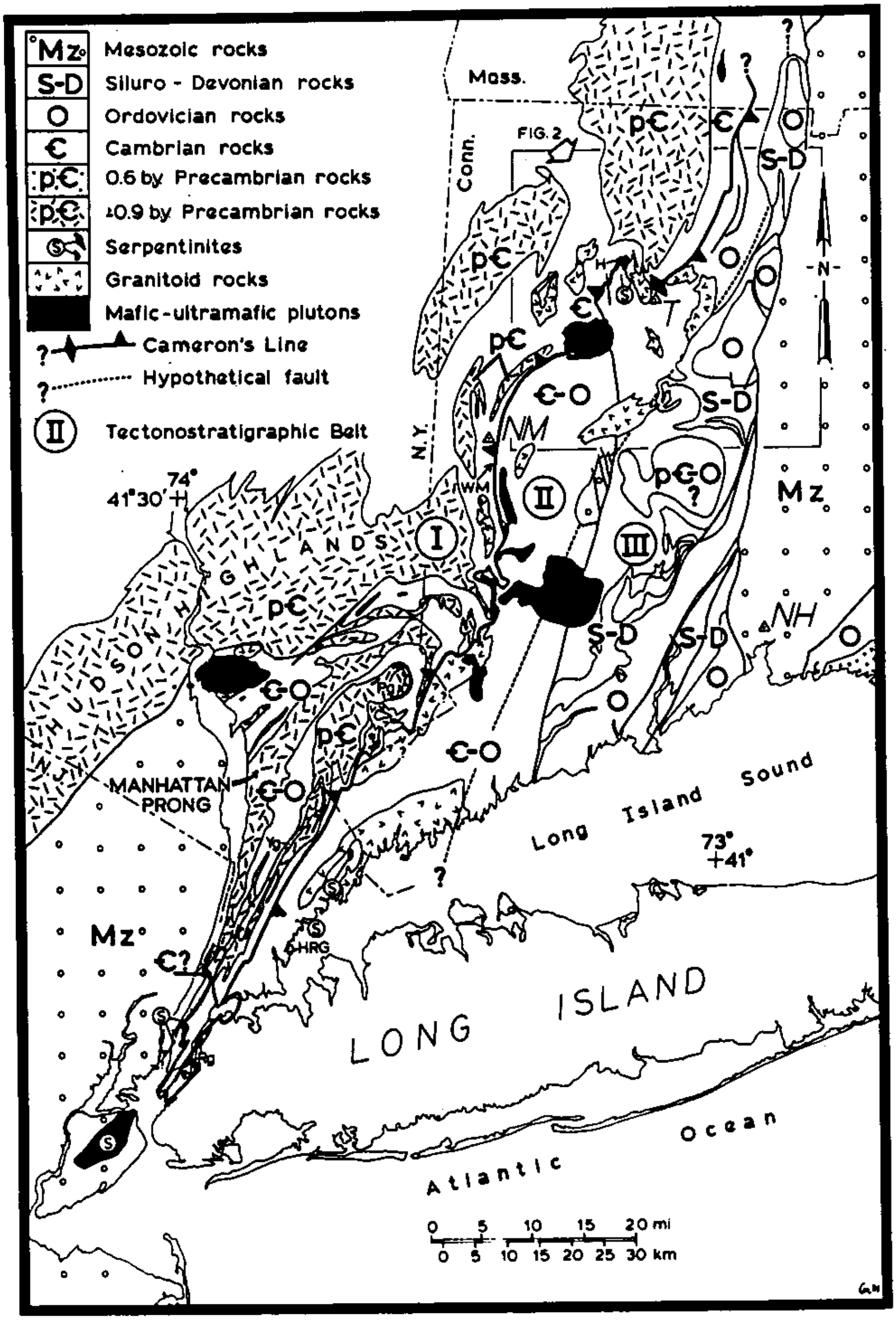


Figure GG-24. Geotectonic map of western Connecticut and southeastern New York. The location of our three field-trip stops and their geographic relationships to the crystalline "corridor" are shown. (Merguerian, 1983, fig. 1, p. 342.)

lithology of these rocks make them ideally suited for use in analysis as indicator stones and as sources for the generation of red-colored tills but similarity with rocks of the Newark Basin complicates direct correlation. All is not lost however, as the presence of low-grade phyllites, -schist, and -metavolcanic rocks containing chlorite and epidote as erratics in concert with these distinctive Mesozoic lithologies **would uniquely** identify a Connecticut source. No such low-grade rocks of volcaniclastic parentage are present in the vicinity of the Newark Basin of New Jersey.

The "crystalline corridor of SE New York and western Connecticut. The bedrock of southeastern New York state is dominated by complexly deformed, metamorphosed rocks that underlie the Manhattan Prong (Figure GG-25). The ages of these rocks range from Proterozoic Y through Cambro-Ordovician. Most of them have been overthrust, but some more than others. Included are some distinctly allocthonous rocks that have been overthrust many km to the NW from their original depositional sites.

The Manhattan Prong is bounded on the northwest by Grenvillian Proterozoic Y rocks of the Hudson-Reading Prong. On the east is a ductile-fault contact (Cameron's Line) marked by a zone of syntectonically intercalated, mylonitic rocks. Cameron's Line, which skirts the New York-Connecticut state boundary, separates rocks of the Manhattan Prong to the west from coeval rocks to the east that were deposited in a dramatically different paleogeographic setting (continental rise and some rocks, on a former deep-sea floor). Rocks to the west of Cameron's Line include the metamorphic rocks of the Manhattan Prong whose Lower Paleozoic representatives [Lower Cambrian Lowerre (=Cheshire) Quartzite, the Cambrian-to-Ordovician Inwood (=Woodville, and Stockbridge) marbles, and overlying Middle Ordovician Manhattan Schist (Unit A) and correlative Annsville Phyllite] constitute a cover sequence that was deposited on the continental basement rocks of an ancient craton. These basement rocks include the Proterozoic Y Fordham Gneiss, the Proterozoic Z Yonkers and Poundridge gneisses and coeval rift-facies strata mapped as the Ned Mountain Formation (Brock, 1989, 1993 ms.). These basement-cover rocks are structurally overlain by allochthonous rocks of the Taconic sequence and their metamorphosed, dominantly massive southerly equivalents [the main body of the "Manhattan Schist" and related amphibolite (Units B and C), the Waramaug Formation, and locally, the Hartland Formation]. Farther north, beyond the Hudson-Reading Prong in New York State, less-metamorphosed lithostratigraphic equivalents of the Lower Paleozoic rocks are found including the Poughquag Quartzite, Wappinger carbonates, the Walloomsac slate and shale, the Normanskill graywackes and shale, and allochthonous rocks of the Taconic Sequence.

Many erratics from the varied lithologies found in southeastern New York and adjacent regions of New Jersey could have been transported to places where they are now found only by a glacier that flowed from NW to SE. For example, abundant rocks

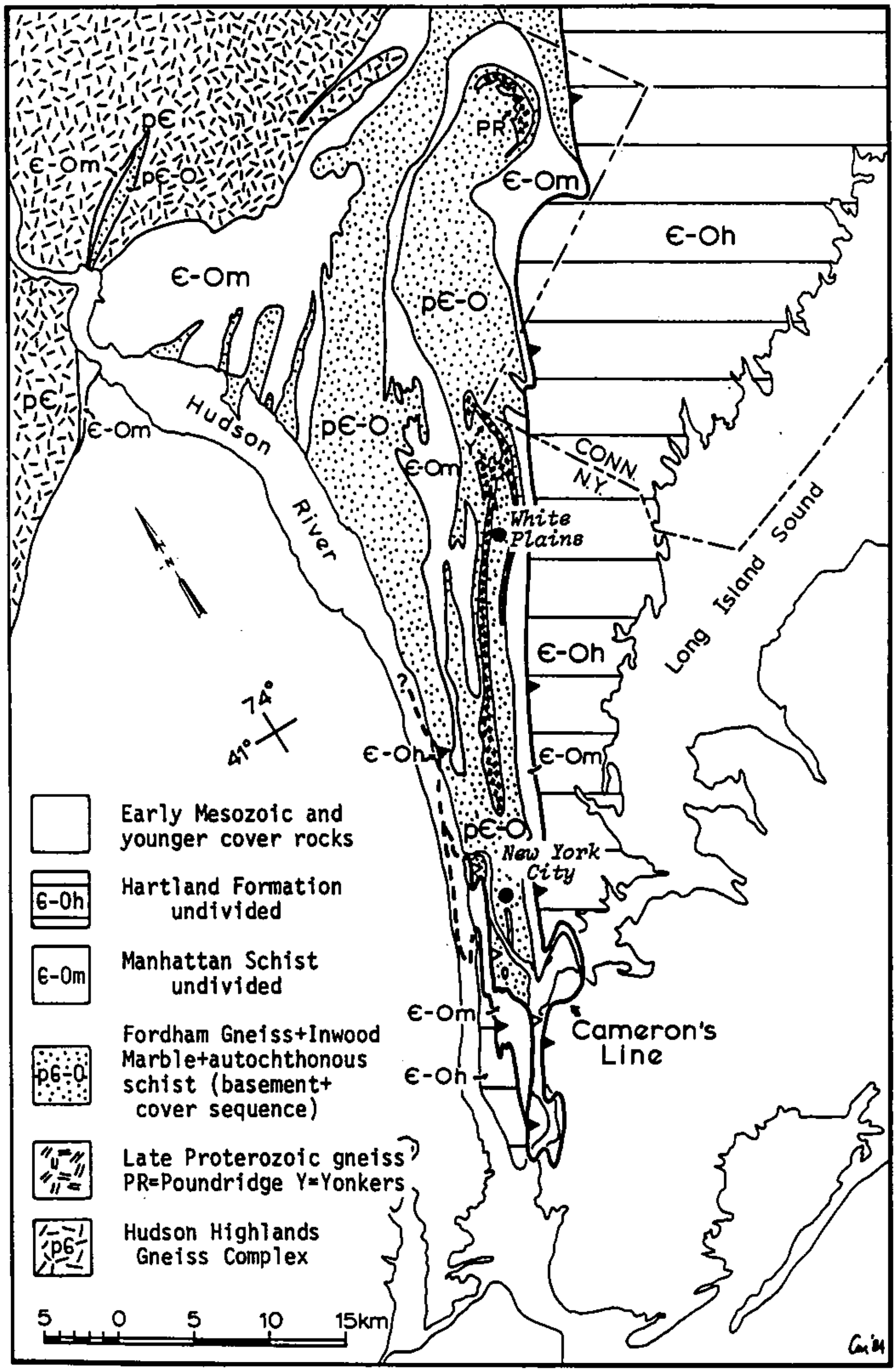


Figure GG-25. Simplified geologic map of Manhattan Prong showing the distribution of metamorphic rocks ranging in ages from Proterozoic to Early Paleozoic. Most intrusive rocks have been omitted. (Mose and Merguerian, 1985, fig. 1, p. 21).

from the Palisades intrusive sheet (Mesozoic) are found as erratics on Manhattan Island.

The western terrane of Connecticut is underlain mostly by metamorphic rocks that form part of the central crystalline core of the Appalachians (Figure GG-26). The age range of these rocks is from Proterozoic Y through Early Paleozoic. Although volumetrically most of the metamorphic rocks are metasedimentary units, some distinctive igneous rocks (both intrusive and extrusive) are present as are some distinctive mylonites associated with a large-scale regional ductile shear zone known as Cameron's Line. (See Figures GG-24 and GG-26.)

We begin with the contrasting metasedimentary rocks found adjacent to Cameron's Line and then summarize some of the distinctive mylonitic rocks and igneous rocks. In westernmost Connecticut north of the "panhandle", rocks of the Manhattan Prong crop out. As they were described above we need not mention them again here.

East of Cameron's Line, the bedrock formations differ significantly from those of the Manhattan Prong to the west of this line. To the east, the Cambrian-to-Ordovician Hartland Formation dominates exposed surfaces of the crystalline highlands of western Connecticut. The Hartland Formation consists of a thick sequence of dominantly well-layered muscovite-rich schist, gneiss, amphibolite, and intercalated mafic- to felsic metavolcanic- and metavolcaniclastic rocks (Merguerian, 1983). Throughout the Hartland terrane of western Connecticut, local bodies of unique ferruginous- and manganiferous garnet-quartz granofels (coticules) are found as highly laminated rocks within the sequence (Merguerian, 1980, 1981). The Cambrian-to-Ordovician Hartland Formation is unconformably overlain by Siluro-Devonian metamorphic rocks of the Straits Schist.

To the east of the panhandle area of southwesternmost Connecticut, Silurian-to-Devonian metamorphic rocks are included in the Straits Schist to the south and north of the Cambrian (?) gneisses of the Waterbury Dome. (See Figure GG-26.) Farther east and cropping out in the vicinity of New Haven, in the extreme southeastern corner of the western terrane, are relatively low-grade (chlorite to garnet) schistose-, phyllitic-, and metavolcanic rocks of the Allingtown and Maltby Lake volcanics (Fritts 1962, 1963). These rocks are a part of the Middle Ordovician Bronson Hill-Ammonoosuc volcanic terrane which trends northeasterly through Connecticut, Massachusetts, and New Hampshire. Thus, as initially pointed out by Crowley (1968) and elaborated on by Merguerian (1983, 1985), in a transect extending from northwest to southeast across the western terrane, the interpreted protoliths of Paleozoic metamorphic rocks of the western terrane of southeastern New York and western Connecticut become less "continental" and more "oceanic"; at Cameron's Line, an abrupt lithologic change is present. (See Figures GG-24 and GG-26.)

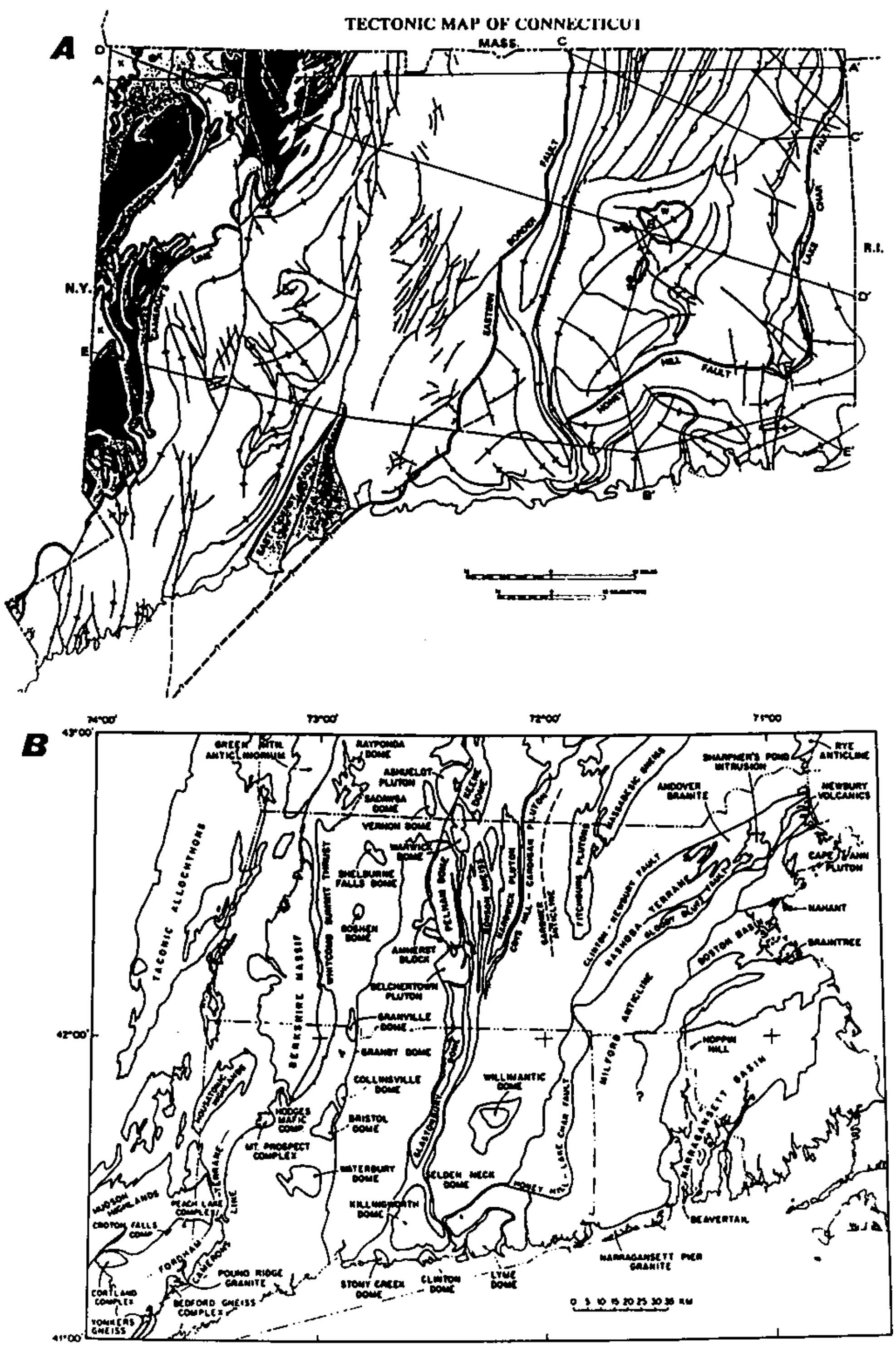


Figure GG-26. Maps of Connecticut and southern New England showing major tectonic features and rock bodies.
A. Tectonic map of Connecticut showing Cameron's Line and three major terranes. (John Rodgers, 1985.)
B. Tectonic sketch map of southern New England showing major domes, folds, and faults. (P. Robinson and L. Hall, 1980, fig. 3, p. 78.)

CM interprets Cameron's Line as a thrust fault within a deep-seated subduction complex that formed during the Middle Ordovician Taconic orogeny adjacent to the Early Paleozoic shelf edge of eastern North America. This might explain the northwest-to-southeast imbrication of early Paleozoic shallow-water "continental" (Fordham-Lowerre-Inwood-Manhattan A plus correlative) lithologies with transitional slope- and rise-lithologies (Manhattan B and C, Waramaug, and parts of the Hartland Formation), from purely deep-water (including volcanic) rocks found west of the New Haven area. Thus, according to many workers, the juxtaposition of these largely coeval belts resulted from an arc-continent collision of the Taconic orogeny. The continental-margin sequence was telescoped and the volcanic arc and its fringing oceanic-basin deposits were overthrust upon it (Merguerian, 1983).

Along the Taconic suture (Cameron's Line) are displayed an impressive zone of mylonitic rocks that experienced abnormally high shear strain under deep burial during the Taconic arc-continent collision. Ductile-fault rocks bear unique metamorphic textures that can be easily identified: in the field, their highly laminated appearance can be seen megascopically; microscopic study of thin sections reveals distinctive mylonitic textures.

With respect to the Taconic orogeny, local plutons are both synorogenic and post-tectonic. The older group of synorogenic plutons cut across Cameron's Line in western Connecticut and southeastern New York. These include a series of mafic- to ultramafic plutons (now largely metamorphosed) that are similar in mineral composition and texture to the Cortlandt Complex of Peekskill, New York (Merguerian and Sanders, 1990a, 1990e). In the panhandle area of southeastern New York and southwestern Connecticut, high-grade Ordovician granitoid- and dioritic orthogneisses (including various phases of the Harrison Gneiss, Brookfield Diorite Gneiss, and Bedford Augen Gneiss) are in great abundance. Similar metaplutonic rocks including norite, hornblendite, and pyroxenite occur farther north near Litchfield and Torrington, Connecticut and are known as the Mount Prospect and Hodges Complexes and the Tyler Lake Granite (Cameron, 1951; Merguerian, 1977 ms., 1985). Together, these orthogneisses represent late synorogenic plutons that were intruded into the developing suture zone during the waning stages of the Taconic orogeny (Merguerian, Mose, and Nagel, 1984). As such, these mineralogically- and texturally distinct metaplutonic rocks should serve as valuable indicator stones.

The younger post-orogenic intrusives include Devonian lamprophyre and potash feldspar-phyric Nonewaug Granite. Other plutonic rocks of still-younger ages include isolated bodies of Permian syenite, -adamellite, and -dacite porphyry. Of additional help, we are investigating the distribution of economic ore deposits in the crystalline terranes to the north- and northwest of Long Island in an effort to locate scarce, but highly useful indicator stones. During an On-The-Rocks field trip in November, 1990, Oliver Wayne found one such erratic, containing pyrrhotite- and chalcopyrite ore minerals, eroding out of the Montauk "till".

Eastern Connecticut and Rhode Island. The crystalline rocks to the east of the basin-marginal fault along the east side of the Hartford Basin underlie eastern Connecticut and Rhode Island. The bedrock formations here include exceedingly complex suites of metamorphic- and metaigneous rocks that range in age from Proterozoic through Permian. They have been cut by a regionally important ductile shear zone having the unlikely but nonetheless real name of Lake Chargoggagoggmanchauggagoggchaubunagungamaugg (*sic*)-Honey Hill Fault Zone [also known as the Lake Char - Honey Hill Fault Zone], which separates metavolcanic-, metaplutonic-, and metasedimentary rocks of the Bronson Hill-Ammonoosuc terrane to the north and west from Proterozoic Z gneisses and Permian intrusive rocks of the Avalonian terrane to the south and east. The Proterozoic Z rocks include the Plainfield Quartzite (a distinctive vitreous feldpathic +/- biotite quartzite), the Waterford Group, and the Sterling Plutonic Group. Within this sequence, many unusual porphyritic gneisses are present that should serve as excellent indicator stones.

The Ordovician rocks of the Bronson Hill-Ammonoosuc volcanic terrane include the Monson Gneiss and overlying Middletown and Brimfield formations as well as the Glastonbury Gneiss. These rocks are overlain by Silurian and Devonian metamorphic rocks of the Bolton Group and cut by the Devonian Maromas Granite Gneiss. To the east, correlatives include the Ordovician Quinebaug, Tatnic Hill, and Brimfield formations and overlying Siluro-Devonian units known as the Hebron Gneiss and equivalents.

Intrusive into these crystalline rocks are many plutons ranging in age from Ordovician to Permian. The distinctive rocks among this group on the Connecticut side of the Lake Char - Honey Hill Fault Zone include the Ordovician Preston Gabbro (+/- diorite), the Devonian Lebanon Gabbro (+/- diorite), and unnamed Devonian norite, diorite, and granitoid gneiss. In places where the mafic rocks are in close proximity to the Lake Char - Honey Hill Fault Zone, the rocks have been transformed into distinctive mafic mylonites. To the east of the Lake Char - Honey Hill Fault Zone are Permian intrusives known as the Narragansett Pier Granite (including a mafic phase) and the Westerly Granite, both distinctive lithologies. (See Foye, 1949; Dixon and Lundgren, 1968; Dixon, 1982; and Rodgers, 1985.)

From our brief summary, it should be obvious that chasing Pleistocene boulders is an exercise that best demonstrates the necessity of having a **well-rounded** knowledge of all fields in geology in order to arrive at a satisfactory conclusion.

Indicator stones in New York City and vicinity

In New York City and vicinity, recognition that indicator stones have been displaced both to the SSE and SSW from their parent areas started in 1828-29 with Dr. L. D. Gale. In Manhattan, Gale found indicator stones of anthophyllitic rock (a kind also made much of in Connecticut by J. G. Percival in 1842), and white marble that had been displaced to the SSW. (For the purposes of this discussion, we will include indicator stones from Queens and from Brooklyn under the heading of "New York City" rather than under "Long Island." As a glance at the map will indicate, however, Brooklyn and Queens are situated on Long Island.)

From the vicinity of Croton Point southward, red-brown color of till on the E side of the Hudson River serves as a kind of collective "indicator stone" of glacial transport across the Hudson river (i. e., by a glacier that flowed, at least locally, from NW to SE). The red-brown color comes from ground-up Newark sandstones and -siltstones.

Erratics of Palisades Dolerite are numerous on the E side of the Hudson River, as in the Ludlow section of Yonkers in the cut made at the Westchester County sewage-treatment plant, and in all the parks we have mentioned previously.

In Fort Tryon Park, a few distinctive erratics and indicator stones are present. North of the stone steps on the walkway leading away from the flagpole terrace (UTM: 589.80E - 4523.64 N), a large dolerite boulder from the Palisades rests on a glacially smoothed bedrock surface. In the dirt here are erratics of sandstone and black chert. Just south of the striae locality at the Cloisters, where the contact between the till and the glacially truncated bedrock surface is exposed, indicator stones of anthracite are present. At this locality, pieces of anthracite could have been brought to New York City on the Lehigh Valley Railroad to be used for fuel. The case for the erratic origin of the anthracite would scarcely be compelling based on specimens from Fort Tryon Park or Riverside Park. However, as we shall see at Stop 6 on today's GANJ field trip on Staten Island, pieces of anthracite in the till exposed in the eroding coastal cliffs demonstrate their erratic origin.

Proof of glacial transport of Carboniferous anthracite from northeastern Pennsylvania to the New York City region by a glacier that flowed from NW to SW (See Figure GG-13.) solves the problem faced by Zen and Mamay (1968) when they tried to interpret fossiliferous pieces of anthracite recovered from a roadcut in the Bronx.

We have found many other indicator stones from the Cortlandt Complex along the bouldery Hudson River "beach" where they have been washed out of one or both of the non-red tills at Croton Point Park, Westchester Co., NY. We have also seen three small examples of Cortlandt-Complex indicator stones washed out of the *Woodfordian* till (not exposed in the low coastal bluff) at Twin Islands, near Orchard Beach, Pelham Bay Park, The Bronx.

Until one has become familiar with the distinctive ultramafic rocks from the Cortlandt Complex near Peekskill (See Figure GG-24.), it is possible to misidentify Contlandt stones as coase Palisades Dolerite. Other dark-colored rocks that might be identified as "trap rock" include Paleozoic amphibolites or Paleozoic mafic plutonic rocks from southeastern New York or western Connecticut and the Paleozoic metavolcanic rocks from SW of New Haven, CT.

In this connection, we raise the point that Woodworth's use of the words "trap boulders" for erratics in a gray till in Corona (Queens) would imply to most readers that this till had been derived from a glacier that had crossed the Palisades ridge. We suggest that the stones Woodworth referred to as "trap boulders" are probably **not** from the Palisades dolerite. If they are not from the Palisades, where could they have come from? Other possibilities include: (1) far-travelled (from the NE) trap rocks from the Hartford Basin; (2) mafic- or ultramafic rocks from the Cortlandt Complex; (3) Paleozoic amphibolites from SE New York; (4) Paleozoic mafic plutonic rocks from SE New York or western Connecticut; and (5) Paleozoic metavolcanic rocks from SW of New Haven, CT. The fact that the color of the till enclosing the "trap boulders" is gray implies to us that Woodford was describing our Till IV, the *Woodfordian*, which was deposited by glacial flow from the NNE. True "trap boulders" from the Palisades would be present only if the glacier had flowed from NW to SE, in which case its color would be reddish brown. By contrast, true trap boulders from the Hartford Basin would be present only if the glacier had flowed from NE to SW, in which case its color should also be reddish brown. Boulders from the Cortlandt Complex or the Paleozoic amphibolites and/or -mafic plutons would be possible only by glacial flow from NNE to SSW, in which case the color of the till would *not* be reddish brown.

In footnote 1 at bottom of p. 652 Woodworth wrote: "Boulders of trap and red sandstone were seen by Sir Charles Lyell in an excavation made in a boulder bed at the Brooklyn navy yard. See Lyell, Charles, Travels in North America. N. Y. 1845. 1: 189-90." Woodworth metioned Lyell's observations in this connection evidently because he thought Lyell was describing the same gray, "trap-rock"-bearing till that Woodworth had seen in Corona. As far as our experience goes, the co-existence in Brooklyn of trap boulders and red sandstone in the same till implies that the glacier had crossed the belt of outcrop of the Newark rocks on the W side of the Hudson River and thus to reach Brooklyn, must have flowed from NW to SE. In every exposure we have seen of till containing such erratic boulders the matrix color is a distinctive reddish brown. Although we have not as yet looked up the Lyell original to see if he mentioned the color of the till at the Brooklyn navy yard, we presume it would be reddish brown and thus we would assign this till in Brooklyn that Lyell mentioned to a glacial episode older than the *Woodfordian* (our Episode III or II). In New York City during the *Woodfordian*, only gray till was deposited by ice flow from the NNE to the SSW.

During the 1920's, when major landscaping was carried out at the Brooklyn Botanical Garden, many large erratics were encountered in the till. These were left as outdoor exhibits. Gager (1932), based on petrographic results by Robert Balk, showed that most of them had come from localities that are located to the NW of Brooklyn, rather than to the NNE.

Indicator stones implying flow from NW to SE have been found on Staten Island (Lower Silurian Green Pond Conglomerate from northwestern New Jersey; and Pennsylvanian anthracite from near Scranton, Pennsylvania. (See Figure GG-13.)

Gratacap (1890, p. 14) found an example of "ripple-marked Potsdam sandstone" in the drift at Tottenville. We suggest that Gratacamp's "Potsdam sandstone" may be the same as the "Lower Cambrian quartzite" boulders visible in the cliffs at GANJ field-trip Stop 4 (Conference House). The provenance significance of true "Potsdam" (outcrops confined to Adirondack borders) would differ considerably from that of the Lower Cambrian quartzite (widespread in the Appalachian fold-thrust belt extending across NW NJ and into SE NY).

Other studies of erratics on Staten Island have been carried out by Hollick (1908, 1915) and by Bourgeois (1972 ms.)

JES has found six notably large (diameters of 3 to 4 m) erratic indicator stones from the Cortlandt complex arranged in three clusters and partially exposed by erosion along the banks of the North Branch of Wicker's Creek in Dobbs Ferry (on the White Plains 7.5-minute quadrangle). Two of these boulder clusters are near the place where the old Croton Aqueduct crosses this branch of Wickers Creek (UTM: 594.90E - 4541.42N; and 594.86E - 4541.40N). A third is located on the N side of Wickers Creek W of the point where the two branches of this creek join (UTM: 594.70E - 4541.22N). These are contained in a grayish-brown till that overlies reddish-brown outwash.

Indicator stones on Long Island and Gardiners Island

Indicator stones from the beaches along the north shore of Long Island and on Gardiners Island have been eroded out of the material underlying the coastal cliffs. Much of this is "stratified drift," but some of it is till. We interpret the coarse stratified sediments as deposits made on Gilbert-type deltas that were built southward into Lake Long Island (Sanders, Merguerian, and Mills, 1993; Sanders and Merguerian, 1994). Whether they came from stratified drift or till, the boulders on the beaches form the basis for important provenance inferences. Some of the boulders have come from the NW and some from the NNE;

the problem is to determine how these provenance directions are related to stratigraphic units.

If Long Island's two terminal-moraine ridges had been deposited by the *Woodfordian* glacier, as so many Pleistocene geologists believe, then we think that a well-defined zone of reddish-brown till and characteristic indicator stones from the Hartford Basin should be present in the glacial sediments in the central part of Long Island. The **absence** in central Long Island of reddish-brown till derived from the Hartford Basin and containing trap-rock boulders in a direction SSW of New Haven, CT is a very compelling argument **against** the concept that Long Island's famous terminal-moraine ridges were deposited by the *Woodfordian* glacier.

A common stone found on north-shore beaches is known popularly as "puddingstone." Such rocks are hematite-cemented "ironstone conglomerates" containing well-rounded quartz pebbles; they are from the Cretaceous and have been derived locally. This kind of rock might be confused with the Green Pond-Schunemunk metaconglomerates, but in the metaconglomerates, the rock breaks across the pebbles rather than around them as in the Cretaceous examples.

Target Rock is a locality where indicator stones from both the NNE and the NNW have been comingled on the beach. The abundant dark, mafic-looking "green" stones are altered volcanics from SW of New Haven, CT, that have been eroded from a gray till (our Till I), which underlies the deltaic outwash.

Indicator stones derived from the NW include rounded boulders of Inwood Marble. These are being eroded from a till (our No. III or No. II) that overlies the deltaic deposits.

Sirkin and Mills (1975) wrote about the erratics at Target Rock as follows:

> "Diabase and purple-red puddingstone conglomerate erratics, along with till fabrics and other rock compositions suggest a northwesterly source area for the till. The diabase may be derived from the Palisades and the puddingstone from lower or middle Paleozoic conglomerates such as the Green Pond Conglomerate found near the New York-New Jersey border northwest of the Palisades."
>
> "On the beach a number of predominantly dark colored (*sic*) erratics of mafic composition have been eroded from the till. Some of these rocks resemble the Harrison Gneiss found to the north and northwest in southern Westchester and Connecticut" (Sirkin and Mills, 1975, p. 320).

We think that Sirkin and Mills are correct in their remark that some of the "predominantly dark colored (*sic*) erratics of mafic composition" found on the beach that have been eroded from the till "resemble the Harrison Gneiss found to the north and northwest in southern Westchester and Connecticut." As with the indicator stones of Inwood Marble, these dark gneisses point to a till deposited by a glacier that flowed from NW to SE.

Our interpretation is that the upper till at Target Rock was deposited by a glacier that flowed from NW to SE, but this is **not** the till that contains the dark greenish Palisades look-alike rocks from the Ordovician Maltby Lakes metavolcanics from SW of New Haven, CT). Thus we infer that only some of the erratics upon which Sirkin and Mills (1975) invoked a NW provenance were correctly assigned. Other indicator stones which they thought came from the NW demonstrate quite the opposite--a NNE provenance.

The beach at Garvies Point Nature Preserve is littered with boulders of great variety and distinctive types include:

plagioclase-phyric gabbro with xenoliths,
amphibole-phyric lamprophyre,
potash feldspar phyric granitic gneiss,
mylonitic granitoid gneiss,
augen gneiss,
epidote amphibolite,
potash felspar pegmatite,
mica-rich red shale (Cretaceous),
hematite-cemented conglomerate (Cretaceous),
and many others.

As at Sands Point, **no** erratics of Triassic-Jurassic Newark-type basin fill rocks are present.

Unfortunately, we do not yet know the provenance of these boulders, some of which are very distinctive. The augen gneiss may be from the Bedford Gneiss of Westchester County and the epidote amphibolite is probably from the Orchard Beach area of Pelham Bay Park.

Along the beach on the NE side of Gardiners Island erratics of red sandstone and dark bluish-gray dolerite are abundant. The nearest place from which these can have been eroded is the Hartford Basin of central Connecticut and Massachusetts. A glacier traveling from NW to SE, such as deposited our Tills III and II, could have transported these erratics to Gardiners Island. The Fundy Basin in Nova Scotia, situated to the NE, also contains bedrock that could have provided these erratics. But, any glacier bringing Newark-type erratics to Gardiners Island would have transported erratics from the Hartford to central Long Island. Because central Long Island lacks such erratics, we prefer the interpretation that the erratics on Gardiners Island came from the Hartford Basin.

Orientations of long axes of drumlins

As mentioned in a preceding section, the long axes of drumlins are parallel to the direction of flow of a glacier and the steeper ends of the drumlins are on the up-flow side.

Well-developed fields of drumlins that we think were deposited by the Woodfordian glacier are present in Rockland County, NY, in the lowland S of the curving NW end of the Palisades ridge (Figure GG-27). Their axes trend N-S; some are several km long and their relief is many tens of meters. A single drumlin having this same N-S orientation is present at Enoch's Nose, Croton Point Park, Westchester County, NY (Figure GG-28).

A few examples of drumlins oriented NW-SE are present in Westchester County, NY, and adjacent parts of SW Connecticut. Localities include: (1) Yonkers, E of North Broadway at the former Boyce Thompson Institute (UTM: 594.6E - 4563.0N, Yonkers quadrangle; (2) in the the Westchester County airport, many drumlins are present astride the NY-CT border with long axes about parallel to the direction of this border (the center of one particularly large example is at UTM: 609.1E - 4547.6N on the Glenville, CT-NY quadrangle); and (3) on the golf course at Pelham Bay Park, SE of Interchange 6 on I-95, near the boundary between New York City and Pelham Manor (UTM: 600.2E - 4526.0N on Mount Vernon quadrangle; Figure GG-29). The trends of these drumlins are about parallel to Magnetic North (local declination is 12°W).

DISCUSSION OF THE ICE-FLOW EVIDENCE IN THE NEW YORK CITY REGION

We conclude from the foregoing that the effects of at least three "generations" of ice flow can be recognized on bedrock surfaces in New York City and vicinity: (1) the oldest includes roches moutonnées and rock drumlins sculpted by glacial flow from NNE to SSW (N15°E to S15°W), a direction that closely parallels the Hudson River; (2) large grooves and various striae as well as roches moutonnées cut by glacial ice that flowed from NW (N 25° to 45°W) to SE, a direction that is across the Hudson River; and (3) the youngest, from NNE to SSW, parallel to the oldest features and also parallel to the Hudson River.

So what about all these features? Our results support the remarkable work of Dr. L. D. Gale in the early 19th century, but we go him one better in finding evidence for three glacial-flow episodes not a single "diluvial current" with flow variations.

We have found convincing evidence that the ice flow from NW to SE was not merely local, as Salisbury and others have inferred, but must have been regional (Figure GG-30). The critical evidence includes erratics of anthracite from NE

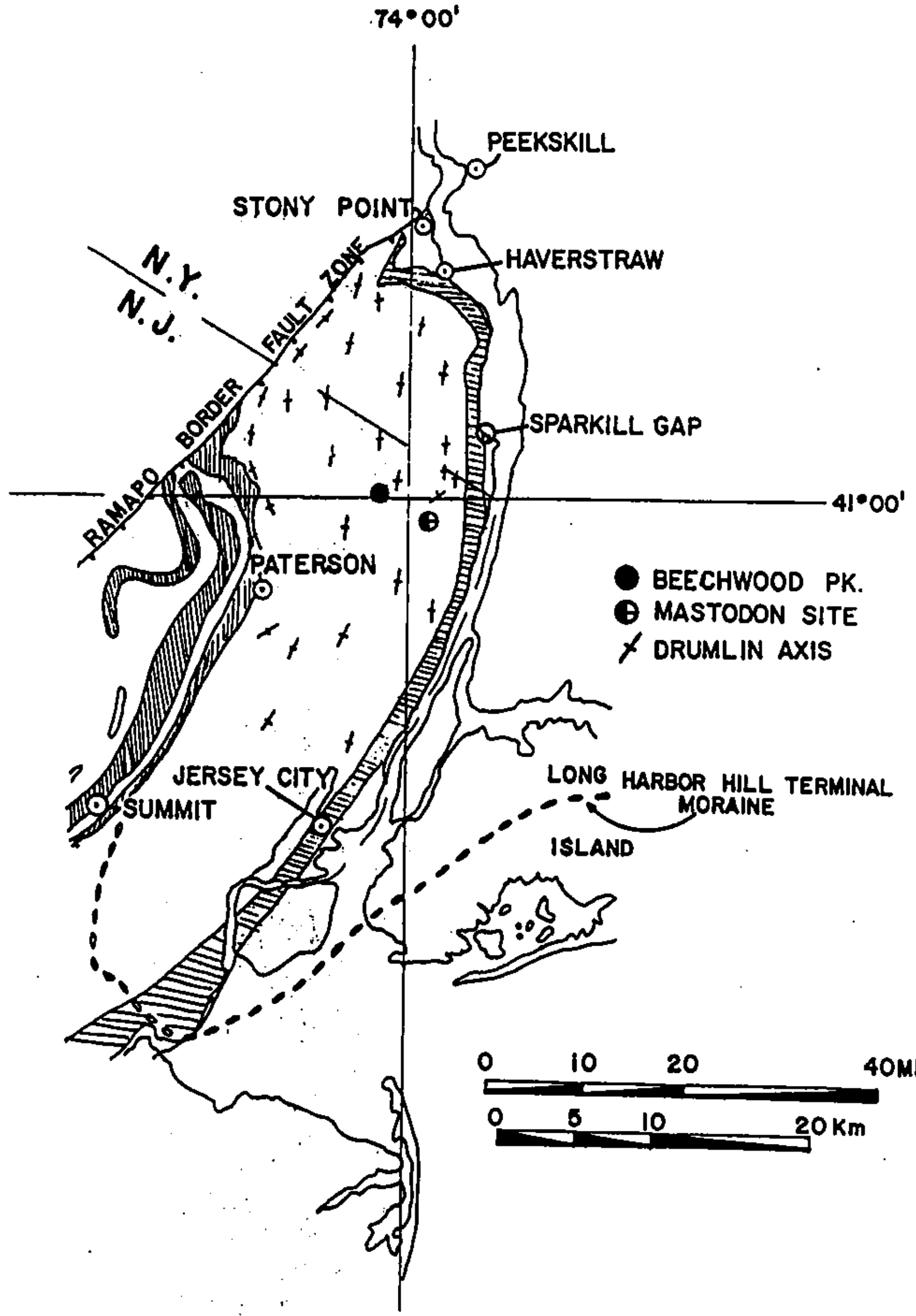


Figure GG-27. Axes of drumlins in the northeastern Newark Basin, Rockland Co., NY and adjacent northern New Jersey. The orientations of all drumlins shown are N-S or NNE-SSW. Closely spaced parallel lines mark prominent topographic ridges underlain by Mesozoic igneous rocks, not subdivided. (Averill, Pardi, Newman, and Dineen, 1980, fig. 1, p. 161.)

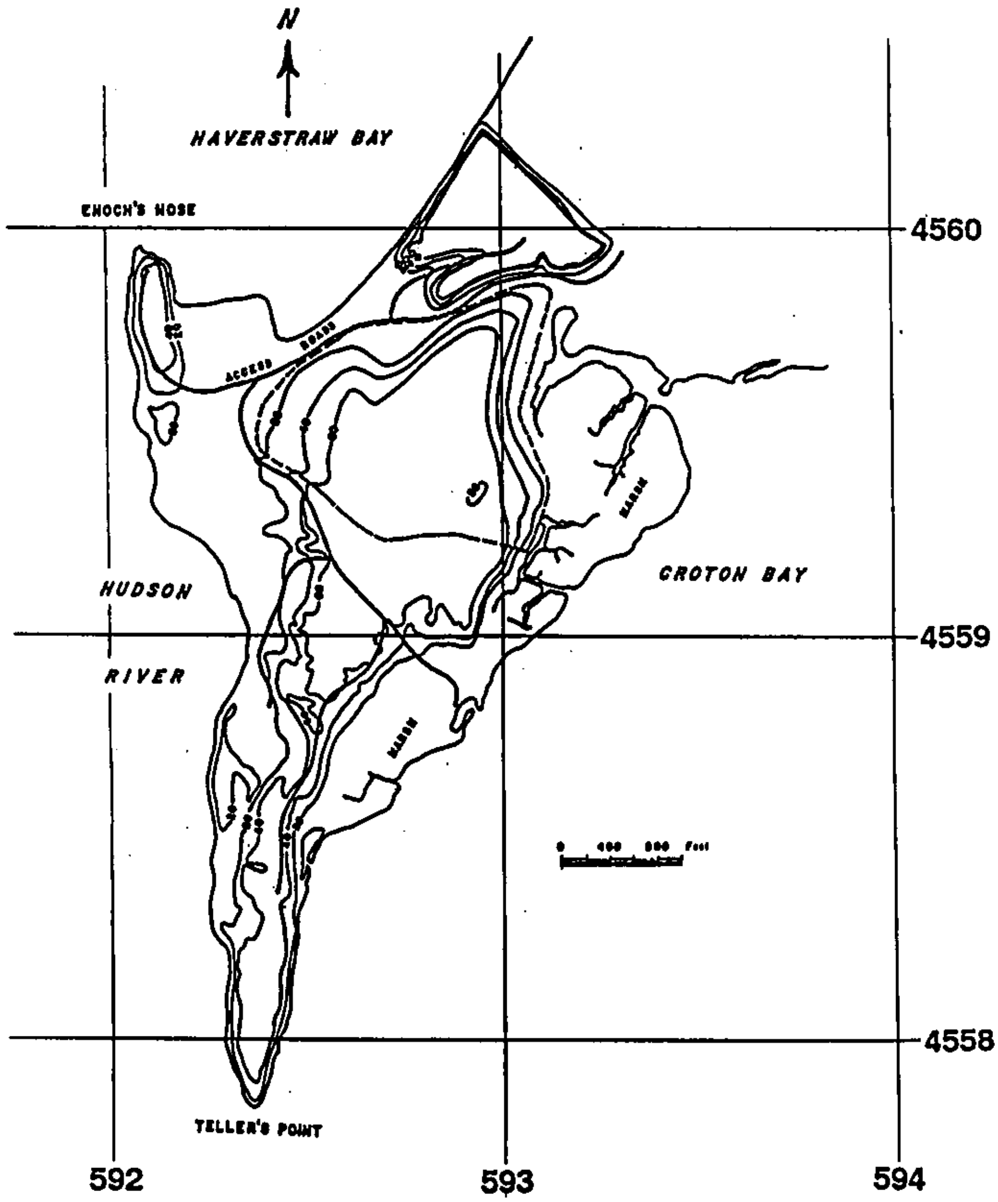


Figure GG-28. Topographic map (contour interval 20 ft) Croton Point Park, Westchester County, NY, in 1974 after the top of the landfill had reached an altitude of 60 feet. The elongate narrow hills trending N-S, at Enoch's Nose and Teller's Point are drumlins made by the most-recent glacier (our Glacier IV). UTM metric grid lines from Haverstraw 7.5-minute topographic quadrangle map of the U. S. Geological Survey added by JES. (Modified by JES from map in Geraghty and Miller, Inc., 1976 ms., fig. 11, p. 35.)

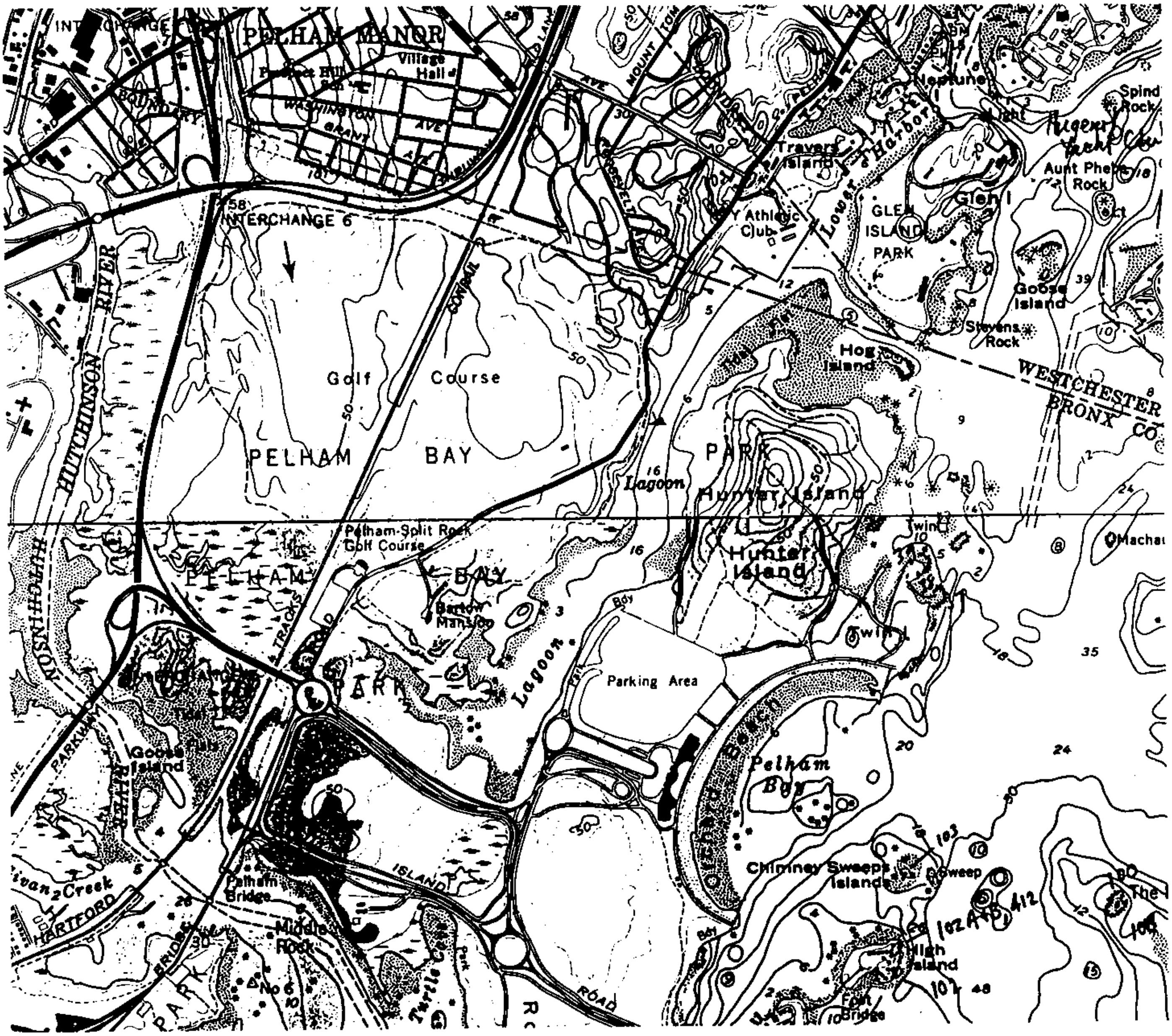


Figure GG-29. Topographic map (contour interval 10 feet) of Pelham Bay Park and vicinity, The Bronx, New York City, showing two small drumlins, with long axes oriented NNW-SSE on the golf course. Arrow (below label for Interchange 6) shows inferred direction of glacier flow, which is the same as the orientation of the dominant set of striae eroded on the bedrock surface that is being uncovered by wave erosion at Twin Island. (Copied from Mount Vernon and Flushing 7.5-minute topographic quadrangle maps of the U. S. Geological Survey; handwritten numbers on the Flushing quadrangle mark CM's field localities.)

Pennsylvania and of Green Pond Conglomerate and the Schunemunk Conglomerate. (See Figure GG-13.)

Despite all these previous findings of two distinct ice-flow directions, nearly all geologists have interpreted them as products of a single glaciation.

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River (Figure GG-31). However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier. (See Figure GG-5.)

STRATIGRAPHY OF SUPERPOSED TILLS AND PLEISTOCENE SEDIMENTS

Although, as mentioned, we have not found any sections in which tills and diagnostic nonglacial sediments are interstratified, we have found sections were two or more tills are superimposed. We mention two examples from Westchester County, NY (Croton Point and Yonkers), one example from northern New Jersey, five examples from Long Island, and one example from Staten Island.

Tills at Croton Point Park, Westchester County, NY

Along the west side of Croton Point Park, immediately across the Hudson River (about 2 km or 1.2 miles) from the Palisades Sill just south of Haverstraw, New York, waves generated by winds blowing across the wide part of the Hudson River (Tappan Zee and Haverstraw Bay) are eroding steep bluffs in the Pleistocene sediments. These bluffs expose one or more tills at Teller's Point on the south and at Enoch's Nose on the north. (See Figure GG-28.)

At Teller's Point **two** tills are present. A red-brown till caps the cliff; at a level of about 3 m above the water can be seen the top of a gray-brown till that persists down to water level. These two different tills harbor uniquely different suites of boulders, cobbles, and pebbles.

The red-brown till contains boulders- and pebbles of various facies of the Palisades trap rock, red-colored sedimentary rocks from the Newark Supergroup, the Green Pond Conglomerate, and chips of anthracitic coal. The dolerite stones show early stages of decomposition: concentric joints and breakdown of silicate minerals. Examples of most of the erratics can be seen in the cliff face and along the "beach," where they have been washed out

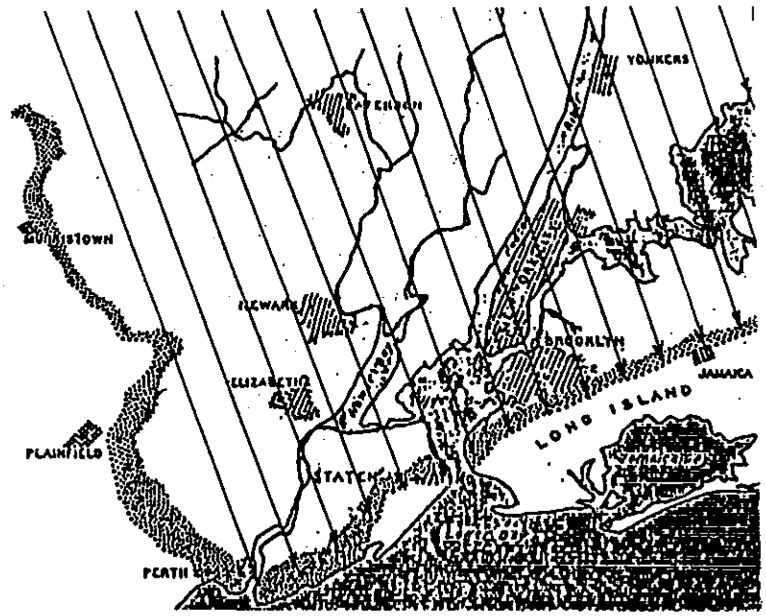


Figure GG-30. Rectilinear flow from NW to SE of inferred pre-Woodfordian glacier. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

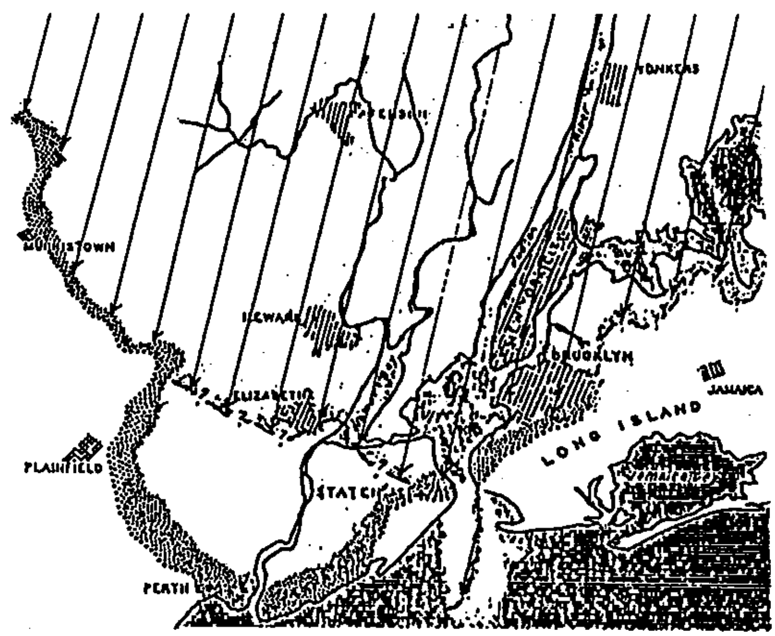


Figure GG-31. Inferred flow pattern of latest Wisconsinan (=Woodfordian) glacier, down the Hudson and Hackensack lowlands from NNE to SSW. On Long Island, this glacier affected only the westernmost parts; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

of the till. Clearly, this red-brown till is a product of NW-SE glacial flow; the erratics have come from **west** of the Hudson.

The lower gray-tan till contains rocks not found west of the Hudson River. Rather, the distinctive rocks eroding out of the lower till consist of igneous- and metamorphic lithologies which crop out to the east of the Hudson, mostly from regions due north of us. The feldspars in the dark, smaller granitic stones in the lower part of the cliff face have totally decayed.

As mentioned in a previous section, these granitic rocks having such totally decayed feldspars are subject to several interpretations, only one of which implies long-time *in-situ* postdepositional weathering.

Whatever is eventually decided about the significance of the granitic stones having decayed feldspars, we are certain from the stratigraphic relationships here and the content of indicator stones from the Cortlandt Complex that the direction of flow of the oldest glacier at Croton Point was from **N (or NNE) to S (or SSW; down the Hudson Valley)** and not from **NW to SE (across the Hudson Valley).**

This locality provided us with the first stratigraphic evidence for an initial glaciation in the New York City area that antdates the accepted advance of glacial from **NW to SE** across the Hudson. What is more, it corroborates our observations at Inwood Hill Park, Central Park, and Fort Tryon Park in Manhattan and in the New Botanical Garden in The Bronx, where NW-SE-trending glacial grooves have been cut into an older NNE-SSW-trending roche-moutonée structure or rock drumlin. (See Figure GG-10.)

At the top of a low bluff at Squaw Cove beach, a few hundred meters N of Teller's Point, gray varved clay containing local dropstones is exposed. A dig in the bluff a few meters to the N of the place where the footpath ends shows that this same gray clay overlies the red-brown till. On the beach at Squaw Cove are many more reddish Newark sandstone boulders and mafic rocks of the Palisades Sill. Fewer boulders of the distinctive mafic- and ultramafic rocks from the Cortlandt complex are present here than at Teller's Point.

The top of the red-brown till undulates; the gray clay is limited to the low spots. Traced along the bluff toward the north, the whole face is higher and consists entirely of red-brown till (Figure GG-32).

Another 100 m or so to the north is a low bluff that exposes the top of the gray clay. The overlying unit is a brownish fluffy sand that strikes us as being comparable to coarse loess (windblown sandy silt).

We infer that the gray clay is same age as the deltaic sand/clays underlying the 70-foot terrace in the northeast part of the park. If so, then the clay represents a more-distal depositional site that was isolated from the influx of deltaic sand from the east. The N-S-trending ridge of till kept the deltaic sands from spreading this far west.

The elongate shape of the promontory at Enoch's Nose suggests that it is a drumlin, shaped by the advance of glacial ice from N to S. (See Figure GG-28.) The bluffs here consist of two red-brown tills with local reddish proglacial-lake type of outwash between two units of till. The bouldery "beach" is strewn with large erratics from the Cortlandt Complex and a few Newark sandstone boulders. The boulders of the Cortlandt Complex on the "beach" suggest that some gray till or other must have been eroded. Possibly the older such till is present but only at or below river level. Possibly these boulders came from the upper yellow-brown till that caps the hill. The Newark sandstone boulders came from the red-brown till.

The bluff at the NW end of the promontory and the large cliff at the north end of the drumlin both display the same red-brown till above and below with red-brown fine-sandy proglacial-lake type of outwash locally in between. The 40-ft terrace level (on which is an oyster midden) forms the boundary between the red-brown till(s) exposed in the eroding bluffs and the youngest yellow-brown till of which the drumlin is composed.

We interpret Kindle's (1949) Croton Point moraine at Enoch's Nose as a drumlin. As mentioned, the capping of this drumlin is composed of yellowish-brown till which is perched above red-brown till. The sequence is (from the base up): red-brown till, red-brown sandy proglacial-lake type of outwash and then red-brown till up to path level where the oyster middens are present. Higher up is the yellow-brown till, but such diggings as we have done to date have not yet exposed the contact between the yellow-brown till and the red-brown till.

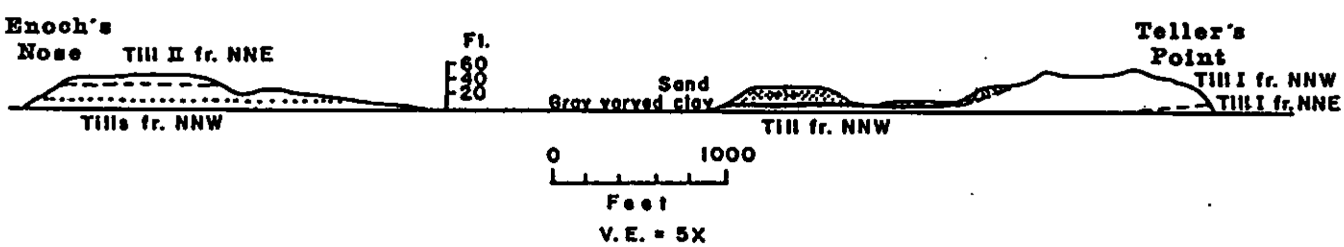


Figure GG-32. Profile-section of Pleistocene sediments along a N-S line from Enoch's Nose to Teller's Point, Croton Point Park, Westchester County, NY, drawn using Geraghty and Miller's June 1974 topographic map (Figure GG-28). The numbering system of the tills shown is by age and flow direction. In Table GG-2, Till II from the NNE is Till IV; the tills from the NNW are Tills III and II, respectively; and Till I from the NNE is Till 1. (J. E. Sanders, in Merguerian and Sanders, 1992e, fig. 42, p. 109.)

We correlate the red-brown till at Enoch's Nose with the red-brown till exposed at Teller's Point and Squaw Cove. Accordingly the entire Croton Point till sequence is (from oldest to youngest): gray-tan till with decayed granitic rocks and ultramafic indicator stones from the Cortlandt Complex, older red-brown till, proglacial-lake type of outwash deposits, newer red-brown till, and yellow-brown till. (See Table GG-2.)

To summarize the Pleistocene history of Croton Point, we offer the following sequence of events:

(1) Several tills starting with gray-tan, then red-brown, then, after red outwash was deposited, another red-brown till, followed by the yellow-brown till. The red-brown tills contain erratics from the west side of the Hudson River whereas the youngest and oldest tills contain only rocks found on the east side of the Hudson River.

(2) After the youngest of the tills had been deposited and the glacier responsible for it had melted away, the region was flooded. All the drainage from the Great Lakes flowed eastward through the Mohawk Valley and down the Hudson. Proglacial Lake Albany was backed up behind the natural dam of till at the Narrows. Deltaic sediments from the ancestral Croton River and possibly drainages to the north were deposited along the east shore of this lake. The water plane presumably stood at about elevation +70 feet (level of the flat terrace underlain by topset beds of the delta that coincide with the uppermost water level). To the west, the depth of water where the clay was deposited away from influence of the delta was 70 feet. The coarse browner clays probably represent the dark suspended load of the river(s). The light clays are winter deposits when river(s) experienced low- flow conditions and/or were shut down altogether because their waters froze solid.

Tills at Yonkers, Westchester County, NY

During construction at the Westchester County sewage-treatment plant in the Ludlow section of Yonkers near the Ludlow station on the Metro-North Railroad and at the former Otis Elevator plant just N of the Yonkers railroad station red-brown till containing large dolerite erratics was exposed. At the sewage-treatment plant, the red-brown till is overlain by red-brown outwash that has been recumbently folded on a small scale. (See Figure 9-36, p. 266 in Friedman and Sanders, 1978.) Overlying this deformed red-brown outwash is brownish silt and sand, an inferred lake deposit. At the former Otis plant, the red-brown till is overlain by a gray till containing numerous large, rounded erratics of Inwood Marble.

Tills in Northern New Jersey

During the excavations made in 1974 to enlarge the Oradell reservoir on the Hackensack River, northern New Jersey (on the Yonkers 7.5-minute quadrangle), two tills having contrasting compositions were exposed. The color of the lower till was reddish brown. On the W side of the Hudson River, reddish-brown color is not diagnostic of flow direction; a glacier flowing from any direction here presumably could pick up reddish-brown Newark bedrock. By contrast, the color of the upper till was light yellow-brown to tan; it contained numerous boulders of Inwood Marble, found only on the E side of the Hudson River.

Averill, Pardi, Newman, and Dineen (1980, p. 168, caption for fig. 8) used the name Tappan Till for the upper till. Averill (*in* Averill, Pardi, Newman, and Dineen, 1980, p. 164) inferred that "the two tills in the Hackensack valley represent two late Wisconsin stades separated by a significant interstade." By contrast we assign the upper till to our Till IV and the one beneath it, to Till III. We consider the age of Till IV to be *Late Wisconsinan* but that of Till III to be Early *Wisconsinan*.

Pleistocene Sediments on Long Island, NY

The Pleistocene sediments on Long Island are dominated by outwash, a situation that was noticed long ago and has been mentioned by many investigators. We describe our observations at five localities (from W to E): Sands Point, Garvies Point, Caumsett State Park, Target Rock, and Montauk Point. In a previous section, we discussed the subsurface stratigraphic relationships at Jones Beach.

Sands Point

Except for a thin (1 m or so) till and overlying loess at the crest, the body of the cliffs E of the place where the trail ends at a wooden stairway to the beach at Sands Point is composed of outwash (the Manhasset Formation of Fuller). The top third consists of pebbly, trough-cross-stratified typical coarse outwash, with flow indicated toward the S or SW.

At the E end of the first stretch of beach E of the trail, strata of sands dip steeply (ca. 45°) into the cliff. At first sight from a distance, this dip appears to be the kind of thing that results from rotational tilting on a slumped block. The proof that these are *true Gilbert-type delta foresets* is that **horizontal sets** of coarse, trough-cross-stratified pebbly outwash overlie the inclined foresets and truncate them along a horizontal surface. Moreover, the composition of the foresets differs from that of the topsets; the foresets are finer and regularly bedded.

Just to the W of where the stairway leads to the beach,is exposed a **red-brown till filling a U-shaped valley carved into the delta deposits.** We infer that this means the delta cannot possibly be of *Wisconsinan* age, but must be older than one of the red-brown tills deposited by a glacier that flowed from NW to SE (our Till III or possibly II). If this red-brown till is our Till III and our age assignment of *Early Wisconsinan* is correct, then at least some N-flowing fluvial valleys were already in existence. Bear in mind that according to Fuller's interpretation, the largest set of valleys opening to the north was eroded during a prolonged interval of low base level (Fuller's Vineyard erosion interval that he correlated with the *Sangamon* interglacial stage).

In an exposure E of where the road leads down to the seawall in distress, a small, shallow boulder-lined U-shaped trough had been cut into the delta topsets and backfilled with till, now totally reworked by outwash streams. (An exactly comparable relationship is shown in Mather's sketch of Figure GG-2; and a closely analogous but larger, boulder-lined channel formerly was visible cutting into the lake sediments at Montauk Point that form the bulk of the eroding cliff S of the lighthouse.) By digging, we uncovered the truncated layers in the topset sands and the fact that any boulders containing biotite have decayed considerably.

Garvies Point

For permission to visit the section we describe at Garvies Point, contact Ms. Kathryne Natale [Chief; tel. (516) 671-0300 or Mr. Douglas Winkler (Asst. Curator) (same #)]. Garvies Point Museum and Preserve, Barry Drive, Glen Cove, N.Y. 11542. (UTM: 613.5E - 4523.7N, Sea Cliff 7-1/2 minute quadrangle).

Two chief features exposed in the slumped- and eroding bluffs south of the stairs here are: (1) the Cretaceous strata; and (2) the Lower Pleistocene till containing decayed granite clasts (the Manetto of Fuller). In addition, the boulders on the beach contain a large variety of erratics.

The exposed Cretaceous consists of varigated clays and -sands with lignite seams and layers of charcoal (products of Cretaceous forest fires). Stratigraphy as found in slump block to south of wooden stairs is:

Yellow-brown sand with local cross strata, underlain by
Whitish clay,
Red-purple clay with local lignite at base, and
Gray clay.

The Cretaceous is overlain by a reddish till consisting of deeply weathered granitic boulders, Cretaceous ironstones, and manganiferous residue at contact with underlying outwash. At the right side of the face that a storm cleaned off for study is a large groove in the underlying Cretaceous. Of significant importance, the orientation of this groove indicates ice flow from the NW or even WNW.

Caumsett State Park

The relationships found at Sands Point generally prevail also at Caumsett State Park. At Caumsett, however, inclined pebbly beds predominate in the foresets. Among the pebbles are **numerous decomposed mafic metamorphic rocks.** We take these decomposed rocks as evidence that the age of this deltaic deposit is pre-*Wisconsinan*.

Target Rock

The cliff exposures at the Target Rock National Wildlife Preserve (UTM: 632.0E - 4531.8N, Lloyd Harbor 7.5 minute quadrangle) were described in a field-trip guidebook prepared in 1975 by Sirkin and Mills. We have examined this cliff both before and after it was eroded by a severe storm.

At Target rock, the lower half of the cliff consists of gray till containing the green erratics from the Maltby volcanics W of New Haven, CT, indicating the ice flowed from NNE to SSW. We correlate this till with the oldest till at Croton Point Park (the gray till containing decayed granite stones; Merguerian and Sanders, 1990a; 1992c). Above this till is 1 cm or so of fine gray clay, and then come ripple-laminated silts/fine sands, with splendid examples of climbing ripples (as illustrated by Sirkin and Mills, 1975, description of Stop 3A). These rippled strata display lateral particle-size changes along the ripple profiles from coarser to finer, with superposition of these yielding "pseudo-bedding." Some of the ripple laminae have been oversteepend. We think they are **not** "small folds that are overturned to the southeast, and represent additional evidence of minor glacial deformation due to overriding by the ice," as interpreted by Sirkin and Mills (1975), but rather examples of the effects of current drag on a bottom where the sediment falling out from suspension becomes cohesive and responds to shearing by the current by deforming (Friedman, Sanders, and Kopaska-Merkel, 1992, p. 252-253). We agree with Sirkin and Mills (p. 320) that "this unit probably represents sedimentation in a proglacial lake that formed between the ice just to the north and the upland to the south."

We infer that these sediments with climbing-ripple laminae and the clay are the bottomset beds, if you will, of the delta foresets exposed at Caumset State Park. Another thin till at the top of the cliff at Target Rock must have come from the NNW; it would have been deposited by a glacier that flowed from NW to SE, to bring the erratics of Inwood Marble and Cortlandt Complex (Sanders and Merguerian, 1991b). Sirkin and Mills (1975) also recognized that two tills are present here.

If our analysis of these tills is correct, then the age of the newly discovered delta deposits must be no younger than mid-*Pleistocene* (younger than old gray till from NNE and older than a till deposited by a glacier that flowed from the NW).

Montauk Point

The significant relationship about the lake deposits at Mantauk is that they are being eroded in a cliff that faces the open Atlantic Ocean. Given the requirement that a terminal moraine is required to serve as a dam along the southern margin of any proglacial lake that now faces the open ocean of extreme eastern Long Island, then the lake sediments near the Montauk lighthouse require us to infer that **a terminal moraine, older than and lying south of the Ronkonkama Moraine, formerly existed seaward of the present S shore of eastern Long Island and has been eroded and submerged** (Figure GG-33).

Based on the increase in gravel in the delta foresets eastward from Sands Point to Caumsett State Park, we think that the vaguely stratified diamictites having displaying prominent

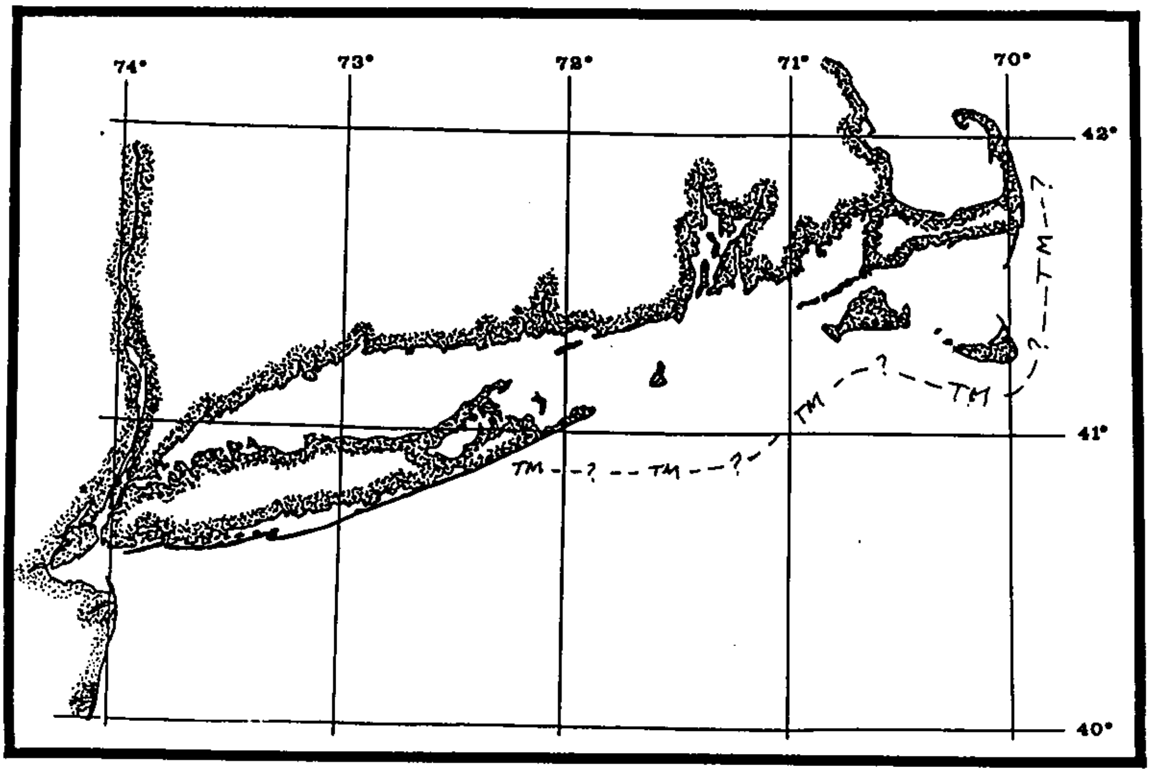


Figure GG-33. Outline map of southern New England and Long Island showing speculative position of a now-vanished terminal moraine marked by TM - - ? - - TM - - ? that we infer must have existed to serve as a dam for the lake in which the lacustrine strata in the coastal cliff at Montauk Point were deposited. (Sanders and Merguerian, 1994, fig. 2, p. 104.)

dips do not represent deformed till as Fuller (1914) and others have supposed but rather are deltaic deposits, products of sublacustrine debris flows.

The abundance of sandy outwash deposited between the terminus of a glacier and its terminal moraine points up the need to distinguish between outwash deposited in fans beyond the terminal moraine from "outwash" deposited in proglacial lakes held in between the ice front on the N and high ground of Long Island or a terminal moraine on the S. [This point is emphasized by Cadwell (1989), who mapped as "lake deposits" some of the "outwash" of Soren (1988).] The delta-foreset +/- topset outwashes are critical for the correct age assignment of the Manhasset Formation (at Sands Point, they are older than a red-brown till that fills valleys; at Caumsett, they contain decayed pebbles; and at Target Rock, they are younger than a gray till with stones from NNE).

By contrast outwash spread southward from a glacier that was standing at its terminal moraine fans out onto the coastal plain. Such outwash would be one of the first glacial deposits submerged by a rising sea. Hence, bay sediments could overlie such outwash as it evidently did in the Jones Beach subsurface.

Tills on Staten Island, NY

On today's field trip, we shall examine two localities where degree of decomposition of tills can be compared (one of which displays a till capped by a well-developed paleosol); a coastal cliff exposing both tills and outwash within which is a giant displaced sheet of Cretaceous sediments; and the glacially eroded bedrock at the Graniteville quarry, part of which is overlain by till that we assign to the *Woodfordian*.

SUMMARY OF GLACIAL GEOLOGY OF STATEN ISLAND

Students of the glacial geology of New York City and vicinity unanimously agree that all of Staten Island has been glaciated. In contrast with Long Island, where outwash predominates, Staten Island's glacial record features widespread till; outwash is exposed only locally near Great Kills and in coastal cliffs at Princess Bay (Figures GG-34 and GG-35). Other bodies of outwash, however, are known from the subsurface, from water wells in the northwestern part of the island (Perlmutter and Arnow, 1953; in the fill of the buried basal-Newark strike valley studied by Lovegreen, 1974 ms.) and from the borings- and excavations made in the construction of the sewer line under Hylan Boulevard (Mueser Rutledge Consulting Engineers, 1990). Moreover, a prominent terminal-moraine ridge extends from the Narrows along the coast of Staten Island (Salisbury, *in* Merrill and others, 1902; Perlmutter and Arnow, 1953; Soren, 1988; Cadwell, 1989; also Figures GG-34 and GG-35).

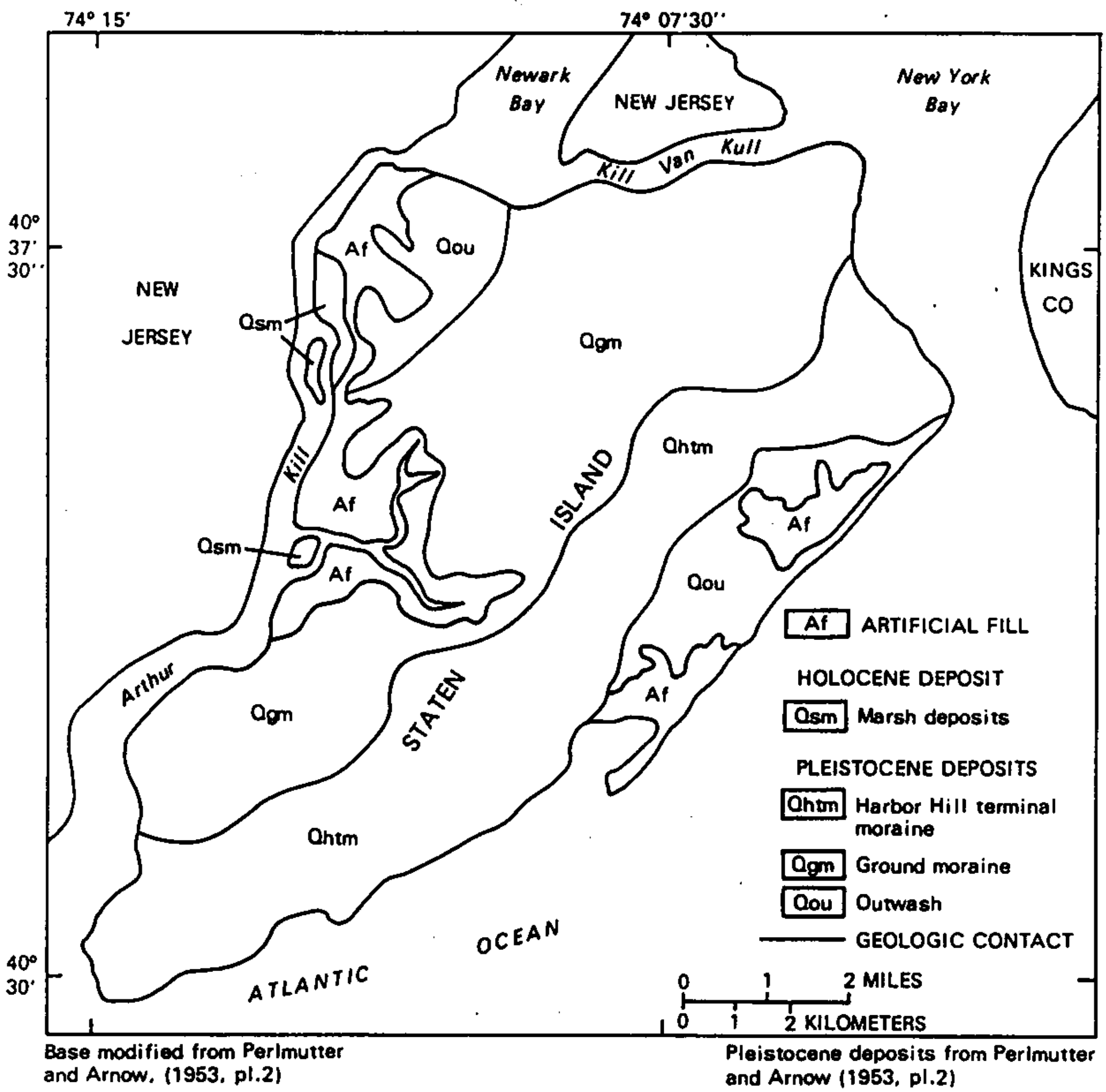


Figure GG-34. Map of surficial deposits on Staten Island, NY. (Soren, 1988.)

On the subject of how many glacial episodes have affected Staten Island, most glacial geologists vote one--the most recent, or *Woodfordian* substage of the *Wisconsinan* stage. In the absence of any compelling evidence of multiple glaciations, such as

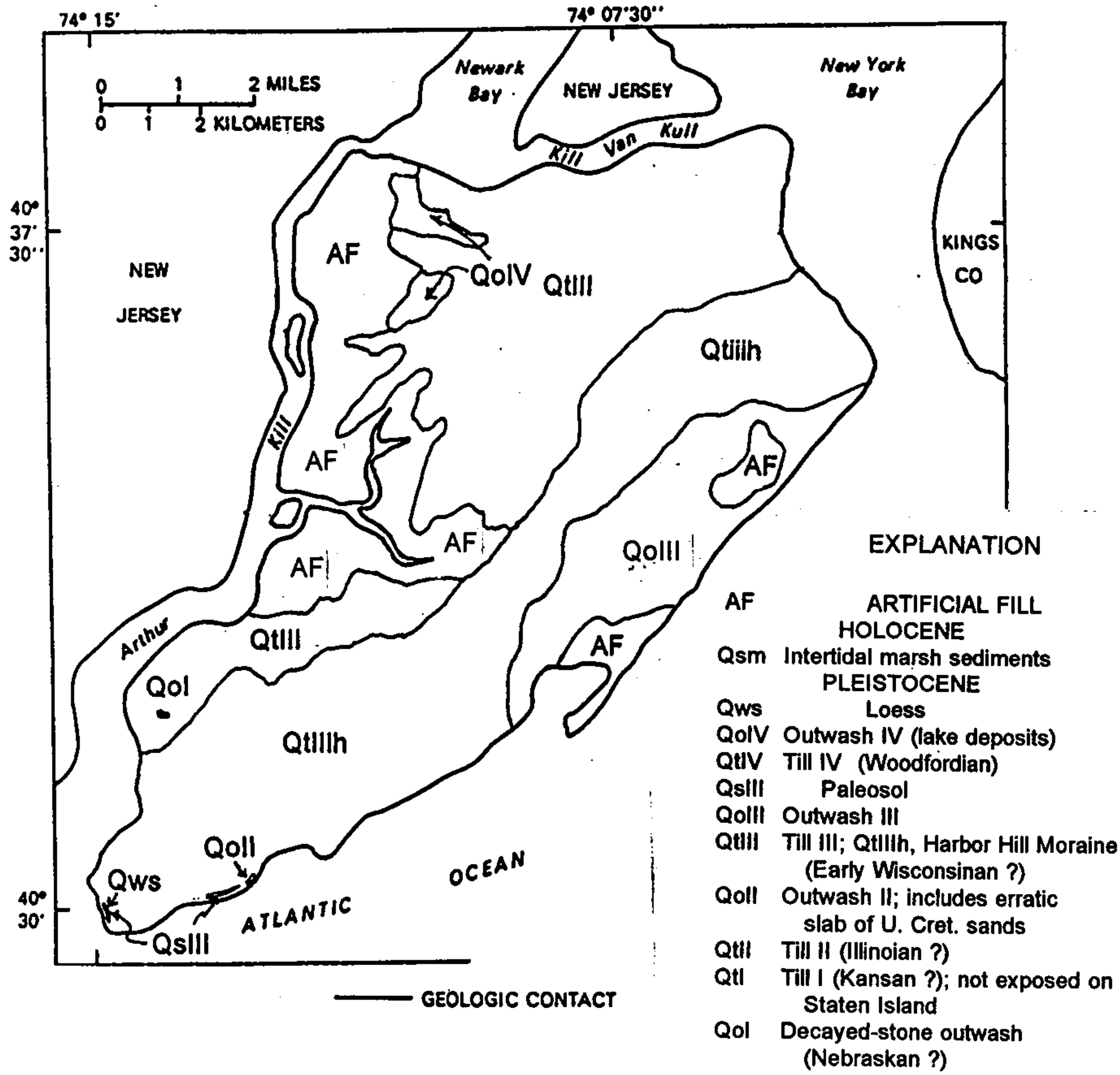


Figure GG-35. Map of surficial deposits on Staten Island made by JES using the outline of Soren's map and most of the contacts from Cadwell's (1989) map, but with additions to show units in our classification.

interstratified glacial- and nonglacial deposits exposed in a single section, the one-glacier-did-it-all school has ruled supreme. Evidence that might be associated with multiple glacial advances, such as striated bedrock displaying striae having contrasting orientations, has been interpreted in terms of ice domes at the margin of the ice sheet or of the behavior of a lobate ice margin. Within each lobe, the ice from a single glacier may flow in different directions.

CONCLUSIONS

As a result of studying the erosive effects on bedrock that enable the directions of flow of an ancient glacier to be inferred, we have arrived at conclusions that differ significantly from those that are generally accepted among specialists in Pleistocene geology. We argue that the youngest glacier that came to New York City and vicinity (our Glacier IV; the *Woodfordian* of standard classification) flowed along a direction that is parallel to the Hudson Valley (from about N10°E to S10°W). In those parts of the New York City area lying E of the Hudson River, the color of the till deposited by this glacier is gray or yellowish brown. Because erratics from the Hartford Basin are not found in the *Pleistocene* sediments on Long Island that are situated in a downflow direction from New Haven, CT, we infer that the *Woodfordian* glacier did not reach most of Long Island, but rather stopped along the coast of Connecticut. It did reach Queens, where it deposited the non-red Roslyn Till.

The next-older till flowed from a direction that is **across** the lower Hudson Valley (direction from N15°W to S15°E). In his study of the *Pleistocene* deposits of Queens, J. B. Woodworth (1901) showed that the Harbor Hill moraine is associated with a reddish-brown till that rests on striated bedrock with striae oriented N25°W-S25°E (magnetic). In our scheme of things, we take this as further, and conclusive, evidence that the Harbor Hill moraine **cannot possibly be of Late Wisconsinan age** (i. e., *Woodfordian*, as most workers believe), but must be **at least one glacier older**. We assign it to the *Early Wisconsinan*.

At Orchard Beach in The Bronx, long axes of drumlins on the golf course trend N15°W-S15°E. Along the water's edge of Long Island Sound, on South Twin Island, we have found a reddish-brown till (our Till III) resting on a striated glacial pavement with the striae oriented N15°W-S15°E, as Woodworth found in Long Island City. The till at Orchard Beach is not associated with any moraine that we know of. Despite the lack of any morainal association, we think that the relationships at Orchard Beach demonstrate two points of great significance: (1) the striae oriented N15°W-S15°E cut at least one older roche-moutonnée structure eroded by a glacier that flowed from about N10°E to S10°W, and (2) the numerous large erratics that have been washed out of the till(s) include several indicator stones from the Cortlandt Complex near Peekskill. We infer that these indicator stones must have been washed out of the *Woodfordian* till, which is not exposed in the low bluff at the water's edge.

At present, the best hope for settling our chronological impasse is amino-acid racemization analysis of shells from the Wantagh Formation. Our inference is that the Wantagh is *Sangamonian*, but as noted above, it could be mid-*Wisconsinan* or even *Yarmouthian*.

In many respects, our work re-establishes the validity of Fuller's (1914) interpretation of the glacial geology of Long Island (See Table GG-1.), which has been out of favor since the mid-1930s. Although we support Fuller in most respects, we differ from the universally accepted post-Fuller position in assigning a *pre-Woodfordian* age to Long Island's prominent terminal moraines. We think it is possible that Fuller was correct in his assignment of the Harbor Hill Moraine to the *Early Wisconsinan*, but we think he was not correct in assigning an *Early Wisconsinan* age to the older Ronkonkama moraine. We think that the correct resolution of the ages of these two moraines depends on the age of the Wantagh Formation. We correlate the Harbor Hill Moraine with the Bellmore Formation, which overlies the Wantagh Formation. If the Wantagh proves to be *Sangamonian*, then the position of Bellmore Formation (and the Harbor Hill Moraine, which we associate with our Till III) becomes *Early Wisconsinan*, where Fuller assigned the Harbor Hill Moraine. The *Sangamonian* age assignment for the Wantagh Formation places the Ronkonkama Moraine in the *Illinoian*. We interpret the Manhasset Formation as extensive deltaic sediments deposited in Lake Long Island that we infer was dammed on the S in part by the Ronkonkama- or a still-older terminal moraine (See Figure GG-33.), so its age assignment is tied to that of whatever terminal moraine held it in on the south. If the Long Island Lake were dammed on the S in part by a terminal moraine older than the Ronkonkama, then that feature has been reduced by erosion and submerged by the sea so that its remnants now exist only as bouldery shoals.

ACKNOWLEDGEMENTS

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NEWARK BASIN-FILLING STRATA AND ASSOCIATED MAFIC IGNEOUS ROCKS

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INTRODUCTION

The tilted- and eroded remnants of the Newark basin-filling strata are exposed along the west side of the Hudson River, from Stony Point southwestward into northern New Jersey to Hoboken. South of Hoboken, the Newark outcrop belt continue on a SW course whereas the Hudson bends to the S. The lower Newark beds cross NW Staten Island. Beyond Staten Island, the Newark strata extend across central New Jersey, into Pennsylvania, and continue as far as Virginia.

In this outcrop belt, the regional dip of the Newark strata is about 15° NW. On today's trip, we shall drive across the SE part of the Newark outcrop belt, but in doing so will not see any Newark rocks; the strata are covered. The only Newark rocks we shall examine today belong to the Palisades Dolerite (or "diabase" of some usage), which was intruded into the lower part of the Newark sedimentary succession.

This short summary concentrates on the general geologic relationships, the stratigraphy, and general geologic history.

GENERAL GEOLOGIC RELATIONSHIPS

The Newark strata form one of the significant "layers of geology" (Levorsen, 1933, 1934, 1943, 1945, 1948, 1954, 1960, 1964) of which four are present beneath Staten Island. From oldest to youngest these are: (I) Paleozoic "basement" metamorphic complex of the Manhattan Prong physiographic subprovince; (II) Newark strata; (III) Coastal-plain sediments; and (IV) Quaternary sediments.

The Newark strata of Layer II nonconformably overlie the older metamorphic terrane of the Manhattan Prong of Layer I and are themselves overlain in angular unconformity by the virtually horizontal Upper Cretaceous sediments of the Atlantic Coastal-Plain succession of Layer III, the basal unit in the wedge of sediments that has been accumulating along the passive eastern margin of the North American continent for the last 170 million years or so. The area of our field trip is shown on the geologic map of the Newark quadrangle (Lyttle and Epstein, 1987).

At Sand Hill, NJ, in an outlier, Upper Cretaceous strata rest on the exposed edge of the Rocky Hill-Palisades sill, a relationship that gives a vague limit for the date of deformation of the Newark rocks (Widmer (1964), A well-developed strike valley exists at the base of the Newark strata. The Hudson River follows this strike valley from Haverstraw, NY to Hoboken, NJ. At Hoboken, the Hudson bends to its left, and flows to the south. By doing so, it leaves the strike valley and flows across the metamorphic rocks. In Jersey City, NJ, and on Staten Island, the rocks of the Manhattan Prong are present **on the W side of the Hudson River.** Farther upstream, the rocks of the Manhattan Prong form the E bank of the Hudson.

Where the Hudson River leaves the basal-Newark strike valley, this strike valley disappears from the modern landscape but does not disappear geologically. The basal-Newark strike valley continues to the SW in the subsurface; it has been filled by Upper Cretaceous- and younger sediments (Lovegreen, 1974 ms.). This buried subsurface valley extends across western Staten Island and has not been identified to the SW in New Jersey.

STRATIGRAPHY

The name Newark, from Newark, New Jersey, is a venerable one in American stratigraphy; it was proposed by W. C. Redfield in 1856. Today, the term Newark has been accorded the status of a Supergroup (Cornet, 1977 ms.; Olsen, 1980c, Froelich and Olsen, 1985; Luttrell, 1989).

The age range of the Newark Supergroup has oscillated back and forth like a geological pendulum. During the 19th century, based on studies of their fossil fish (Redfield, 1856, 1857), they were assigned to the Jurassic. By contrast, the dinosaurs suggested Late Triassic. Given this situation, these strata were referred to as the Jura-Trias (for instance, Darton, 1902 in the New York City Folio 83 of the U. S. Geological Survey).

Many geologists, however, took the Newark strata to be synonymous with Triassic (Cook, 1968, 1879, 1882, 1887, 1888, 1889). By contrast, Kümmel (1897, 1898, 1898a, 1898b) initially used only "Newark." When he became associated with the U. S. Geological Survey Folio projects, however, he used "Triassic" Kümmel (1914).

But geologists who were inclined toward tidiness in classification were uncomfortable with the notion that a well-behaved formation should span the boundary between two geologic periods. Accordingly, when Pirsson and Schuchert (in their Textbook of Geology published in 1915) proposed the name "Palisades Disturbance" for the episode of crustal unrest that was supposed to mark the end of the Triassic Period, they decided that all the Newark strata were of Late Triassic age. Thus, they started a line of thought that lasted for 60 years. In addition, they also started a tradition that might be expressed by the title of a modern book: "We learned it all in kindergarten." In my analogy, "we" is all geologists trained in the United States, "kindergarten" is the first-year course in geology, and "learned it all" refers to knowledge about the Newark strata. Based on the Pirsson-Schuchert scheme of things, Widmer (1964, p. 85) wrote: "There are no known Jurassic sediments in eastern North America."

Modern students (Cornet and Traverse, 1975; McDonald, 1975 ms., 1988, 1992; Cornet, 1977 ms.; Olsen, 1978, 1980a, 1980b, 1984 ms.; Olsen, McCune, and Thomson, 1982; Olsen and McCune, 1991; Fowell and Olsen, 1993;) have re-established what the real old-timers knew all along: the age range of the Newark strata is Late Triassic and Early Jurassic. (For a general summary of the geologic literature on the Newark Group up to 1984, see Margolis, Robinson, and Schafer, 1986.)

The names of the formations of the Newark Supergroup (with thicknesses in the Watchung syncline) are (Olsen, 1980b):

Formation	**Thickness (m)**
Boonton (sedimentary strata; top eroded)	500 +
Hook Mountain Basalt (two flow units)	110
Towaco Formation (sedimentary strata)	340
Preakness Basalt (2, poss. 3 flow units)	300
Feltville Formation (sedimentary strata)	170
Orange Mountain Basalt (at least 2 flow units, one of them pillowed)	150
Passaic Formation	6000
Lockatong Formation	150
Stockton Formation	350
Total (Watchung syncline)	**8070**

Where the three well-known sheets of extrusive basalt (First-, Second-, and Third Watchung basalts; named by Paul Olsen, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a Newark-type reddish-brown sandstone, -siltstone, or -shale, or even a coarse conglomerate with reddish-brown sandstone matrix, the problem of assigning the correct formation verges on hopeless. Ultimately, some mineral- or lithologic criteria may prove to be helpful for stratigraphic assignment.

On Staten Island, only the basal formation, the Stockton Arkose and its overlying Lockatong Formation are present. The parts of the Stockton that are not red are light gray. They can be distinguished from the overlying gray Cretaceous sands by the large content (25 to 33% or more) of feldspar. The Lockatong is typically a dark gray, tough rock named argillite. Toward the SW, the thickness of these two formations is much greater than in the Watchung syncline. In the Delaware Valley, for example, the thickness of the Stockton is 1650 m and that of the Lockatong, 1200 m (McLaughlin, 1959, p. 85).

As far as we are concerned today, the important thing about the Newark strata is the red-brown color of most of them. This color has left its imprint on most of the Pleistocene sediments.

The Lockatong Formation is the unit into which the tabular, generally concordant Palisades sheet has been intruded.

Paul Olsen (1986) has given the name Van Houten cycles to lake deposits made during a change from deep water to shallow water (or even no water) and back to deep water again. Such changes characterize lakes in closed drainage basins. The water-level fluctuations are controlled by climatic changes.

Studies of the cyclicity by Van Houten (1962, 1964) and Olsen (1984, 1986, and continuing from the Newark-basin cored borings) have indicated cycles having periods coinciding with the climatic cycles computed by Milankovitch based on variations in the Earth's orbital elements.

The finding of such Milankovitch-type cycles in rocks as old as Late Triassic-Early Jurassic demonstrates that the computer-modelling gurus who claimed that the Milankovitch periodicities break down within a few million years have got their mathematics all wrong.

MAFIC IGNEOUS ROCKS

Newark mafic igneous rocks include both intrusives (the Palisades sheet) and extrusives (the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere.

A subject of recurrent interest among geologists has been about possible identity of times of extrusion and extrusion of the mafic materials. Initially, the Palisades sheet was viewed as a product of a single charge of magma. More recently, however, evidence has been found that this sheet is composite and formed as a result of several discrete injections of magma. The major questions have centered on whether the Palisades sheet was intruded at the same time as one or more of the extrusive basalts.

See Puffer's article for further details about the igneous rocks.

GENERALIZED GEOLOGIC HISTORY

The topic of formulating a geologic history of the Newark strata is colored by one's interpretation of the strata in the first place. Views on the postdepositional geologic history have ranged all the way from nothing of significance to a long and complex series of tectonic activities. (For a review of the intellectual history of the Newark rocks, see Merguerian and Sanders, 1989, 1991, 1993a, and 1993b.) Most modern geologists are concentrating on the relationships between the Newark strata and the basin in which they were deposited (Olsen, 1984 ms., 1988a, 1988b; Olsen, Froelich, Daniels, Smoot, and Gore, 1991; Olsen, Schlische, and Gore, 1989; Klitgord and Hutchinson, 1985; Manspeizer, 1988; Schlische and Olsen, 1988; 1990).

If one accepts the premise that the Newark strata were deposited in horizontal positions, then one needs to infer tectoic movement to explain the observed dips of the Newark strata. Some argue that the floor of the basin was being rotated toward the basin-marginal fault during deposition, so that by the time the uppermost strata were deposited as horizontal layers, the older layers had acquired their modern-day dips. Because of the relationships between strata and ancient lava flows, however, I prefer the position that most of the tilting took place after the strata had been deposited. (I have not been privileged to look at any continuous seismic profiles across the Newark Basin, so my position on this matter may be totally disproved by what such profiles disclose.)

No matter. It is clear that whatever happened to the Newark took place prior to Late Cretaceous time, when the Upper Cretaceous coastal-plain strata started to be deposited.

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COASTAL-PLAIN SANDS AND CLAYS OF LATE CRETACEOUS AGE

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INTRODUCTION

The strata underlying the coastal plain began to accumulate after the Atlantic Ocean began to open and eastern North America had become a passive continental margin.

The coastal-plain strata consist of sands that have been cemented only locally (the hematite-cemented sandstones and conglomerates, or "ironstones"), and the interbedded clays have not become fissile. Hereabouts, the exposures show only the Upper Cretaceous part of the sequence. Elsewhere, however, younger units are present. The youngest widespread marine unit in the coastal-plain succession is of Miocene age.

A characteristic of the coastal-plain sands is their great mineralogic maturity. They generally lack feldspar and contain only quartz and resistant varieties of heavy minerals, such as zircons. Notably absent are any particles derived from the Newark Supergroup. The absence of Newark debris supports the conclusion that the coastal-plain strata formerly extended far enough inland to bury the Newark outcrop areas. Some of the distinctive heavy minerals show that the crystalline central core of the Appalachians was not covered, but was providing debris. Simiarly, sand composed of serpentinite particles indicates that the Staten Island Serpentinite was exposed.

GENERAL GEOLOGIC RELATIONSHIPS

The coastal-plain strata belong to the large category of basin-margin sediment fillings whose interpretations have been revolutionized as a result of new concepts of seismic stratigraphy. These new concepts have grown out of detailed analyses of the new generation of continuous seismic-reflection-profile records collected from moving research ships. Instead of confining the analysis of the seismic records to evidence of buried geologic structures, the chief goal of seismic surveys and the only point of interest by most geophysicists, a group of geologists at the Exxon Research Laboratories in Houston, TX, under the leadership of Peter Vail, have shown how these new seismic records contain evidence of the profound influence exerted by changes of sea level on the sedimentary strata that accumulate at the margins of the oceanic basins. Analysis of data from passive continental margins collected worldwide has enabled Vail and his co-workers to compile a sea-level curve. The notion that the stratigraphic record exposed on the continents records numerous changes of sea level had been proposed early in the 20th century, by the American geologist A. W. Grabau among others and various European geologists such as the Termier's or Umbgrove. Subsequently, the pendulum of geologic fashion in interpreting strata swung in the opposite direction and the effects of sea-level changes were not much emphasized. But, now it's back to Grabau and then some, but with one difference: the new "young Turks" think that they invented (not re-invented) the great wheel. They do not mention Grabau, T. C. Chamberlin, Charles Schuchert, E. O. Ulrich, or Stuart Weller, to name a few of the notable early American proponents of the interpretation that the continental stratigraphic record had accumulated in response to numerous, extensive changes of sea level. To be sure, the main emphasis of many of these early American studies was to use the gaps in the stratigraphic record as boundaries between systems, for example. In contrast, armed with the new regional look made possible by the seismic-profile records, the seismic stratigraphers are able to show how sea-level changes are expressed--not only in the areas where formerly the breaks resulting from an episode of emergence were emphasized but also in the basins, where deposition was continuous. The seismic expression of strata deposited at a high stand of the sea differs from that of strata deposited at a low stand. Therein lies the secret of success of the new interpretations.

Given such a powerful stimulus, nearly all stratigraphers are now reevaluating their data in terms of sea-level changes. An example is R. K. Olsson's (1988) use of benthic Foraminifera from the Upper Cretaceous in the coastal plain of New Jersey for making estimates of paleodepths of the Cretaceous sea. Combining the information from all sources, Olsson has prepared the stratigraphic chart of the formations of the New Jersey coastal.

Late in the Miocene Epoch, the coastal-plain sands and -clays were elevated and truncated by erosion to form a surface upon which the Quaternary glaciers acted.

STRATIGRAPHY

The local representatives of the Upper Cretaceous is the Raritan Formation, which was named by G. H. Cook (1888):

"*Raritan clays*.--Include (descending): sand, clay, and lignite, 50 ft.; clay and sand, 40 ft; stoneware clay bed, 30 ft.; sand and clay 50 ft.; South Amboy fire-clay bed, 20 ft.; kaolin, 13 ft.; feldspar, 5 ft.; micaceous sand bed, 20 ft.; laminated clay and sand, 30 ft.; pipe clay, 15 ft.; Woodbridge fire-clay bed, 20 ft.; fire-sand bed, 15 ft.; Raritan fire-clay bed, 15 ft.; Raritan potter's clay bed, 25 ft. Underlies Clay Marls [Matawan group] and rests on Archean." [As thus defined Cook's *Raritan clays* are 347 ft. thick and include Magothy fm. of present nomenclature.]

From that beginning, various changes were proposed by Clark (1893, 1904); Kümmel (1911); Kümmel and Knapp (1904); and Berry

(1906). Modern usage is contained in Owens, Minard, and Sohl (1969) and Owens and Sohl (1969). (I have dug these references out of various bibliographies and have not read most of them; I'll "take the fifth" on any questions.)

For up-to-date information, consult Olsson (1980, 1987, 1991).

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INDOOR RADON LEVELS IN NEW YORK AND NEW JERSEY

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ABSTRACT

Approximately 71,000 indoor radon measurements from homes in New Jersey and eastern New York have been used to create state-size radon hazard maps. Areas of highest indoor radon include Dutchess County in eastern New York, and Hunterdon, Morris and Warren Counties in western New Jersey.

INTRODUCTION

Attempts to identify areas with an unusually high number of homes that contain elevated indoor radon concentrations is a popular activity that has scientific merit. It is estimated that 8 to 25 percent of all current lung cancer deaths are due to exposure to airborne radon (Puskin and Yang, 1988). The concern has intensified since the discovery that inhaled radon passes through the lungs to be dissolved in body fluids and tissues (Pohl and Pohl-Ruling, 1967; Lykken and Ong, 1989; Henshaw and others, 1990), and consequently may initiate soft tissue cancers.

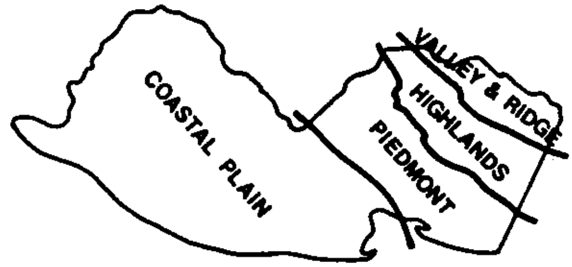
Previous studies have shown that most homeowners are sufficiently concerned about radon hazards to properly use indoor radon monitors obtained from commercial testing companies (Mose and Mushrush, 1988; Mose and others, 1988; Mushrush and Mose, 1988, 1989; Mushrush and others, 1989). Homeowner concern is so great that even if the indoor radon monitors are supplied directly by a testing company, without any involvement of a science advisor beyond that provided by written instructions, the indoor measurements are quite indicative of the actual radon situation.

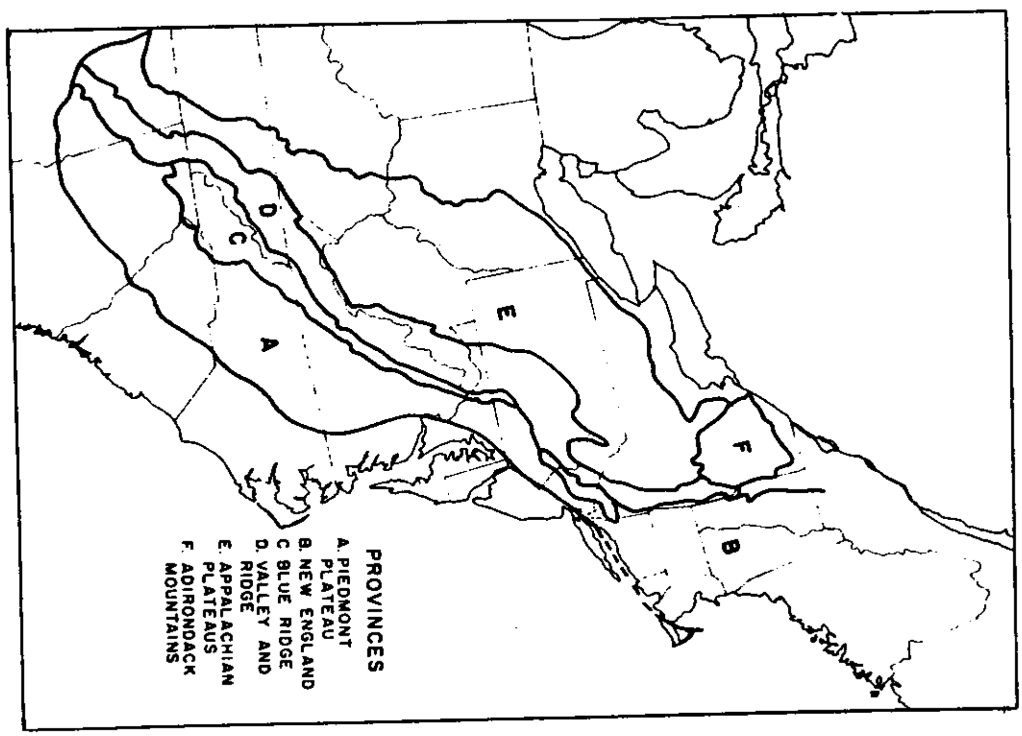
DISCUSSION

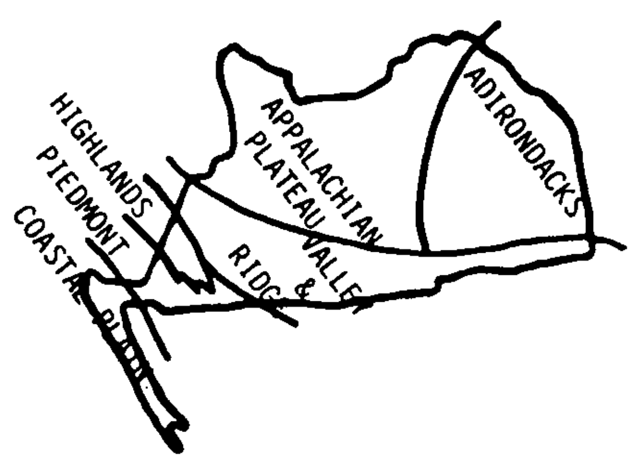
Approximately 71,000 indoor radon measurements were sent to us by several companies: Tech/Ops Landauer in Ilinois, Key Technology and The Radon Project in Pennsylvania, Enrad in Maryland, and Air Chek in North Carolina. Indoor radon varies across New York and New Jersey, but each geological province carries a characteristic indoor radon risk:

I. The Coastal Plain Province comprises the southeastern half of New Jersey and Long Island in New York. The Coastal Plain is composed of sediments (mostly terrestrial and marine sand and clay strata) which range in age from Cretaceous to Holocene (135 million years old to the present), and which owe their origin to the opening of the modern Atlantic Ocean. As shown in Figure 1, the Coastal Plain is characterized by the lowest range of indoor radon (less than 3 pCi/l; estimated risk is 1 radon-induced lung cancer death per 100 deaths from all causes).

II. The Piedmont Province comprises the most densely populated portion of New Jersey and New York. The Piedmont is composed of Latest Precambrian through


COASTAL PLAIN
VALLEY & RIDGE
HIGHLANDS
PIEDMONT


PROVINCES
A. PIEDMONT PLATEAU
B. NEW ENGLAND
C BLUE RIDGE
D. VALLEY AND RIDGE
E. APPALACHIAN PLATEAUS
F. ADIRONDACK MOUNTAINS
A
B
C
D
E
F


HIGHLANDS
PIEDMONT
COASTAL
APPALACHIAN PLATEAU
VALLEY &
RIDG
ADIRONDACKS

RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE

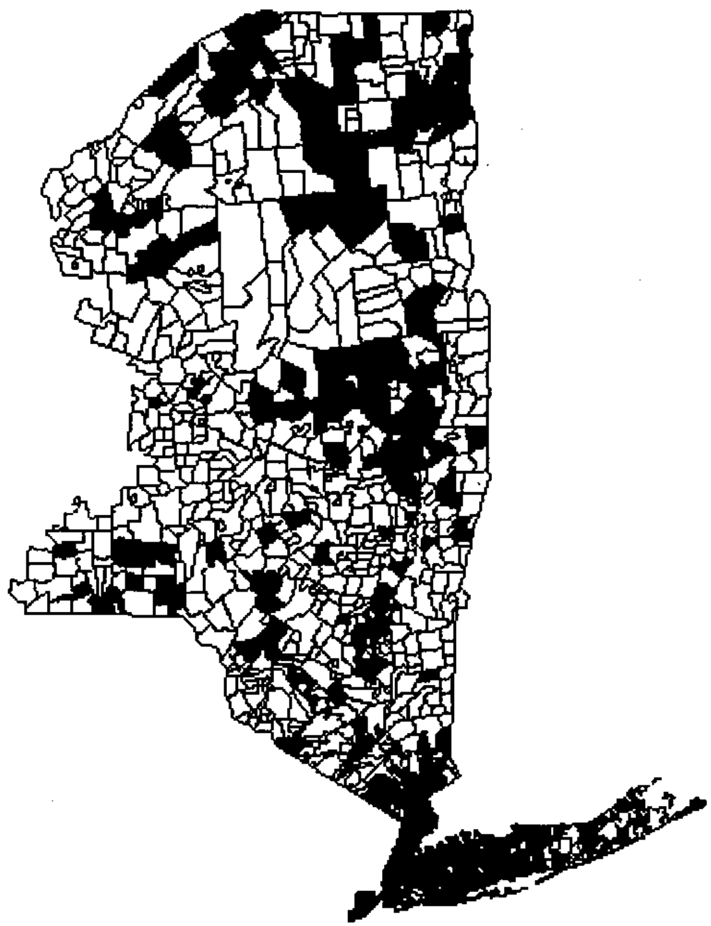
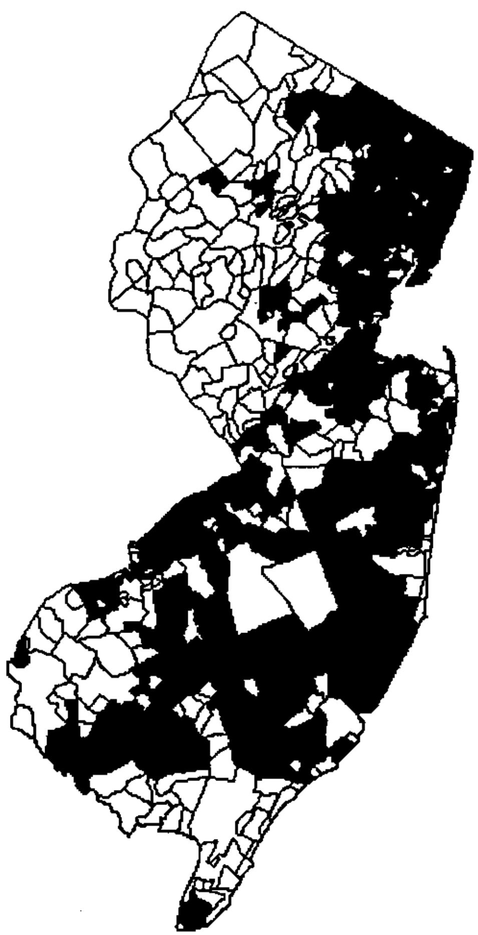


FIGURE 1a

RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE



AVERAGE RADON /ZIPCODE
MEASURED IN pCi/L

■ UP TO 3

FIGURE 1b

RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE

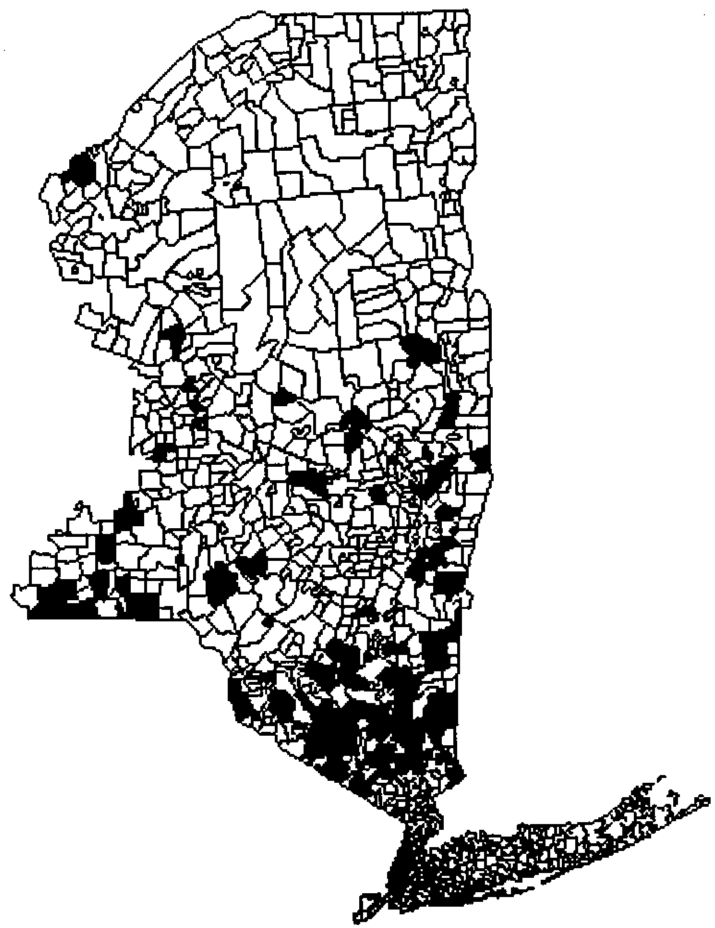


FIGURE 2a

RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE

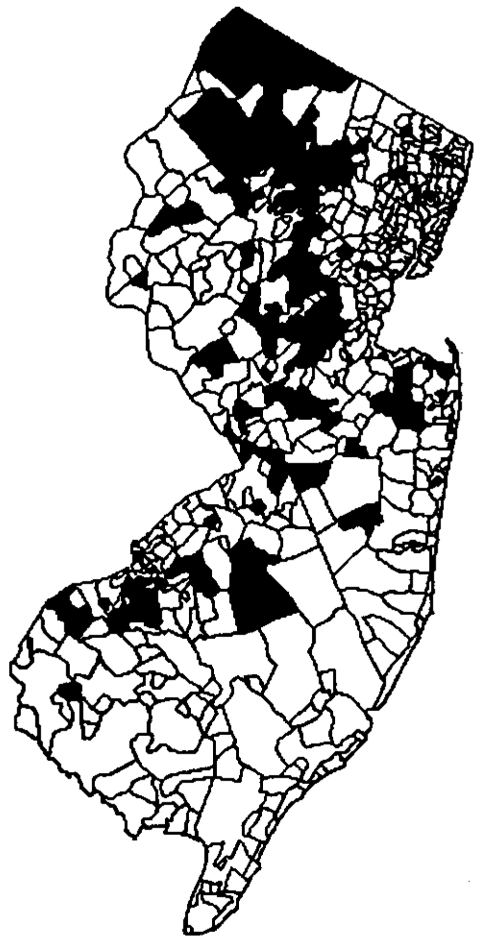


FIGURE 2b

RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE

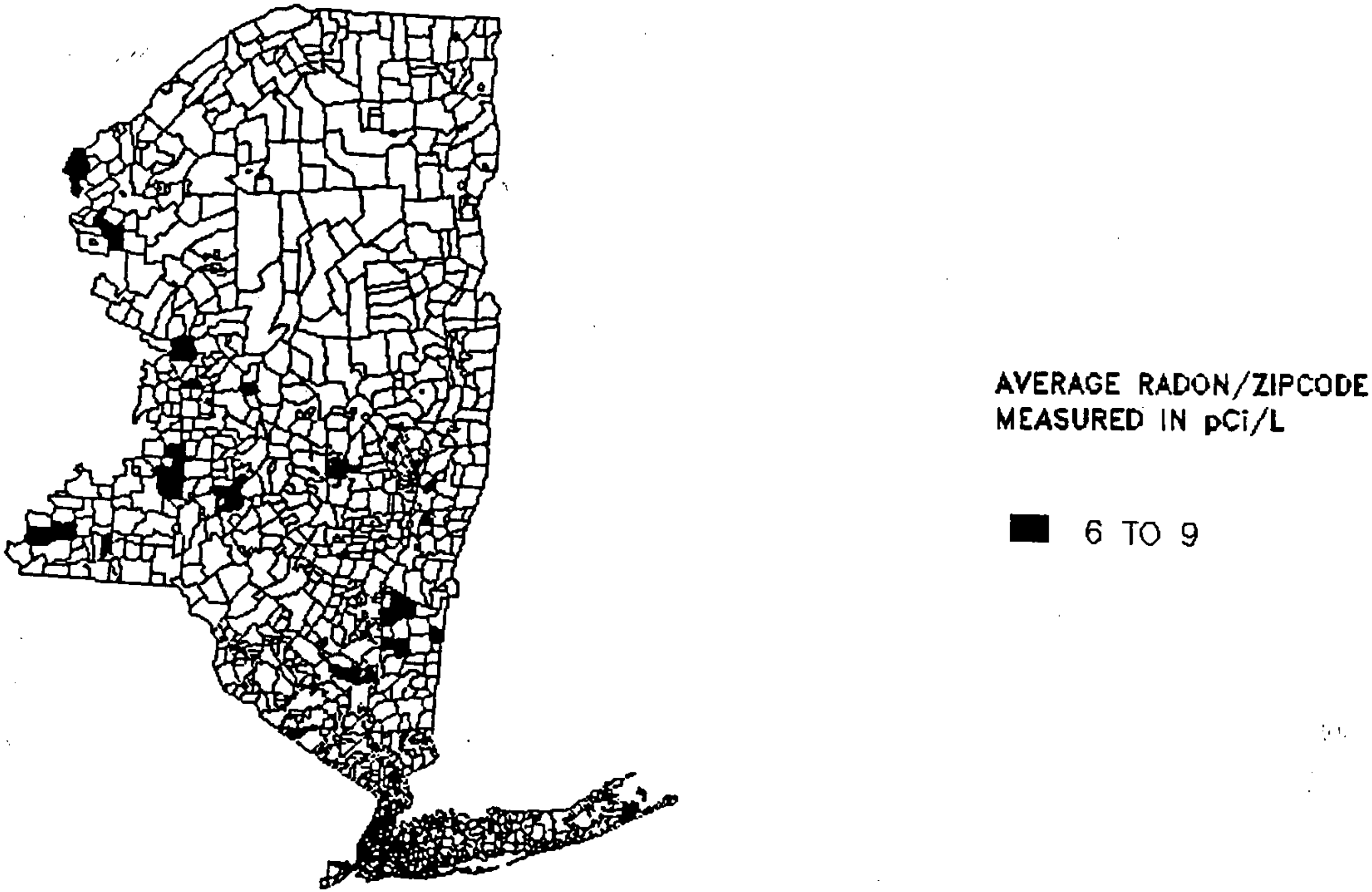
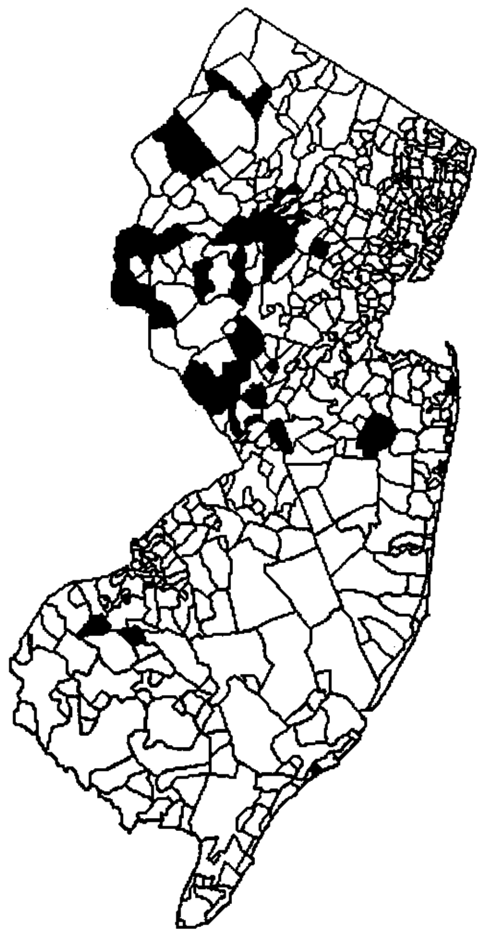


FIGURE 3a

RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE



AVERAGE RADON /ZIPCODE
MEASURED IN pCi/L

■ 6 TO 9

FIGURE 3b

RADON HAZARD MAP OF EASTERN NEW YORK BY ZIPCODE

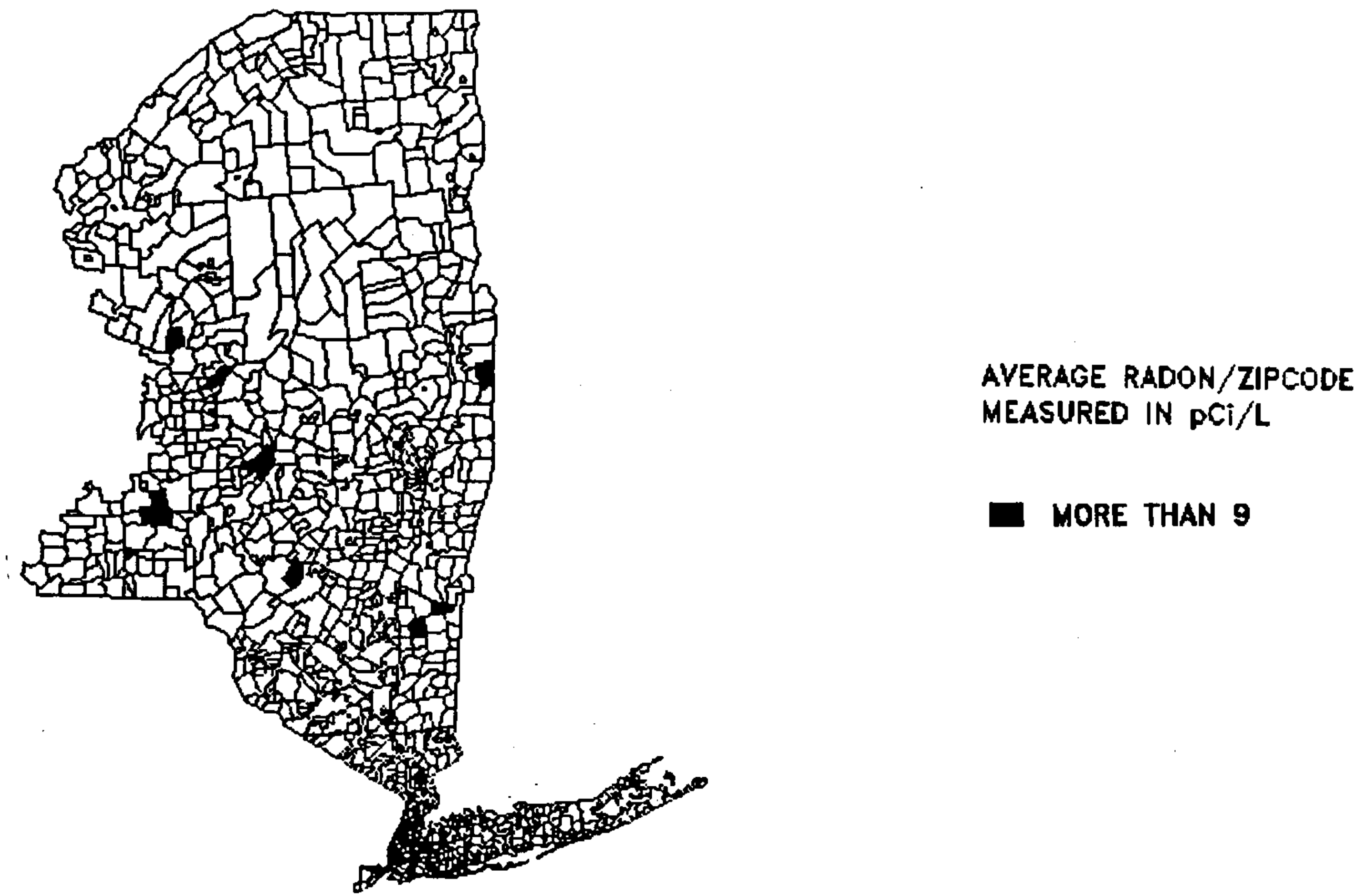


FIGURE 4a

RADON HAZARD MAP OF NEW JERSEY BY ZIPCODE

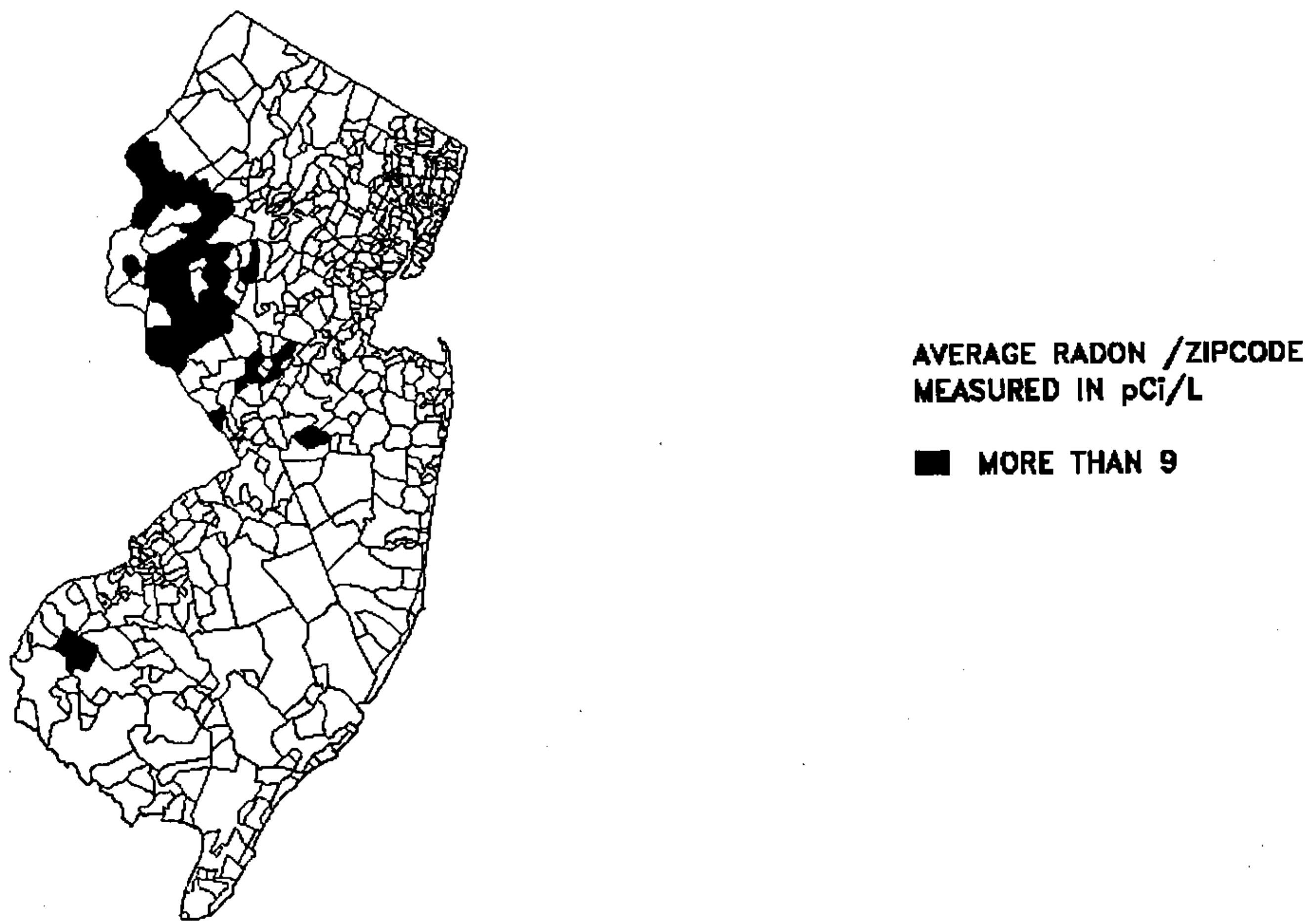


FIGURE 4b

Ordovician rocks (@ 600 to 450 million years old) which were recrystallized deep in the Earth during the more recent of the two Appalachian mountain building events. In New York, part of this terrane is covered by red terrestrial sandstone and shale, plus basaltic volcanic rocks, which range in age from Late Triassic through Early Jurassic (230 to 190 million years ago). These cover rocks accumulated in a fault-bounded valley ("rift basin") which formed due to tensional forces just prior to the opening of the modern Atlantic. In New Jersey, most of the ancient Piedmont rocks are covered by the rift basin rocks.

In southeastern New York and in northeastern New Jersey, the Piedmont and its rift basin cover rocks are covered by glacial till, deposited during glacial advances over the past 2 million years. This glaciated area is characterized by average indoor radon of less than 3 pCi/l (Figure 1), though areas of 6-9 and over 9 pCi/l are concentrated in Dutchess County, New York. In New Jersey, south of the glaciated zone, indoor radon increases (Figures 2-4), averaging about 3-6 pCi/l in Somerset County (@ 2 lung cancer deaths per hundred), about 6-9 pCi/l in eastern Hunterdon County (@ 5 lung cancer deaths per hundred), and over 9 pCi/l in western Hunterdon County (@ 8 lung cancer deaths per hundred).

III. The Highlands Province comprises the oldest and most mountainous portion of New Jersey and New York. Rocks of this province are mainly granites and gneisses, Late Precambrian in age (1300-800 million years old), which were formed during the older of the Appalachian mountain building episodes. Where glaciated in New York and New Jersey, most areas average 3-6 pCi/l (Figure 3), but near and south of the glacial termination, indoor radon averages quickly increase to over 9 pCi/l (Figures 3 and 4).

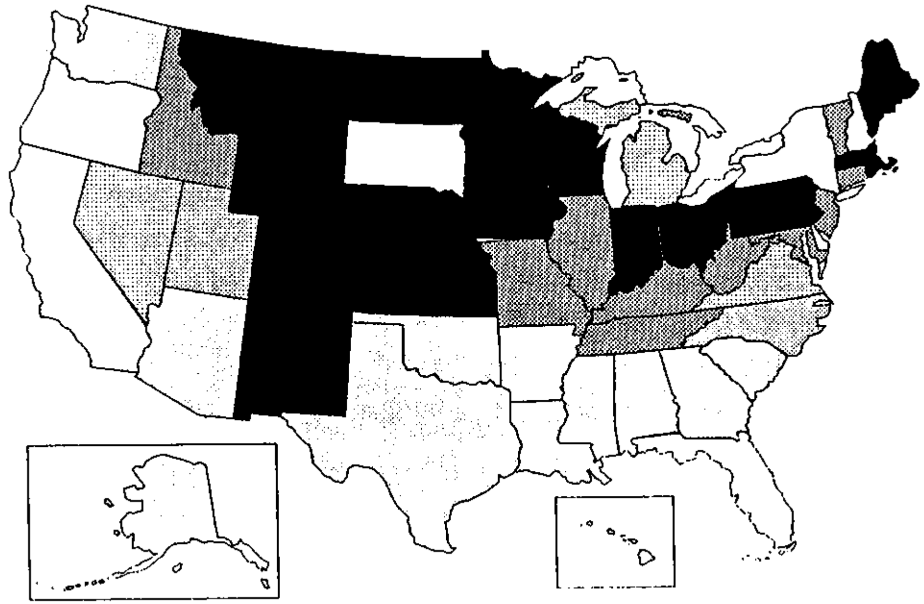
IV. The Valley and Ridge Province is underlain by faulted and folded terrestrial and marine sedimentary rocks that range in age from Cambrian through Devonian (570 to 345 million years ago). These rocks were deformed during the Appalachian mouintain building event that recrystallized the older rocks of the Piedmont Province. The glaciated portion in New York and northern New Jersey averages less than 6 pCi/l (Figures 1 and 2). South of the glaciated area (Warren County in New Jersey), indoor radon increases to averages of over 9 pCi/l (Figures 3 and 4).

V. Two additional provinces are found only in New York. The Plateau Province, which consists of undeformed Cambrian through Devonian strata, and the Adirondack Province, a circular uplift area which is geologically similar to the Highlands Province. The Plateau Province shows a high variability in indoor radon; the Adirondacks are uniformly low in indoor radon (Figures 1-4).

STATEN ISLAND

Indoor radon studies are particularly significant in areas of relatively high population density. State and federal public health agencies evaluate both local indoor radon levels (Figure 5) and population density (Figure 6) when promoting radon awareness through the news media. Maps of the United States have been generated using average indoor radon in counties and townships (Figure 7). By combining these zip code averages with geological and aeroradioactivity maps, United States maps of "radon potential" have been developed (Figure 8).

Cumulative 42 State/EPA Indoor Radon Survey Results



Estimated Percent of Houses with Screening Levels Greater than 4 pCi/L

Note: These results represent screening measurements and should not be used to estimate annual averages or health risks.

State	Avg. RN Level	Highest Level	% >4pCi/l
AK	1.7	192	8
AL	1.8	180	6
AR	1.2	24	5
AZ	1.6	51	7
CA	0.9	29	2.4
CO	4.6	81	39
CT	2.9	81	19
FL	1.9	270	10
GA	1.8	76	8
HI	0.1	6	.4
IA	8.9	130	71
ID	3.5	59	20
IL	2.9	92	19
IN	3.6	72	26
KS	2.9	27	21
KY	2.8	66	17
LA	0.5	8	.8
MD	3.1	140	19
MA	3.4	61	24
ME	4.1	103	30
MI	1.8	162	9
MN	4.8	70	46
MO	2.6	52	17
MS	0.9	23	2
MT	7.3	162	42
NC	1.4	35	7
ND	7.0	184	63
NE	5.5	123	54
NJ	2.8	100	16
NM	3.2	105	23
NV	2.0	47	10
OH	4.3	265	29
OK	1.1	25	3
PA	6.2	114	37
RI	3.5	64	19
SC	1.1	81	3
TN	2.7	100	16
TX	1.7	66	4
UT	1.8	68	13
VA	2.7	155	13
VT	2.5	47	16
WA	1.7	152	9
WI	3.4	142	27
WV	2.6	111	16
WY	3.6	81	26

FIGURE 5

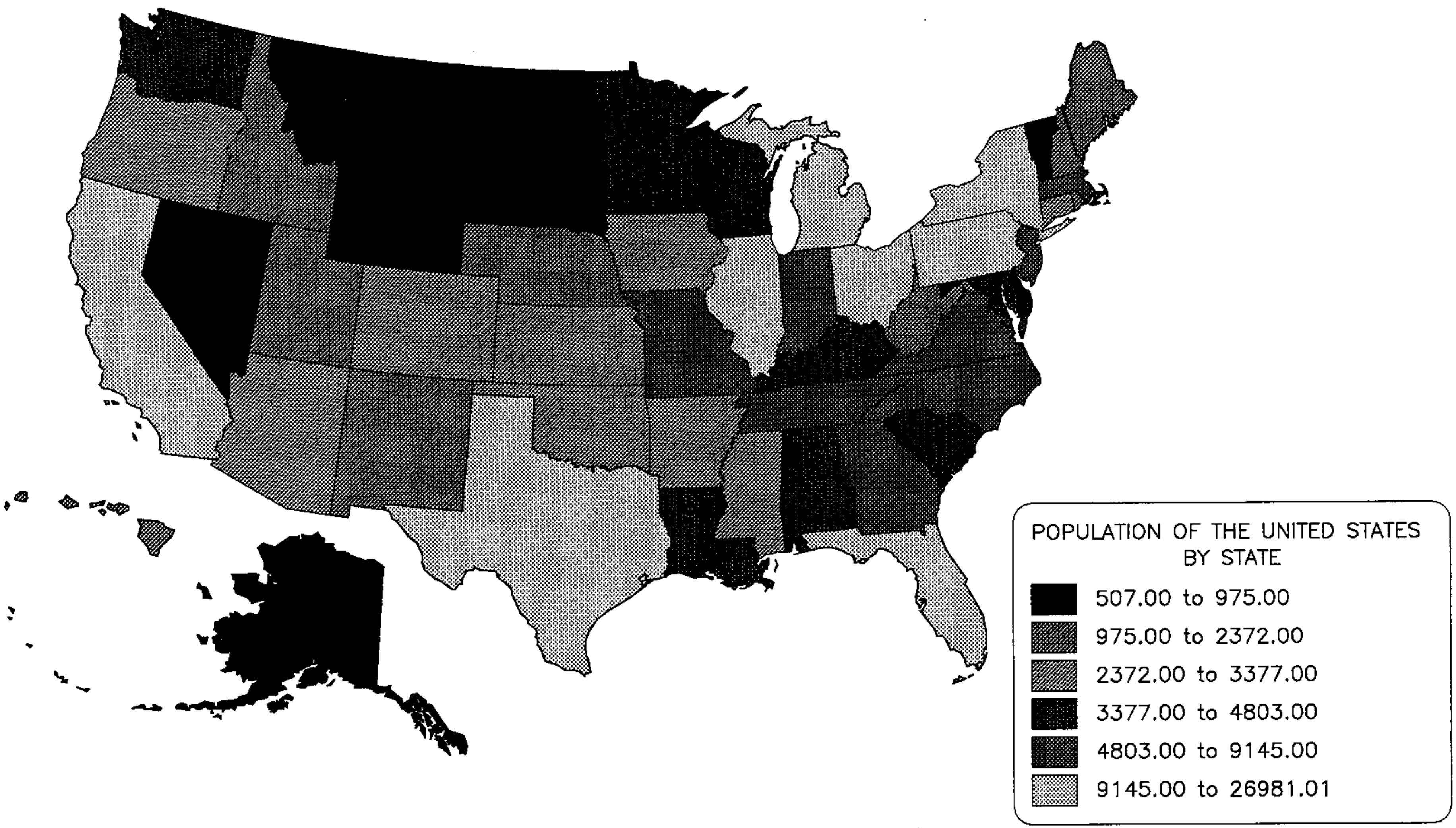

POPULATION OF THE UNITED STATES
BY STATE
507.00 to 975.00
975.00 to 2372.00
2372.00 to 3377.00
3377.00 to 4803.00
4803.00 to 9145.00
9145.00 to 26981.01

FIGURE 6

EPA Map of Radon Zones

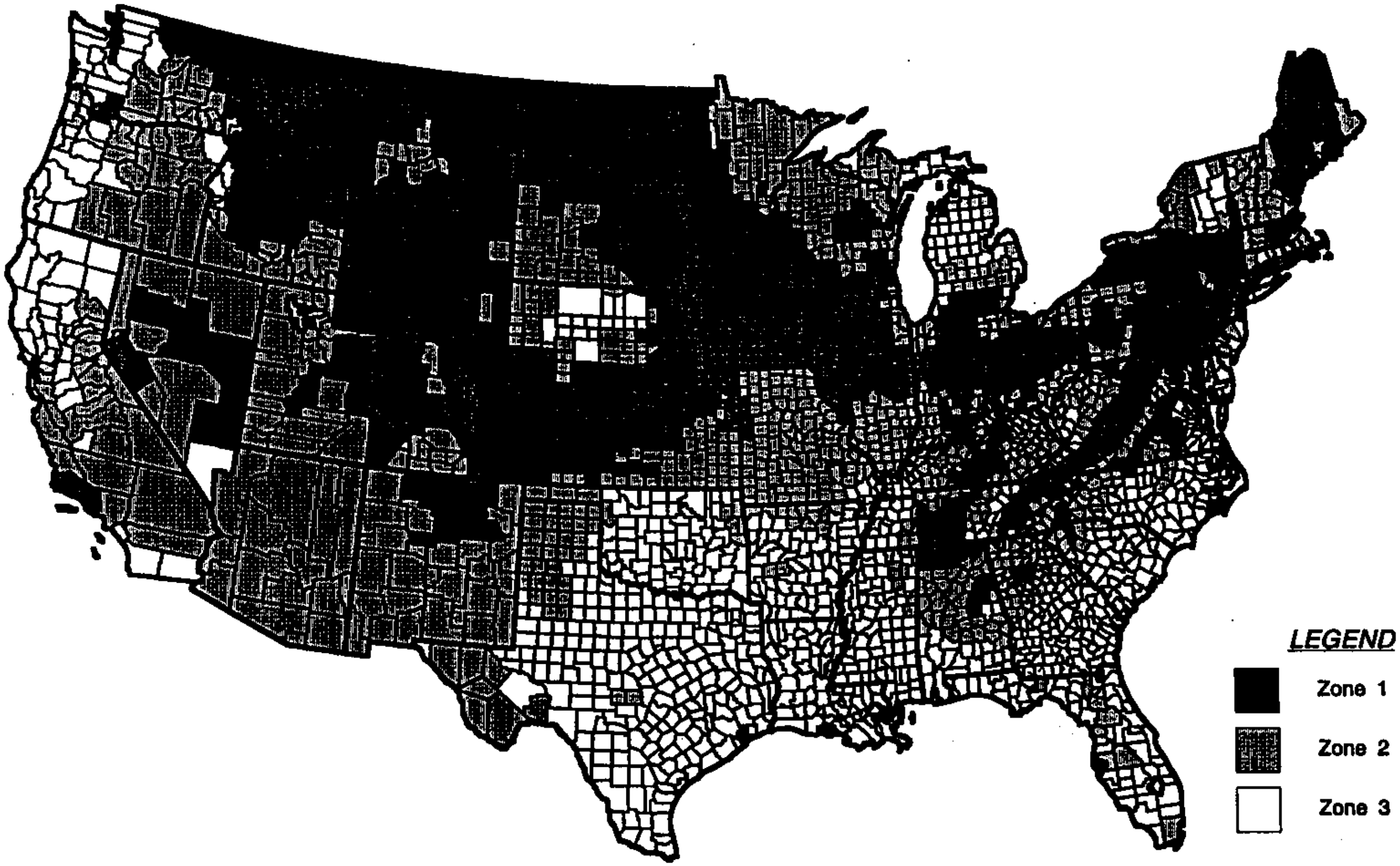


FIGURE 7

GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES
by the U.S. Geological Survey

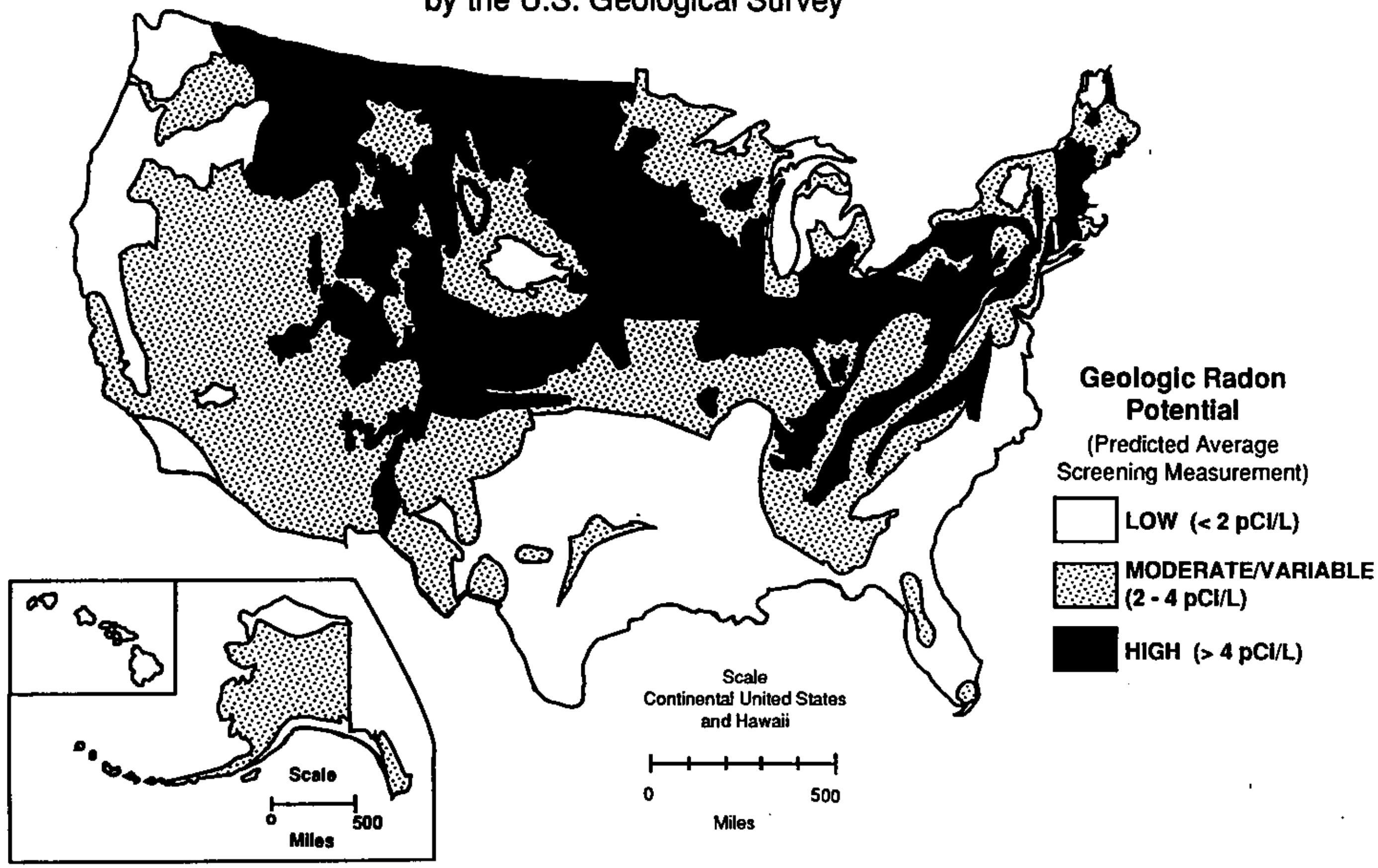


FIGURE 8

A compilation of indoor radon, population and estimates of radon related lung cancer can be similarily developed for Staten Island. The locations of the Staten Island zip code areas are shown on Figure 9; the populations are shown on Figure 10.

Staten Island Zip Code Area	1980 Population	Number Tests	Average Radon	Lung Cancer Cases/Year
10301	35000 people	33	2.0 pCi/l	0.14
10302	14100	15	0.8	0.02
10303	14000	18	0.6	0.02
10304	31800	28	1.7	0.11
10305	40300	33	1.3	0.10
10306	44200	64	2.1	0.19
10307	6300	11	0.5	0.01
10308	15600	52	0.9	0.03
10309	6000	37	1.2	0.01
10310	18300	19	1.5	0.05
10312	53400	90	0.7	0.07
10314	73100	110	1.2	0.18
			TOTAL = 1 person/year	

In this compilation, the 1980 population is presented so as to estimate the current per-year number of radon-related lung cancer. This tabulation is done with the assumption that a long exposure is required to develop radon related lung cancer (e.g., the years between 1980 and the present). It is also assumed that while many individuals move into and away from Staten Island each year, the lifetime radon exposure history of the average long-term Staten Island resident is similar to the average person who recently moved to Staten Island.

The tabulation presented above shows that all the zip code areas have average indoor radon levels of less than 4 pCi/l, the "action level" promoted by the US-EPA. A comparison with the geology of Staten Island (Figure 11) does not reveal which, if any, geological units represent particularly safe or unsafe radon risk areas. The average indoor radon levels are mostly between 1 and 2 pCi/l. By inference, the average home on Staten Island has an indoor radon level between 1 and 2 pCi/l. This observation, while useful as a predictive tool, can unfortunately serve to reduce public interest in having private homes tested. Even at the relatively low average values, some homes (est. = @5%) exceed 4 pCi/l.

To calculate the number of radon-related cases of lung cancer which develop in each zip code area each year, this formula is used:

Lung Cancer Cases = (1980 population) (average indoor radon) (0.000002)

In this formula, 0.000002 is a risk factor, derived from US-EPA estimates of the incidence of radon-related lung cancer. This factor is for the general population, and is based on several studies of metal-ore mining groups who were exposed to radon-enhanced air during the 1950's and 1960's. Groups of miners exposed to higher radon levels were found to develop lung cancer more frequently than groups exposed to lower radon levels.

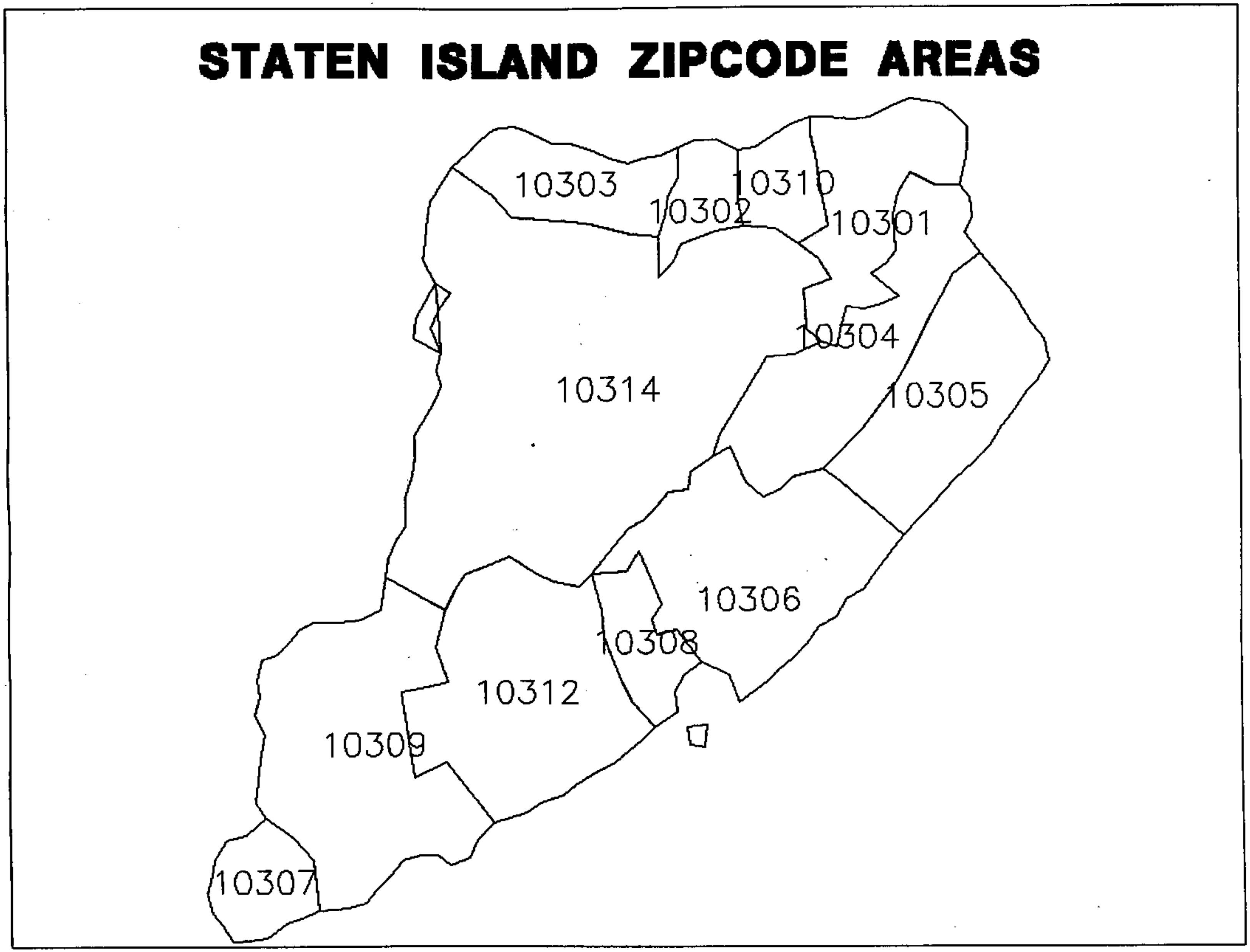

STATEN ISLAND ZIPCODE AREAS
10303
10302
10310
10301
10304
10314
10305
10306
10308
10312
10309
10307

FIGURE 9

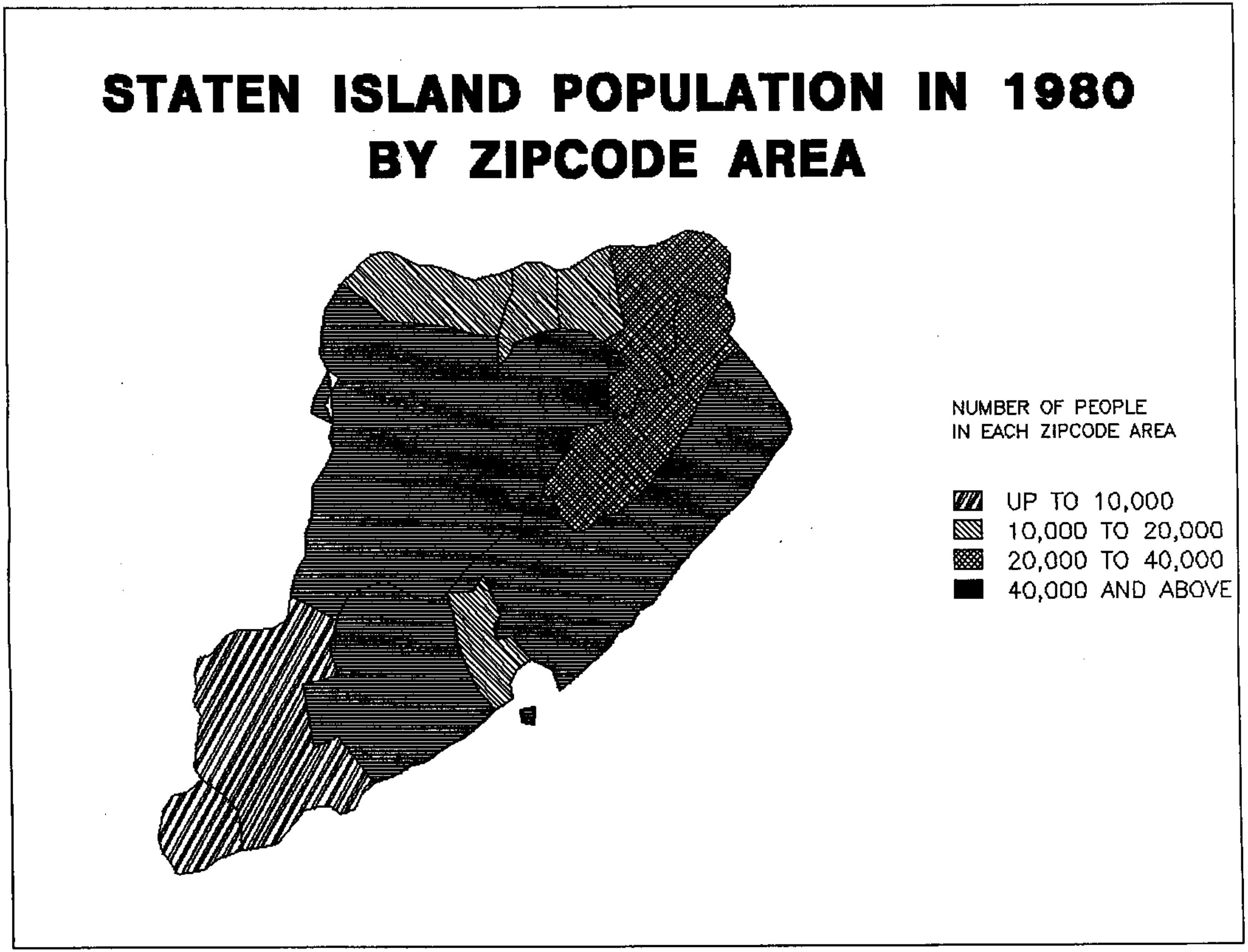

STATEN ISLAND POPULATION IN 1980
BY ZIPCODE AREA
NUMBER OF PEOPLE
IN EACH ZIPCODE AREA
UP TO 10,000
10,000 TO 20,000
20,000 TO 40,000
40,000 AND ABOVE

FIGURE 10

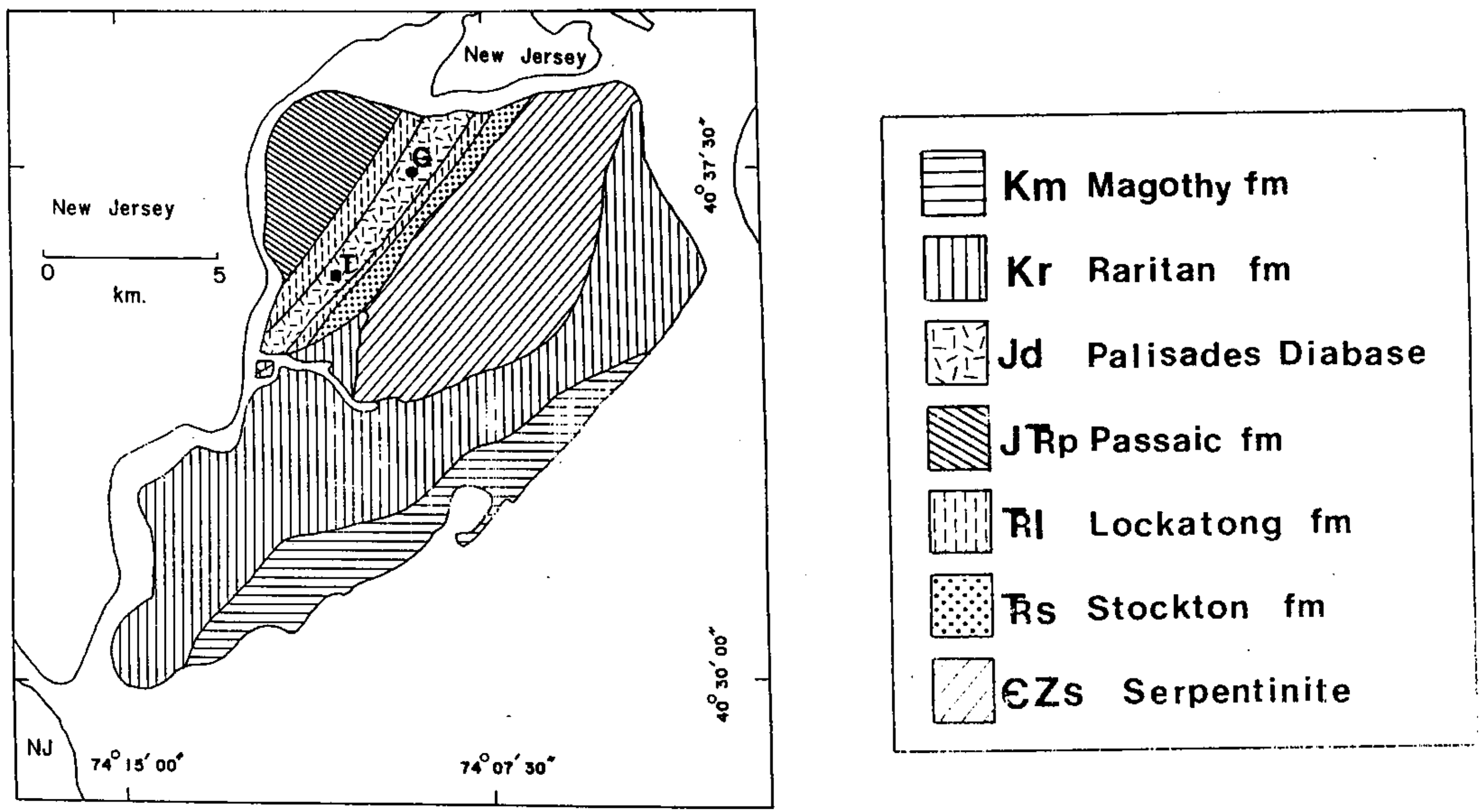

New Jersey
New Jersey
0
5
km.
G
T
NJ
74° 15' 00"
74° 07' 30"
40° 37' 30"
40° 30' 00"
Km Magothy fm
Kr Raritan fm
Jd Palisades Diabase
J₸p Passaic fm
₸l Lockatong fm
₸s Stockton fm
ЄZs Serpentinite

FIGURE 11

Estimates of the Staten Island radon-related lung cancer deaths show that in total, all of Staten Island probably generates about one radon-related lung cancer death each year. The estimate for a generation (multiply by 20) or for a lifetime (multiply by 70) are of course higher than the per-year estimates, but the degree to which these lung-cancer cases are preventable is of some import. For more than half of the homes, where indoor radon is less than 2 pCi/l, remediation to reduce indoor radon is not likely to be effective. While remediation can be very effective in homes with indoor radon levels of 4 to 400 pCi/l, most remediation methods commonly used today are not very effective below 2 pCi/l. However, for the estimated 5% of the Staten Island homes with indoor radon above 4 pCi/l, remediation would serve to reduce the radon-related lung cancer risk to these home occupants.

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Puskin, J.S., and Yang, Y., 1988, A retrospective look at Rn-induced lung cancer mortality from the viewpoint of a relative risk model: Health Physics, v. 54, p. 635-643.

Geological Collections at the Staten Island Institute of Arts and Sciences

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The Staten Island Institute of Arts and Sciences houses geology collections focusing on the New York-New Jersey area. The Staten Island collection contains about 1200 catalogued specimens of rocks, minerals and fossils. Many of the specimens were collected in the late nineteenth and early twentieth centuries by Arthur Hollick. More recent collections from the 1950s through the 1990s are represented as well. Also included in this collection are the type specimens of plant fossils collected by Hollick in the Kreischerville clay pits.

The non-Staten Island regional collection contains about 400 catalogued specimens of rocks and minerals from New York City, lower New York State and New Jersey.

In addition to the above collections, there is also a world-wide collection of about 2700 minerals and fossils, many from historically important localities.

The SIIAS is also a repository for publications of the United States Geological Survey. The collection contains the following serials: Bulletins, Professional Papers, Water Supply Papers, Monographs, Annual Reports, and Abstracts of North American Geology. There are a number of non-serial publications as well. Most of the serial runs date from the late nineteenth century to the present time.

Access to both the geology collections and the USGS materials is available to qualified researchers. Research appointments can be made by contacting the science curator.

The Naming of Staten Island

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Staten Island was first given a name by its Native American inhabitants, the Lenape, who called it "Eghquaons", meaning high sandy banks. This was later anglicized into the name "Aquehonga". Another Lenape term for Staten Island was "Motanucke" - land of periwinkles. The oft-cited term "Monocknong" is of doubtful meaning (Leng and Davis, 1930).

When Henry Hudson sailed into New York Harbor in the early 17th century, he saw Staten Island, and had some rather unsatisfactory dealings with its inhabitants. He named it "Staaten Eylandt", in honor of the States-General, the governing body of Holland (Clute, 1877).

Clute, J.J. 1877. Annals of Staten Island, from its discovery to the present time. Press of Chas. Vogt. New York.

Leng, C.W. and W.T. Davis. 1930. Staten Island and its people. Vol. 1:79. The Lewis Historical Publishing Co., Inc. New York

Hydrologic Reconnaissance Of The South Beach Freshwater Wetlands

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INTRODUCTION and LITERATURE REVIEW

The South Beach Freshwater Wetland (SBW) is a state designated wetland (NA-7) contained within a 204 acre area of contiguous, low-lying land in northeast Staten Island. Figures 1a and 1b are maps of the wetland and vicinity. The SBW is bordered by Sand Lane and Quintard Street to the north, Father Capadanno Boulevard to the east, South Beach Psychiatric Center and Staten Island Hospital to the south, and Mason Avenue to the west.

Historically, the site was part of a 1.1 square mile salt march that extended from South Beach to New Dorp that received surface runoff and groundwater from an area of 6.4 square miles (Figure 2). Four major creeks joined within the marsh at the site now occupied by the Psychiatric Center, and flowed out to sea around the foot of Seaview Avenue. The creeks serving the wetlands have been mostly routed into storm sewers, yet it still received groundwater from an area of about 3.6 mi^2 serving as the area's primary groundwater discharge zone.

The DEC's Draft Programmatic Environmental Impact Statement on Staten Island's Freshwater Wetlands Restoration released in 1990 (DEC DEIS 1990) provides a good introduction to the present status of Staten Island's wetlands, the adverse impacts of eliminating and disturbing wetlands, and some ways to minimize these impacts on ecological systems. The severest impacts are a result of direct habitat loss through development, but habitat fragmentation has eliminated many species of plants and animals. As a result, biological diversity has been severely reduced (DEC DEIS 1990). Since wetlands serve as resting and feeding grounds for migratory birds, they are key components of the Atlantic Migratory Flyway. Many of the wetlands have been destroyed making the few that remain increasingly valuable.

Development of wetlands is regulated by the federal government under the Clean Water Act, and a Section 404 permit is required from the Army Corps of Engineers under the federal wetlands program. In New York State, the standards for permit issuance contained in the Freshwater Wetlands Permit Regulations (6 NYCRR Part 663) generally prohibit construction, excavation, filling, or other development projects in wetlands if these projects diminish wetland benefits (especially those enumerated by the Freshwater Wetlands Act, Section 24-0105(7) of the Environmental Conservation Law) (DEC DEIS 1990). In New York State, freshwater wetland adjacent areas are defined by the Freshwater Wetland Law (Article 24 of the State Environmental Conservation Law) as bands 100 feet wide encircling to freshwater wetlands. These adjacent areas may be widened beyond 100 feet. The primary purpose of wetland adjacent areas is to buffer and protect wetlands (DEC DEIS 1990).

The South Beach Wetland offers a tremendous opportunity for a freshwater wetland enhancement program which could be designed to:

1) improve its flood protection value,
2) provide critical freshwater march habitat for fish and waterfowl,
3) serve as a valuable open space for recreational use, and
4) provide research opportunities for scientists and environmental engineers.

One of the primary questions that must be addressed when evaluating the success of a created, restored, or enhanced wetland is, to what extent does the wetland provide biological and hydrological functions similar to those of the original or desired "reference" wetland? (Erwin 1989). Wetland evaluation methods are discussed in the literature (Golet 1973, Winchester and Harris 1979, Reppert et at. 1979, U.S. Army Engineer Division 1980, U.S. Fish and Wildlife Service 1980, Lonard et al. 1981, Adamus and Stockwell 1983, Euler et al. 1983, Lonard et al. 1984, and Marble and Gross 1984).

Soren (1988) provides much of the known information about Staten Island's hydrogeology and groundwater occurrence. All wetlands are strongly influence by hydrology and are dependent on water supply. The drainage of water into the SBW has been greatly altered by urbanization of its watershed and the routing of water through culverts. The hydrologic impacts of urbanization have been well described by Leopold (1968), Rantz (1971) and others. The immediate hydrologic effect is to increase the speed of water transmission in channels. Sediment yield is increased, and the reduction of drainage density tends to increase sediment load (Dunne and Leopold, 1978). In addition, non-point source pollutants from urban areas runs off and is concentrated and stored in sediments where flow is minimal.

For a review of life histories and zoogeography of fishes of the Atlantic Coastal Plains, refer to Hubbs and Lagler (1965) and Hocutt and Wiley (1986), and McClane (1974).

The drainage criteria that New York City Department of Environmental Protection uses is the rational method, and is described in (Dunne and Leopold, 1978) and Cronshey (1986).

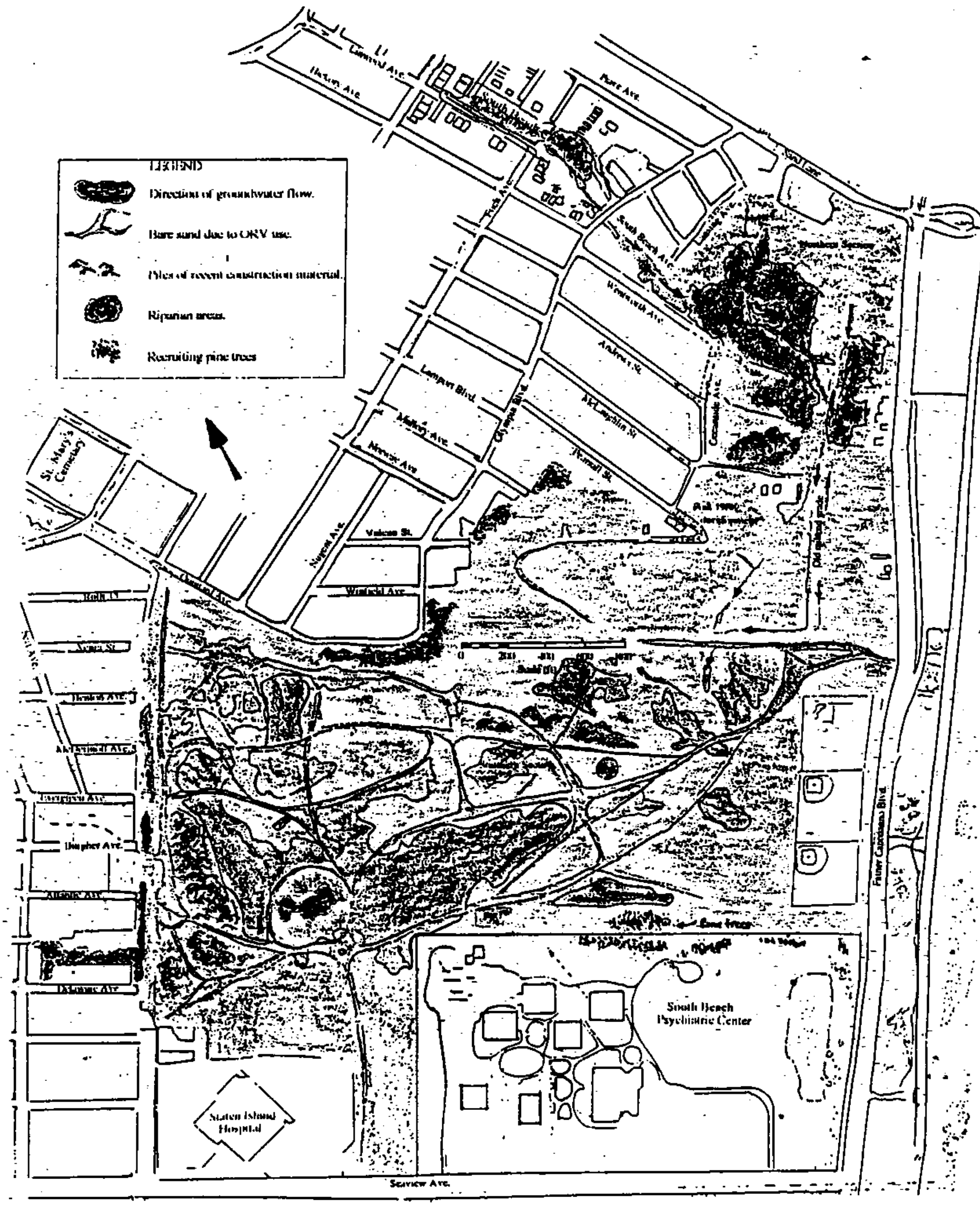

Figure 1a: A diagrammatic view of the South Beach Freshwater Wetlands and vicinity. Note the extensive off-road vehicle trails crossing the Southern Section (from 1988 photoquads, # 6-1176, 6-1174, courtesy of New York City Department of Planning, Staten Island Office).

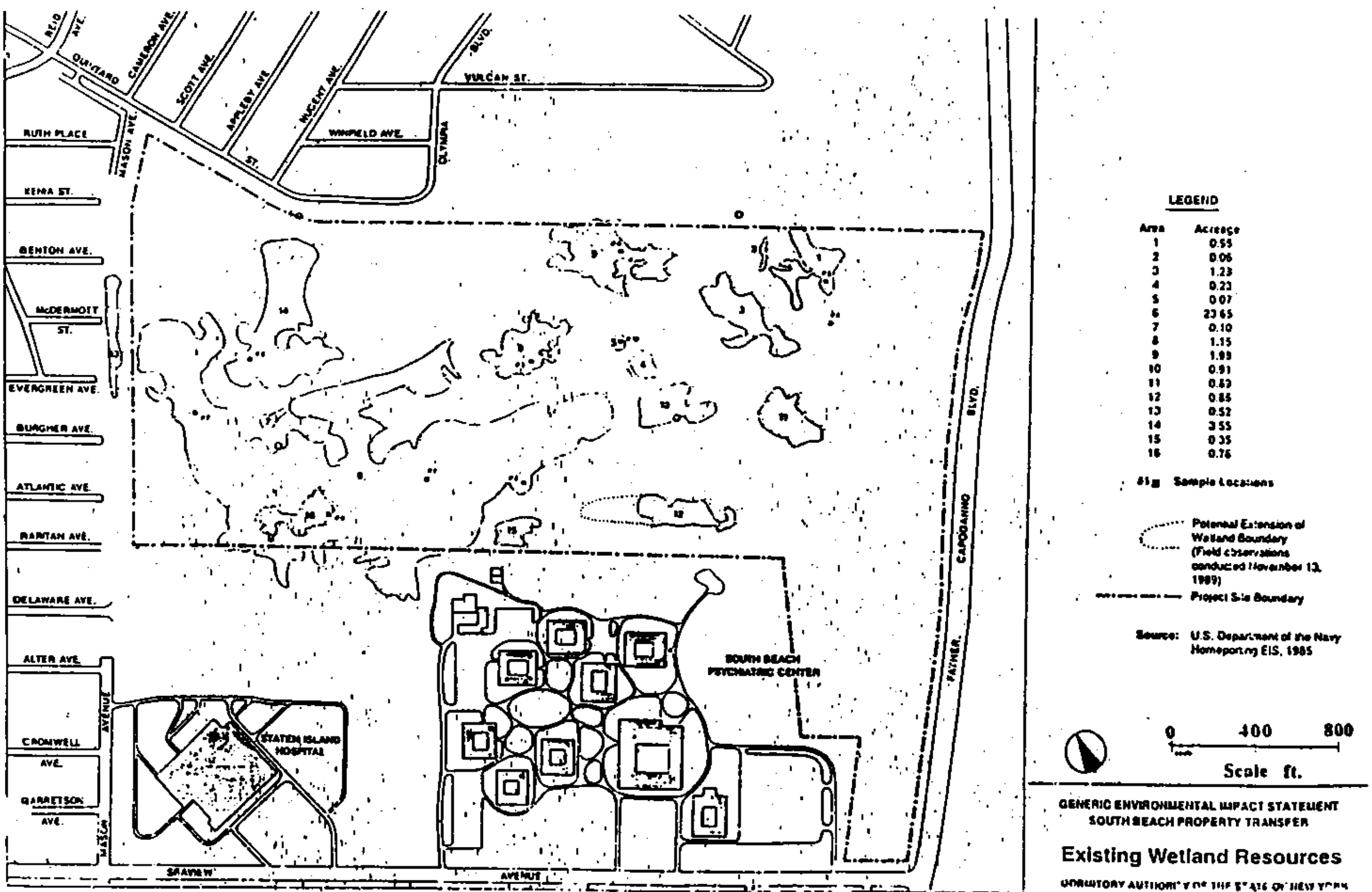

Figure 1b: Map of the existing wetland resources at South Beach, from the Generic Environmental Impact Statement. Property Transfer. (Source: U.S. Department of the Navy, Homeporting EIS, 1985).

METHODS

Mapping

The existing features of the site were mapped using large-scale (1:4,800) black and white aerial photoquads from 1970 and 1988. These were overlayed with mylar and the pertinent geographic features outlined manually. Features such as existing water courses, vegetational boundaries, and streets were identified. Color enhancement was also done on several figures using manual techniques with colored pencils which were then copied with a color copying machine.

Borough of Richmond topographic survey sheets developed in the early 1900's (Scale 1:1,800) were used to evaluate site-specific topographic and hydrologic conditions prior to urbanization. New York City Department of Water Resources Drainage Plans and I & I Maps were used to obtain specific information on sewer locations, size, gradients, and other pertinent information, and to evaluate the design criteria and procedures used by the Department of Environmental Protection for routing storm water.

Field Investigations

Having spent the first 25 years of my life living in the area, I have seen the Perrines and South Beach Creek watersheds go through a great deal of changes. The information contained within this report is a synthesis of my lifelong experiences there. In addition, I conducted field investigations between January 3rd and 9th, 1992 with the following objectives:

1) Photo-document some of the site's most important features.
2) Identify flood-prone areas and sources of non-point source pollution.
3) Evaluate the watershed's physical response to a moderate rainfall.
4) Evaluate topographic/vegetative gradients and boundaries in relation to the location of groundwater.
5) Measure general physical parameters of the creeks to evaluate their ability to transport water and sediment.

Basic measurements such as bankfull width and depth were made with a tape measure. Substrate size distribution was estimated by occular techniques. Gradient was estimated in the field with a clinometer and compared with values of invert elevations recorded on the city's drainage plan maps. The 1909 topographic survey maps to determine historic gradients of specific reaches and compared with field measurements. Individual reaches of the creeks were separated based on physical parameters and described separately.

DRAINAGE BASIN CHARACTERISTICS AND HYDROGEOLOGY OF SOUTH BEACH WETLANDS WATERSHED

In order to more fully understand the present hydrologic conditions at the South Beach Wetland, a description of the hydrogeology of the watershed, hydrologic inputs to the wetland, and the hydrologic changes brought about by the recent suburban development will be presented. An adequate understanding of the hydrology and topography of the site and its watershed is the first step for any wetland evaluation.

Drainage Basin Characteristics and Hydrogeology

Figure 2 shows the historic drainage area as depicted on the 1900 U.S. Coast and Geodetic Topographic Survey of Staten Island, NY. The area of the original drainage basin was 6.4 mi^2, about 10% of the total land area of Staten Island. The extent of the salt marsh is depicted in orange. The outwash plain of Grasmere, South Beach and Dongan Hills consisted of stratified fine to coarse sand and gravel and was either open fields, under cultivation, or forested, and is depicted in light green. The serpentine upland was steep, largely forested and shown in dark green.

Surface and Subsurface Hydrologic Inputs into the SBW

The past and present drainage basin boundaries, the locations of hydrologic inputs to the site, and the location of DEC-designated wetlands NA-6 (Brady's and Camerons Ponds), NA-7 (the South Beach Freshwater Wetland), NA-8 and NA-9 are depicted in Figure 3. Much of the area downgradient of Richmond Road has been urbanized and the drainage culverted. The creeks draining the New Dorp and Grant City areas (NA-8 and NA-9) once converged with the Perrine's and South Beach Creek drainages as stated earlier, but today, the Seaview Avenue storm sewer routs the creeks from NA-8 and NA-9 under the street, eliminating any former surficial hydrologic connections. There is no reason to suspect, however, that groundwater cannot pass freely under this area.

Because of its complex surficial and subsurface geology, Staten Island possesses a complex set of hydrologic conditions (DEC DEIS, 1990). The SBW is fed by both groundwater and surface water. Groundwater contributes a greater percentage of the water entering the wetland since much of the surficial drainage has been routed into storm sewers which bypass the site and flow directly into the Bay. Although Soren (1988, pg. 4) claims no streams occurs eastward toward the Narrows or Atlantic Ocean between St. George and Sequine Point, Perrines Creek and South Beach Creek do in fact exist, and will be described in detail.

Precipitation, Groundwater Recharge and Movement

Little site-specific precipitation data are available. U.S. Weather Bureau records of 1948-

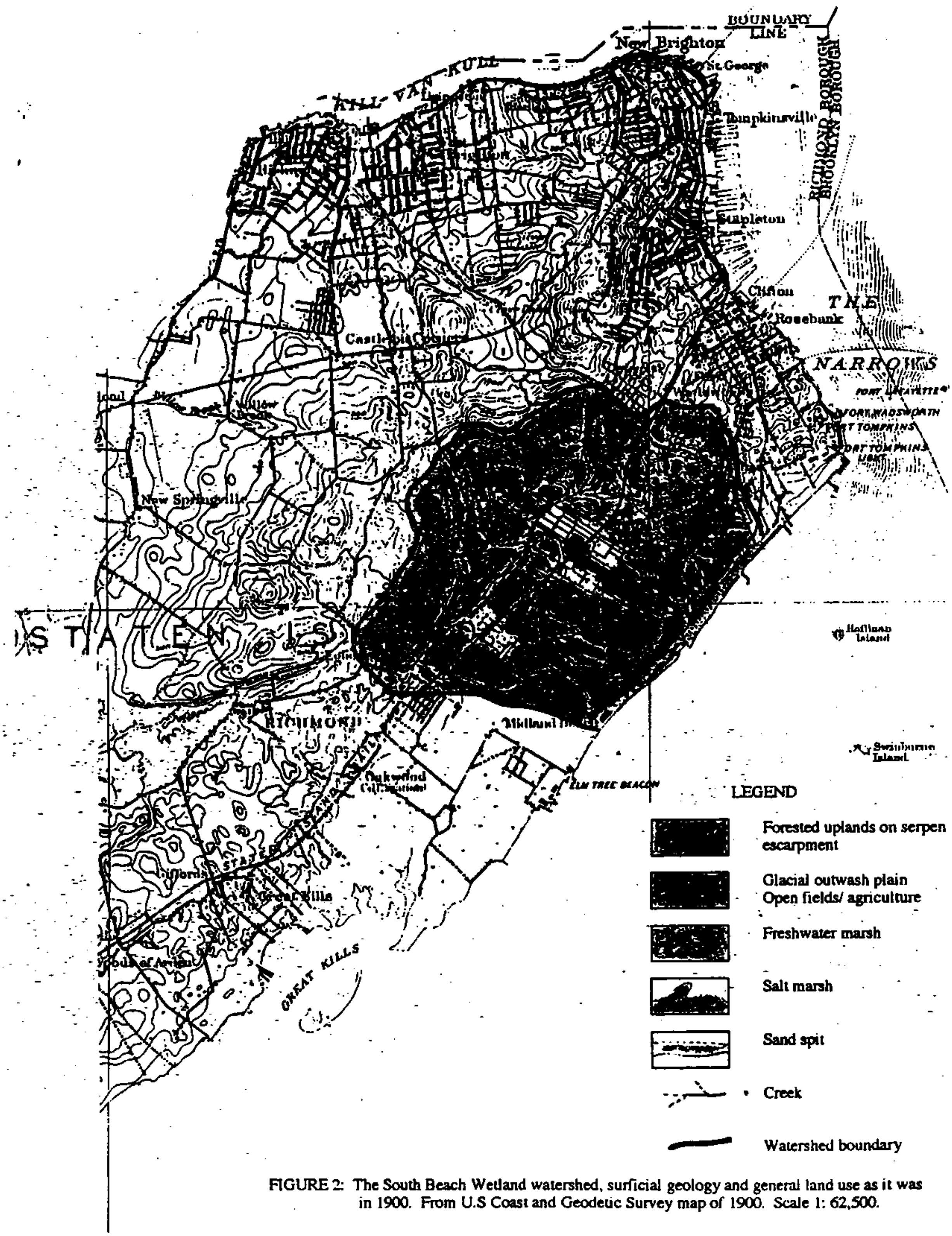

FIGURE 2: The South Beach Wetland watershed, surficial geology and general land use as it was in 1900. From U.S Coast and Geodetic Survey map of 1900. Scale 1: 62,500.

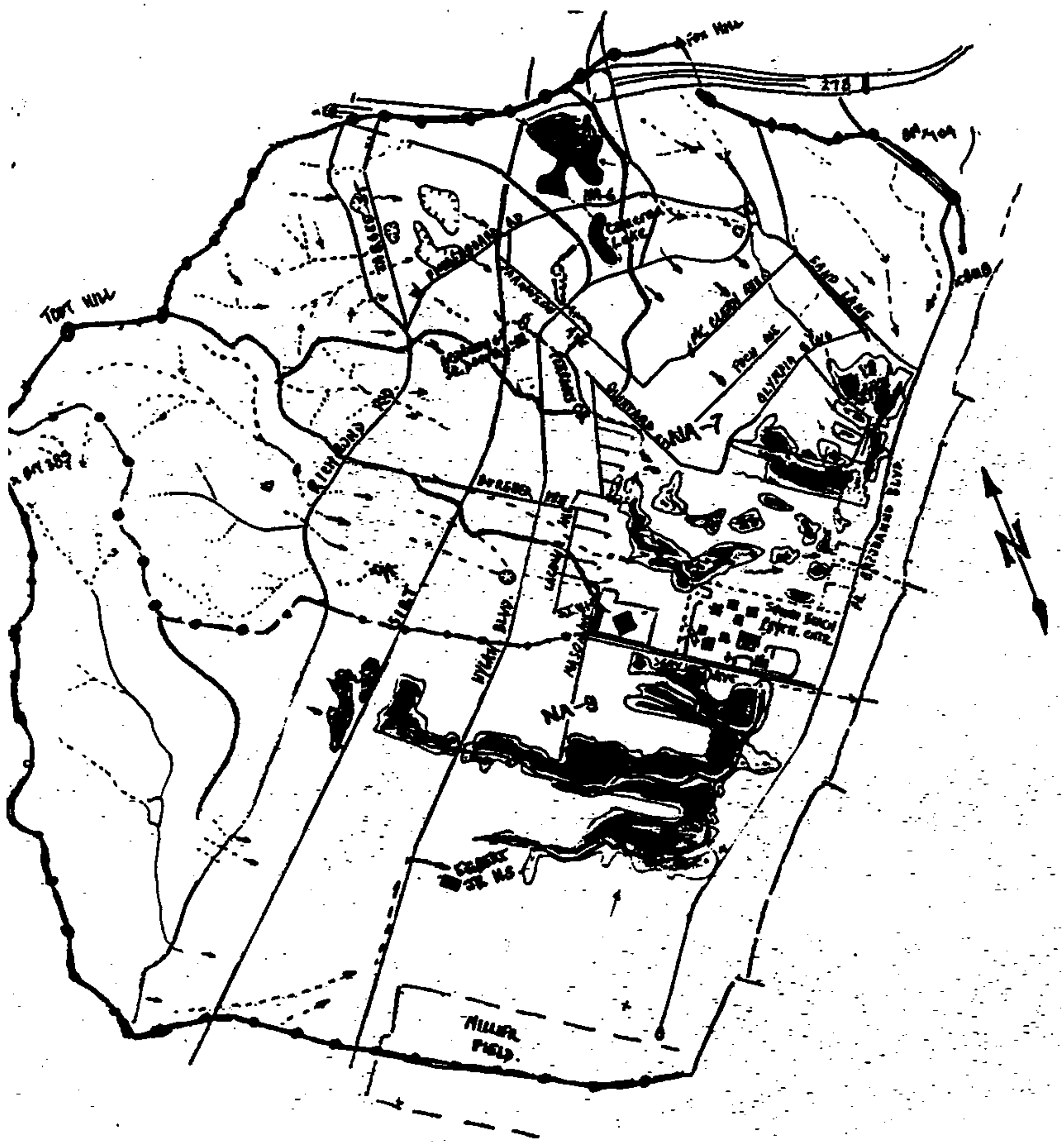

Figure 3: The extent of regional drainage basins and the creeks feeding the SBW. Blue-colored arrows indicate the direction water flow. The wavy blue arrows in the SBW indicate the direction of groundwater flow through the wetland. The green lines indicate drainage basin divides. The orange areas are state-designated wetlands (Scale 1: 24,000).

1968 indicate an average annual rainfall is about 44 inches in north-central Staten Island (Westerleigh), with the average monthly precipitation of 3.5 inches except in July and August when it averaged 4.5 inches (Soren 1988).

The streams and groundwater of Staten Island derive most of their water from precipitation, but leaking water mains, sewers and individual wastewater disposal systems may contribute significant amounts of water (Soren 1988). Streamflow during dry periods is maintained by groundwater recharge into their channels. Perrines Creek is a perennial stream, while South Beach Creek flows intermittently. In general, during rain storms, water enters the ground in areas with permeable soils and flows through the aquifer. This water is freely transmitted in a southeasterly direction toward the SBW in the upper glacial deposits of the outwash plain and discharges into the wetland. Figure 4 shows a cross section from the upper watershed near Todt Hill, southeast toward the SBW along Evergreen Avenue. Geologic units, average surface gradients, and major landmarks are depicted. The depressions on the hills are zones of recharge where precipitation enters the aquifer. From here, the water flows southeastward under Richmond Road and the SIRT tracks, picking up pollutants from the land above, and eventually reaches the wetland. The relative contribution of groundwater has become increasingly more important since much of the surficial runoff is routed through sewers under the SBW. Since the aquifer is unconfined, surface water is directly connected to the water table. The levels of water in the area is generally a reflection of the regional water table, and rise and fall in concert with the water table (Soren 1988).

The Upper Watershed

The upper, western limit of the watershed is the steep, serpentine escarpment of central Staten Island from Emerson Hill, south of Moravian Cemetery. The Wisconsin ice sheet reached its southern terminous here at the end of the Pleistocene Epoch about 12,000 years ago and is responsible for the steep topography of the region (Soren 1988). Much of this area has remained undeveloped and groundwater recharge occurs here flowing southeastward toward the SBW.

Outwash Plain

Southeast of the terminal moraine, lies an outwash plain consisting of sand and gravel beds with very little disseminated clay and silt (Soren 1988). This material was washed from the terminal moraine by large volumes of meltwater as the glacier receded. Water within the outwash plain is almost everywhere under unconfined conditions. It reaches its greatest thickness of about 125 ft in area between Arrochar and New Dorp and overlies the deeper Cretaceous sands and interbedded clays forming the groundwater system, known as the Staten Island aquifer, that supplies the SBW (Soren 1988).

Due to their course character, these deposits have high hydraulic conductivity and yield large amounts of water (Soren 1988). Prior to the recent urban development, many bogs and swamps were found in this area which represented zones of recharge where stormwater percolated

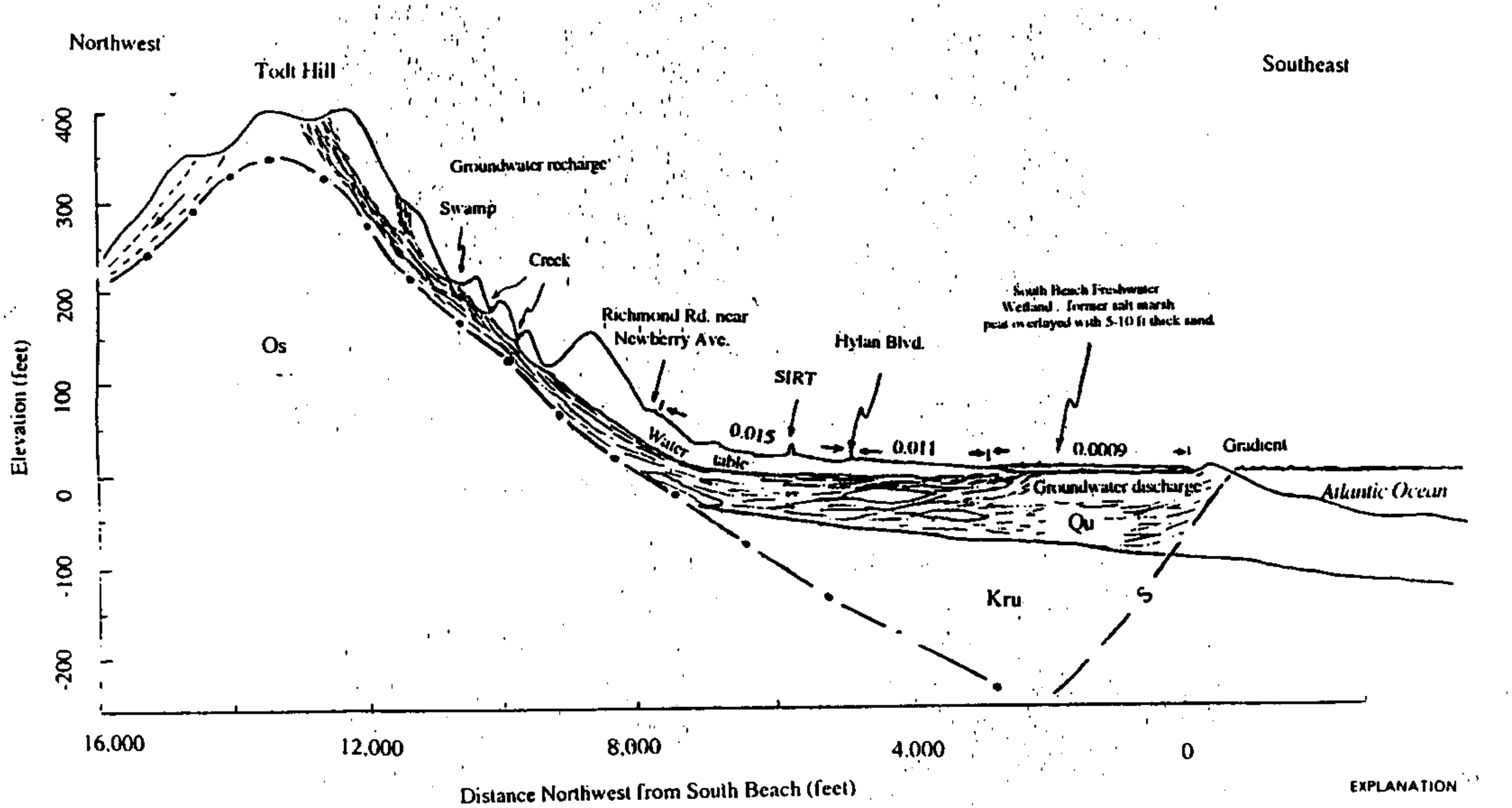

Figure 4: A cross section of the SBW watershed from Todt Hill, southeast along Evergreen Street, and across the SBW. Zones of groundwater recharge are seen in the upper watershed which flows southeastward discharging into the SBW. Topographic data from 1909 Borough of Richmond Topographic Survey, geologic data from Soren (1988). Vertical exageration is approximately 13 x.

into the ground; and zones of discharge, where groundwater surfaced. Few of these sites remain. Urban development has drastically changed the hydrology of the basin by increasing overland flow, impacting water quality, and exacerbating flooding problems, and routing storm water through sewers making water unavailable for plants and animals.

The Salt Marsh

Southeast of the outwash plain is the low-lying region from South Beach to Midland Beach that includes the SBW. This area was formerly a salt marsh, about 1.1 mi^2 in area. The marsh received runoff from four major streams, and tides reached beyond what is now Hylan Boulevard. Perrines Creek flowed into the marsh near Reid Avenue at Quintard Street and flowed south-southeastward through the marshlands toward the site now occupied by the South Beach Psychiatric Center with a rather high sinuosity of 1.5* Its average width was about 25 feet.

The four streams converged within the salt marsh in the area now occupied by the South Beach Psychiatric Center and flowed out to sea just south of Seaview Avenue and was known as New Creek. The marsh contained deep deposits of salt marsh peat, and was separated from the ocean by a thin strip of recent beach sand sorted by ocean currents and deposited on the beach.

RESULTS

I will present a brief history, results of field investigations, and a summary of cartographic analysis of the South Beach Wetland, Perrines and South Beach Creeks.

The South Beach Wetland

The South Beach Freshwater Wetland consists of two adjacent sections with different histories and physiographies (Richter 1987) which will be described separately.

The Southern Section

General History

The southern section, comprising about 75% of the total area of the wetland, is bordered by Quintard Street to the north, Father Capadanno Boulevard to the east, the South Beach Psychiatric Center and Staten Island Hospital to the south, and the proposed extension of Mason Avenue to the west. This section is part of a larger parcel of land that the state of New York

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*NOTE: Sinuosity is a ratio of the channel length between two points on a channel to the straight line distance between the two same points. Channels with sinuosities of 1.5 or more are called "meandering".

amassed through condemnation in the early 1950's for building a State University Campus (Kosinski 1990). In the 1960's, the state-owned land was hydofilled with sand dredged from Raritan Bay to depths of 5 to 10 feet, an estimated volume of 30 to 60 million ft^3. In 1965, two box culverts which carry storm water below the site and out to Lower New York Bay, were installed to prepare it for this development.

The Dormitory Authority floated specific-purposed bonds to pay for the land and future campus. In the late 1960's, the South Beach Psychiatric Center was built and completed in the early 1970's. At the same time, the Seaview Avenue storm sewer was installed, routing the creeks from New Dorp, now part of NA-8 and NA-9.

In the mid 1980's the State University finally rejected the site because of flooding and cost, and the Dormitory Authority transferred funds to acquire Willowbrook State Psychiatric center. Shortly thereafter, the U.S. Navy considered plans to build a 1,500-unit, low-density, low-rise residential housing for the homeport. Even after scaling down to 350 units, the plan was rejected because of the flooding problems and costs associated with building on the wetlands.

In 1986-87, the DEC developed an inventory of all wetlands on Staten Island. The South Beach Freshwater Wetland (NA-7) was determined to contain 89 acres of wetlands: 38% wet meadow, 49% emergent marsh, and 13% open water. The site classified as a Class I wetland since it was resident habitat of a state threatened animal species, the northern harrier. In addition, it was concluded that species richness and numbers of shorebirds were greater than for all but a few localities on Staten Island, and was one of the few places in the county where snipe and fowler's toads were found in such high numbers (Richter 1987). This section, "with its shallow wetlands, open water bodies, and dense cover, provides habitat for many species of shorebirds, ducks, and passerines" (Richter 1987).

Nonetheless, the land is still not protected. Under the Accelerated State-Owned Land Disposition Program, the State of New York is attempting to help finance its ballooning debt. Many of the surplus lands it is trying to sell are environmentally sensitive. In April 1994, the Office of General Services under Commissioner John Hudacs was asked by Dr. Henrik Dullea, the chairman of the Real Property Planning and Policy Review Committee, to prepare and forward a current list of surplus property to the DEC and OPRHP for immediate review. Dullea developed a list of environmentally significant state-owned land for which full environmental reviews had not been compiled. In early 1990, Governor Cuomo announced a moratorium on selling environmentally sensitive land, but this list did not include the SBW.

Since 1989, the Staten Island Hospital has been negotiating with the Dormitory Authority to purchase 137 acres of the land for senior housing under the Disposition Program. I spoke with Dale Tate, the assistant to the president of the hospital in early January, 1992 about the sale. She stated that the deal was still being negotiated and could not comment on the outcome.

Ecological History and Field Investigations

Historically, the site was part of a 1.1 mi^2 salt marsh that extended from South Beach to New Dorp that received surface runoff and groundwater from an area of 6.4 mi^2 (Figure 2). Four major creeks joined within the marsh at the site now occupied by the Psychiatric Center and flowed out to sea around the foot of Seaview Avenue. When the tide gates were installed, salt water was no longer able to intrude, and freshwater conditions dominated. When the site was hydrofilled, the channels and salt marsh peat were buried, and a whole new set of conditions drastically altered the ecology of the site. The present condition of this area is the result of almost 30 years of primary succession on the hydrofill. An ecological positive feedback mechanism is thought to be taking place (Richter 1987) whereby organic matter produced by the plants is deposited on the ground which then starts decomposing. This causes the soil to become less pervious and allows water to remain for longer periods of time after a rain event. As a result, the water holding capacity of the soil is increased, thereby enhancing the growth of wetland plants. However, continued disturbance from ORV use and fires sets back ecological succession, providing and effective negative feedback preventing the growth of wetland plants.

Groundwater from at least 3.6 mi^2 of area reaches the site discharging in zones of greater porosity thereby establishing conditions suitable for wetland plants. A series of shallow basins have formed at these sites. Most of these basins support wet meadow vegetation such as *Andropogan, Apocynum, Juncus, Equisetum, Leersia, Phragmites,* and *Sorgastrum.* Willows (*Salix* sp.) and cottonwoods (*Populus* sp.) are scattered along the subsurface water course that flows diffusely southeastward through the site. Most of the water eventually reaches a storm sewer where it flows under Father Capadanno Boulevard and into Lower New York Bay under a concrete groin. The wetlands can be expected to further develop and expand in size if succession continues (Richter, 1987). But this will only happen if the site is protected from development.

In Figure 1a, groundwater flow is depicted by wavy arrows and wetland areas depicted in blue-green. Water tends to stagnate in ditches near the foot of Evergreen Avenue and Xenia Street.

Numerous trails of bare sand criss-crossing the site . These trails have been made by off-road vehicle riding. A series of small puddles were identified starting from the northern corner of the South Beach Psychiatric Center (SBPC) fenceline, and heading north. Historically, a tidal creek flowed south through this area, but the Psychiatric Center was built directly above it. The SBPC runoff now flows subsurface northward for about 200 feet, and is then deflected toward the southeast after coming in contact with the main groundwater flow from the northwest. A gallon of spent motor oil had been dumped in one of the puddles in this area.

The lodgepole pine trees planted on the SBPC property in the early 1970's have reached maturity, and over 100 trees have established within the SBW in the area shown in Figure 1a.

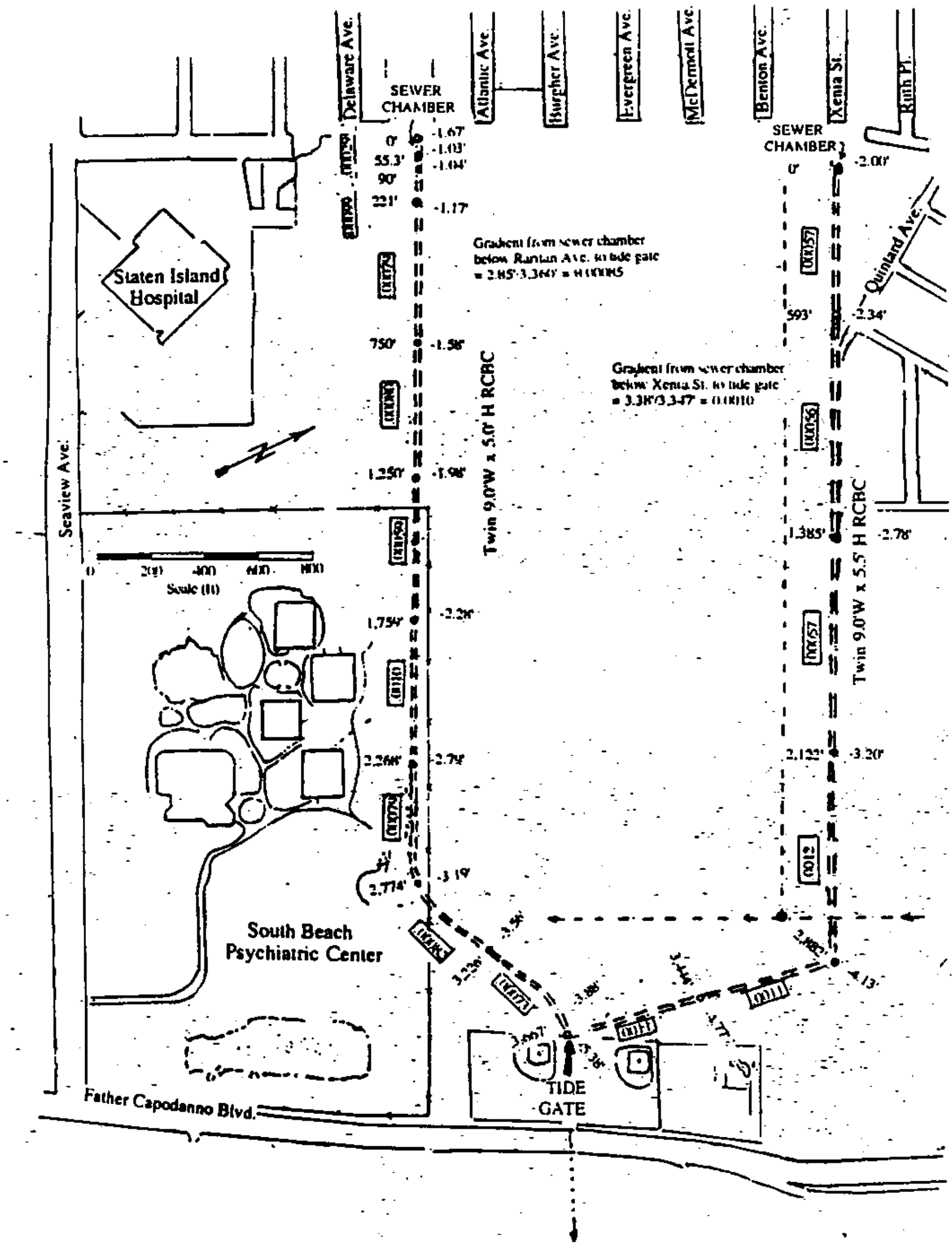

Figure 5: The two storm sewers reaching the site at its western edge. The Perrine's drainage enters below Xenia Street, and another enters below Raritan Avenue. The numbers to the left of the sewers are the invert elevations, (elevations of the bottom of the sewer at each manhole); and the boxed numbers are the gradients between manholes.

Most were between 4 and 6 feet tall, 8 to 10 years old, and were growing as far as 70 feet from the fenceline. Some had already reached maturity and were bearing cones.

Numerous fire scars were seen throughout the site. Stolen cars are commonly driven onto the site and set on fire. These fires can spread rapidly across the grasslands and the high fire frequency at the SBW continuously set back succession throughout much of the site thereby inhibiting the establishment of more mature plant communities. However, if carefully times and controlled, fires can be used as a management tool to maintain grasslands where desired. *Andropogan* grass for example, which occurs at the site, is a fire-adapted grass.

Flooding problems are common in the low-lying land adjacent to the site, especially on Quintard Street. In July, 1991, about 3 feet of standing water flooded several homes on Quintard between Olympia Boulevard and Nugent Avenue. According to one Quintard homeowner, the flooding problem was exacerbated when the townhouses on Quintard Street were constructed in the late 1980's. A several foot high berm was piled on the south side of the street which has been blocking water from draining away. Lower Quintard Street is naturally flood prone since it is nearly at sea level, and according to the 1909 topographic map, was within the former salt marsh. The flooding problem in this area could be alleviated by allowing the water to flow southeastward from the Quintard/Olympia Boulevard corner into the wetlands.

Stormwater and Sanitary Sewers

Two main storm sewers reach the site near Mason Avenue at the western edge. One enters the site below Xenia Street draining Perrine's Creek, and the other enters below Raritan Avenue (Figure 5). These sewers were installed in 1965 to carry storm water under the wetland and directly out to sea under the groin.

The Xenia Street storm sewer starts at a connecting chamber near the foot of Xenia Street A twin 9.0' wide x 5.5' high reinforced concrete box culvert (RCBC) runs below the SBW in a southeast direction. It was designed to accommodate a storm intensity of 3.8" of rain for 28.7 minutes using a weighted coefficient of runoff of 0.63 (NYC Drainage Plan, 1972), and has an average gradient of 0.00074 for the first 2,882 feet. A connecting chamber then adds a storm sewer from the north where the culvert height is increased to 6.0 feet. The gradient increases to 0.0011 for the last 2,860 feet before meeting the Raritan Street sewer. Another box chamber is located just below Xenia Street, but I presently do not know why it was installed.

The Raritan Street sewer is also a twin RCBC with dimensions of 9.5 feet wide x 6.8 feet high with an average gradient of 0.00080 under the SBW. These sewers, constructed in 1965, meet at a tide gate near the East Shore Little League baseball diamonds to become a twin 10' wide x 6.8' high sewer that flows another 977 feet under Father Capadanno Boulevard, finally exiting into lower New York Bay under the concrete groin.

The linear gradients from the chambers of each sewer to the tide gate where they meet, was calculated by dividing the change in invert elevation by the linear distance from each point. From the Xenia Street chamber, the gradient is 3.38 ft/3,347 ft = 0.0010. This means that for every 1,000 feet in distance, the drop in elevation is about 1 foot. The gradient from the Raritan chamber is 2.85ft/3,360ft = 0.00085.

An 18" sanitary sewer, constructed in 1974 runs southeastward 195 feet south of Xenia Street storm sewer. It joins with another 18" sewer that flows 2,100 feet from Sand Lane under the proposed Quincy Street at an average gradient of 0.00018. The sewer then flows southwestward across the site for 2,140 feet, about 825 feet west of Father Capodanno Boulevard, at a gradient of 0.00070. It eventually flows to the Oakwood Beach Sewage Treatment Plant.

The Northern Section

The northern section is bordered by Sand Lane to the north, Father Capodanno Boulevard to the east, Lansing and Oceanside Avenues to the west, and grades into the southern section from the northeast. It has remained at its original elevation at or near sea level and is roughly 2,200 ft by 800 feet, or 50 acres. It is mostly privately owned, and has been illegally filled in as residential developments encroach on it. Loss of tidal circulation has caused the development of stagnant bodies of water with emergent vegetation composed largely of common reed (*Phragmites communis*), an ubiquitous urban weed which thrives in partially filled, contaminated, nutrient-loaded wetlands. Nonetheless, this section has much open water and I have often seen waterfowl here. In addition, this area is vital for flood protection for the South Beach community.

This area is an illegal dumping ground for discarded household appliances, construction rubble, and stolen cars. Seven derelict cars were found near the corner of McLaughlin and Oceanside Avenues, and 5 recently stolen cars were seen on Andrews Avenue.

Perrines Creek

Perrines Creek receives water from 2 tributaries. The upper watershed is Emerson Hill. During rainstorms recharge occurs here. Much of this groundwater once discharged in the low-lying area between Targee St., Fingerboard Rd. and Clove Rd. (Figures 2 and 3) This area has been mostly paved over and much of the rain that falls now enters storm sewers. Some discharges into Brady's Pond which forms the upper reach of the North Tributary. Figure 6 shows the Perrine's Creek watershed from Brady's Pond to Reid Avenue. The dark green areas are relict riparian forest sites and the orange border represents the surficial drainage area. The lower watershed has a drainage area of 252 acres and is bounded by the Staten Island Expressway to the north, the Staten Island Advance to the west, Steuben Street to the east, and Reid Avenue to the south. Since lower watershed is supplied primarily from groundwater from Emerson Hill, if was difficult to assess the drainage area of the entire watershed.

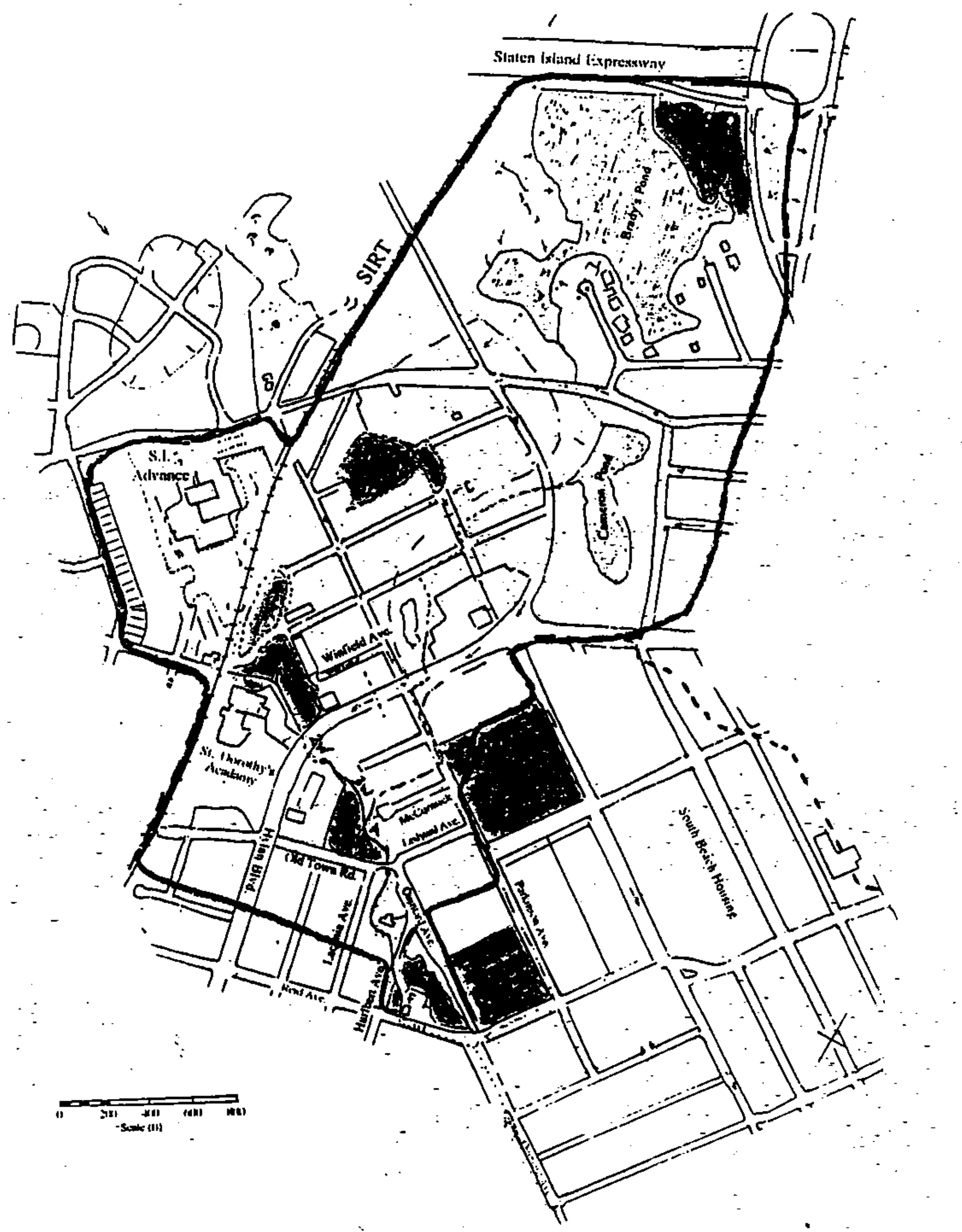

Figure 6: The lower Perrine's Creek watershed. The total drainage area from Brady's Pond to Reid Ave. is 252 acres. Brady's Pond, is 15.5 acres in area, and is spring-fed. Groundwater from Emerson Hill discharges into it. The West Tributary drains an area of about 56 acres originating behind St. Dorothy's Academy. The former marshlands in the upper left of the figure have been completely covered with condominiums. Dotted line around the perimeter indicates area of surface water drainage and arrows indicate direction of surface water flow.

The North Tributary

Brady's and Cameron Ponds form the upper reaches of the North Tributary. Brady's Pond, the largest privately owned lake in New York City, is approximately 15.5 acres in area and has an estimated average depth of about 4 feet. Its storage volume is about 62 acre-feet. It drains into Cameron Pond, which is 3 acres in area. Combined, the storage volume of the two ponds is about 70-75 acre-feet.

Water flows from Cameron Pond into a storm sewer near the corner of Clove Road and Windemere Avenue. The creek is routed through a sewer down Clove Road, across Hylan Boulevard to Parkinson Avenue, and empties through an 18" corrugated metal culvert between the base of McCormick and Ledyard Avenues into a pool where is becomes a free-flowing stream. Here it has a bankfull width between 6 to 10 feet and a bankfull depth of about 0.5 feet. It joins the west tributary less than 100 feet above Old Town Road in a block-lined channel.

The West Tributary

The west tributary has a surficial drainage area of about 56 acres. Surface water drains from the vicinity of the Staten Island Advance and is culverted under the SIRT tracks near the northwest corner of St. Dorothy's Academy where it enters a 5' wide x 5' high block-lined channel. Reach 1W flows through a wooded area around the Academy grounds. Two springs seep out from behind apartments at the end of Winfield Avenue and drain into the main channel. I noticed a strong chemical odor and a silvery sheen in water emanating from one of these springs. The source of this contamination is unknown and should be investigated. The woodlands between St. Dorothy's and Parkinson Avenue is a groundwater discharge zone and contains a relict riparian hardwood forest of Sweet gum and Oak woodlands and should be considered for protection.

The creek is culverted under Hylan Boulevard (Reach 2W) and surfaces in a pool behind the Staten Island Savings Bank parking lot. This pool also receives water from a storm sewer draining southeast from Hylan Boulevard. Piles of rubble and household wastes had been dumped around the creek and adjacent marsh. I found several discarded car tires and metal in the creek.

The creek then flows southeast, 600 feet toward its confluence with the west tributary immediately above the Old Town Road crossing (Reach 3W). This area is depicted as a 2700 ft^2 marsh on the 1909 topographic map (Figure 7). Today, a linear, deeply entrenched channel with gravel and sand-dominated bed exists with a bankfull width between 6 and 10 feet and bankfull depth of about 0.5 feet. The gradient was 2-4%.

The Main Stem of Perrine's Creek

Most of the length of the tributaries are now sewered, but a 900 ft open reach remains between Ledyard and Reid Avenues, although is threatened by continuing development. Killifish

Figure 7: Lower Perrine's Creek watershed as depicted on the 1908 Borough of Richmond Topographic Survey map. The West Tributary drained into a 2,700 ft^2 marsh was located north of Old Town Rd behind what is now the Staten Island Savings Bank. Much of the adjacent land was under cultivation. Soils were stratified sand and fine gravels laid down by receding glaciers. Some landmarks that exist today are depicted for reference.

and freshwater eels once used the creek as migration corridors. Figure 7 shows lower Perrines Creek as depicted in 1908.

The two tributaries join immediately above Old Town Road. The road crossing is in disrepair and has been closed to traffic since 1990. On January 6, 1992, at least 10 small fish, possibly killifish were seen in the pool immediately below Old Town Road. This pool forms the top of Reach 4 and flows southward, parallel to Laconia Street for about 240 feet. This reach is deeply entrenched with a bankfull width of 10 to 12 feet and a bankfull depth of about 1 foot. The substrate consists of sand and cobble-sized material. The recent widening of Quintard St and new housing developments on its south side have constricted the creek's floodplain and destroyed much of the riparian zone and natural flood protection qualities that existed here. Figure 7 shows this reach as depicted in the 1909 topographic map.

The creek is then deflected eastward around the 123 Hurlbert Street lot and picks up water from a small culvert from Hylan Boulevard near Reid Avenue. After passing this lot, the creek crosses Hurlbert Street which had been closed to traffic since the summer of 1991 for repairs. Four 18 inch diameter corrugated metal culverts were being placed across the read in early January, 1992.

After crossing Hurlbert Street, the creek flows about 150 feet through a wooded section (Reach 5). The final 30 feet of this reach was seen actively eroding the left bank and the west side of 137 Reid Avenue lot. This presents a major problem for the homeowner and bank stabilization needs to be considered.

From here, the creek enters a 3 foot wide x 2 foot high reinforced concrete box culvert (T 24-14) constructed in 1937 where it flows under Reid Avenue to Quintard Street and then to the northwest corner of the South Beach wetland at Mason Street. A sewer was being repaired during the reconnaissance. Water was being pumped out of the sewer and flowed south toward the Xenia Street chamber.

South Beach Creek

The South Beach Creek drainage heads around St. Joseph Hill Academy and Hylan Boulevard. Most of the upper watershed is sewered, but a 2670 foot stretch between McClean Avenue and Olympia Boulevard still remains open.

The separated the creek into two separate reaches. Figure 8 shows the free-flowing reaches. Reach 1 starts behind 370 McClean Avenue and runs parallel to Linwood Avenue. This reach is linear for 700 feet with an average gradient of nearly 2%. The bed is composed of small gravels and cobbles, and the banks largely composed of clayey fill material. The gradient is nearly 2%.

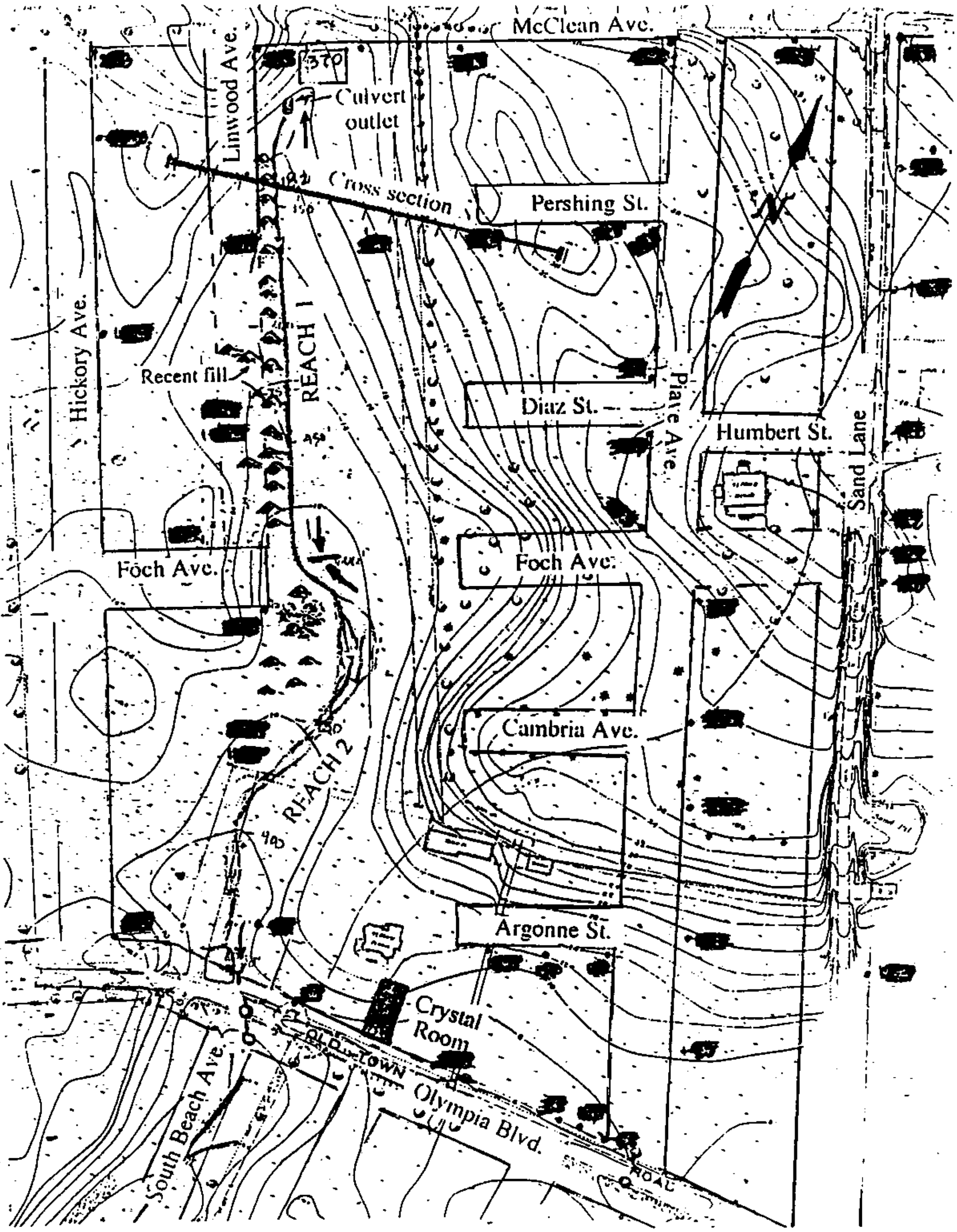

Figure 8: The free-flowing reaches of South Beach Creek from McClean Avenue to Olympia Boulevard showing the present road system superimposed on the 1909 topographic map. The highlighted numbers represent the elevations depicted on the 1977 edition of the NYC Department of Water Resources Drainage Plan. (Scale: 1"= 400').

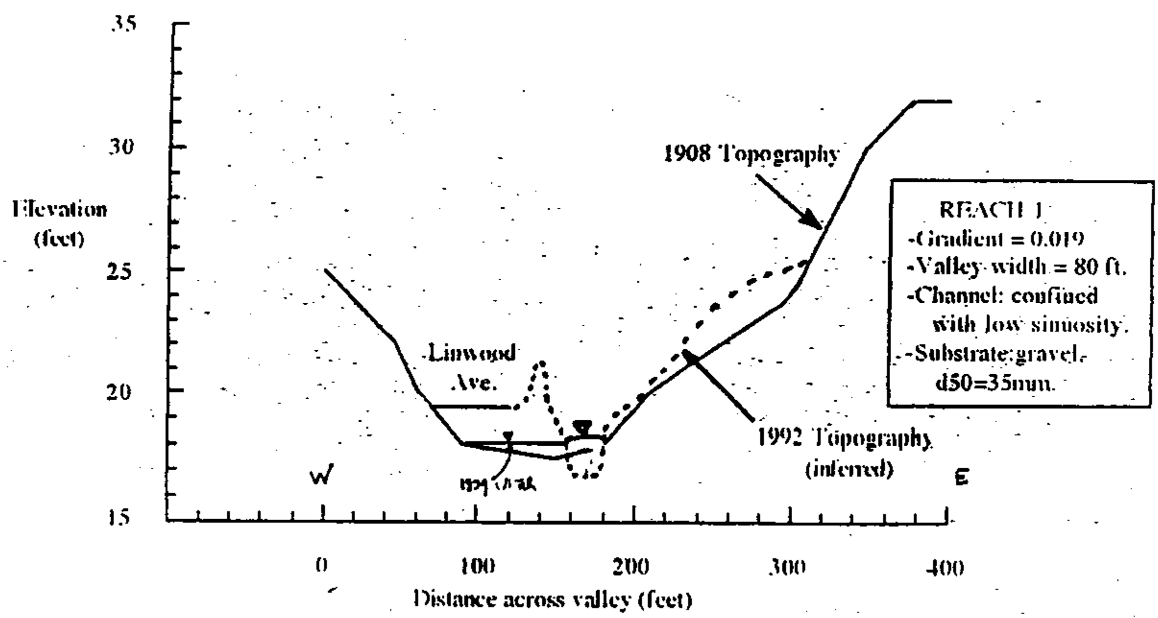

Figure 9: A 500 foot wide cross section of the South Beach Creek valley form the 1909 topographic map about 170 feet below McClean Avenue.

Once the creek reaches Foch Avenue, the gradient flattens and substrate becomes sandy. During heavy rains, the creek flows across the full valley width of 50-60 feet. Fill material had been dumped on the west side of the valley, south of Foch Avenue. Thick riparian vegetation stabilizes the sandy soil and helps reduce the velocity of the runoff.

The creek then flows through a grassy area west of the Crystal Room toward Olympia Boulevard. It is then routed into a 2 foot wide x 1 foot high culvert and flows under South Beach Avenue. During the rain storm of January 9th, water flowing through the culvert under Olympia Boulevard was upswelling through a manhole cover. This is a fairly common occurrence and is largely due to the fact that 1) South Beach Avenue was build immediately over the creek, 2) its base is virtually at sea level, and 3) the wetland below presently has little storage capacity.

Hurricane Evacuation Study

The U.S. Army Corps of Engineers prepared a report regarding areas of maximum hurricane surge elevations. The possible flood elevations indicated were derived from the National Hurricane Center's Sea, Lake, and Overland Surge from Hurricanes (SLOSH) Model. Elevations reflect worse case combinations of directions, forward speed and landfall points. Four categories of inundations were included in the model. Since the South Beach Wetland area is a natural basin, it is most susceptible to storm surges and as such, should not be further developed.

CONCLUSIONS

The South Beach Wetland offers a tremendous opportunity for state, city, and/or private land management agencies to cooperatively manage the site and enhance its values for flood protection, freshwater marsh habitat for waterfowl, and much needed open space for Staten Island's citizens. Ironically, this environmentally sensitive site is not protected and is threatened by development.

From this survey, it became apparent to me that the remaining open reaches of the streams and the adjacent riparian areas must be preserved and restored because they can provide for the detention of flood waters and serve as valuable corridors for fish and wildlife.

It is essential that the state of New York develop an overall land management program under the terms of the state Environmental Quality Review Act. The South Beach Freshwater Wetland is a perfect example of an area in desperate need of such a program.

It makes little sense that the South Beach Freshwater Wetland (NA-7) and the remaining open reaches of its two main inflows are not protected from further development. The low-lying area of the SBW is highly susceptible to storm surges from strong hurricanes and provides tremendous opportunities for flood protection, wetlands/wildlife enhancement, and much needed open space. The relict open reaches of Perrines and South Beach Creeks provide riparian habitat and floodwater detention. Any long-term management plan must take into account the mixed ownership around the periphery of the wetlands. Acquisition of the wetland and its periphery would be the first step to any management of the site.

But who is going to take the financial burden? The state? They're proposing to buy 2 sites in the Greenbelt. Definitely needed acquisitions, but let us not forget the fertile outwash plains and salt marshes of northeast part of Staten Island that Verazzano saw on the port as he sailed up the lower bay 500 years ago that today offers the best flood protection and wetland opportunities that Staten Islanders have to sustain them into the 21st century. Although its been used as a dumping grounds by both the city and private individuals, it's far from a waste land.

I also talked to some of the adjacent homeowners who expressed dissatisfaction with the flooding problems and vandalism. Those who own property within the designated wetland are frustrated because they are not allowed to develop their land.

The approach of any management objectives for the wetlands should be based on a larger scale than any previous land use objectives, all of which proved unfeasible. For example, the Dormitory Authority's plan to build a campus and the U.S. Navy's homeport development plan were both unsuccessful because of the absurdity to build on the site which is the primary groundwater discharge zone for nearly 10% of Staten Island.

Flooding problems that plague Hylan Boulevard in Dongan Hills and in South Beach could be alleviated with a better understanding of how to take advantage of the flood routing and storage values that the remaining stream corridors possess.

Having spent the first 25 years of my life in the area, I've seen dramatic changes that have taken place in both the Perrines and South Beach watersheds. I find it sickening that the last remaining vestige of wetlands northeast Staten Island possess should be destroyed forever. Wetlands have been considered "in the way" of development for a long time. Staten Island's natural heritage is in danger of being lost forever.

The South Beach Freshwater Wetland is not a pristine place, but protection is essential. Presently the state does not recognize this wetland for protection. Methods for protection should include giving landowners conservation easements for not developing their land, land trades, rezoning, transfer of development rights, and the use of Federal and State Wetland Regulations. Please refer to DEC DEIS (1990) for a more complete listing of methods.

The site is an ideal place for a comprehensive wetland management plan designed to improve the site's flood storage capacity, increase fish and wildlife habitat, and the attractiveness of the site for much needed open space for Staten Island's citizens.

RECOMMENDATIONS

The following recommendations address possible solutions to some of the problems at the South Beach wetland site and would enhance the long term viability of the site as a wetland/open space preserve. Of course, specific objectives would be necessary should any restoration project of the site be performed. Wetland evaluation is needed prior to a project to set goals and develop a plan (Erwin, 1989).

Re-establish Perrines Creek.

Channels should be designed to efficiently transport water away from residential areas and into ponds for storage. The re-establishment of Perrines Creek in the western half of the site would provide a conduit for runoff. This would entail determining where the channel is located and dredging a new channel. Fish species such as killifish could be introduced to feed on insect larvae to help control mosquito populations.

Re-introduce native fish species to the system.

Once a creek channel network is re-established through the SBW, native fish species could be re-introduced. These creeks could provide fishing opportunities for Staten Islanders. Below, I describe two fish species that were abundant in the Perrines Creek watershed.

Eastern Banded Killifish (*Fundulus diaphenus diaphenus*) once gathered by the thousands to spawn in Perrines Creek where I used to catch them for bait. These fish, which could tolerate slightly brackish water, spawn between April and September. They prefer sand substrates to deposit their eggs (McClane 1974). Their diet includes small crustaceans, mollusks, worms and plant material, and in turn are eaten by predatory fish such as largemouth bass.

Freshwater (American) eels (*Anguilla rostrata*) migrate up creeks to reach maturity. When mature, they swim to the tropical Atlantic Ocean to spawn (Hocutt and Wiley 1986). I used to catch them in Brady's Pond as recently as the mid 1970's. These were probably landlocked fish that cannot return to the ocean to spawn and are thus doomed. The present status of the eel population in Brady's Pond is unknown, but it is unlikely they can still migrate through the thousands of feet of storm sewers to reach it. The 4,000 foot storm sewer under the SBW is probably an effective migration barrier to eels. This barrier would be eliminated if a free-flowing creek was created through the SBW.

eliminate unauthorized vehicular access.

Blocking vehicular access would insure the re-establishment of plants on the soil made bare by off-road vehicle use. Even moderate ORV used inhibits the establishment of plants and the noise has a detrimental impact on the local fauna by disrupting their behavior patterns. The site now serves as a dumping ground for stolen cars which also damages vegetation. In addition, the random fires set by the car thieves markedly alters the ecology of the site.

A tree planting program should be initiated.

The lodgepole pine trees that are recruiting on the site from the South Beach Psychiatric Center demonstrates that favorable conditions exist for their growth, probably due to the abundance of groundwater. Areas to be forested should be identified and a tree planting program should be initiated. Native riparian hardwoods such as red maple (*Acer rubrum*), Pin Oak (*Quercus palustris*), Sweet Gum (*Liquidamber communis*), cottonwoods (*Populis* sp.), alders (*Alnus* sp.), and willows (*Salix* sp.) should be planted. A border of conifers such as the pine trees around the site would help insulate it from urban noise and light pollution.

In addition, increased forest cover would serve the following purposes:
1) Increase the structural diversity of the site.
2) This structural diversity would attract a wider variety of birds. Raptors would be offered more perch sites and birds that nest in trees would be given a greater variety of sites to nest.
3) Increase habitat for invertebrates which provide food for waterfowl, songbirds and other wildlife.
4) Increasing forest cover on the SBW would increase the surface roughness to surging storm water. Roughness is a commonly used term used in hydraulics which describes a surface's resistance to flowing water. The bare sand and grasses presently occupying the site offers little resistance to storm surges.
5) Improve soil-binding capacity which would also enhance the protective value to storm surges.
6) Evapotranspiration would be increased.
7) Trees would improve the aesthetic qualities of the site.

What should be done with on-site debris?

One of the first objectives should be to identify the type, quantity and location of the debris presently found on the site. Much of the debris on site is metal from burned cars which could be sold as scrap. For example, there were 12 derelict cars in the vicinity of Andrews Avenue. At $25 per ton, and each car weighing about 1 ton, a scrap collector can collect $300 of metal from this one location. A more comprehensive determination of the location and quantity of metal debris would assist a scrap collector evaluate the value of metal at the SBW.

The concrete rubble on the site may be used as wetland structure should wetland creation be a management objective. This can be used to line stream channels and create berms serving two purposes: 1) The cost of hauling it offsite is eliminated, and 2) it provides instream structure and habitat for aquatic plants and animals. This has been used successfully in the restoration of wetlands (Butcher's Slough). The other inert fill material which have been dumped may be piled onto a clay-lined area and topped with a 2 to 3 foot layer of soil and revegetated with native plants.

Fires can be used as a management tool to encourage specific plant species.

Numerous fires set by vandals occur at the South Beach Wetland, taxing the local fire departments. The role of fire in aiding the spread, perpetuation, and persistence of Phragmites-dominated wetland communities such as those found at the site is not well known (DEC DEIS, 1990). Nonetheless, controlled burns have been used effectively as a management tool particularly in grasslands communities. This is presently being done at Hempstead Plains where the Nature Conservancy is using fire as a feasible management tool. This should be coupled with studies monitoring vegetational changes, animal use, and soil nutrient cycling.

Encourage the Local Citizens to Become Active in Trying to Get the Site Protected

Local citizens need to be informed about the site and should be encouraged to get involved in finding out about how to protect it. Advertised walks should get some people out there to learn more about the site and appreciate the value of the site as open space.

Proposed streets and street extensions should be demapped.

Many streets that are mapped on the city's I & I maps cut through much of the site. These streets should be demapped as they alter the natural drainage of stormwater and encourage flooding.

The Southwestern Section

Mason Avenue, Raritan Avenue, and Perine Avenue: The water seen in the ditch along the proposed Mason Avenue stagnates and presents a breeding ground for mosquitoes and is a health hazard to neighborhood children since it concentrates urban pollutants. A creek should be created to drain water away from the neighborhood toward the southeast.

The Northwestern Section

Quintard Street, Patterson Avenue, Lava Street, and Mallory Avenue: As stated earlier, Quintard Street is prone to flooding. The water that should drain toward the southeast is blocked from doing so because of the berm located adjacent to the street. These proposed streets would exacerbate the flooding problem and inhibit the natural flow of water.

The Northern Section

Winfield Avenue, Vulcan Street, McLaughlin Street, Andrews Street, Wentworth Avenue, Orlando Street, Tuscany Court, Wills Place: The proposed extensions of these existing streets would destroy the virtues of the wetlands in the northern section of the SBW and would increase flooding problems already plaguing the area, further pollute the water, eliminate critical habitat for waterfowl and aquatic-dependent invertebrates and those animals dependent on them for survival.

The streets crossing the reaches of free-flowing creeks: Although most of the length of both creeks have already been sewered, the remaining open reaches need to be preserved since the riparian zones around these creeks draining into the SBW serve as important corridors for wildlife. Steps must be taken to insure that these reaches are not further degraded.

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Editorial Note: Photographs and one figure were not included due to copying problems.

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GLACIAL GEOLOGY OF STATEN ISLAND

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The fundamental question pertaining to the Pleistocene features of the New York City region is: "Did one glacier do it all? or was >1 glacier involved?" Prior to Fuller's (1914) monographic study of Long Island's glacial stratigraphy, the one-glacier viewpoint predominated. Fuller's classification included products of 4 glacial advances. In 1936, MacClintock and Richards rejected two of Fuller's key age assignments, and made a great leap backward to the one-glacier interpretation. Subsequently, most geologists have accepted the MacClintock-Richards view and have ignored Fuller's work; the one-glacial concept has become a stampede. What is more, all previous workers, Fuller included, have classified LI's two terminal-moraine ridges as products of the latest Pleistocene glaciation (i. e., Woodfordian).

Provenance data from coastal cliffs in a terminal-moraine ridge in southern Staten Island prove that ice flowed regionally across Staten Island from NW to SE (**across** the Hudson Valley) not NNE to SSW, (**down** the Hudson Valley) with local diversions to the SE, the pattern inferred by many one-glacier advocates. Much-decayed stones in outwash gravels that overlie Cretaceous sands at the AKR Excavating Corp. imply a pre-Wisconsinan age. Finally, glacial striae and -crescentic marks on the dolerite exposed at the Graniteville quarry are inferred products of two ice-flow directions: an older NW to SE cut by a younger NNE to SSW.

Although the critical stratigraphic data required to demonstrate our multi-glacial interpretation are not yet available, we think existing data strongly imply that on Staten Island are products of at least 3, possibly 4, glacial advances. We regard their ages as: Nebraskan (?) for the much-decomposed outwash at AKR; Kansan (?) +/- Illinoian (?) for the coastal exposures of "terminal-moraine" materials derived from the NNW (including a well-developed paleosol and giant "erratic" slab of displaced Cretaceous sediments); and Wisconsinan (Woodfordian) for the till overlying the striae trending NNE-SSW at Graniteville. We do not know the location on Staten Island of any Woodfordian terminal-moraine ridge. Elsewhere, this ridge follows the S coast of CT.

THE GEOLOGY OF WESTERN STATEN ISLAND, NEW YORK, NORTH AND SOUTH OF THE FALL LINE

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A hydrogeologic investigation performed as part of the Fresh Kills Leachate Mitigation System Project at the Fresh Kills Landfill on Staten Island, New York, has provided detailed information on the geology of western Staten Island, north and south of the Fall Line.

The landfill site occurs within two physiographic provinces; the Piedmont and the Coastal Plain. The Fall Line roughly bisects the site, with the Piedmont section occurring to the north and the Coastal Plain occurring to the south.

Four major geologic units occur on the site. They are: bedrock/residual clay, Cretaceous deposits, Pleistocene (glacial) deposits, and Holocene (Recent) deposits.

Five major types of bedrock have been identified in the area: the Palisades Diabase, the Stockton Formation, the Lockatong Formation, the Staten Island Serpentinite, and different types of schist. Residual clay, formed from the weathering of the bedrock, mantles most of the bedrock surface. The residual clay is tens of feet thick in some places.

Cretaceous deposits occur in the southern portion of the site. They are composed of a complex interbedded sequence of sand and silt and clay, that form a southerly thickening wedge of sediment over 100 feet in thickness in some places. Microfossil analysis conducted as part of this investigation indicates that Upper Cretaceous strata is present in the sequence.

Pleistocene (glacial) deposits occur throughout most of the study area. Glacial lodgement till occurs throughout much of the site, primarily above the residual clay north of the Fall Line and above the Cretaceous sediments south of the Fall Line. Glaciolacustrine silt and clay occurs primarily below the former tidal marsh areas of the site, in the lower lying areas of the pre-landfill terrain. In certain areas of the site, it is postulated that the lodgement till and/or glaciolacustrine deposits have been removed by glacial Lake Hackensack drainage, meltwater drainage from the glacier, or by human activity. Glacial sand and non-lodgement diamict are found throughout the site. These deposits are primarily associated with two kame features that extend across portions of the site. In the areas adjacent to the kames, complex interbedding of the glaciolacustrine, glacial sand, and non-lodgement diamict occur.

The Holocene (Recent) deposits are primarily found in the areas of a former tidal marsh depositional environment. These sediments consist of a fairly complex distribution of sand, silt, clay, and peat, although individual units can be correlated across portions of the site. Fill consisting of refuse or clean fill covers most of the site.

Guide to field stops and road log for the Geology Of Staten Island

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This trip begins at GANJ XI Headquaters in the Newark Basin. The Newark Basin(Figure 1,2), one of many Mesozoic Basins in the eastern United States, is a block faulted , deeply eroded half graben(Olsen and Van Houten, 1988). See Sanders(this guidebook, pages 201-216) for a summary of Newark Basin stratigraphy and associated mafic igneous rocks).

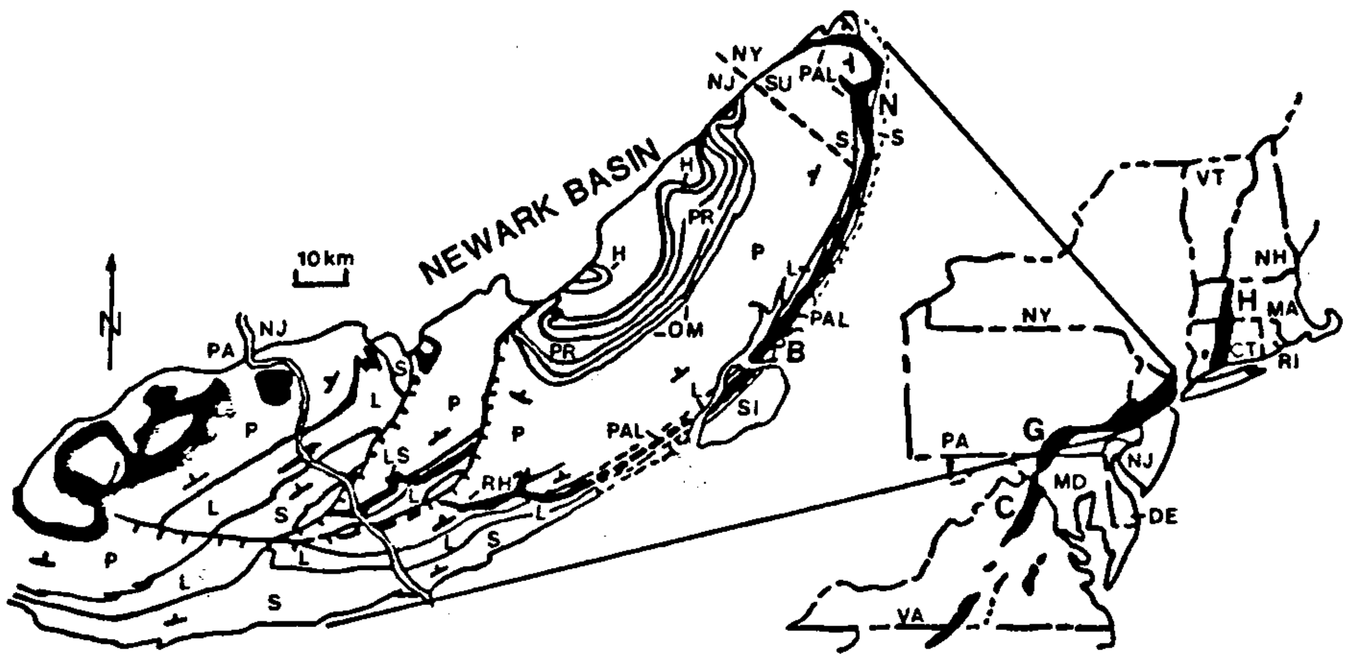

Figure 1: Simplified Geologic Map (After Schlische and Olsen, 1988, Husch 1992) of the Newark Basin. Other Mesozoic Basins are Culpeper (C), Gettysberg (G), and Hartford (H). SI = Staten Island; PAL=Palisades sill; S=Stockton fm.;L=Lockatong fm.;P=Passaic fm.; OM=Orange Mtn Basalt;PR=Preakness Basalt; H=Hook Mtn Basalt. N=Nyack NY.

Figure 2 Geologic Map of Field Trip Region. From Lyttle and Epstein, (1987)

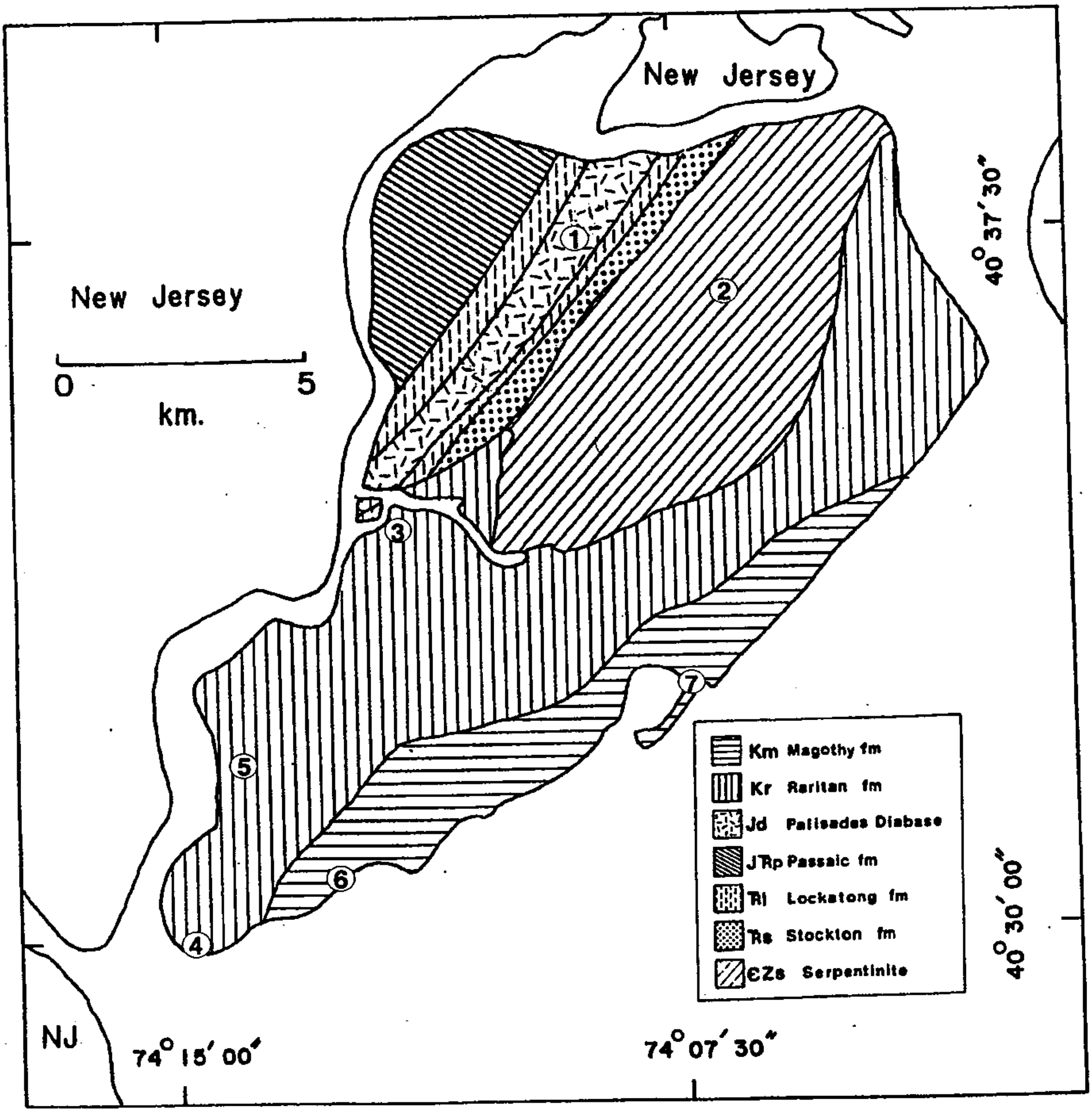

Figure 3 Geologic Map Of Staten Island showing field trip stops.
(After Lyttle, and Epstein, 1987)

Road Log begins in the parking lot of the Quality Inn, Somerset, NJ

Mileage		Remarks
Inc.	Cum.	
0.0	0.0	Board buses at front entrance of motel. The object of this exercise is to be able to go NW on Easton Ave. (Rte. 527) , not SE, as one will do by exiting at the first driveway. Pay close attention.
0.1	0.1	Speed bump and STOP sign beyond. After stop, proceed.
0.1	0.2	STOP sign for World's Fair Dr., opp. United Jersey Bank Building; turn Left into World's Fair Dr.
0.1	0.3	Traffic light, Easton Ave. Rte. 527; turn Left. Bear L on curve for I-287 southbound.
0.4	0.7	On I-287 southbound.
0.2	0.8	On bridge crossing the Raritan River; we are, to borrow a song title: "On the banks of the old Raritan."

The Raritan River in these parts exposes the Newark basin-filling strata that were the basis for the name Brunswick (for New Brunswick) Formation. As originally proposed, the Brunswick included everything above the Lockatong Formation, including the interstratified extrusive sheets of mafic igneous rock known as the First-, Second-, and Third Watchung basalts. Refer to the table on page 203 of this field guide for the modern names proposed by Paul Olsen, in which the Brunswick has been elevated to Group status, thus the Newark boosted up from Group to Supergroup. No Newark strata are visible along our trip route across the strike of the Passaic Formation.

0.5	1.3	Passing Embassy Suites Hotel behind trees on R.
1.0	2.3	Passing ramp for exit to Possumtown Rd, Middlesex, and Highland Park.
1.3	3.6	Just after sign announcing exit for NJ 529 in 1 mi., a closed-off ramp.
1.0	4.6	Passing ramp on Right for Exit to Rte. 529 N, Dunellen & Edison
0.3	4.9	Passing ramp on Right for Exit to Rte. 529 S.
1.2	6.1	Passing Mile Post (MP) 5 on Right .
0.5	6.6	Passing HQ bldg. of Gdynia America Lines on Right .
1.1	7.7	Passing ramp on Right for Rte. 550 to Metuchen & New Durham.
0.9	8.6	Passing beneath overhead powerline & over AMTRAK RR.

1.0	9.6	Passing ramp on Right for U.S. 1 S and Rte. 531.
0.5	10.1	Passing ramp on Right for U.S. 1 N and Rte. 531.
0.9	11.0	Passing exit on Right for NJ Tpk. (I-95), I-287 is now NJ 440 N. As a first approximation, the New Jersey Turnpike may be considered as the boundary marking the eroded edge of the coastal-plain strata, which overlap the tilted Newark strata with angular unconformity.
0.1	11.1	Passing ramp on Right for Rte. 514 W.
0.3	11.4	Passing ramp on Right for Rte. 514 E.
0.8	12.2	Passing ramp on Right to Smith St. - Industrial Ave.
0.5	12.7	Passing ramp on Right for U.S. 9 S.
0.2	12.9	Passing ramp on Right for Garden St. Pkwy (GSP) S.
0.3	13.2	Passing ramp on Right for U.S. 9 N and GSP N.
0.9	14.1	Passing ramp on Right for NJ 35 (Amboy Rd.), Perth Amboy.
0.9	15.0	Passing ramp on Right for State St., last NJ exit.
0.1	15.1	Enter ramp for Outerbridge crossing.
0.9	16.0	Enter bridge deck, Outerbridge Crossing over Arthur Kill.
0.4	16.4	Leave bridge deck.
0.6	17.0	Stop at toll barrier; pay Caesar.
0.4	17.4	Bear Right for Exit 2, West Shore Expressway, 440 N.
0.1	17.5	On Rte. 440 N.
1.1	18.5	Passing ramp to Exit 3 (Woodrow Rd.) on R.
0.8	19.3	Overpass for Bloomingdale Rd. above.
0.7	20.0	Passing Exit 4 on Right , Huguenot Ave.& Arthur Kill Rd.
0.4	20.3	Passing over Arthur Kill Rd.
0.1	20.4	Landfill "mountain" on Left; Sec. 1/9
1.3	21.7	Landfill mound on Right.
0.3	22.0	On bridge over Fresh Kill.
0.5	22.5	Passing Exit 7 on Right . (Victory Blvd.).
1.6	24.1	Leave Rte. 440 on Right , Exit 8 ramp to South Ave.
0.3	24.4	At end of ramp, Turn Right into South Ave.
0.1	24.5	Traffic light; Travis Ave. on Right .
0.4	24.9	Passing entrance on Right to Teleport facility. During construction, Palisades sill exposed here; Benimoff and Puffer have obtained samples for chemical analysis
1.2	26.1	Passing under I-278; just beyond, traffic light for ramps.
0.1	26.2	Lisk Avenue on Right .
0.1	26.3	Traffic light for Amador Ave. on Right .
0.3	26.5	Traffic light at Forest Ave; turn Right .
0.3	26.8	Traffic light at Amity Place.
0.1	26.9	Traffic Light for Union Ave.; A & P on Right .
0.3	27.2	Pull over to Right and park for STOP 1: Graniteville Qy.

Stop 1: Old Graniteville quarry (a misnamed place; had a knowledgeable geologist given the name it might have been Doleriteville or even "Diabaseville"; its UTM grid coordinates on the Elizabeth 7 1/2 minute quadrangle map are: 570.8E, 4497.6N). Walk south on trail for a few hundred meters to the crest of a small rise.

First the Pleistocene.

STOP LEADERS: John E. Sanders and Charles Merguerian

Along the sidewalk, we noticed a place where red-brown till rests on the mafic bedrock along a sharp contact. We dug back the till here to expose the contact, hoping to find some well-defined striae that would indicate the direction of flow of the glacier. We found only the general rounded shape of the surface cut on the bedrock. Using the direction of its long axis, we think glacial flow here was from about N10°E to S10°W. If this is correct, then it is the first confirmation known to us of an effect of the Woodfordian glacier on Staten Island. (On Staten Island, red-brown color of till is not diagnostic of flow from NW to SE; till from a glacier that flowed from NNE to SSW is also reddish brown.)

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. Crossing sets of features eroded by the ice on the mafic bedrock confirm the effects of at least two glaciers: an older one from NW to SE and a younger one from NNE to SSW.

Next The Fused Xenolith of Lockatong Argillite in The Palisades Sill

STOP LEADER: Alan I. Benimoff

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 the margins of a xenolith of sodium rich Lockatong Argillite .(Benimoff and Sclar, 1978, 1980, 1984, 1988, 1992; 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, from Benimoff and Sclar, this field Guide, p. 37) reveal that diffusion of calcium, magnesium, iron, and sodium ions occurred across the liquid-liquid interface as shown in figure 4.

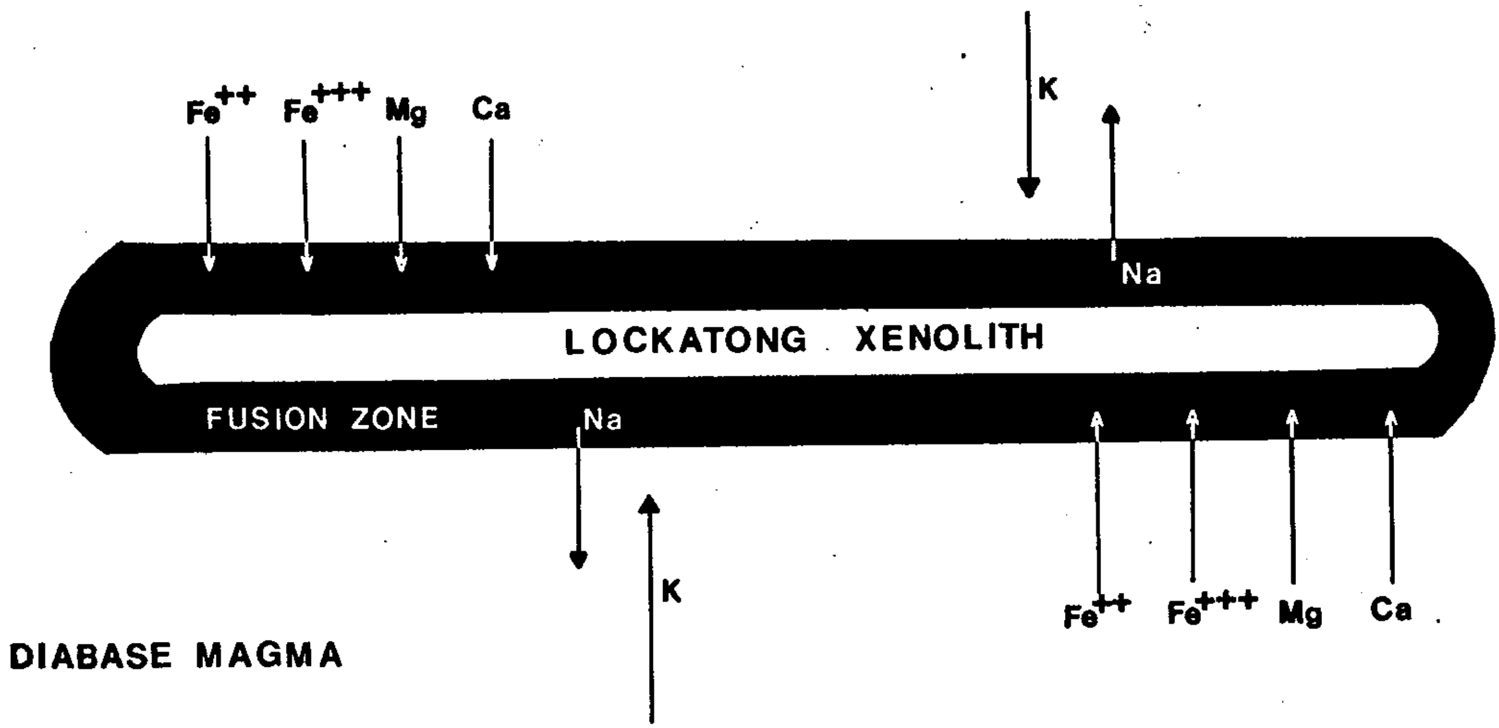

Figure 4 Schematic diagram of fused xenolith(not to scale) immersed in Palisades diabase magma showing proposed diffusion directions for several ions. From Benimoff and Sclar (1988)

0.0	27.2	Re-board buses; continue on Forest Ave.
0.1	27.3	Most-important street (Sanders St.) on Right .
0.1	27.4	Traffic light; Richmond Ave.
0.1	27.5	Traffic light; turn Right on Willow Rd. for 440 S; move Left.
0.1	27.6	Enter ramp on Left for 440 S.
0.1	27.7	On Rte. 440 S.
0.6	28.3	Make first exit on Right to I-278 E; but keep to Left.
0.1	28.4	Enter ramp on Left for I-278 E (toward Verrazano Bridge).
0.5	28.9	On I-278 E. View ahead to Todt Hill.
0.2	29.1	Curve Right ; view on Right toward new campus of The College Of Staten Island(CSI)
0.5	29.6	Passing exit on Right for Bradley Ave.
1.0	30.6	Passing exit on Right for Todt Hill Rd/Slosson Avenue. (Patches of coarse gravel mark slump sites.)
0.2	30.8	Passing over Slosson Avenue.
0.2	31.0	Serpentinite exposed on L and Right; phantom exit on Right. (That is STOP 2, but the longest way around is the shortest way for buses to get there.)
0.5	31.5	Exit from I-287 on Right at Richmond Road; to Hylan Blvd.
0.3	31.8	Traffic light; Clove Rd., turn Left; cross I-278.
0.1	31.8	Narrows Rd. N.
0.1	31.9	Turn Left after Clove Rd. on Right .
0.4	32.2	Traffic light Renwick Ave.; turn Left.
0.1	32.3	Turn Right into Milford Drive (I-278 Service Rd.)
0.2	32.5	At dead end, park buses. Prepare for walk in woods to STOP 2 in road cut for never-built exit ramp.

STOP LEADER: John H. Puffer, description is co-authored with Mark Germine

CAUTION: At the outcrop, stay on the unused roadway, do not go near the highway(I-278). Watch out for deep holes and falling rocks.

STOP 2: STATEN ISLAND META-PERIDOTITE

Take the trail leading west and up the hill from the parking-lot. At about 100 m from the trail-head, take the right trail fork north toward I-278. An abandoned paved roadcut that connects with I-278 is the most extensive exposure of meta-peridotite on Staten Island.

The Staten Island meta-peridotite, described by Puffer and Germine (this guidebook), consists largely of highly foliated to massive serpentinite containing variable amounts of relic olivine and minor amounts of anthophyllite schist. The rock exposed at the I-287 roadcut includes examples of both the highly foliated and massive types of serpentinite. In general the serpentinite exposed within a few cm of the closely spaced network of astamosing shear planes, visible on both walls of the road cut, tends to be green, highly foliated and includes megascopically 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 I-278 rock, in volume percent, is 88 % serpentine, 3 % olivine, 2 % talc, 2 % anthophyllite, 3 % opaque oxide, and 2 % carbonate. About 1/2 of the serpentine is lizardite with highly variable concentrations of chrysotile ranging from absent to 70 percent making up most of the remaining 1/2 of the serpentine content. Minor antigorite is also present including the fibrous variety (picrolite, Benimoff and others. in prep). Olivine is commonly found in the massive, black rock typically as relic micro-islands 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 consists largely of finely disseminated magnetite, minor medium grained chromite, and traces of picotite. The carbonate content is composed principally of dolomite and magnesite.

Chrysotile is not readily recognizable in most hand specimens or thin-sections of samples from the I-287 roadcut. In thin section, only lizardite was recognized in one sample, but using transmitting electron microscopic (TEM) techniques (Puffer and Germine, this guidebook), abundant chrysotile was found as tubules with an outer diameter of 200-300 microns (Germine, 1981). Fiber lengths are typically only 0.5 to 6 microns which is beyond the resolution of polarizing light microscopy, although some fibers were measured at up to 8 microns.

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. We also performed selected area electron diffraction analyses (SAED) and energy dispersive x-ray spectroscopy (EDXS) on several particles, confirming chrysotile as the major component and lizardite as comprising most of the remainder, with a minor talc component.

The TEM measurement of 54 percent is somewhat higher than the XRD estimate of 28 to 42 percent for the same combined sample (Table 3, Puffer and Germine, this guidebook), however, if corrections are made for electron density of the chrysotile, which is an indication of mass, both measurements fall within the error limits of the XRD analyses. XRD analyses are analyses by mass, while the TEM analyses are by volume.

The same kind of analyses was conducted on another sample of serpentinite from the I-287 roadcut (Sample 8p, Figure 1, Puffer and Germine, this guidebook). It contains 38 percent chrysotile as confirmed by SAED and EDXS. The results were within the error range of our XRD estimate (Table 3).

At least two varieties of massive chrysotile were recognized in samples of serpentinite at the Route 287 roadcut (Germine, 1981) using TEM techniques. 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 meerschaum-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 were 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 the I-278 roadcut 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 posses the flexibility that is a characteristic of asbestos (Germine and Puffer, 1989). Asbestiform anthophyllite from the I-287 roadcut consists of straw-colored aggregates on anthophyllite fiber in association with gray to yellowish-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 measuring 1 to 3 mm thick are also described by Germine (1981).

The Staten Island peridotite is interpreted by Puffer and Germine (This Guidebook) as the base of an ophiolite complex that was separated from the upper gabbroic and basaltic portions during Taconic abduction. It is located on Cameron's Line which separates Manhattan Schist to the west from the Hartland Formation to the east.

0.0	32.5	Buses turn around while we go for a walk.
0.2	32.7	Stop sign; Renwick Avenue; stay on Milford Drive.
0.5	33.2	Hewitt Ave.
0.1	33.3	Turn Left onto Clove Road
0.1	33.4	Turn Left onto Narrows Road North
0.1	33.5	Enter I-278 West
0.6	34.1	Passing Todt Hill Road /Slosson Avenue Exit
0.9	35.0	Passing Bradley Avenue Exit
0.8	35.8	Passing Victory Boulevard Exit
0.4	36.2	Passing NY 440 North Exit
0.5	36.7	Passing Richmond Avenue Exit
0.2	36.9	Passing South Avenue Exit
0.6	37.5	Enter NY 440 South(The West Shore Expressway)
1.3	38.8	Passing South Avenue Exit
1.2	40.0	Passing Victory Boulevard Exit
0.9	40.9	On bridge crossing Fresh Kill.
0.6	41.5	Leave Rte. 440 at Exit 5 on R; follow W. Service Rd.
0.3	41.8	Turn Right; entrance to landfill.
0.3	42.1	Passing methane plant on Left.
0.1	42.2	Guard shack; stop; if OK, proceed ahead.
0.2	42.4	Blinking light; gravel rd. for heavy equipment crossing.
0.1	42.5	Turn Right into Plant No. 1 Information Center; STOP 3.

STOP 3: The Fresh Kills Landfill
Stop Leaders: Norma Itturino and Timothy Pagano

Refer to the map on page 287

The Fresh Kills landfill is currently the only municipal solid waste landfill serving the five boroughs of the City of New York. Located on the western shore of Staten Island, the landfill is owned and operated by the City and has received household waste since 1948. The Fresh Kills landfill is an integral part of New York City's solid waste management plan, and will remain so through the next decade.

The landfill is divided into four sections, as shown in the accompanying figure. Sections 1/9 and 6/7 are the largest landfills, and lie to the west and east of the full landfill property area. Sections 3/4 and 2/8 are approximately half the size of Sections 1/9 and 6/7, and lie to the north and south of the full landfill area. Sections 2/8 and 3/4 have operated as truck-fed landfills. Section 2/8 received its last load of garbage in June 1993 and Section 3/4 ceased receiving waste in November 1992. Both are in the process of final closure.

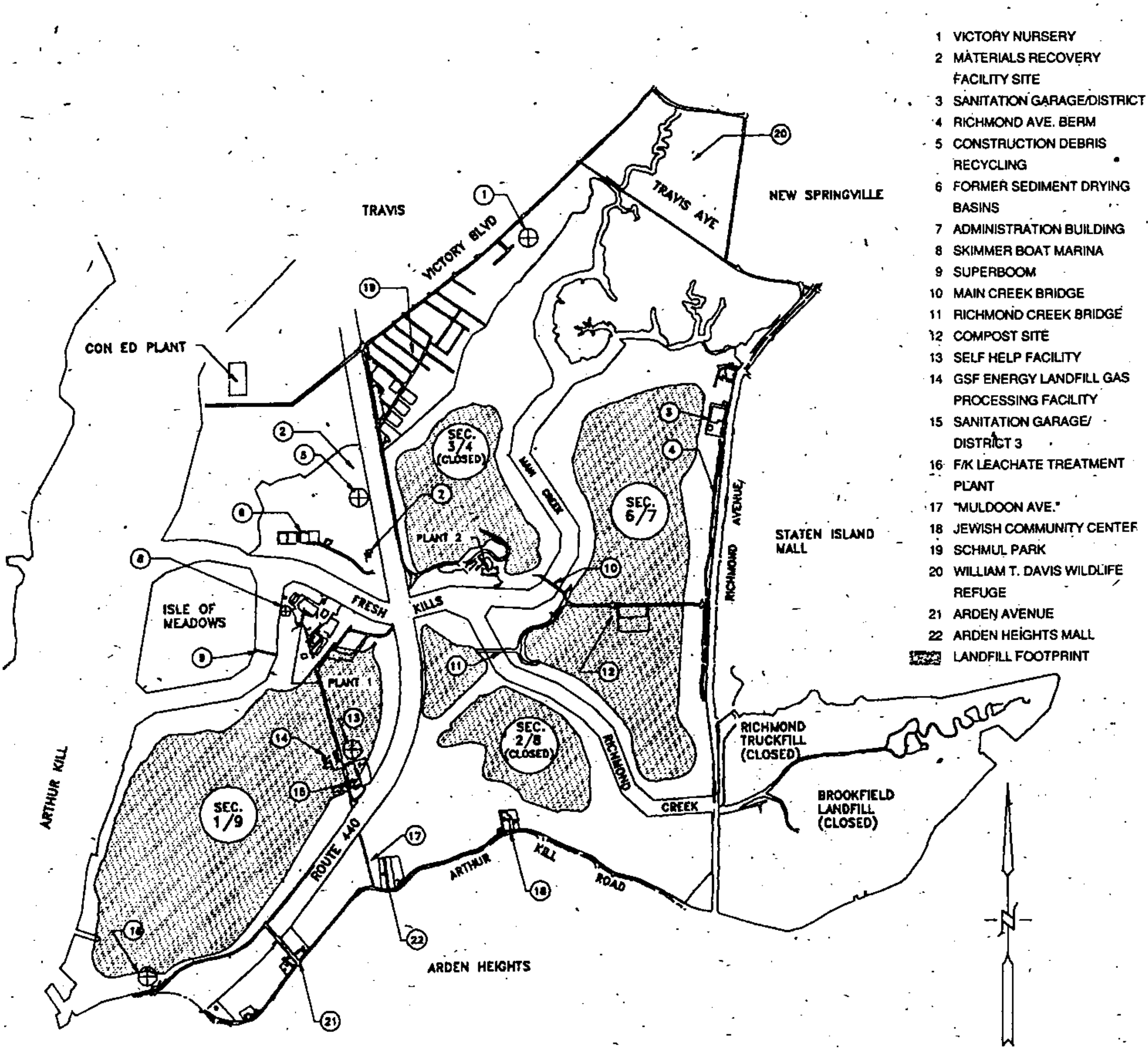

Figure 5. Map of the Fresh Kills Landfill. Stop 3 is at Plant 1. From The New York City Department of Sanitation, DOS Fact Sheet No. 6 March 1994.

On leaving STOP 3, retrace route Turn L out of Parking lot; blinker light.

0.2	42.7	Passing Guard shack.
0.1	42.8	Passing Methane plant on Right . (Muldoon Ave.)
0.2	43.0	Turn Right into W. Service Road. View on Right of landfills Secs. 1/9; will be highest point in coastal zone of East coast eventually.
0.7	43.7	Arden Ave.continue on West Service Rd.
0.4	44.1	Traffic Light; Arthur Kill Road
0.1	44.2	Enter 440 South
0.6	44.8	Passing Exit 3
0.1	44.9	Abandoned LNG tanks on Right
1.4	46.3	Bear Right NY 440 Turns Right
0.6	46.9	Leaving 440 South Exit 1(Last Exit in NY)
0.3	47.2	Turn Right onto Veterans Road
0.2	47.4	Turn Right onto Tyrellan Ave.
0.2	47.6	Turn Right onto Boscombe Ave.
0.2	47.8	Boscombe Ave. now Page Ave.
0.2	48.0	Passing Richmond Valley Road
0.1	48.1	Passing over Railroad Tracks
0.3	48.4	Traffic Light; Amboy Road
0.6	49.0	Traffic light, Page Ave.; Turn Right on Hylan Blvd.
0.3	49.8	Main St.; continue on Hylan Blvd.
0.4	50.2	End of Hylan Blvd.; Conference House; STOP 4 and LUNCH UTM 563.20 E 4483.50 N; view out over Arthur Kill

Stop 4: Cliffs near Conference House (Arthur Kill quadrangle, UTM coordinates: 563.20 E, 4483.50 N). eroding coastal cliff in terminal moraine; paleosol; loess (post-Woodfordian?) Walk across grass toward eroding bluff in terminal moraine. Bring shovels for digging.

We have not made a full dig here, nor have we seen this cliff shortly after any severe storm. Therefore, we are not certain whether the appearance of till all the way to beach level is illusory or not. In any case, what is exposed here is a red-brown till containing diagnostic erratics from well to the NW (anthracite erratics from Pennsylvania and the "braunschweiger-sausage" rock from the Lower Silurian Green Pond Formation in the Appalachian folded belt of NW New Jersey. Several light-colored erratics of Lower Cambrian quartzite protrude out of the cliff. JES is not certain what is the directional significance of the serpentinite erratics.

The till is capped by about 0.5 m of discolored, decayed material that JES interprets as a paleosol. One of the best arguments in support of this view is that discolored zones extend downward along what must have been tree roots. We do not know the age of this paleosol. The "guessing" method yields mid-Wisconsinan as the youngest possible time of origin. Reasonable options only get older from there. In the words of Don ("Get Smart") Adams, "Would you believe post-Illinoian, pre-Wisconsinan, i. e. Sangamonian?"

JES and CM take this paleosol as further support for their interpretation that the Harbor Hill Moraine is **not** a product of a fluctuating Woodfordian ice margin. In our version of the surficial-geologic map of Staten Island, we show the terminal-moraine unit as being of Illinoian (?) age.

At the very top of the cut is 0.5 to 1 m of "fluffy" fine sand/silt that we interpret as a post-Woodfordian loess. JES thinks that this unit probably is the "surficial loam" mentioned in the New York City Folio.

0.0		Leave Conference House; go ENE on Hylan Blvd.
0.5	50.7	Tottenville Swimming Pool on Right.; move Left for upcoming Left turn
0.7	51.4	Traffic light, Page Ave.; turn Left.
0.6	52.0	Traffic light; Amboy Rd.; view ahead of Outbr. Crossing.
0.4	52.4	Passing Richmond Valley Rd. on Left.
0.2	52.6	Page Ave. becomes Boscombe Ave.
0.2	52.8	Turn Left into Tyrellan Ave.
0.1	52.9	Crossing over Rte. 440.
0.2	53.1	STOP; turn Left onto Veterans Rd. W.
0.2	53.3	Passing North Bridge Street on Left; ramp to Outerbridge Crossing.
0.2	53.5	Stop; turn Right Left on Arthur Kill Rd.
0.3	53.8	Arthur Kill Rd. curves to Right ; Kreischer St. on Left.
0.1	53.9	Arthur Kill Rd. curves to Left.
0.3	54.2	Passing Manley St.
0.1	54.3	Turn Right into AKR Construction Co. STOP 5. UTM: 564.68 E; 4487.42 N

Stop 5: AKR Excavating Co. cut, 4288 Arthur Kill Road, Kreischerville, State Island, about 1 mile N of Outerbridge Crossing, Arthur Kill 7 1/2-minute topographic quadrangle map (UTM grid coordinates: 564.68E, 4487.42N). Red-brown till overlying decayed-pebble outwash, which rests on white, charcoal-bearing Cretaceous micaceous sands and gray clays.

Stop Leaders: Charles Merguerian and John E. Sanders

The owner is Mr. Frank Agugliaro, one of the good-old boys, who has always cordially approved our requests to dig in this bluff, not only for today's trip, but on many previous occasions.

The face to the left of the entrance displays significant geologic relationships that are nowhere else exposed in the New York metropolitan area. These include both sedimentologic- and stratigraphic features. In the Pleistocene outwash are spectacular examples of trough cross strata. Among the clasts in this outwash are abundant recycled sedimentary strata including many Newark red-brown siltstones, white quartz, and pieces of the Cretaceous ironstone sandstone and -conglomerate; and rare granitic rocks. The siltstones have been decomposed; they can be easily broken by hand. The feldspars in the granites have been completely decomposed.

The degree of decomposition of the feldspars in the granitic rocks here matches those in Fuller's Mannetto Gravel on Long Island. However, unlike the examples of tills containing decayed feldspars that we have seen on Long Island and at Tellers Point at Croton Point Park in Westchester County, **all** decomposable clasts at this AKR site have been decomposed. Because of the possibility that the ice could have picked up frozen pieces of granitic rocks containing already-decomposed feldspars at the locality found in the Delaware aqueduct (Berkey and Fluhr, 1948), decomposed feldspars alone are not necessarily indicators of intense postdepositional weathering, hence of great age. Rather, such decayed-feldspar-only sediments may contain unique indicator stones.

We take the evidence of decomposition of **all susceptible clasts** at AKR to imply great age; we correlate this decayed-pebble outwash with our till No. I and assign an Early Pleistocene (Nebraskan) age. This place was not shown on the maps of the surficial geology of Staten Island (Figs. GG34, page 176, this Guidebook), but we have added it to our version (Fig. GG35, page 177, this Guidebook). Somebody please check and see if it is shown on the New York City Folio map.

This decayed-pebble outwash overlies light gray- to white, cross-stratified sand containing lignitic plant debris and interbedded layers of light gray clay (Raritan Formation, Upper Cretaceous, the oldest exposed part of the coastal-plain succession).

Special features include:

(A) Trough cross strata on all scales in decayed-pebble sands.

Trough cross strata result from the forward migration of sand ridges whose downstream sides consist of a series of spoon-shaped, or cuspate faces (comparable to the curving slip face on a barchan dune). As sand avalanches down all parts of the curving downcurrent face, it deposits layers having comparable curvature. Such trough cross strata are found in many modern settings, but are particularly common in braided streams.

(B) Extreme degree of decomposition of pebbles.

A comparison of the degree of hardness of the pebbles in this deposit with those to be seen shortly at Stop 6 (coastal cliffs at Princess Bay) and at Stop 4 (coastal bluff at Conference House) is instructive. At Stop 6, only the green rocks show much indication of decomposition. Here, **all** pebbles have been much decomposed. A few white granitic rocks are present. The feldspar in them has become clay.

(C) Abundance of Newark debris in decayed-pebble, cross-stratified sands and the total lack of Newark debris in the Raritan Formation (Cretaceous).

In the decayed-pebble, cross-stratified sediment, Newark debris is extremely abundant. The first pebble from the Newark has yet to be found in the Upper Cretaceous sands. As mentioned, clasts of Upper Cretaceous ironstone-conglomerate clasts been found in the outwash.

(D) Contrasting compositional maturity of the Pleistocene sands vs. Cretaceous sands.

Rock fragments and minerals that readily decompose during chemical weathering (such as feldspars) are parts of the definition of **compositional maturity**. The presence of such particles indicates immaturity and their absence, maturity. Examination with a hand lens of some of the outwash will demonstrate its maturity contrast with the Cretaceous sand.

(E) Planar contact between the two contrasting units.

Not a large area is visible here, but what can be seen indicates a planar boundary between the outwash and the Cretaceous sand. As far as we know, the pits nearby that were formerly worked as sources of clay show that this Cretaceous is *in situ*. As mentioned above, the age of the outwash is not known, but from the extreme degree of decomposition displayed by its susceptible clasts, we have assigned it to the Nebraskan.

(F) Colors of sediments below the contact between the two contrasting units.

On several occasions, we have dug out the contact between the decayed-pebble, cross-stratified sand and the Upper Cretaceous sands/clays. Red and purplish iron stains are present in the otherwise-white Cretaceous sands. We have not made a detailed study of the significance of these iron stains. They could have resulted from the effects of pre-Pleistocene erosion of Cretaceous strata exposed at a former land surface, or from the effects of circulating ground water after the Pleistocene sediments had covered the Cretaceous.

(G) Composition of the Cretaceous strata.

For the most part, the Cretaceous exposed in the face of the exposure that parallels the driveway consists of mineralogically mature white sand. Planar cross strata on several scales (set thicknesses from a few cm to half a meter or more) are present. The sand contains much detrital muscovite and also bits of carbonized plant debris (charcoal; Hollick took this charcoal to be products of ancient forest fires). At a dig at the extreme western end of the exposure that is not parallel to the driveway, we found that the Pleistocene is underlain by gray Cretaceous clay. This is not surprising; many of the abandoned pits in this are were dug in the days when the clay was removed and sold commercially.

As mentioned in (C), the Upper Cretaceous sands lack any reddish debris recycled from the Newark basin fill. This point was first emphasized by Douglas Johnson (1931). We agree with Johnson that this absence of Newark debris can best be explained by inferring that the Upper Cretaceous sea lapped far enough inland to have submerged the Newark outcrop areas.

Turn Left; retrace route to Veterans Rd. W.

0.1	54.4	Passing Winant St. on Right.
0.3	54.7	Left curve; Kreischer St. on Right.
0.4	55.1	Passing Veterans Rd. West on Left: continue on Arthur Kill Rd.
0.1	55.2	Passing beneath Rte. 440 to Outerbridge Crossing.
0.1	55.3	Turn Left into South Bridge St.
0.2	55.5	Intersection Page Ave.; turn Right.
0.3	55.8	Richmond Valley Rd. on Left; turn Left .
0.2	56.0	On bridge over S.I. Rapid Transit RR tracks.
0.1	56.1	Traffic light; Amboy Rd.; continue on Page Ave.
0.7	56.8	Intersection Hylan Blvd.; turn Left.
0.2	57.0	Richard Avenue crosswalk.
0.2	57.2	Mt. Loretto sign on Right.; prepare for upcoming Right turn.
0.6	57.8	Sharrott Road; turn Right at beach, get out of buses; walk to low bluffs on Right; buses turn around

STOP 6: Princess Bay; exposure by light tower

Stop 6: Cliffs along Princess Bay (Arthur Kill quadrangle, 566.700 E, 4484.200N); Pleistocene till and -outwash with giant "erratic" of horizontal, well-stratified Cretaceous strata. (We have used the name Princess Bay, because that is the name shown on U. S. Geological Survey's Arthur Kill 7.5-min quadrangle; however, some older maps show "Prince's Bay"). Make excursion on foot along beach toward cliffs. Bring shovels for digging.

En route to cliff, notice the relationships between the beach and the mouth of the small stream that flows into Raritan Bay here from the marshes to the west. Several topics will engage our attention here. As we approach the cliffs, notice how a small stream draining a marsh has been diverted and forced to flow southwestward along the cliffs before it finally turns eastward and enters the bay. This path followed by the stream has resulted from longshore drift of sand from the northeast to the southwest.

The cliffs expose several tills and interbedded outwash. In the face closest to the creek, the sequence from beach upward is red-brown till, red-brown outwash, and red-brown till, capped by what may be about a half meter of loess and the modern soil.

Near the navigation tower, a considerable body of yellowish and whitish sands and light-colored clays [some layers containing bits of charcoal that Hollick (1906) inferred came from ancient forest fires]. Included are firmly cemented quartz-rich sandstones and -conglomerates. The cement is hematite. Although we do not know of any fossils that have been obtained from these yellowish-whitish-brownish sediments exposed near the navigation tower, on the basis of their mineralogic maturity and general appearance, we think that they can be assigned with confidence to some part of the coastal-plain Cretaceous. Although generally obscured by slopewash from above, after severe storms (or big digs by JES and friends), the "natural" sediments underlying the coastal-plain Cretaceous sediments in the face by the navigation tower are coarse brownish, immature outwash and one thin layer of red-brown till. Evidence found in the 1987 borings for the sewer line later constructed along Hylan Boulevard show the same relationships as seen here: Pleistocene below and above, with Cretaceous in the middle. At still-greater depth, the borings encountered *in-situ* Cretaceous.

The outwash is very significant. It is another feature that was not shown on either of the two most-recent surficial-geology maps of Staten Island. This omission proved to be costly. The pre-bid information provided to potential contractors bidding on the the job of building the sewer under Hylan Blvd. went by the surficial-geology map that shows till all along the route. The soil-test borings showed what proved to be outwash, but these did not raise any red flags at the time. When excavations actually started, however, they disclosed a large body of coarse, extremely permeable outwash such as is exposed near the light tower. Ground water flowed into the excavations in such quantities that the contractors were not able to "stem the tide" by drilling wells and pumping. Eventually, they had to install refrigeration pipes and make artificial permafrost. Only after that, were they able to complete construction, but at costs far greater than estimated.

We suggest that the best interpretation of this example of Cretaceous sediments surrounded by Pleistocene sediments is that the Cretaceous is a gigantic glacial erratic that became incorporated in the Pleistocene sediments. In many localities on Long Island, sheets of Cretaceous sediments have been thrust upward by the ice and are now engulfed in Pleistocene till. Examples of ice-thrust deformation include those Gardiners Island and in various localities on Long Island described by Fuller, 1914; and from the Port Washington sand pits by Mills and Wells, 1974). In these (and other) examples where flowing ice has created overthrusts, one of the obvious aspects of the affected sediments is the geologic structural features formed by deformation. Pleistocene thrusting under permafrost conditions would have involved frozen-solid Cretaceous materials!

Quite by contrast, before us here is an **apparently nondistorted slab of Cretaceous that has become incorporated within well-bedded Pleistocene outwash sediments.** Bedding in both the Pleistocene and "Cretaceous" is essentially horizontal. The existence of coarse outwash sediments above and below implies that the slab of displaced Cretaceous was transported here not by ice-thrust deformation but rather by water. Accordingly, we may be looking at the effects of a body of Cretaceous sediment that became frozen in a sheet of ice and was floated here by meltwater as a sediment-laden ice + debris raft. After it became stranded here on the surface of an outwash fan, and while it was still frozen, this slab may have been covered and buried by other coarse outwash. Thus, when the ice in the "raft" eventually melted, no significant motion could take place and thus the bedding in the Cretaceous would not be distorted.

	57.8	Continue ENE on Hylan Blvd
0.3	58.1	Passing Woodvale Ave.
0.4	58.5	On Bridge Over Lemon Creek
0.2	58.7	Traffic Light: Seguine Ave.
0.6	59.3	Traffic Light: Luten Ave.
0.4	59.7	Traffic Light; Wendy drive
1.1	60.8	Traffic Light; Arden Ave.
0.5	61.3	Traffic light; Richmond Ave.
0.4	61.7	Traffic Light; Armstrong Ave.
0.3	62.0	Traffic Light; Nelson Ave.
0.2	62.2	Traffic Light; Cleveland Ave.
0.5	62.7	Traffic Light; Keegans Lane
0.3	63.0	Traffic Light; Bay terrrace
0.1	63.1	Traffic Light; Justin Ave.
0.3	63.4	Turn Right into Great Kills Park - Gateway National Rec. Area
1.0	64.4	Park near "Port-o-Potties;" STOP 7. Entrance marked "Only Govt. vehicles."

Beach Erosion At Great Kills Park, Gateway National Recreation Area.

STOP LEADER: Alan I. Benimoff

0.1	64.5	Exit parking lot.
0.9	65.4	Traffic light; turn Left into Hylan Blvd.
0.3	65.7	Traffic light, Justin Ave.
0.1	65.8	Traffic light, Bay Terrace.
0.3	66.1	Traffic light, Keegans Lane

0.5	66.6	Traffic light, Cleveland Ave.
0.1	66.7	Traffic light, Nelson Ave.
0.4	67.1	Traffic light, Armstrong Ave.
0.3	67.4	Traffic light, Richmond Ave.
0.6	68.0	Traffic ight, Arden Ave.
0.9	68.9	Traffic light, Wendy Drive.
0.5	69.4	Traffic light, Huguenot Ave.
0.1	69.5	Traffic light, Luten Ave.
0.6	70.0	Traffic light, Seguine Ave.
0.3	70.3	On Bridge over Lemon Creek
0.4	70.7	Passing large cemetery on Right .
0.3	71.0	Sharrott Rd. on Left.
1.1	72.0	Traffic light, Page Ave.; turn Right.
0.7	72.7	Traffic light, Amboy Rd.
0.2	72.8	Bridge over St. Is. Rapid Transit RR.
0.2	73.0	Passing Richmond Valley Rd. on Left.
0.2	73.2	Page Ave. now Boscombe Ave
0.3	73.5	Turn Left into Tyrellan Ave.
0.1	73.6	Crossing over Rte. 440.
0.2	73.8	Stop sign; T intersection; turn Left into Veterans Rd. W.
0.2	74.0	Turn Left on N. Bridge St. for ramp to 440.
0.0	74.0	Bear Left for entrance to 440 N and Outerbridge Crossing.
0.1	74.1	Enter 440 South
6.0	80.1	NJ 440 N becomes I-287 N.
10.0	90.3	Leave I-287 N at Exit 6, Follow signs for New Brunswick NJ 527 S
0.6	90.9	Bear right for entrance into the parking lot of the Quality Inn.

END OF FIELD TRIP

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Disclaimer and Correction To The Meeting Announcement

The meeting announcement was incorrect as listing the host as The College Of Staten Island/CUNY. This trip and meeting is not being hosted by The College Of Staten Island/CUNY. GANJ XI is sponsored by The Geological Association Of New Jersey.