Highlights of Staten Island Geology

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Introduction

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

The Staten Island Serpentinte

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

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

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

Hollick (1909) suggested that the Staten Island serpentinite is a fault-bounded horst-block , Crosby (1914) Miller, (1970), Merguerian and Sanders, (I 994) share that interpretation. A petrographic study of the Serpentinite was accomplished by Behm (1954). He concluded that the serpentinite body can be subdivided into two major zones as follows:

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

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

Okulewicz(I 979) reported that the serpentinite protolith was hartzburgite, consisting essentially of olivine (90%), enstatite (6%) and magnetite (3%). Some serpentinized dunites exist in the northern part of this body. Serpentinization occurred under greenschist facies conditions. The most abundant serpentine mineral is lizardite, with chrysotile present as fracture fillings and in veins. Chrysotile shows a small but variable concentration throughout the serpentine body. Benimoff et al. (1992a) reported on a Ni-Cr rich splintery antigorite whereby they analyzed it using **H**igh **R**esolution **T**ransmission **E**lectron **M**icroscopy.

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

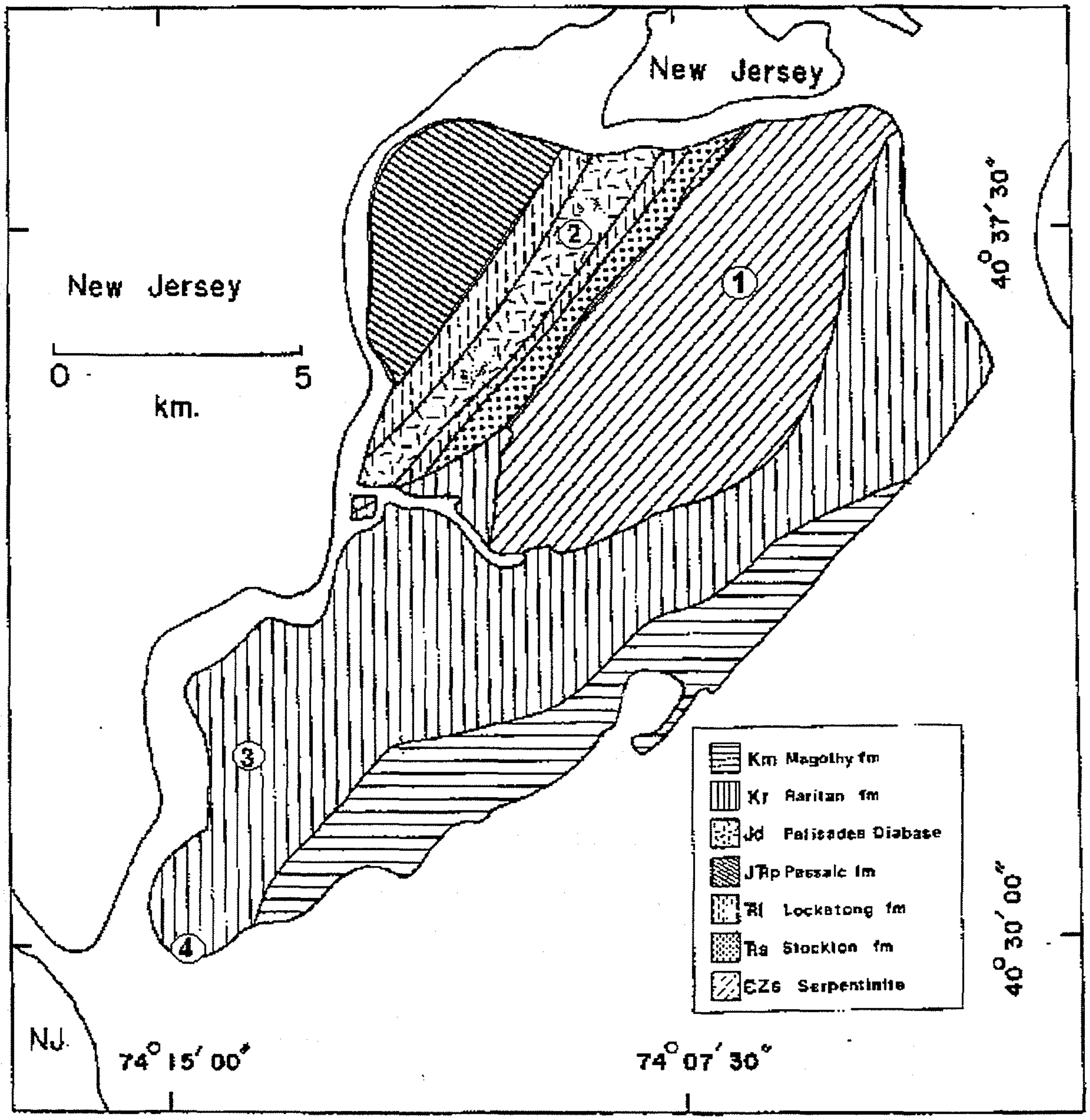

Figure 1. Geologic bedrock map of Staten Island, New York modified from Lyttle and Epstein, (1987). Field trip stops are indicated by numbers.

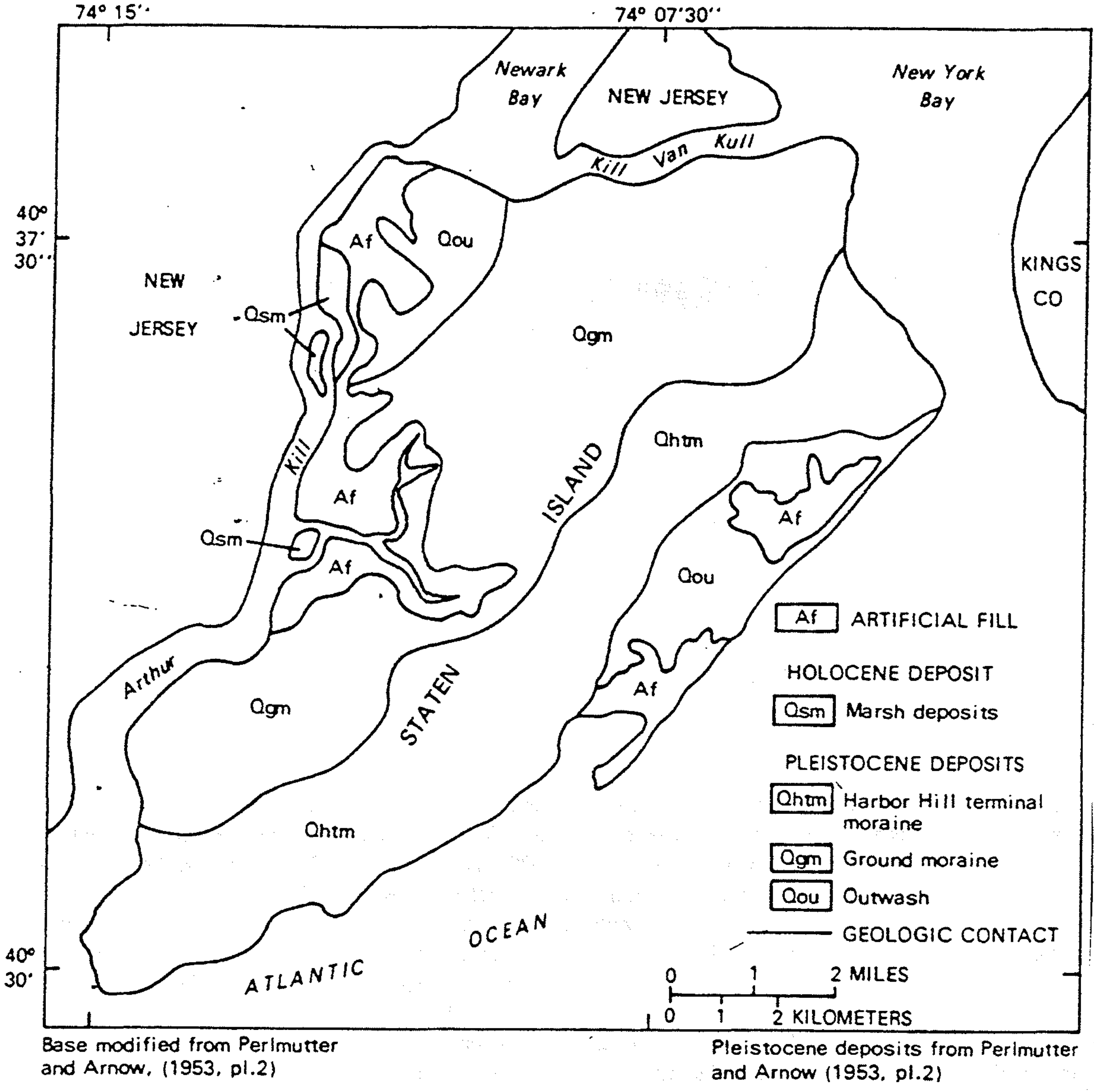

Figure 2. Surficial geologic map of Staten Island, New York(from Soren, 1988)

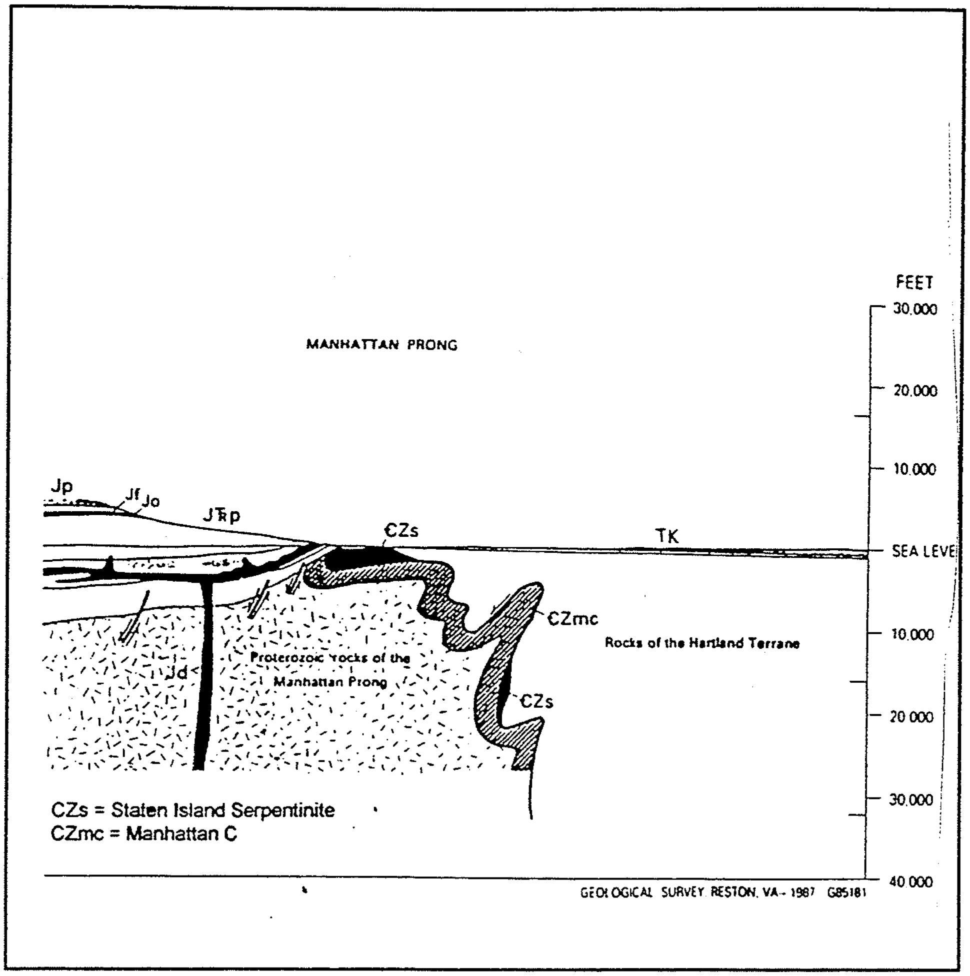

Figure 3. Cross section through Staten Island(From Lyttle and Epstein, 1987)

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

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

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

The Mesozoic Igneous Rocks of Staten Island, New York

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

The Granitevile Quarry

It is an exceptional occurrence wherein one can observe the parent of an igneous rock adjacent to that igneous rock. This is the case at the Graniteville Quarry (Stop 2 on this field trip) where marginal fusion of a xenolith of sodium-rich 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, 1980a,1980b, 1984, 1988, 1992, 1996 and Sclar and Benimoff(1993), and a summary of these studies is presented below.

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. Benimoff and Sclar(1978, 1984) concluded 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. They have categorized the coarse-grained rock of the interface zone as a melanocratic pyroxene trondhjemite. The chemical analyses of these rocks is shown in table1.

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

Chemical Analyses, weight % oxides

	XA	**XB**	**TA**	**TB**	**D-1**	**D-2**
SiO_2	74.8	63.5	58.4	58.2	51.8	52
Al_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 diabase at Graniteville is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34-44}Fs_{17-31}Wo_{35-42}$) (Benimoff and Sclar, 1984) The augite contains exsolution lamellae of pigeonite on (001), and typically exhibits simple contact twinning on (100). A granophyric intergrowth of quartz and K-feldspar is present in minor amounts. Grains of titanomagnetite with oxidation lamellae of ilmenite and discrete grains of ilmenite are common.

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

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

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

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

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

Travis Quarry

A steeply dipping albitite dike 10-15 cm thick in the Palisades Sill at the Travis Quarry, was reported by Benimoff et al. 1988). The dike is exposed continuously on strike for 3.5 meters, and may be traced 30 meters along strike (N 12° E). The leucocratic dike is coarse grained (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 2.

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

Chemical Analyses, weight % oxides

	TV01	TV02	BBAL	BBDB	TL01	CSI01
SiO_2	62.7	52.3	60.1	52.5	51.88	53.29
Al_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

Bayonne Bridge Toll Plaza

Another steeply dipping albitite dike 12 cm thick in the Palisades Sill at the south end of the Bayonne Bridge was reported by Benimoff and Sclar (1990). The dike strikes N 30° E. The leucocratic phaneritic albitite dike is composed dominantly of subhedral albite and subordinately of interstitial augite which is partly altered to actinolite and chlorite.Chemical analyses and CIPW norms of the diabase (BBDB) and the albitite dike (BBAL) are given in Table 2.

Interpretation of the albitite dikes

Based on the chemical and mineralogical characteristics of the leucocratic dikes in the Palisades Sill, Benimoff and Sclar concluded that the parental magma of these dikes was derived from fusion of xenoliths of Lockatong argillite in the Palisades Sill , and that these leucocratic intrusions are not late magmatic differentiates of the diabase sill. Late differentiates are quartz-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 above. 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).

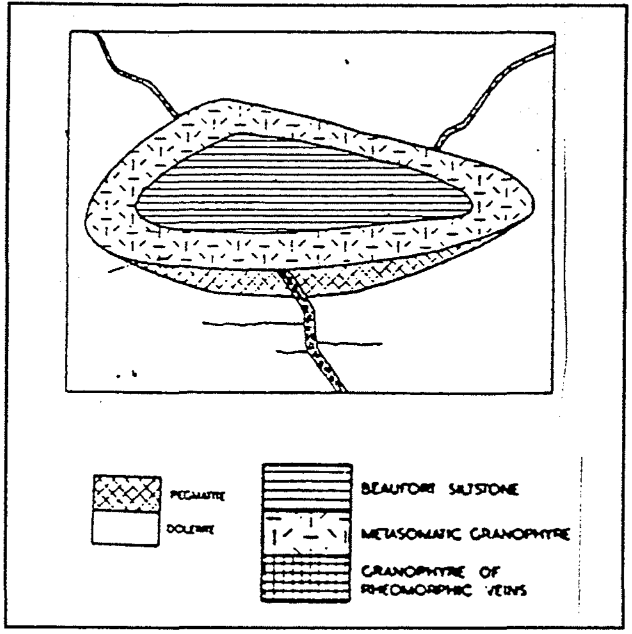

Figure 4. Sketch of the xenolith and pegmatite enclosed in the Karroo Dolerite(from Walker and Poldervaart 1949).

Walker and Poldervaart (1949) studied the field relationships of the reaction products of the Karroo dolerite magma with associated sedimentary rocks and reported that examples of assimilation are rare. They concluded that rheomorphism and transfusion or metasomatism of sedimentary rocks occur more commonly. The former process includes all processes whereby sedimentary rocks are fused sufficiently so that they are capable of flowing, and the latter processes as due to emanations of alkali-rich fluids reacting with minerals of the sedimentary rocks to produce new minerals.They describe(Figure4) a lenticular siltstone xenolith that measured 15.24 m x 2.43 m about 30 m from the upper contact of a sill 183 m thick. Surrounding the xenolith is a zone of granophyre that exhibits sharp boundaries with the dolerite and the xenolith. They report that "rheomorphic veins" originate from the granophyric zone. Although they propose a transfusion-type of process for the origin of the granophyre, Benimoff et al.(in prep.) propose that it is equally as probable that the granophyre is a fusion product of the xenolith. The spatial arrangement of the "rheomorphic veins" suggest that the granophyric magma is the source of the "rheomorphic veins". If this granophyre is a fusion product of the xenolith, then some of the leucocratic " veins" that occur in the Karroo dolerite also have their source in the associated sedimentary rocks(Benimoff et al., in prep.).

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

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

Glacial and Cretaceous deposits

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

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

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

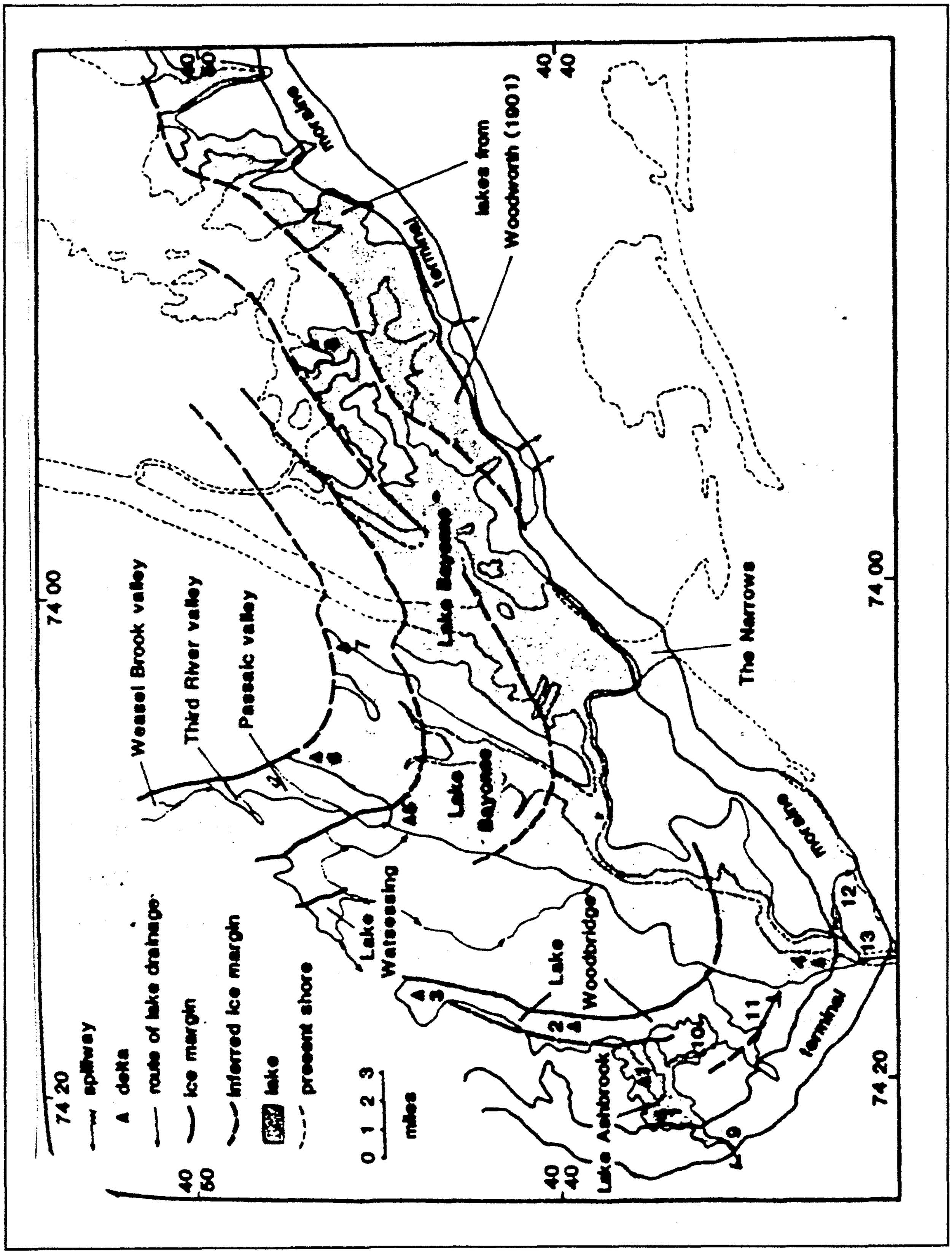

Figure 5. Map showing terminal moraine, inferred ice margins and glacial lakes(from Stanford and Harper, 1991)

References

Behm J.J., 1954, The petrology of the serpentinite of Richmond County (Staten Island), N.Y., Proc. of the Staten Island Inst. of Arts and Sciences, v. 16, p. 1-39.

Benimoff, A. I. and Sclar, C. B. (1978) Pyroxene trondhjemite derived by partial fusion of a xenolith of Lockatong argillite in the Palisades sill, Staten Island, N. Y. (abstr.) Geological Society of American Abstracts with Programs, 10, 33.

Benimoff, A. I. and Sclar, C. B. (1980a) Partial fusion of a xenolith of Lockatong argillite in the Palisades diabase, Graniteville quarry, Staten Island: The petrochemistry of coexisting silicic and basic magmas. Geological Society of American Abstracts with Programs, 12, 24.

Benimoff, A. I., and Sclar, C. B. (1980b) "Two Chemically Divergent Magmatic Liquids." Cover Story, EOS, Transactions American Geophysical Union, 61.

Benimoff, A. I. and Sclar, C. B. (1984) Coexisting silicic and mafic melts resulting from marginal `fusion of a xenolith of Lockatong argillite in the Palisades sill, Graniteville, Staten Island, New York. American Mineralogist, 69, 1005-1014.

Benimoff, A. I. and Sclar, C. B. (1988) The Graniteville quarry, Staten Island, N. Y.: an outstanding location for illustrating igneous phenomena. Northeastern Geol. 10, 30-42.

Benimoff, A. I., Sclar C. B., Okuliewicz, S., and Behm, H. J. (1988) "A Leucocratic Albitite Dike in The Palisades Sill, Travis Quarry, Staten Island, New York"'GSA Abstracts with Programs V. 20. No. 1, 5.

Benimoff, A. I., and Sclar, C. B. (1990) "An Albitite Dike in the Palisades Sill at the South end of Bayonne Bridge, Staten Island, NY. Geological Society of America Abstracts with Programs, 22, No. 2, p. 4.

Benimoff, A. I., and Sclar, C. B. (1992b) REE Geochemistry of a Partly Fused Xenolith in The Palisades Sill, Staten Island, NY: A Test of The Igneous Source-Rock Concept in REE Geochemistry. V. M. Goldschimdt Conference Program and Abstracts, The Geochemical Society, A-8.

Benimoff, A. I. and Sclar, C. B.(1994) The Mesozoic Igneous Rocks of Staten Island, New York: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 25-58.

Benimoff, A. I. and Sclar, C. B.(1996) Natural Cationic Diffusion Profiles Across a Liquid-Liquid Boundary Between Chemically Dissimilar Coexisting Magmas: a Trondhjemite-Diabase Interface. EOS, Transactions American Geophysical Union, Spring Meeting paper V21-04.

Benimoff, A. I., Moore, P. B., Rice, S. B.,and Sclar, C. B. (1992a) A Ni and Cr-bearing splintery antigorite from the serpentinite of Staten Island, N.Y.,*Geological Society of America Abstracts with Programs*, 24,(3) 7.

Benimoff, A. I., Puffer, J. H., and Sclar, C. B. (1989)A Trondhjemite Dike in the I-95 Cut of The Palisades Sill, NJ, GSA Abstracts with Programs, 21, No. 1:4.

Crosby, W.O. (1914) Physiographic relations of serpentine with special reference to the serpentine rock of Staten Island. Journal of Geology 22, No. 6 582-592.

Haskin , L. A., Haskin, M. A., Frey, F. A.(1968) Relaive and absolute terrestrial abundances of the rare earth elements. In *Origin and distribution of the Elements*, ed. L. H. Ahrens, pp 889-912. Oxford, Pergamom Press.

Hess, H. H., 1955, Serpentines, orogeny, and epeirogeny: p. 391-407 in Poldervaart, Arie, ed., Crust of the Earth (a symposium),Geological Society of America Special Paper 62, 762 p.

__________ (1962) History of ocean basins. Geological society of America, Buddington Volume 599-620.

Hollick, C. A., (1909) Notes in connection with specimens recently obtained from serpentines of Staten Island, N.Y.: New York Academy of Sciences, Annals, v. 19, p. 315-317.

Hozik, M. J. (1992) Paleomagnetism of Igneous Rocks in The Culpeper, Newark, and Hartford/Deerfield Basins *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism:Geological Society Of America Special Paper 268,279-308.

Husch, J. M., (1992) Geochemistry and Petrogenesis of the Early Jurassic Diabase from the Central Newark Basin of New York and Pennsylvania *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism:Geological Society Of America Special Paper 268,169-192.

Johnson, M.E., and Richards, H.G. (1962) Stratigraphy of coastal plain in New Jersey: American Association of Petroleum Geologists Bulletin, v. 36, no. 11, p. 2150-2160.

Lewis, J. V. (1907) The origin and relations of the Newark rocks. New Jersey Geological Survey Annual Report, 1906, 99-129.

Lewis, J. V. (1908a) Petrography of the Newark igneous rocks of New Jersey. New Jersey Geological Survey Annual Report, 1907, 99-167.

Lewis, J. V. (1908b) The Palisades diabase of New Jersey. American Journal of Science, 26, 155-162.

Lyttle, P. T., and Epstein, J. B., 1987 Geologic Map of the Newark 1° x 2° Quadrangle, New Jersey, Pennsylvania, and New York. USGS Miscellaneous Investigation Series, I-1715.

Miller, W. H., (1970) Structural geology and tectonism of the Staten Island Serpentinite:, Brooklyn College of City University of New York, Department of Geology, Brooklyn, New York Master's Thesis, 67 p.

McPhee, J. (1993) *Assembling California*, Farrar, Straus, and Giroux, New York, 304p.

Merguerian, C, and Sanders, J. E., (1994) Trip 19: Geology of Staten Island and vicinity, 16 October 1994 : New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 78.

Ohan, A. A., Kureshy, A.; and Kaarsberg, E., (1975) Geological aspects of Staten Island, New York, p. 195-212 in Wolff, M. P., ed., Guidebook to Field Excursions: New York State Geological Association, Annual Meeting, 47th, Hofstra University, Hempstead, *N.* Y., October 1975, Hempstead, New York, Hofstra University, Department of Geology, 327 p.

Okulewicz, S.C., (l979) Petrology of the Staten Island alpine ultramafic body: Masters Thesis, Brooklyn College, New York, 92 pp.

Olsen P., (1980) Fossil great lakes of the Newark Supergroup in New Jersey: in Manspeizer, W., Ed. Field studies in New Jersey geology and guide to field trips, 52nd Annual Meeting of the New York State Geological Association, Newark College of Arts and Sciences: Rutgers University, p. 352-398.

Owens, J.P., and Sohl, N.F., (1969), Shelf and deltaic.paleoenvironments in the Cretaceous-Tartiary formations of the.New Jersey coastal plain: in Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions, Geological Society of America Annual Meeting, Rutgers University Press, New Brunswick, N.J., p. 235-278.

Pagano, T. S.(1994) The geology of western Staten Island, New York north and south of the fall line: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 61-84.

Pearce, T. H. (1970) Chemical variation in the Palisades Sill. Journal of Petrology, 11, 24-32.

Puffer J. H.(1994) The Staten Island Meta-Peridotite: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 1-24.

Puffer, J. H. and Student, J.J., (1992) Volcanic Structures, Eruptive Style, and Posteruptive Deformation and Chemical Alteration of the Watchung Flood Basalts, New Jersey *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism:Geological Society Of America Special Paper 268,261-278.

Puffer J. H., Husch, J. M., and Benimoff, A. I. (1992) "The Palisades Sill and Watchung Basalt Flows, Northern New Jersey and Southeastern New York: A Geological Summary and Field Guide". New Jersey Geological Survey, Open File Report OFR 92-1, 27 pages.

Sanders, J. E., and Merguerian C. (1994) The Glacial geology of New York City: In: Benimoff, A. I. (Ed.) *The Geology Of Staten Island, New York Field Guide and Proceedings* Eleventh Annual Meeting of The Geological Association Of New Jersey, 93-200.

Roberts-Dolgin, G. (1989)The Geology of Staten Island and western Long Island, Kings County and Queens counties, New York pages 51-57,in C.A. Baskerville ed., Geology and engineering geology of the New York metropolitan area. 28th International Geologic Congress Field Trip Guidebook T361.

Sclar, C. B. and Benimoff, A. I. (1993) An occurrence of magmatic sphalerite, The Canadian Mineralogist, 31(3) 691-694.

Sirkin, L. A., (1986), Pleistocene stratigraphy of Long Island, New York, in Cadwell, D. H., ed., The Wisconsinan Stage of the First Geological District, eastern New York: New York State Museum Bulletin 455, 6-21.

Soren, J. (1988) Geologic and geohydrologic reconnaissance of Staten Island, New York: United States Geological Survey Water Resources Investigations Report 87-4048, 22 p.

Stanford S. and Harper, D. (1991) Glacial lakes of the lower Passiac, Hackensack, and lower Hudson Valleys, New Jersey and New York. Northeastern Geol. 13, 271-286.

Steiner, J. C., Walker, R. J., Warner, R. D., and Olson, T. R.,(1992) A Cumulus-Transport-Deposition Model for the Differentiation of The Palisades Sill *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society Of America Special Paper 268,193-218.

Shirley, D. N. (1987) "Differentiation and Compaction in the Palisades Sill, New Jersey", J. Petrol. 28, Part 5, 835-865.

Tollo, R. P., and Gottfried, D., (1992) Petrochemistry of Jurassic Basalts from Eight Cores, Newark Basin, New Jersey: Implications for the Volcanic Petrogenesis of the Newark Supergroup *in* Puffer, J. H., and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism:Geological Society Of America Special Paper 268, 233-260.

Van Houten, F. B. (1964) Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation Central New Jersey and adjacent Pennsylvania Geological Survey Bulletin, 169, 497-531.

Van Houten, F. B.(1965) Composition of Triassic Lockatong and associated Formations of Newark Group Central New Jersey and adjacent Pennsylvania. American Journal of Science, 263, 825-863.

Van Houten, F. B. (1969) Late Triassic Newark Group, north-central New Jersey and adjacent In S. Subitsky, Ed., Geology of Selected Areas in New Jersey and Pennsylvania Adjacent , p. 314-347. Rutgers University Press. New Brunswick, New Jersey .

Van Houten, F. B. (1971) Contact metamorphic mineral assemblages, Late Triassic Newark Group,.N .J.: Contributions Mineralogy and Petrology, 30, p. 1- 14.

Walker, F. (1940) The differentiation of the Palisades diabase, New Jersey. Geological Society of America Bulletin, 51, 1059-1106.

Walker, K. R. (1969a) The Palisades Sill, New Jersey: A Reinvestigation. Geological Society of America Special Paper, 111.

Walker, K. R. (1969b) A mineralogical, petrological and geochemical investigation of the Palisades Sill, New Jersey. Geological Society of America Memoir, 115, 175-187.

Walker F., and Poldervaart, A., (1949), Karroo dolerites of the Union of South Africa: Geological Society of America Bulletin, v. 60, p. 591-706.

Wasserman, G., (1956), Magnetic survey of the Staten Island serpentinite: New York, New York, New York University, Department of Geology, Masters thesis, 65p.

Yersak, T.E., (1977) Gravity study of Staten Island and vicinity: Rutgers University, New Brunswick, New Jersey, M.S. thesis, 47 p.

Field Guide to Stops

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

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

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

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

At this locality, we see an extraordinary example of two coexisting magmatic liquids, now represented by the diabase of the Palisades Sill and a pyroxene Trondhjemite derived by fusion of the the margins of a xenolith of sodium rich Lockatong Argillite .(Benimoff and Sclar, 1978, 1980, 1984, 1988, 1992, 1996; Sclar and Benimoff,1993). The diabase is composed dominantly of plagioclase ($An_{61}Ab_{38.8}Or_{0.2}$) and augite ($En_{34\text{-}44}Fs_{17\text{-}31}Wo_{35\text{-}42}$).The trondhjemite is composed dominantly of quartz-albite granophyre in which are enclosed large discrete crystals of albite($Ab_{99}An_{0.52}Or_{0.44}$) and Ca-rich pyroxene . Minor constituents include interstitial calcite, titanite, ilmenite, optically homogeneous titanomagnetite, nickelian and cobaltian pyrrhotites, apatite, and sphalerite. The modal mineral percentages are clinopyroxene 38, albite 38, quartz 18, titanite 2.7, calcite 1.3, and opaques 2.0. The xenolith is now a hornfels and exhibits a granoblastic texture. The hornfels is composed dominantly of albite and quartz and subordinantly of calcite, titanite, apatite, ilmenite, and actinolite. The modal mineral percentages are albite 66, quartz 30, titanite 2.3, calcite 0.9, apatite 0.5, and actinolite 0.3. Normative albite ranges from 56.4 to 80.2 wt.%, whereas normative quartz ranges from 7.0 to 35.4 wt.%.Chemical analyses(Table 1) reveal that diffusion of calcium, magnesium, iron, and sodium ions occurred across the liquid-liquid interface.

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

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

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

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

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

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

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

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

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

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

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

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