The Uniform Composition of CAMP Diabase Types and the Absence of Wall Rock Contamination at Northern New Jersey and Staten Island, New York Locations

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ABSTRACT

This field trip will focus on five contrasting and distinct late Triassic to early Jurassic lithologies. These rocks are trondhjemite, syenite, and their sedimentary protoliths, and diabase sills that are part of the Central Atlantic Magmatic Province (CAMP). All five of these lithologies are exposed at six widely spaced northern New Jersey and Staten Island, NY locations, some of which will be visited on this field trip. Chemical and petrographic analyses of closely spaced samples collected at each of these locations demonstrates a genetic linkage of the syenite and trondhjemite to sedimentary lithologies and a near absence of magma mixing with CAMP diabase. This lack of contamination helps explain the province wide uniformity of CAMP diabase types.

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. More recent studies of the Palisades and related Mesozoic intrusions and flows within the Newark Basin portion of CAMP were made by Puffer (1992), Steiner et al. 1992, Husch (1990, 1992), Houghton et al. 1992, Tollo, et al. 1992, Puffer and Student (1992), Hozik (1992) and Puffer and Husch (1996). Inasmuch as this field trip deals with syenitic and

trondhjemitic fusion at Mesozoic Diabase intrusive contacts with sedimentary rocks of northern New Jersey and Staten Island, New York, the reader is referred to Puffer and Husch (1996) for a recent comprehensive study of the Palisades-Rocky Hill-Lambertville (PRHL) megasheet.

Two contrasting and distinct felsic igneous rocks were generated during the intrusion of early Jurassic diabase into Triassic sedimentary rocks: 1) a trondhjemite characterized by a K_2O and Na_2O contents of about 0.1 and 7 percent respectively and 2) a monzonite to syenitic lithology characterized by K_2O and Na_2O contents of about 4 and 7 percent respectively. One or both of these lithologies are exposed at six widely spaced locations throughout northern New Jersey and Staten Island: 1) the lower contact of the Palisades sill along a series of road-cuts at and north and south of Ross Dock where Lockatong Argillite has fused into syenite and trondhjemite; 2) the interior upper portion of the Palisades sill at a road-cut near the George Washington bridge where trondhjemite dikes are exposed; 3) near the northern and southern contacts but within the Palisades related Snake Hill diabase intrusion where intergrown or commingling trondhjemite and syenite veins are exposed at a rock quarry; 4) and the interior upper portion of the Palisades sill at a rock quarry near Granitville where the margins of a Lockatong argillite xenolith has fused into trondhjemite; and 5) at the lower contact of a Palisades related sill with Lockatong argillite where a syenitic migmatite is exposed along a stream near Brookville New Jersey. Sites 1 and 3 will be observed on this field trip. If time permits site 4 will be included.

The felsic fusion products of sites 1 -5 are absent at most Palisades diabase contact exposures and may be localized due to concentrations of halite or brackish water contained within the intruded sediments that acted as a flux. Alternatively fusion products at most locations may have been swept away by currents of intruding diabase that finally quenched against dehydrated and refractory residual hornfels. Melting experiments are planned where the fluxing effect of salt on Lockatong argillite will be measured.

The chemical compositions and by-modal nature of the felsic fusion products are due to a combination of controlling factors that are currently being evaluated by Benimoff and Puffer (in prep.). These factors include: 1) contrasts in the chemical composition of the host sedimentary rock layers intruded by the diabase, 2) heat driven metasomatism, particularly potassium, among the sediments during conversion to hornfels, 3) the degree of superheating experienced by the metasediments before fusion was initiated, 4) element partitioning between melt phases and refractory residues during fusion, 5) the degree of partial melting of the metasediments, and 6) the degree of mixing of fusion products with diabase magma after fusion.

Alternative interpretations such as the possibility that the fusion products were the result of diabase magma fractionation or liquid immiscibility were also considered but rejected on the basis of new geochemical data presented herein. It will also be shown that the fusion products occur as distinct igneous bodies that did not mix with CAMP diabase melt or materially alter its composition at any of five Newark Basin sites.

FUSION PRODUCT OCCURRENCES

Walker (l969a) reported the occurrence of (1) leucocratic patches in the normal dolerite of the Palisades Sill that he interpreted as the product of assimilation of Newark group sediments, and (2) reomorphic "veins" and "dikes" up to 15 inches thick in the Palisades Sill. Benimoff and Sclar (l984) reported the occurrence of a xenolith of sodium-rich Lockatong

argillite in the Palisades Sill the outer shell of which fused and crystallized to a pyroxene trondhjemite. In addition, two albitite dikes (Benimoff et al. 1988; Benimoff and Sclar, l990) and a trondhjemite dike (Benimoff et al. 1989) were found in the Palisades Sill and these dikes were interpreted on mineralogical and geochemical grounds as products of fusion of Lockatong argillite xenoliths.

Barker and Long (l969) reported the occurrence of syenite along the lower contact of the Stockton Diabase, (a Palisades related diabase intrusion) near Brookville, New Jersey and interpreted it as the product of magma mixing of fractionated Palisades diabase and fused Lockatong argillite. Benimoff et al. (1996, 1997,1998), however, determined that the chemical composition of the syenite closely matched the composition of the intruded Lockatong argillite suggesting high degrees of partial fusion took place with little evidence of diabase mixing. The chemical data including REE's supported phase equilibria studies suggesting that wet fusion of syenitic melt could occur at temperatures approximating those at the base of the intrusive.

Puffer et al. (l994) and Puffer and Benimoff (l997) also reported the occurrence of "microsyenite" and "granitoid" veins and trondhjemite veins intruded into the diabase of Snake Hill, New Jersey and interpreted them as the fusion products of metasomatized hornfels.

The most recent focus of our work takes us back to the Palisades Sill where probably the clearest exposures of both syenitic and trondhjemite occur at the lower contact near Ross Dock. The entire progression of contact metamorphic, metasomatic, fusion, and intrusion processes is being systematically sampled and analyzed along traverses perpendicular to the contact. Preliminary results confirm earlier interpretations suggesting that high degrees of partial melting are responsible for the syenitic and trondhjemitic rocks and that minimal mixing of diabase has occurred.

Field occurrences of leucocratic rocks interpreted as products of sedimentary fusion induced by early Jurassic diabase intrusions include:

1. The base of the Palisades Sill from Englewoods Cliffs to Cliffside Park along the road to Ross Dock near the George Washington Bridge (STOP 1)
2. Dikes within the Palisades Sill I-95 road cut, Fort Lee, New Jersey
3. Snake Hill, New Jersey (STOP 2)
4. Graniteville, Staten Island, New York (Optional Stop 3)
5. At the upper contact of an early Jurassic diabase intrusion exposed in a rock quarry at Brookville, New Jersey.
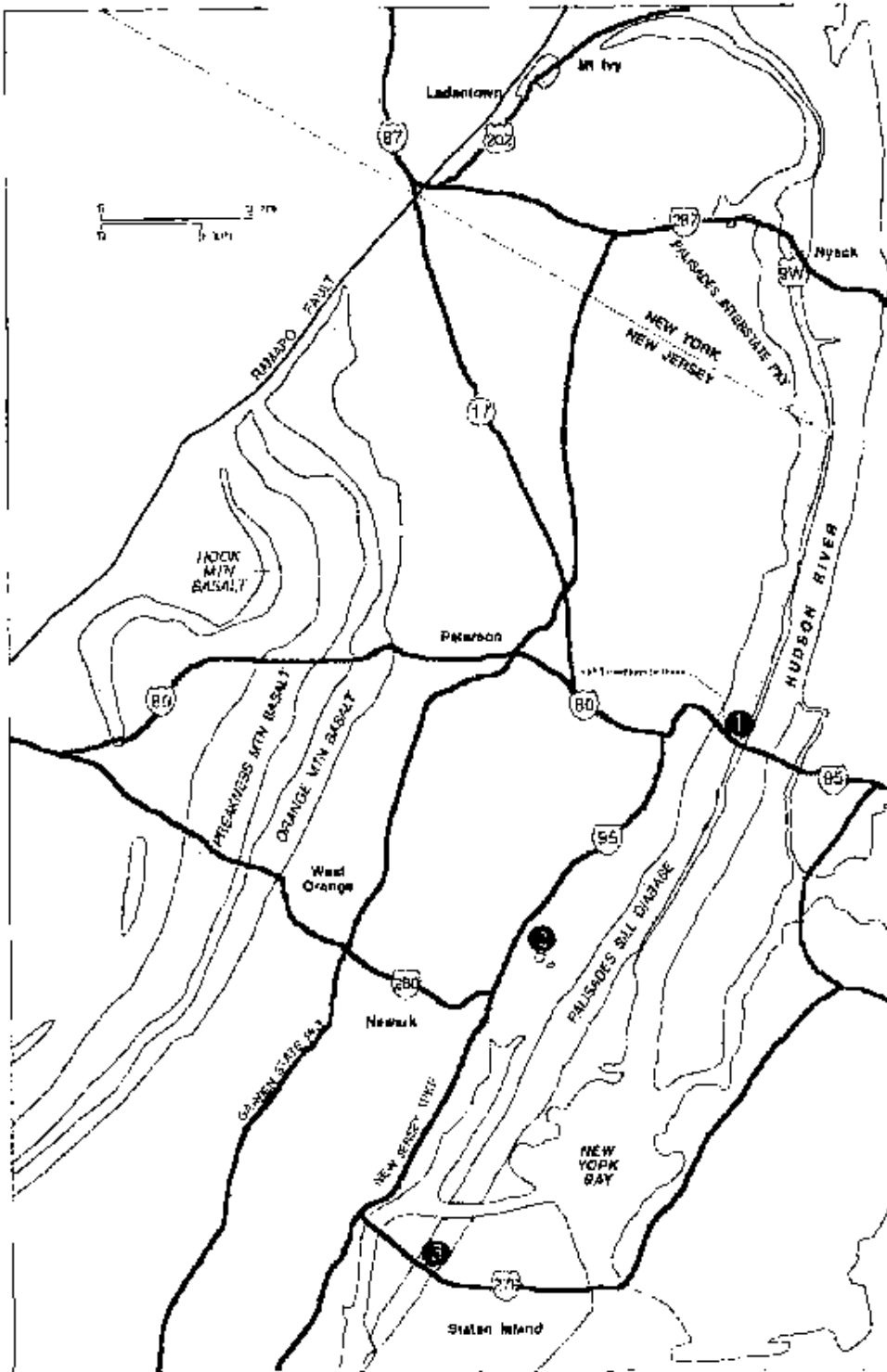
Figure 1: Map showing Jurassic Rocks of the northern Newark basin. The three field trip locations are shown. Modified from Puffer et al. 1992)

1. The Base of the Palisades Sill From Englewood Cliffs to Cliffside Park

A series of road-cuts, active and recent construction sites, and natural outcrops along the west bank of the Hudson River (Figure 1) has resulted in a discontinuous five mile long exposure of the basal contact of the Palisades Sill with the underlying Lockatong Formation and Stockton Formation.

Palisades diabase

The Palisades diabase exposed along the basal contact is fine grained massive chill-zone rock. The diabase is aphyric and subophitic and contains very few xenoliths. A few large xenoliths have been observed but they are typically spaced at least 100 meters apart. The rock is free of any obvious alteration effects except for along widely spaced faults where some chlorite and carbonates are exposed on slickensides. The lower contact is largely parallel to the bedding planes of the underlying metasediments but is locally discordant. Flow of the diabase through Lockatong argillite has excavated a few channel like cuts several meters across that truncate underlying Lockatong bedding plains at about 30 °. In addition, anticlinal dome like structures consisting of Lockatong Formation that rise a few meters into overlying diabase have been observed (Figure 2). It is at these dome-like structures where most fusion seems to have taken place.

Figure 2. Lower contact of the palisades Sill along the road to Ross Dock. Migmatites are present to the right of the meter stick in an anticlinal dome structure.

Lockatong Formation and Fusion Products

The lithology of the Lockatong Formation has been described in detail by Van Houten (l980) and the exposures along Englewood Cliffs have been described by Olsen (l980). In general the Lockatong formation consists of short detrital and chemical cycles averaging several meters thick. Gray detrital cycles are most common in the northwestern part of the Newark basin including area near Englewood Cliffs unlike the reddish-brown chemical cycles (Van Houten, l980). The detrital cycles are composed of: 1) black pyritic shale, 2) dark gray carbonate-rock mudstone and 3) gray calcareous argillite. These laminated (varved) lake sediments are interbedded with lenses of fine-grained feldspathic sandstone. These detrital sedimentary rocks are composed of sodic plagioclase, illite and muscovite, some K-feldspar, chlorite, calcite, and a little quartz (Van Houten, l980). These sedimentary rocks have been metamorphosed into hornfels near the Palisades Sill and as described by Van Houten (l969) have been recrystallized into: 1) gray layers consisting of biotite and albite with minor analcime and diopside; 2) black layers consisting of biotite and albite with minor orthoclase, calcite and a trace of amphibole; and 3) light greenish gray to pink layers consisting of diopside and grossularite with minor chlorite, calcite, biotite, feldspar, amphibole and prehnite. The gray hornfels is described by Olsen (l980) as "bedded and disturbed laminated siltstone"; the black hornfels as "laminated siltstone" and the light greenish gray to pink hornfels as "platy siltstone". In addition, layers of metamorphosed "buff arkose" are found interbedded with these hornfels types Olsen (l980).

Olsen (l980) has identified several individual meta-detrital cycles consisting of basal laminated siltstone overlain by multiple layers of bedded, platy, and massive siltstones in exposures south of Englewood Cliffs and has correlated nine of these cycles 12 km through six exposures along the base of the Palisades Sill from Kings Bluff, Weehawken to Ross Dock, Fort Lee including the area from Englewood Cliffs to Cliffside Park (Figure 3). In particular, four meters of the section at Ross Dock directly below the Palisades diabase contact where considerable fusion has occurred includes 0.3 m of "buff arkose" in contact with the diabase, underlain by 0.2 m of bedded siltstone, underlain by 2.9 m of "buff arkose" underlain by 1 m of "platy and bedded siltstone" and 0.5 m of "laminated siltstone" (Figure 3).

These lithologies in the sequence described by Olsen (l980) are largely devoid of any clear evidence of fusion. However, at three locations within 2 km of Ross Dock fusion has occurred resulting in syenitic rock intergrown with black laminated siltstone forming a migmatite. This style of fusion is confined to the contact zone within distinctly domed structures (Figure 2) that are characterized by discordant contacts and the uplift of the black "laminated siltstone" to close proximity to the diabase contact. The bedding at these domed structures is disrupted and may have involved movement of volatiles derived from brackish groundwater within the lacustrine Lockatong sediments. The salt content of these volatiles may have helped flux the melting process.

In 1948, the annual GSA meeting was held in NYC, specifically at the old Hotel Penn. One of the field trips associated with this meeting was to the Palisades Sill. The field trip leaders were Walter Bucher, a professor of geology at Columbia University, and S.J. Shand. Charles B. Sclar (former Professor Emiritus, Lehigh University, deceased) was a young geologist and a participant on this trip. At one of the stops at the basal contact of the Palisades Sill 1/4 mile north of the George Washington Bridge was an exposure of Lockatong Argillite impregnated

with salmon colored leucocratic granitoid migmatitic material. According to C. B. Sclar (personal communication) Walter Bucher was intrigued and very interested in this occurrence. In his "effervescent" way Bucher called this phenomenon *palingenesis* in a small scale and implied that the homfels was an example of a rock with a low melting component which due to heat of the adjoining Palisades Sill actually melted *in situ.* C. B. Sclar put a labeled and dated specimen that remained largely unstudied until two years ago (1999) The same site that was visited in 1948 was then revisited and found be consistent with the earlier interpretation of Bucher.

Three clearly exposed examples of these domes occur within 2 km of Ross Dock, where fusion has occurred resulting in syenitic rock intergrown with black laminated siltstone forming a migmatite and trondhjemite veins. The major element compositions of these leucocratic rocks and the surrounding dark rocks are given in tables 4 and 5 respectively and their CIPW norms are given in Tables 6 and 7. The bedding at these domed structures is disrupted and may have involved movement of volatiles derived from brackish groundwater within the lacustrine Lockatong sediments. The high salt content of Lockatong Argillite may have helped flux the melting process. Both the syenite and the trondhjemite are sodic, typically containing 4 and 7.5% Na_2O respectively, but the K_2O and Rb is highly partitioned into the syenite typically containing 5 % and 125 ppm vs. only 0.5% and 25 ppm for the trondhjemite. Both the syenite and trondhjemite have similar REE contents that are comparable to the Lockatong Argillite.
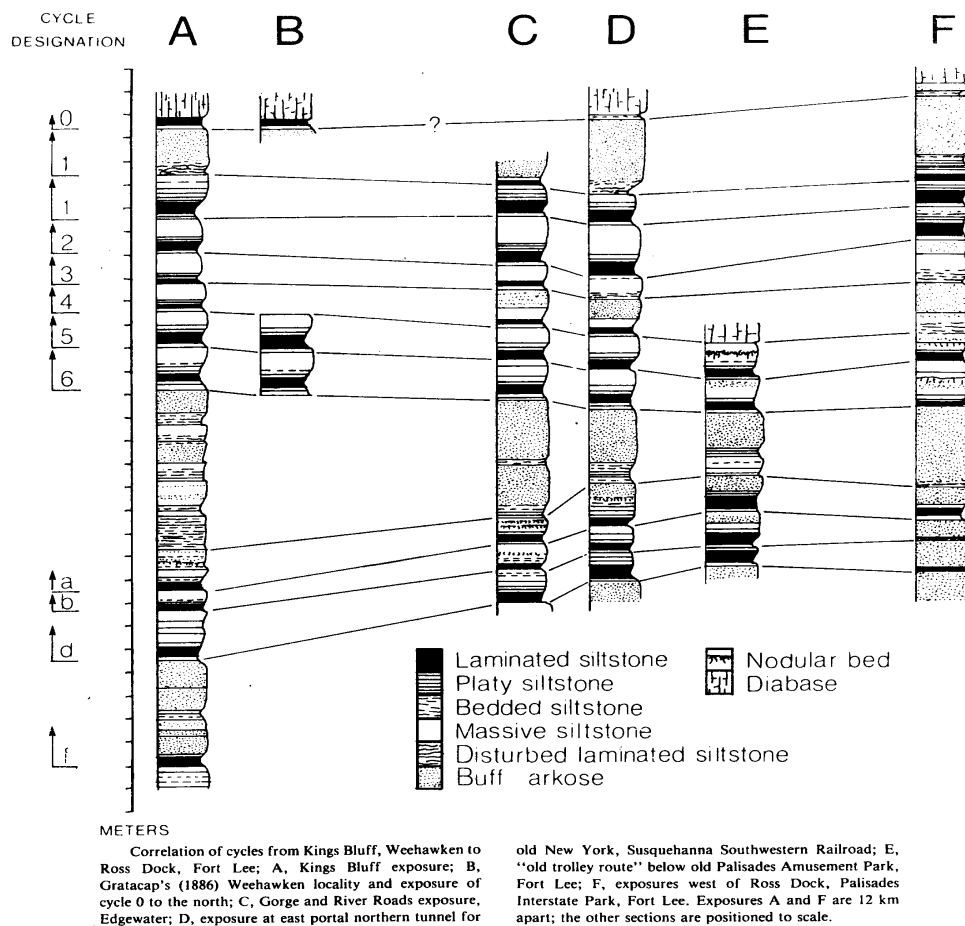

Correlation of cycles from Kings Bluff, Weehawken to Ross Dock, Fort Lee; A, Kings Bluff exposure; B, Gratacap's (1886) Weehawken locality and exposure of cycle 0 to the north; C, Gorge and River Roads exposure, Edgewater; D, exposure at east portal northern tunnel for old New York, Susquehanna Southwestern Railroad; E, "old trolley route" below old Palisades Amusement Park, Fort Lee; F, exposures west of Ross Dock, Palisades Interstate Park, Fort Lee. Exposures A and F are 12 km apart; the other sections are positioned to scale.

Figure 3. From Olsen ,1980

Our complete chemical analyses of the leocrocratic component of the migmatite when plotted(Figures 4, 5, and 6) on primitive mantle normalized spider diagrams (Sun and McDonough, 1989) provide compelling evidence that the igneous components of the migmatite are fused Lockatong argillite. For example, all three lithologies display distinctly negative Nb anomalies. However, the chemistry of these lithologies differs from that of the Palisades Diabase.

Table 1: Major Elements of Leucocratic Rocks

	G2D-L2	G2E-L	G2CL	G127L1	G5L1	G5L2	G2AL1	G3L	G4L	HTQ
SiO_2	65.6	76.2	72.7	71.8	64.6	73.3	75.7	72.8	71.4	52.3
Al_2O_3	12.7	12.7	12.9	10.1	14.5	14.5	11.8	13.6	13.8	14.1
CaO	3.9	0.3	0.5	3.4	2.2	0.6	0.7	1.7	3.1	10.7
MgO	3.4	0.6	1.0	4.5	5.0	1.0	0.9	10.8	2.3	7.8
Na_2O	3.7	4.4	4.2	2.9	7.3	8.5	4.0	5.7	7.8	2.4
K_2O	5.1	4.0	5.4	2.6	1.0	0.4	4.3	2.7	0.1	0.4
Fe_2O_3	1.9	1.2	1.5	1.3	2.8	0.5	0.9	1.3	0.6	11.2
MnO	0.1	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.2
TiO_2	0.2	0.2	0.3	0.1	0.4	0.3	0.2	0.3	0.3	1.1
P_2O_5	0.2	0.1	0.2	0.1	0.1	0.1	0.3	0.1	0.1	0.1
Cr_2O_3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
LOI	1.8	0.3	0.3	1.8	1.2	0.3	0.5	0.8	0.7	
Sum	98.9	100.1	99.0	98.8	99.3	99.4	99.4	100.3	100.2	100.4

Table 2: Major Elements of dark rock surrounding the leucocratic rock

	G2CD	G2BD	G127D1	G127D3	G5D	G2AD
SiO_2	54.60	55.40	53.00	71.40	54.60	53.20
Al_2O_3	18.60	17.60	17.70	13.40	19.40	17.70
CaO	1.09	0.65	1.62	1.04	1.29	1.08
MgO	3.90	4.59	3.89	0.97	5.60	3.91
Na_2O	3.23	4.68	4.09	3.81	4.59	3.71
K_2O	5.60	5.40	7.09	5.82	6.53	6.62
Fe_2O_3	9.57	8.40	8.89	1.35	4.40	10.10
MnO	0.13	0.08	0.13	0.02	0.04	0.09
TiO_2	0.85	0.91	0.82	0.17	0.86	0.85
P_2O_5	0.27	0.15	0.28	0.17	0.17	0.14
Cr_2O_3	0.02	0.01	0.01	0.01	0.02	0.01
LOI	1.16	1.38	0.60	0.55	1.10	0.85
Sum	99.20	99.50	98.40	98.90	98.80	98.60

Table 3 CIPW Norms of Leucocratic Rocks

	G2D-L2	G2E-L	G2CL	G127L1	G5L1	G5L2	G2AL1	G3L	G4L
Q	15.0	33.89	25.79	33.43	8.13	20.56	33.94	10.96	18.31
or	30.1	23.70	32.09	15.25	5.73	2.36	25.29	16.07	0.53
ab	31.1	37.40	35.29	24.45	61.43	71.50	34.10	47.81	66.26
an	3.1	0.79	0.44	6.97	4.11	0.46	1.31	3.72	2.24
ne	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.0	0.80	0.00	0.00	0.00	0.00	0.06	0.00	0.00
di	11.7	0.00	0.18	7.21	4.70	0.76	0.00	2.32	9.47
hy	3.1	1.52	2.33	7.81	10.27	2.04	2.29	25.82	1.34
wo	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ol	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ac	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mt	0.2	0.00	0.00	0.25	1.54	0.00	0.00	0.00	0.00
il	0.4	0.02	0.02	0.22	0.84	0.02	0.02	0.09	0.06
hem	1.6	1.16	1.47	1.11	0.88	0.47	0.92	1.34	0.55
ti	0.0	0.00	0.60	0.00	0.00	0.72	0.00	0.72	0.56
ap	0.4	0.23	0.39	0.14	0.25	0.19	0.70	0.25	0.12
cc	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pero	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
wus	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ru	0.0	0.20	0.00	0.00	0.00	0.00	0.16	0.00	0.00

Table 4 CIPW Norms of dark rock surrounding the leucocratic rock

	G2CD	G2BD	G127D1	G127D3	G5D	G2AD
Q	3.0	0.0	0.0	24.2	0.0	0.0
or	33.1	31.9	41.9	34.4	38.6	39.1
ab	27.3	39.6	23.1	32.2	31.1	29.8
an	3.6	2.2	6.2	2.3	5.3	4.4
lc	0.0	0.0	0.0	0.0	0.0	0.0
ne	0.0	0.0	6.2	0.0	4.2	0.9
kal	0.0	0.0	0.0	0.0	0.0	0.0
C	5.9	3.2	1.0	0.0	2.8	2.8
di	0.0	0.0	0.0	1.0	0.0	0.0
hy	18.5	6.0	0.0	2.0	0.0	0.0
wo	0.0	0.0	0.0	0.0	0.0	0.0
ol	0.0	8.7	12.8	0.0	9.8	14.3
ac	0.0	0.0	0.0	0.0	0.0	0.0
mt	3.4	3.5	3.4	0.0	3.4	3.4
il	1.6	1.7	1.6	0.0	1.6	1.6
hem	0.0	0.0	0.0	1.4	0.0	0.0
ti	0.0	0.0	0.0	0.4	0.0	0.0
ap	0.6	0.3	0.6	0.4	0.4	0.3
cc	0.0	0.0	0.0	0.0	0.0	0.0
pero	0.0	0.0	0.0	0.0	0.0	0.0
wus	0.0	0.0	0.0	0.0	0.0	0.0
ru	0.0	0.0	0.0	0.0	0.0	0.0
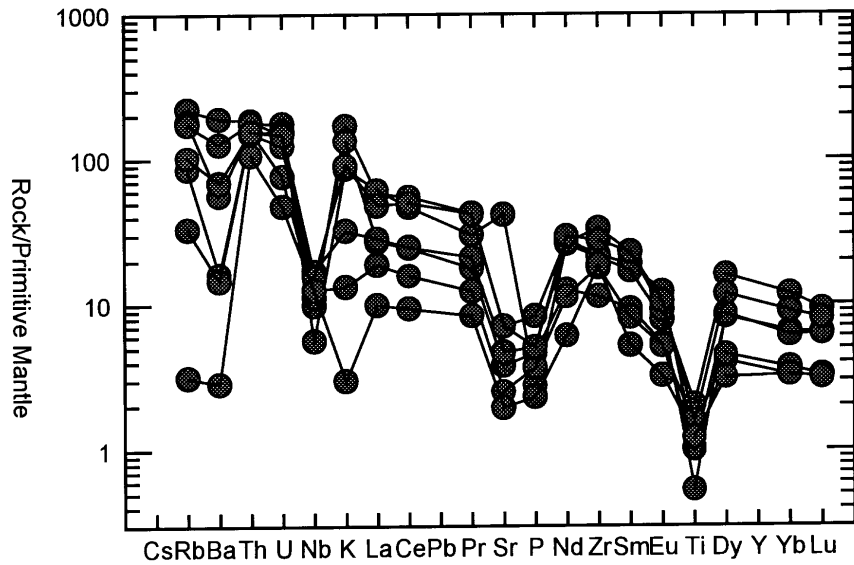
Figure 4. Sun and McDonough(1989) mantle normalized plot of dark rock surrounding the leucocratic rock.
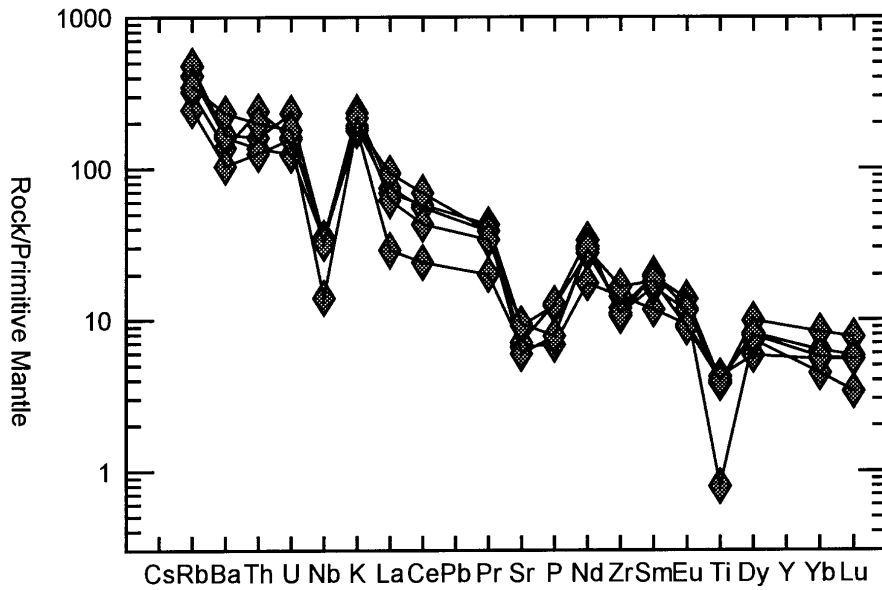
Figure 5. Sun and McDonough(1989) mantle normalized plot of the leucocratic rock.
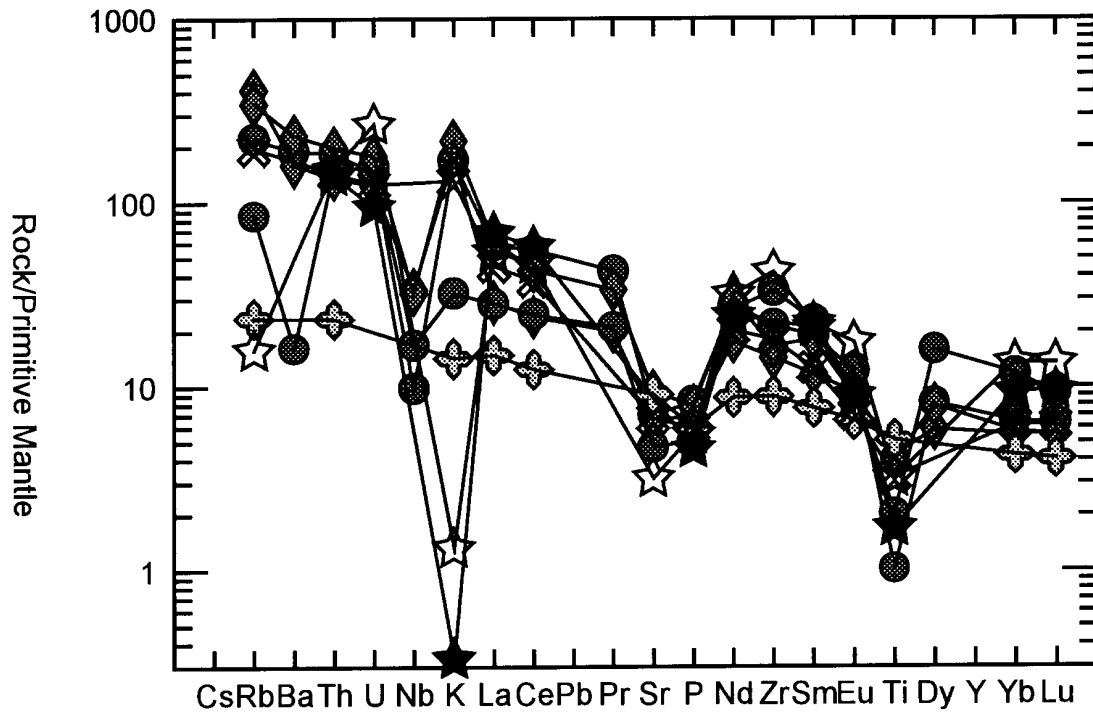
Figure 6. Sun and McDonough(1989) mantle normalized plot. Circles represent leucocratic rocks along road to Ross Dock; Closed diamonds represent the dark rocks that surround the leucocratic rocks along the road to Ross Dock; Solid star represents the I-95 trondhjemite dike.; X represents the North American Shale Composite; Shaded plus sign represents HTQ from Tollo and Gottfried, 1992; Open Star is the Lockatong hornfels xenolith from Graniteville.

Again, our complete chemical analyses of the leucocratic rock and its surrounding dark rock when plotted on primitive mantle normalized spider diagrams(Sun and McDonough, 1989) provide compelling evidence that the leucocratic component of the migmatite and the other leucocratic rocks along this traverse are genetically related to the Lockatong argillite and not genetically related to the Palisades Diabase(see Figures 4, 5, and 6). The leucocratic component is a fusion product of the Lockatong argillite. Also note the similarity of the leucocratic component to the North American Shale Composite(NASC). By comparison, the HTQ magma analysis plot as a line with a different slope, and magnitude. This data rules out magmatic fractionation of a basaltic magma as a process capable of generating the leucocratic rocks of this study.

2. DIKES WITHIN THE PALISADES SILL I-95 ROAD CUT, FORT LEE, NJ

FIELD OCCURRENCE

Exposed in the I-95 road cut within the upper 70 meters of the Palisades Sill (Figure 1) is a group of at least 3 trondhjemite dikes which have been described by Benimoff et al (1989).

Proceeding down section into the I-95 cut from the upper contact of the Palisades Sill a 20 to 30 cm thick leucocratic dike is encountered. A 6 -12 cm thick calcite vein has apparently precipitated into another joint in the dike approximately parallel to its contact. This westernmost dike in a parallel group of leucocratic dikes and calcite veins is designated dike 2. East of dike 2 dike 1 is exposed. Both trondhjemite dikes are near vertical and strike N 27° E which is parallel to a major joint set in the sill. The thickness of dike 1 is about 2 meters. Five samples across the width of the dike were selected for chemical analysis (Table 5) . The network of calcite veins exposed along I-95 may be the result of similar injection into cooling joints but at a lower temperature. Some of the calcite veins contain about 10 percent sulfides and may have precipitated out of hydrothermal vapors injected into cooling shrinkage joints in the Palisades from a Lockatong sedimentary source.

PETROGRAPHY

Dike 1 is a leucocratic holocrystalline microphanerite composed almost exclusively of quartz and albite. The rock is porous and most of the pores are miarolitic cavities. The microtexture observed in thin section is unusual because it consists of a granophyric intergrowth of quartz and albite. Thin sections reveal an intergrowth of clear grains of quartz in a turbid matrix of albite; also present are opaque grains, which, as' determined in reflected light, consist dominantly of discrete grains of ilmenite and subordinately of discrete grains of hematite which are not exsolution intergrowths. Accessory minerals include skeletal sphene, and hematite as minute flakes disseminated in the silicates. Most quartz grains are in approximately parallel optical continuity. This texture is interpreted as an igneous texture resulting from simultaneous crystallization of quartz and albite from a eutectic melt. Chemical analyses of each of the five samples of the dike are presented in Table 5. Total Fe is expressed as Fe_2O_3; FeO was not determined. However the total iron is very low (<1.8% and the silica is very high 77 - 80% (34 - 41.5% normative quartz). Na_2O (6.5-7%; 54-60% normative albite) is exceptionally high and K_2O is extremely low (<0. 8% normative - orthoclase). In addition, CaO and MgO are each less than 1%.

An AFM diagram (Figure 7) compares the dike compositions, samples PD - 71, and PD-72 through PD - 76, with the Palisades differentiation trend of Walker (1969), a leucocratic albitite dike from the Travis quarry on Staten Island (Benimoff et al., 1988), and a "white vein" in the Palisades Sill (Walker 1940). The lower left apex represents the sum of Na_2O plus K_2O. While AFM diagrams are very useful in demonstrating magmatic differentiation, in this case it is misleading because Na_2O and K_2O are combined. In the dike of this study the ratio of Na_2O to K_2O is very high and there is hardly any K,O, whereas in the normal differentiation trend of a tholeiitic magma, the granophyre is composed of K-spar and quartz, in which K_2O is dominant over Na,O. Therefore, it is unlikely that these dikes are late tholeiitic trend or calc-alkaline trend differentiates of the Palisades magma.
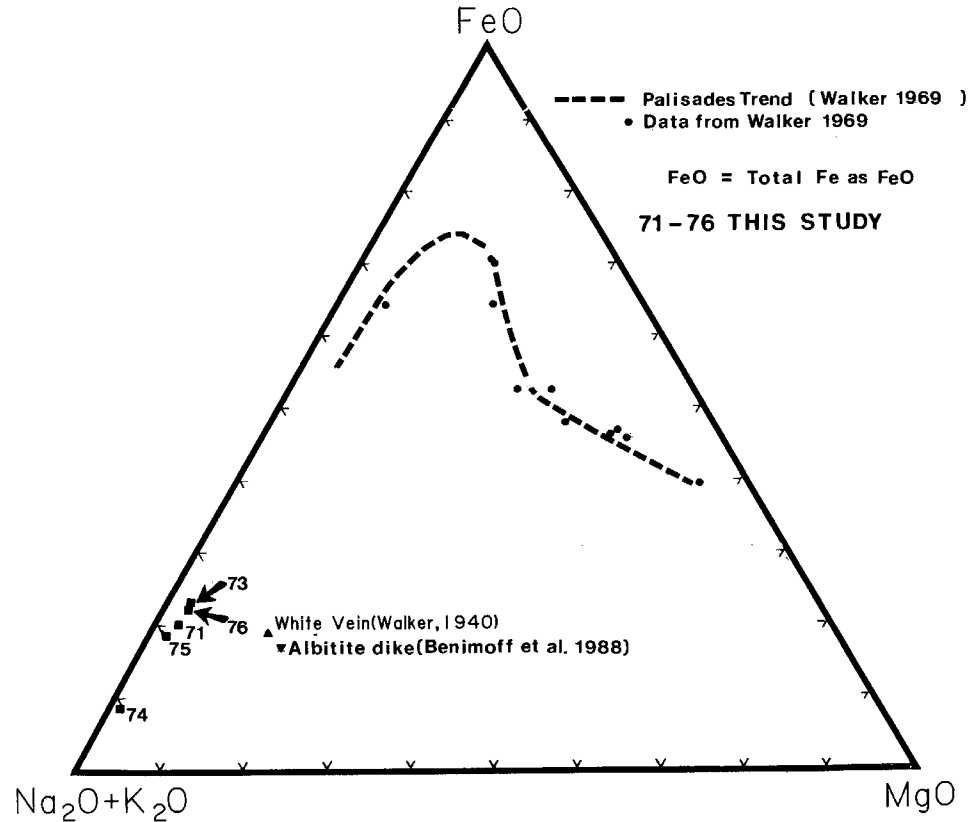
Figure 7. AFM diagram . The dashed line is the Palisades differentiation trend of Walker, 1969a. Closed circles data from Walker, 1969a; 71-76 represent the I-95 Dike 1. Albitite Dike(see table 1) and White vein of Walker, 1940 shown for comparison.

DISCUSSION

The plot of the mafic index verses liquidus temperatures for basaltic magmas of Tilley et al. (1964) is instructive. The chilled margin of the Palisades Sill (W-889LC-60, Walker 1969) has a mafic index of 0.5755 which yields a liquidus temperature of about 1200° C on the basis of the experimental work of Tilley et al. 1964. If this leucocratic dike is not a magmatic differentiate of the Sill then what is its source? At Graniteville in Staten Island, N.Y., Benimoff and Sclar (1984) described a partly fused xenolith of Lockatong Argillite enclosed in the Palisades Sill which crystallized to trondhjemite composed principally of albite-quartz granophyre. The unmelted (hornfesed) xenolith at Graniteville has a normative compositional range between the two vertical lines at the bottom of Figure 13. Clearly, rocks of such composition would melt if immersed in a magma which has a temperature of 1200° C.

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Furthermore, the Lockatong xenolith has a very high Na/K ratio, and the same ratio of normative quartz/normative albite that occurs in the trondhjemite dikes. Consequently, the source of the I-95 dike was probably a previously metasomatized xenolith of Lockatong argillite which floated up to about the center of the sill and melted to yield a high Na_2O, low K_2O, silica-rich melt which could have been the parental magma of the dike.

The Lockatong Formation is a complex lacustrine suite(Olsen, 1980) that is dominated by sodic argillite. The Lockatong has been thermally metamorphosed into hornfels up to pyroxene grade facies grade by the intrusion of the Palisades Sill (Van Houten, 1972). The pyroxene facies hornfels exposed above and below the sill along the I-95 section includes a black variety consisting primarily of biotite and plagioclase and a pale green variety consisting of garnet and pyroxene. The black and pale green hornfels are interbedded at irregular 1 to 10 cm intervals. The green hornfels has been interpreted by Van Houten, (1972) as having been derived from carbonate rich beds in the Lockatong argillite. Common discordant pale green bands of calcium rich pyroxene and garnet are interpreted as having been developed from carbonate veining through the argillite. If the liquidus temperature of the sill is 1200° C, then the solidus temperature is about 1050° C (Yoder and Tilley, 1962). The quartz - albite intergrowth texture of the dikes are consistent with the interpretation the magma of the dike was at or near the eutectic composition on the dry albite - SiO_2 phase-equilibrium diagram, and the that eutectic temperature on this diagram is 1062° C. As noted above, the abundant miarolitic cavities in the dike record the presence of a gas phase, probably H_2O and CO_2, which would depress the eutectic temperature.

Therefore, a magma of the trondhjemite composition could have been liquid, while the diabase was solid and jointed. In support of this model, it should be noted that the I-95 dike does not show any chilled margins, which means that it was injected into the diabase parallel to the joints while the solid diabase was still hot. As shown in Table 5, the concentration of Fe, Mg, and Ca is extremely low in the dike. This indicates that virtually no diffusion took place across a liquid - liquid interface such as at Graniteville (Benimoff and Sclar, 1984) where the diabase magma and xenolith derived liquid coexisted and where Fe, Ca, and Mg and other ions diffused across the liquid - liquid interface. Consequently, the diabase magma and the dike magma did not coexist for any great length of time because if they had, there would have been diffusion of ions across the liquid - liquid interface as shown by the Graniteville xenolith. Therefore, the dike was liquid while the diabase was solid.
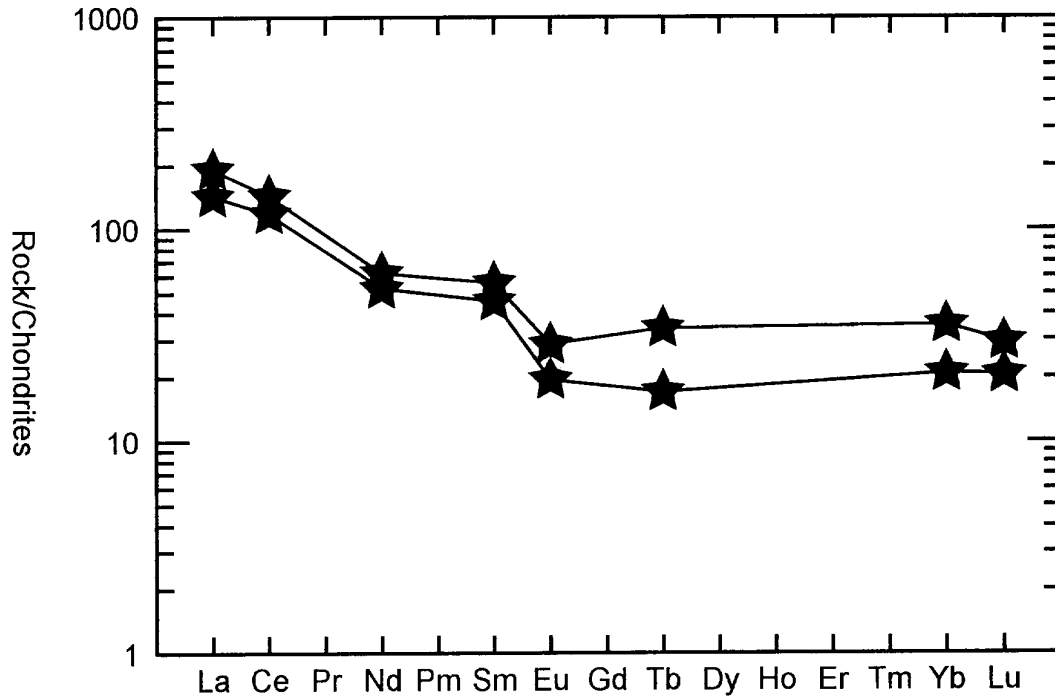
Chondrite normalized REE plots of dike 1 and dike 2 are shown in Figure 8. The Palisades trondhjemite dikes are very highly enriched in REE (Figure 8) exceeding the chondrite values of) by a factor of 20 to 200. Such high values are commonly interpreted as the result of very high degrees of fractionation (over 90 percent if a Palisades diabase magma source is assumed) but may also be interpreted as the product of very high degrees of partial They have parallel trends and therefore must have a common source. Relative to the diabase host rock the dikes are enriched in light REE's and show a negative Europium anomaly instead of the positive europium anomaly of the diabase. The negative Eu anomaly of the dikes is consistent with the development of a partial melt from the plagioclase rich residue of the Lockatong hornfels.

Table 5: Major Element Analyses and CIPW Norms of Leucocratic Rocks in the Palisades Sill

|	I-95 Dike 1					I-95 Dike 2		Travis	Bayonne
	1	2	3	4	5	6	7	8	9
	PD-71	PD-73	PD-74	PD-75	PD-76	PD-84	PD-85	TV01	BBAL
SiO_2	76.89	77.09	78.6	80.17	79.8	57.81	58.03	62.7	60.1
Al_2O_3	12.15	11.94	12.18	11.14	11.07	14.71	14.49	17.7	16.2
TiO_2	0.74	0.62	0.64	0.43	0.36	0.5	0.49	0.37	0.85
Mgo	0.19	0.19	0.04	0.12	0.21	2.73	2.61	2.21	0.97
FeO			...	...	...	...	...	1.4	0.7
Fe_2O_3	1.74	1.98	0.65	1.41	1.75	0.61	0.42	0.79	1.36
MnO	0.02	0.02	0.01	0.01	0.01	0.6	0.07	0.07	0.04
CaO	0.94	0.72	0.71	0.51	0.44	6.31	8.14	3.68	4.55
Na_2O	7.03	7	7.25	6.51	6.42	9.01	9.31	8.79	9.39
K_2O	0.13	<.01	<0.01	<.01	<0.01	0.06	0.06	0.48	0.36
P_2O_5	0.18	0.16	0.11	0.12	0.09	0.02	0.08	0.02	0.08
CO_2	...	...	...	...	...	7.32	5.13		...
LOI	0.53	0.51	0.86	0.39	0.65	0.97	1.02	1.54	4.7
Total	100.54	100.24	101.06	100.83	100.81	100.65	99.85	99.75	99.3
Q	33.56	34.36	35.59	40.78	40.53	4.32	1.22	0.27	1.59
or	0.77	0.06	0.06	0.12	0.06	0.35	0.31	2.83	2.12
ab	59.38	59.11	61.29	55	54.22	75.31	65.43	74.36	79.46
an	1.21	1.13	0.66	1.12	1.36	...	...	7.42	1
di	1.95	1.21	0.22	0.55	0.2	...	5.04	7.97	...
hy	0.84	1.77	...	1.39	2.41	2.28	2.41	3.1	...
en	...	...	...	...	...	...	...	...	2.42
hm	...	...	0.1	0.42	0.1			...	0.42
mt	0.5	0.57	0.04	0.41	0.51	...	...	1.14	2.25
ii	1.41	1.18	1.22	0.82	0.68	0.95	0.77	0.7	...
tn	1.6	0.99	1.51	0.44	0.17	...	...	...	...
ru	0.06	0.2	0.01	0.24	0.28	...	...	...	...
ap	0.4	0.35	0.24	0.26	0.2	0.05	0.16	0.34	0.2
cc	...	...	...	...	...	16.65	10.09	...	6.25
wo	...	...	0.78	...	...	...	...	...	...
ns	...	...	...	...	...	0.12	0.89	...	...
ac	...	...	...	...	...	0.37	11.8	...	...
Total	101.68	100.93	101.72	101.55	100.72	100.4	98.12	98.13	95.71

1 PD-71: I-95 trondhjemite dike (dike 1), New Jersey (Benimoff et al. 1989), west contact.

2 PD-73: I-95 trondhjemite dike (dike 1), New Jersey (Benimoff et al. 1989), 0.3 m from west contact.

3 PD-74: I-95 trondhjemite dike (dike 1), New Jersey (Benimoff et al. 1989), center of dike.

4 PD-75: I-95 trondhjemite dike (dike 1), New Jersey (Benimoff et al. 1989), 0.3 m from east contact.

5 PD-76: I-95 trondhjemite dike (dike 1), New Jersey (Benimoff et al. 1989), east contact.

6 PD-84: I-95 trondhjemite dike (dike 2), New Jersey.(Benimoff et al. 1989)

7 PD-85: I-95 trondhjemite dike (dike 2), New Jersey.(Benimoff et al. 1989)

8 TV01: albitite dike, Travis Quarry, Staten Island, New York (Benimoff et al.1988).

9 BBAL: albitite dike, South End of the Bayonne Bridge, Staten Island, New York, Benimoff and Sclar, 1990

Figure 8. Chondrite normalized REE plot of I-95 Dike 1 and 2 compositions.

Because it is difficult to isolate the mesostasis granophyre which results from the differentiation of a tholeiitic magma for REE analyses, there is a paucity of REE analyses in the literature for any granophyre derived from a tholeiitic magma. The highly fractionated slope of the Palisades trondhjemite REE pattern with distinct enrichment in LREE is consistent with liquid extracted from a garnet rich residue.   The REE slope of the Palisades trondhjemite resembles the slope commonly seen in dacites or trondhjemites interpreted as having developed from partial fusion in an island arc or continental arc setting out of an eclogite residue at high pressures. Although the Palisades trondhjemite dikes were presumably generated under low pressures the proposed Lockatong source residue includes a green pyroxene garnet hornfels assemblage that is not unlike the eclogite residue.
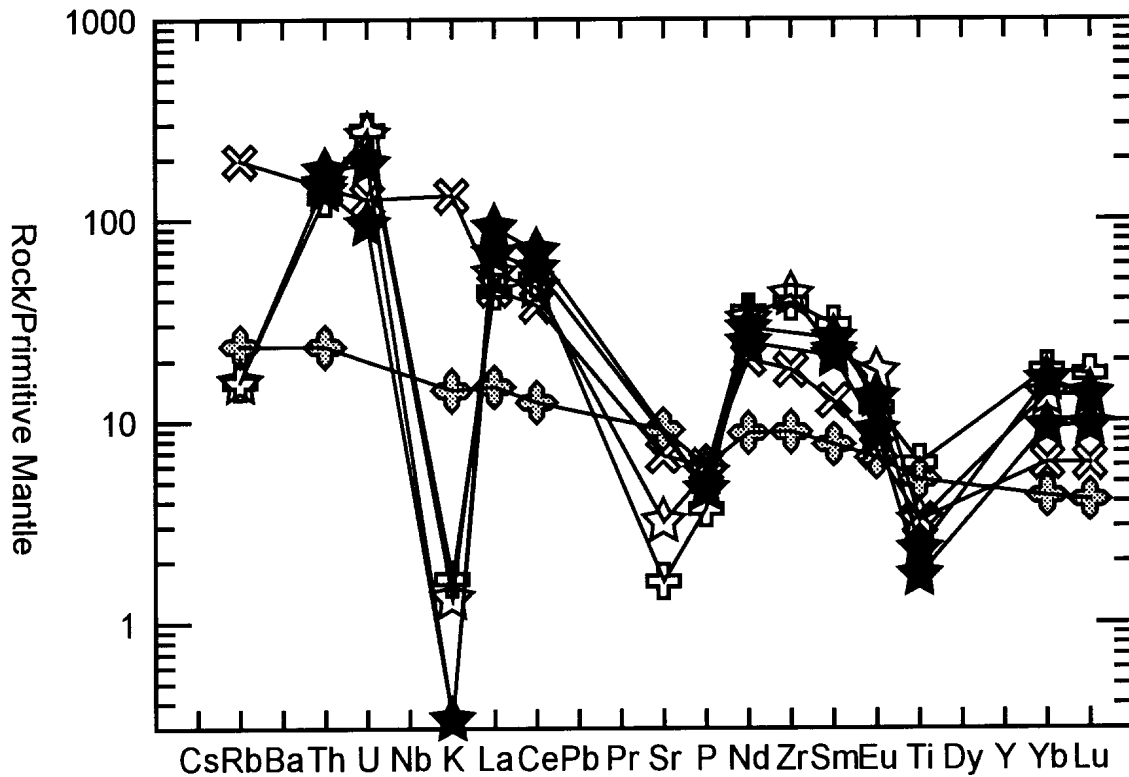
Figure 9. Sun and McDonough(1989) mantle normalized plot. Solid stars represent the I-95 trondhjemite dike.; X represents the North American Shale Composite; Open plus sign is a represents a sample of the Graniteville Quarry Trondhjemite; Shaded plus sign represents HTQ from Tollo and Gottfried, 1992; Open Star is the Lockatong hornfels xenolith from Graniteville. Note the similarity of the chemical signatures of the I-95 trondhjemite and the Graniteville Quarry Trondhjemite.

Our complete chemical analyses of the trondhjemite when plotted (figure 9) on primitive mantle normalized spider diagrams(Sun and McDonough, 1989) provide compelling evidence that the I-95 dikes are intrusions of fused Lockatong argillite. This data is consistent with our previous interpretation(Benimoff and Sclar, 1984);Benimoff et al. 1989). The general slope of the trondhjemite curve is negative. Furthermore, the range of the trondhjemite data plots within the range of the Lockatong argillite data and both display 3 very distinct negative anomalies: potassium, phosphorous and titanium. The trondhjemite data also plot very close to the North American Shale Composite(NASC) except for potassium. By comparison, all Palisades diabase analyses including fractionated granophyres plot as lines with different slopes, magnitudes and do not display the 3 negative anomalies. Our new data rules out magmatic fractionation as a process capable of generating the trondhjemites of this study. The difference in potassium between the trondhjemite and the NASC maybe due to hydrothermal leaching of potassium out of the Lockatong argillite before fusion occurred.
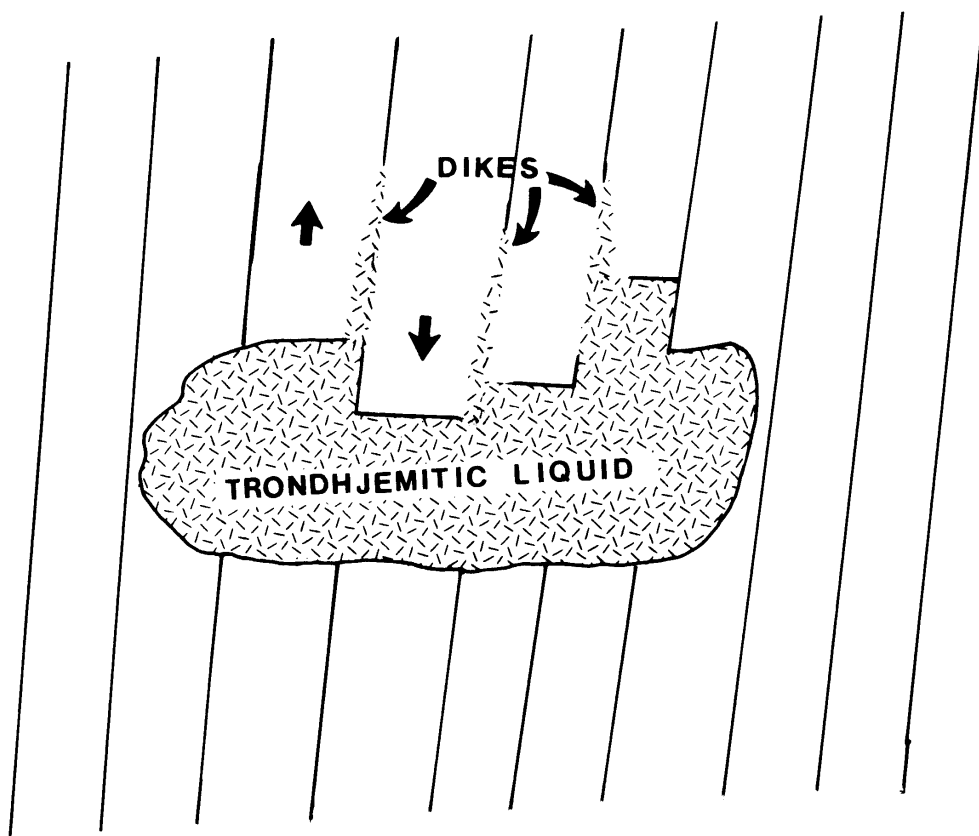
Figure 10. Cartoon showing foundering of joint blocks into pool of trondhjemitic magma resulting in injection of dikes parallel to joint blocks.

The mechanism of injection of the tabular vertical trondhjemite dikes may involve several processes that were occurring simultaneously. Partial fusion of Lockatong argillite would have resulted in a volume increase and a driving force for magma migration into low pressure sites(Figure 10). A low pressure environment was made available as soon as the volume reduction joints associated with diabase crystallization were developed. Since the Palisades intruded under a thick layer of Mesozoic sediments it is at least plausible that a vacuum may have been temporarily maintained long enough to enhance injection.

3. THE LAUREL HILL(SNAKE HILL) DIABASE QUARRY

Laurel Hill (also known as Snake Hill and Fraternity Rock) is an almost completely exposed elliptical body of early Jurassic diabase about 500 m in diameter, located 2.5 km west of the underlying Palisades sill (Figure 1). The diabase body has discordantly intruded the Triassic siltstones of the Passaic Formation and has generated a contact-metamorphosed and partially fused hornfels zone around the margins of the intrusion. On the basis of field observations of exposed discordant contacts and well-log data collected at seven sites near Laurel Hill, the intrusion appears to be a hypabysal volcanic neck. On the basis of chemical analytical data (Puffer and Benimoff , l997) Laurel Hill is co-magmatic with the Palisades Sill.

Field evidence of wall-rock fusion is found near igneous-sedimentary contacts, particularly along the southern contact exposed beneath the New Jersey Turnpike overpass (Figure 1). Passaic Formation red beds exposed <50 m from Laurel Hill diabase have been metamorphosed into a gray, fine-grained hornfels. As the igneous contact is approached the hornfels becomes increasingly mixed with a poorly defined discontinuous zone of leucocratic igneous rock up to 4 m thick that is recognized on the basis of an igneous texture. The leucocratic rock zone is approximately parallel to the contact of the diabase intrusion and is the source of a swarm of veins intruded into the diabase body.

Chemical analyses of Passaic wall rocks collected near Laurel Hill are bimodal with respect to alkali content (Table 3). Beds of potassic hornfels (4-9 %K2O) are interlayered with beds of sodic hornfels (4-9% Na_2O). Fusion of these hornfels produced two contrasting melts: fused potassic and fused sodic sediments.

About half of the leucocratic veins, and most of the fusion zone that crystallized in situ adjacent to the diabase intrusion, are composed of medium-grained potassic granitoids (Benimoff et al. l995). The potassic granitoids, ranging from quartz syenite to quartz monzonite, are equigranular mixtures of K-feldspar and plagioclase in varying proportions, together with about 5-15% quartz and minor amphibole, pyroxene, and ilmenite. The granitoids chemically contrast with the diabase but closely resemble the potassic wall rocks.

The melting of the potassic meta-sediments around the margins of the Laurel Hill diabase was probably fluxed in part the chlorides and sulfates in the sediments of the Passaic Formation and by any brackish groundwater content. In addition, Gardien el al. (l995) have experimentally demonstrated the important fluxing effect of muscovite on the fusion of biotite, quartz and Na feldspar. They have shown that anhydrous fusion of a muscovite + biotite + Na feldspar assemblage can begin at temperatures as low as 750oC at 1 Gpa. The potassic hornfels at Laurel Hill contain each of these minerals, although the pressure during fusion at Laurel Hill was probably closer to 0.05 Gpa corresponding to <2 km of burial. It may also be significant that the

Table 6. Chemical Compositions of Leucocratic Rocks in the Laurel Hill Diabase and Surrounding Wall Rocks.   (from Puffer and Benimoff, 1997)

	Passaic Formation Wall-rock			Leucocratic rocks		
sample #		4	1	68	67	P-1
wt.%	ave. 14	potassic	sodic	Granitoid	Trondhj	Pegmatite
SiO_2	61.58	57	67.75	56.01	63.58	53.45
TiO_2	0.88	0.98	0.9	0.95	0.81	2.29
Al_2O_3	15.65	16.31	14.45	16.35	13.66	11.66
FeOt	5.7	7.74	3.75	8.11	5.46	12.27
MgO	3.67	5.71	3.91	5.04	2.34	4.49
MnO	0.09	0.12	0.05	0.05	0.09	0.32
CaO	1.8	2.3	0.51	1.94	1.09	8.78
Na_2O	4.77	3.79	6.54	5.12	7.86	3.83
K_2O	2.55	4.87	0.22	3.51	0.08	0.56
P_2O_5	0.16	0.11	0.17	0.08	0.26	0.4
LOI	2.85	0.92	1.69	1.97	4.58	1.74
Total	99.71	99.85	99.94	99.13	99.81	99.79
ppm						
Cr	87	87	70	111	92	37
Ni	42	52	44	62	54	8
Rb	89	201	38	86	47	nd
Sr	185	213	110	406	188	nd
V	151	166	128	177	149	511
Zn	65	79	60	82	58	nd
Zr	337	177	332	184	415	128

experimental fusion of this mineral assemblage generated a peraluminous melt consistent with the peraluminous norms of Laurel Hill potassic wall rocks and granitoids. Potassic wall-rock sample 4 (table 3) contains 0.9% normative corundum, and potassic granitoid sample 68 (table 6) contains 0.8% normative corundum.

Evidence of a high degree of partial melting includes the close chemical correspondence of the potassic granitoid and the potassic meta-sediments around Laurel Hill (table 6) and the presence of only minor quantities of mafic rock near the diabase that could be interpreted as a mafic refractory residue.

About half of the leucocratic veins, but a minor fraction of the fusion zone that crystallized in place, are medium-grained trondhjemites. Trondhjemite veins are composed of albite with about 10 to 35% quartz and minor quantities of actinolite, pyroxene, ilmenite, and sphene. Some of the quartz is granophyrically intergrown with albite. The chemical composition of the trondhjemites closely resembles the sodic Passaic hornfels and siltstone layers that were the probable sources of the trondhjemite magma. Schairer and Bowen (l956) show that eutectic melting of an albite and quartz assemblage, such as the sodic Passaic beds, occurs at 1062°C to yield a trondhjemite liquid. The resulting liquid contains about 35% normative quartz, consistent with typical normative values found in the Laurel Hill trondhjemites. The experimental work of Schairer and Bowen (l956) was anhydrous at 1 atm pressure, but in the presence of brackish groundwater and pressures corresponding to the approximately 2 km depth of burial, fusion temperatures <1062°C might be expected.

4. THE GRANITEVILLE QUARRY, STATEN ISLAND, NEW YORK

It is a real treat to view the parent of an igneous rock adjacent to that igneous rock. Such is the extraordinary case at the Graniteville Quarry(Figure 11) where a xenolith of sodium-rich Lockatong argillite enclosed in the basaltic magma of the Palisades sill resulted in coexisting silicic and mafic melts. This phenomena has been exhaustively studied by Benimoff and Sclar, 1978, 1980, 1984, 1988, 1992, and Sclar and Benimoff(1993), and their work 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. Here at the Graniteville Quarry all three contiguous rocks are preserved in the arrested state.

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 0.5 m 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 formed.

Mineral compositions were obtained with an ARL microprobe using wave-length dispersive and energy-dispersive analysis. Raw data were corrected by means of the Bence-Albee interactive routine. Natural and synthetic standards were utilized. The bulk chemical compositions of whole-rock samples were obtained by X-ray fluorescence analyses; FeO was determined by wet chemical analysis.

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[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.
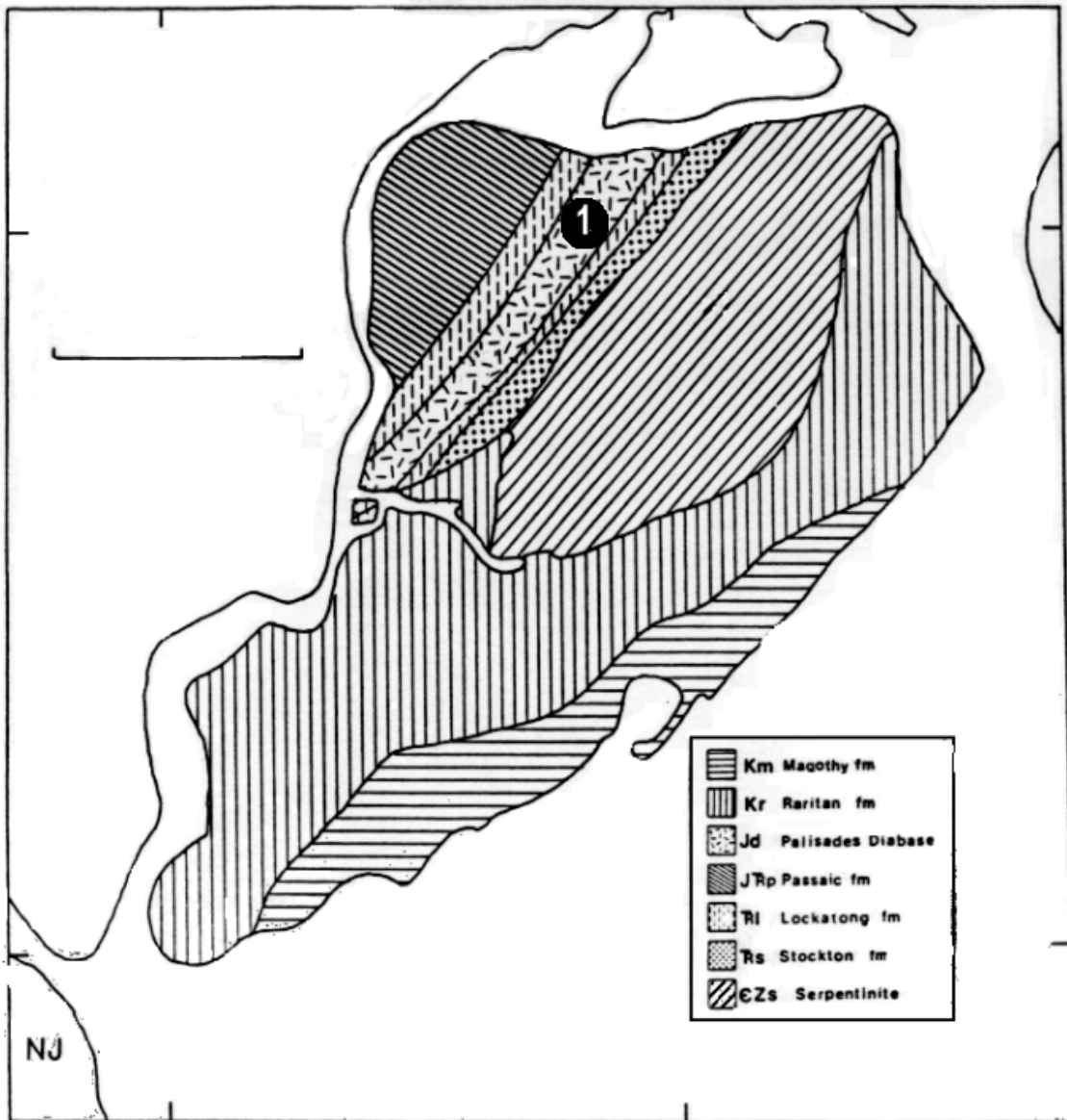
Figure 11. Geologic Map of Staten Island, NY showing the location of the Graniteville Quarry(1).

THE DIABASE

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 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. No attempt was made to use the Buddington and Lindsey (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 containing large discrete crystals of albite 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.

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 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 + sphene + calcite. There is a complete chemical gradation in pyroxenes 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 euhedral crystals 5 to 30 mm in length; typical cross-sections are shown in Figure 3. 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 + sphene + calcite.

Albite and quartz

Albite ($Ab_{99}An_{0.52}Or_{0.44}$) occurs as 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. 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

Sphalerite

Sphalerite is present as euhedral crystals embedded selectively in the albite of the granophyre. As seen in thin section dark well-defined cores contain 13-16 mole% FeS, whereas pale yellow-brown rims contain between 0.2 and 2.0 mole percent FeS. Electron microprobe data 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 nicols, the rim appears illuminated because of internal reflections.

Enclosed selectively in the albite of the albite-quartz granophyre, we found, in thin sections, about a dozen isolated euhedral to subhedral crystals of sphalerite 30-70 µm in diameter. These crystals are transparent, with a high refringence. They are isotropic and optically zoned, with a dark-brown core and pale brown to colorless rim. Also enclosed in the trondhjemite are minute interstitial anhedral grains of Ni- and Co-bearing pyrrhotite, although nowhere is the pyrrhotite in contact with the sphalerite crystals.

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.

Compositional data were obtained with an ARL electron microprobe using wavelength-dispersion analysis. Standards were synthetic ZnO for zinc and pyrite for iron and sulfur. Operating conditions were 15 kV and 40 nA. The raw data were corrected for atomic number, absorption, and fluorescence effects (ZAF). Results of the electron-microprobe analysis shows that these isotropic grains are zoned zinc sulfide, with a relatively high-iron core (10-16 mole % FeS) and low-iron rim (1-5 mole % FeS). The core-rim boundaries are abrupt and show concentration gradients in excess of 3 mole % FeS per µm. Some of the grains have an asymmetrically zoned rim composed of alternating relatively high-iron (5 mole % FeS) and relatively low-iron (1 mole % FeS) zones.

Table 7.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_2O					1.15	0.23
Total	97.59	100.49	99.68	97.85	98.96	98.69
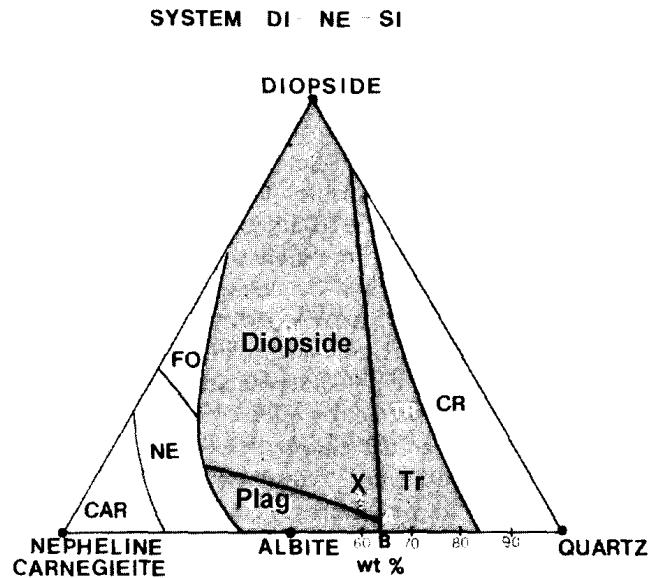
Figure 12. The System diopside-nepheline-silica(Shairer and Bowen, 1960).
The deduced composition of Trondhjemite magma is shown by X which lies at a temperature of 1150°C.

Minor minerals

The carbonate phase in the trondhjemite is calcite which occurs as single-crystal interstitial fillings. 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 titanomagnetite 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.

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, sphene, sphalerite, albite-quarts 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-quartz) as determined by Schairer and Yoder (1960) (see dark region of Figure 12). If crystallization commenced at x, which is close

to 1160°C, the temperature of crystallization of the trondhjemite deduced in subsequent discussion in this paper, 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 granophyre crystallized until the albite-quartz eutectic was reached at 1062°C, which is the dry minimum melting temperature in the quartz-albite system(see figure 4) at one atmosphere (Schairer and Brown, 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 hornfelsic texture. The hornfels is composed dominantly of albite and quartz and subordinately 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 meta-sedimentary rock. Normative albite ranges from 56.4 to 80.2 wt.%, whereas normative quartz ranges from 7.0 to 35.4 wt.%.

The hornfels was derived from the Newark Supergroup (Olsen, 1980)of sedimentary rocks which is associated with 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 low in potassium, which is characteristic of some parts 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 13) 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 7. Hess (1956) noted 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 correlated with a liquidus temperature of 1220°C. The iron-enrichment index of specimen D-2 is 0.67 which correlated with a liquidus temperature of approximately 1160°C. 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 lies between W-N-60 and W-R-60 of Walker, thus placing upper and
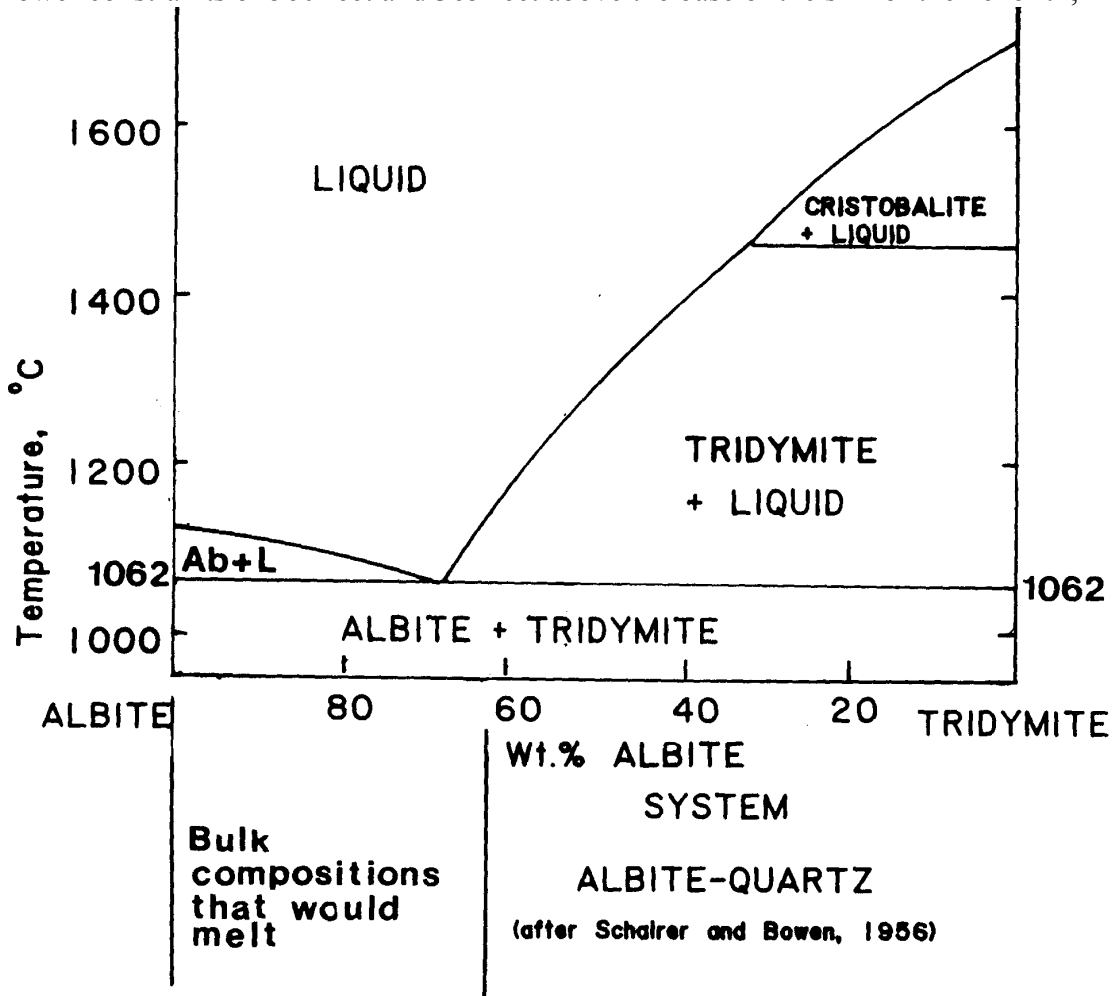 lower constraints of 560 feet and 365 feet above the base of the sill for the xenolith;

Figure 13. The dry albite-SiO_2 equilibrium diagram of Schairer and Bowen (1956)

(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 1969a;

(3) the mafic fractionation indices [(Fe) + Fe$_2$O$_3$)(100%)/(MgO +Fe$_2$O$_3$)] of W-N-60 and D-2 are respectively 66.55 and 66.92(Figure 15) , and (4) D-2 plots directly on the differentiation trend for the Palisades Sill (Figure 14). D-2 plots closer to W-N-60 than any of the Englewood Cliff specimens of Walker (1969a).

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.
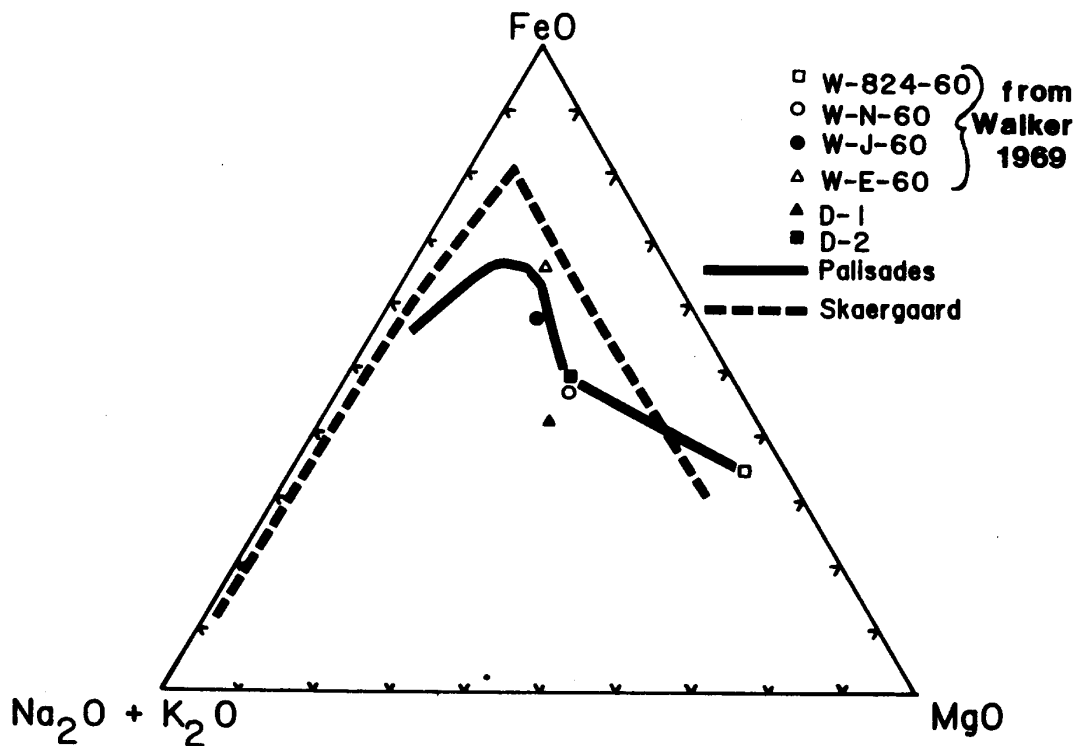
Figure 14. MgO-FeO-(Na2O+K2O) diagram which shows the composition of the Palisades Diabase from the Englewood Cliffs section of walker (1969a). D-2 falls directly on the Palisades diabase differentiation trend of walker(1969a). D-1 shows Fe -depletion and alkali enrichment. FeO represents total Fe expressed as FeO.
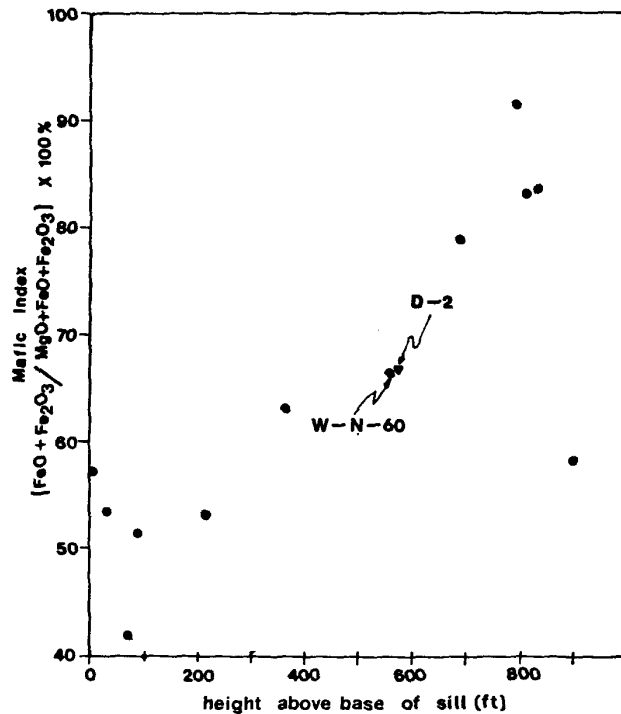
Figure 15. Plot of mafic Index vs. height above the base of the Palisades Sill. D-2 plots adjacent to W-N-60 of Walker (1969)a.

There are differences between the bulk chemical composition of the trondhjemite and that of the Lockatong hornfels (see Table 7), 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 liquid 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 14, 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 liquid 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 $\Delta\overline{\mathbf{H}}_{\mathbf{mix}}$

(enthalpy of mixing), is greater than the entropy of mixing term $\mathbf{T}\Delta\overline{\mathbf{S}}_{\mathbf{mix}}$ 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 16). 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), 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 17). Therefore, the diabase and the trondhjemite do not appear to be in an immiscible relationship.
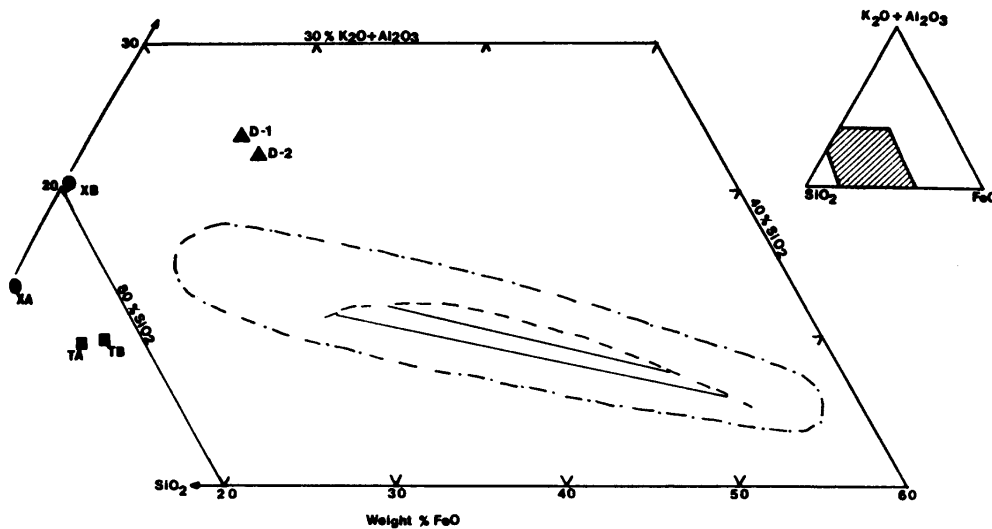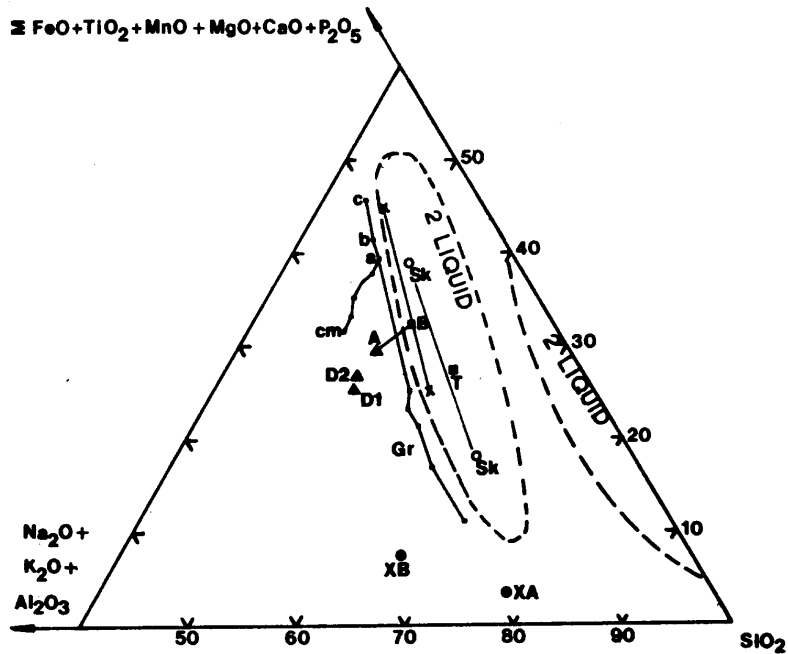

Figure 16. FeO-(Al_2O_3 + K_2O)-SiO_2 diagram (Watson, 1976).

Figure 17. Diabase, trondhjemite, and xenolith compositions plotted on on the hypothetical pseudoternary phase diagram, [SiO$_2$] - [Na$_2$O-K$_2$O-Al$_2$O$_3$] - [FeO + TiO$_2$ + MnO + MgO + P$_2$O$_5$] (see Grieg, 1927).The high-temperature and low-temperature imiscibility fields are marked by dashed lines(system fayalite-leucite-silica (after Roedder, 1951). Also plotted are the compositions of (1) The Rattelsnake Hill basalt (A)and its mesostasis (B) (Philpotts, 1979, and 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 reprent the upper zone;Gr=melanocratic granophyres. T= specimens TA and TB; The x's represent immiscible liquids in the Rattelsnake Hill basalt (Philpotts, 1979).

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 have been devolatilized before melting of its margins occurred. The high viscosity of the trondhjemitic silicic 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 in excess of 1800°C (Kullerud 1966). Nevertheless, all 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. In this paper, we report evidence 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. However, it is important to note that several of the polytypes of wurtzite (3R, 9R, 12R, 15R, 21R) have symmetry *R3m* (Kostov & Min_eva-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 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 conclusion 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 REE plots of the xenolith, the trondhjemite, and the contiguous Palisades diabase were prepared from REE analysis obtained by INAA. The trondhjemite and the xenolith plots are characterized by a pronounced negative europium anomaly (Eu 20-30 times chrondrites), LREE concentration of 80-100 times chrondrites, and HREE concentrations of 30-50 times chrondrites. By comparison, the diabase shows a positive europium anomaly (EU 19-26 times chrondrites), LREE concentrations of 18-40 times chrondrites, and HREE concentrations of 10-17 times chrondrites. It is concluded that the REE signature of an igneous rock does indeed reflect that of the source rock. Furthermore, a plot of trondhjemite and xenolith compositions on a Sun and McDonough(1989) spider diagram(Figure 18) present compelling evidence of a parent(xenolith) - daughter(trondhjemite) relationship between the two. When we compare the chemical signatures of the three contiguous rocks namely the xenolith, the trondhjemite and the Palisades diabase we conclude that the trondhjemite was derived from the fusion of the xenolith of Lockatong argillite. The general slope of the trondhjemite curve is negative. Furthermore, the range of the trondhjemite data plots within the range of the Lockatong argillite data and both display 3 very distinct negative anomalies: potassium, phosphorous and titanium. By comparison, all Palisades diabase analyses including fractionated granophyres plot as lines with different slopes, magnitudes and do not display the 3 negative anomalies.
Our data rules out magmatic fractionation as a process capable of generating the trondhjemites of this study.
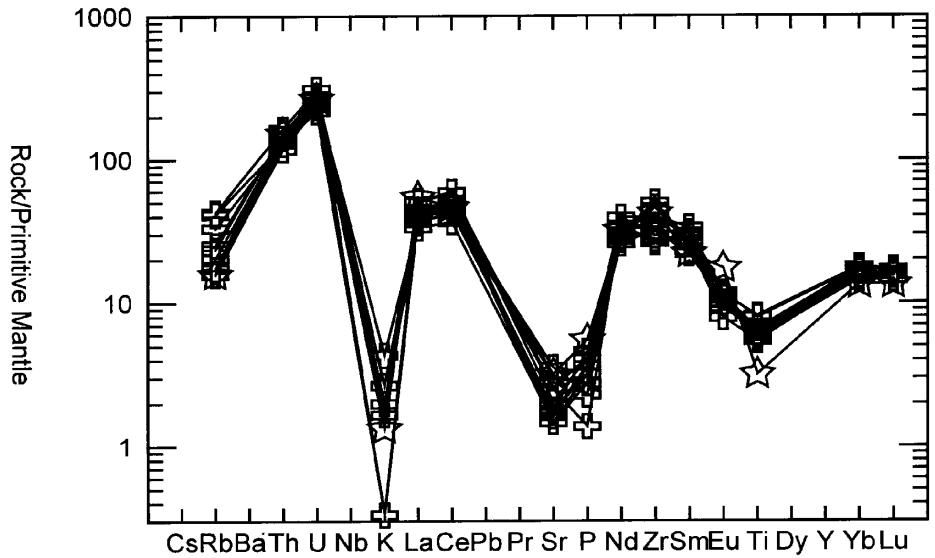
Figure 18. Sun and McDonough(1989) mantle normalized plot. Trondhjemite compositions from Graniteville represented by open plus sign; Xenolith from graniteville represented by open star.
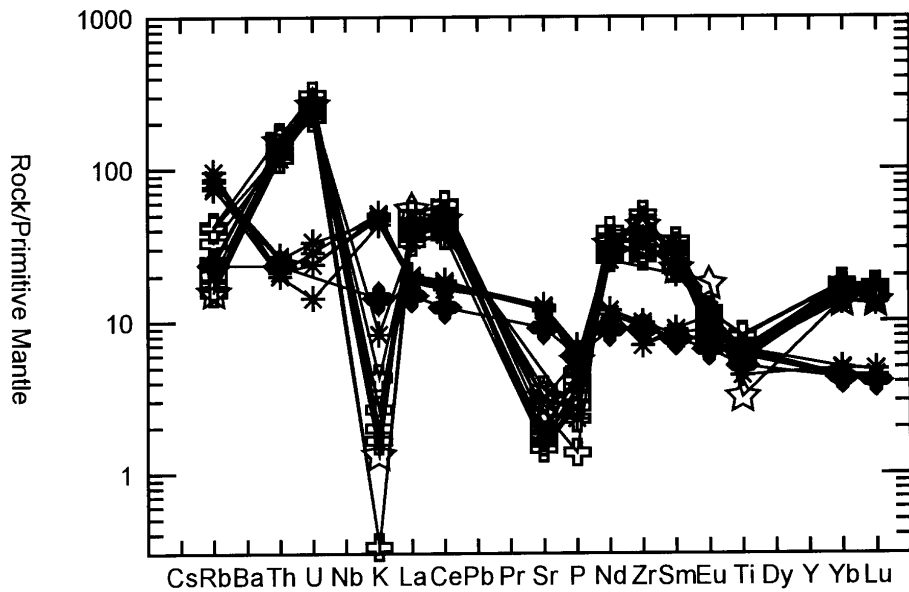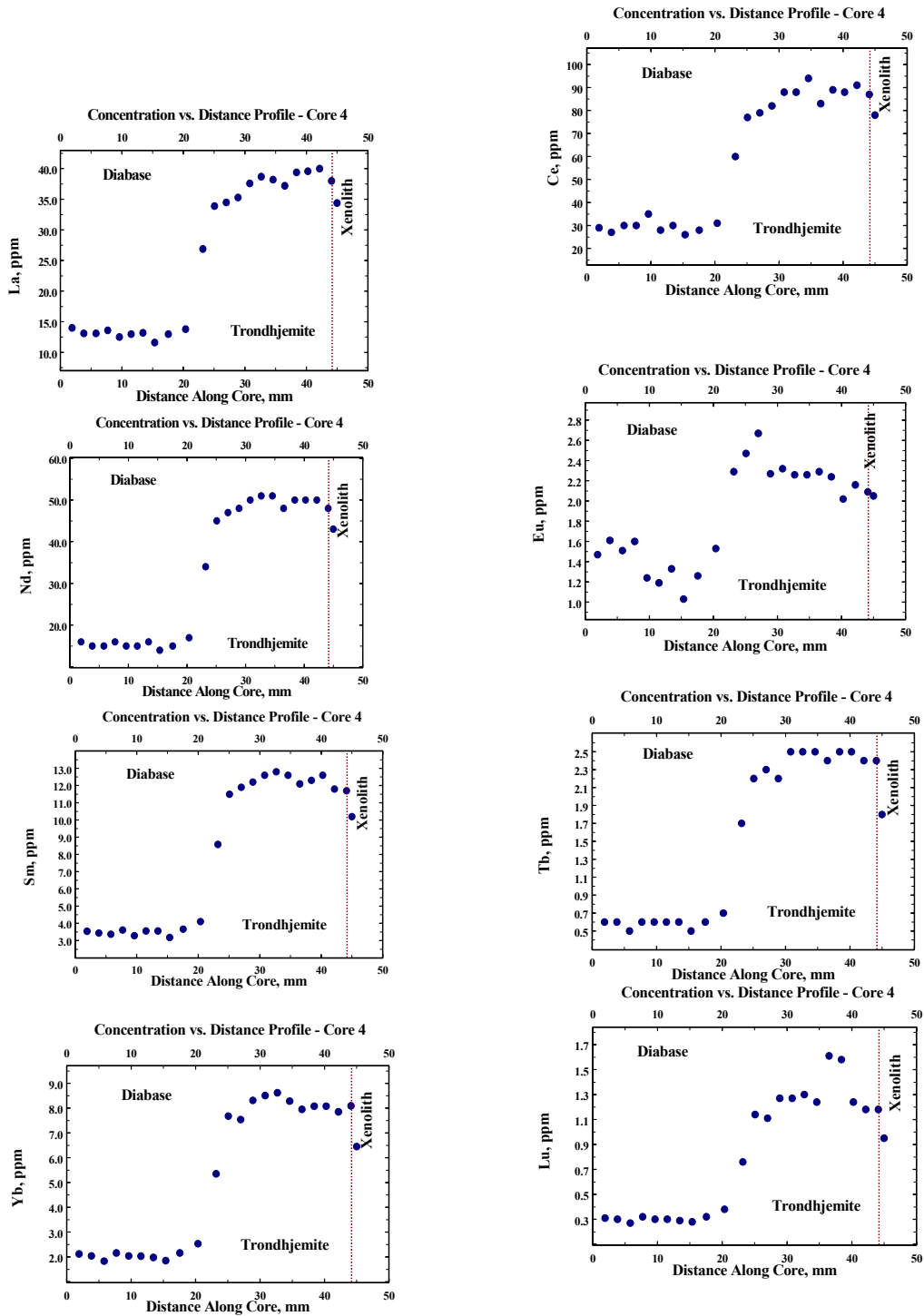

Figure 19. Sun and McDonough(1989) mantle normalized plot. Trondhjemite compositions from Graniteville open plus sign; Xenolith from Graniteville represented by open star. For comparison diabase samples from graniteville represented by an asterisk; and HTQ from Tollo and Gottfried, 1992 is represented by a closed plus sign.

DIFFUSION OF IONS ACROSS THE LIQUID-LIQUID INTERFACE

This discovery of a partly fused xenolith of Lockatong argillite in the Palisades Sill at Graniteville, Staten Island, NY provides a natural laboratory for the study of cationic diffusion profiles across a magmatic liquid-liquid interface which involves coexisting trondhjemite magma, derived by fusion of a xenolith of Lockatong argillite,and basaltic magma of the enclosing sill. Drill cores oriented normal to the liquid-liquid boundary(ie., normal to the trondhjemite-basalt contact) were cut normal to the cylindrical axis of the drill cores with a diamond wafering blade

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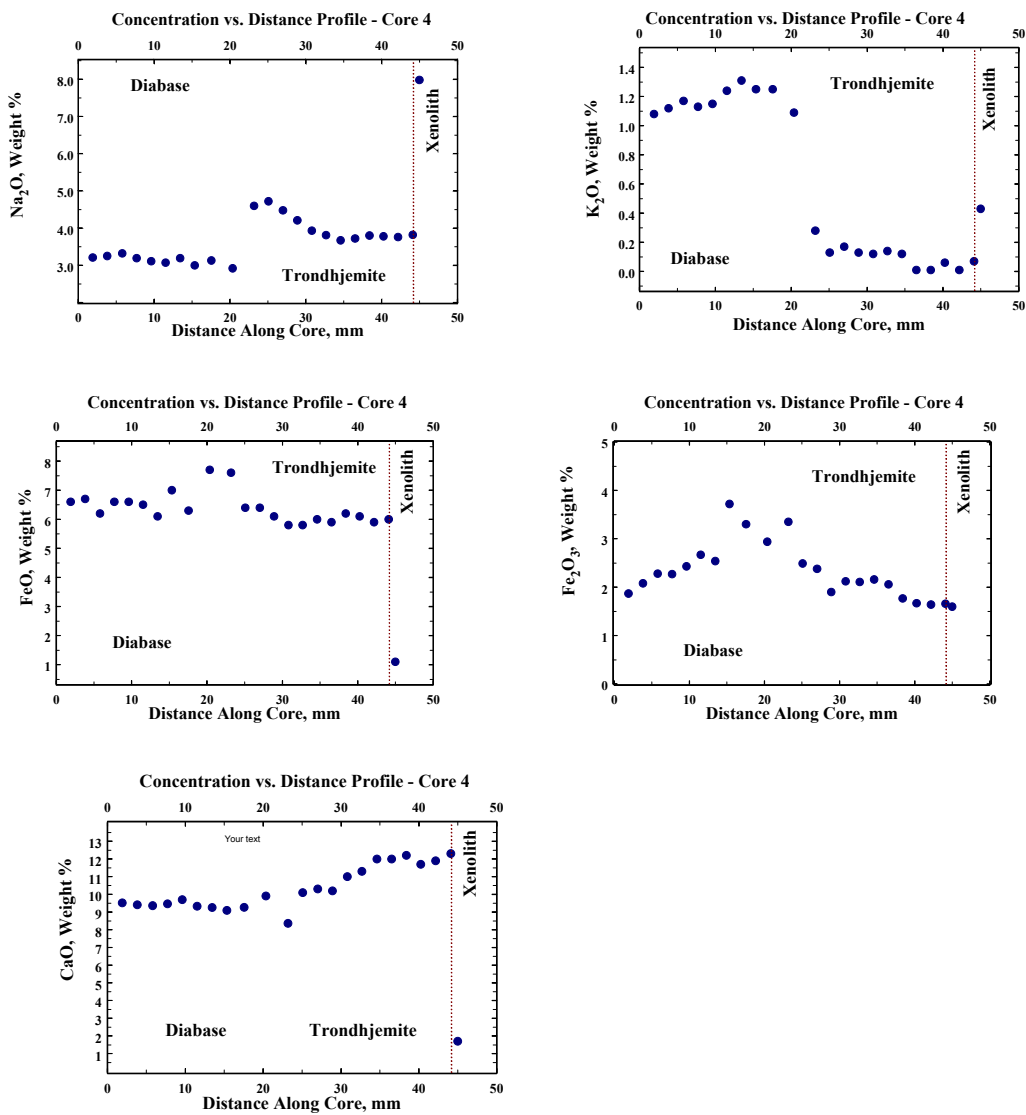
Figure 20. Concentration profiles of selected major elements . The Diabase-Trondhjemite contact is at 22mm.

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(La, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Ce, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Nd, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Eu, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Sm, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Tb, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Yb, ppm vs. Distance Along Core, mm)

Concentration vs. Distance Profile - Core 4

Diabase

Xenolith

Trondhjemite

(Lu, ppm vs. Distance Along Core, mm)

Figure 21. Concentration profiles of selected REE's . The Diabase-Trondhjemite contact is at 22mm.

into discs approximately 1.5mm thick, and each disc was analyzed for major, minor and trace elements including REE's over a distance of 3 cm on the trondhjemite side and 1.2 cm on the diabase side of the magmatic interface. Theoretical models of the two-magma system suggest that at time equals zero the slope of the concentration-distance curve at the liquid-liquid boundary would be 90° whereas at time equals infinity the slope would be zero so that the magnitude observed of the slope between 0 and 90° would be a measure of the relative rate of diffusion for each ionic species. The relative diffusivities of selected major oxides and REE are shown in Figures 19 and 20. Despite the overprint of crystallinity and mineralogy in these holocrystalline rocks, trends in the slopes of the concentration-distance curves for ions of the same charge appear to relate the relative diffusion rates of different ionic species to ionic size and thus steric hindrance in the magma(Benimoff and Sclar, 1996).

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 fused within the Palisades sill. 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 shows 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.

5. AT THE UPPER CONTACT OF AN EARLY JURASSIC DIABASE INTRUSION EXPOSED IN A ROCK QUARRY AT BROOKVILLE, NEW JERSEY.

Syenitic rock is exposed along the banks of a stream that flows along the upper contact of the Stockton Diabase sill (a Palisades correlative) with the Lockatong Formation (Figure 22). The syenite was first described by Ransome (l899) and Lewis (l908), then by Milton (l964), Barker and Long (l969) and Benimoff et al. (1996, 1997 and 1998). The Stockton Diabase is approximately 500 m thick and is truncated by a southeast-dipping normal fault near the syenite occurrence. The upper contact of the Stockton Diabase strikes about N. 45° E. and dips 30° NW but as observed by Barker and Long (l969) the contact is complicated by several apophyses.

The syenite is composed principally of orthoclase perthite, albite, and quartz, with minor biotite, pyroxene, and amphibole with variable concentrations of calcite.

The Lockatong meta-argillite hornfels at Brookville is composed principally of sodic plagioclase, biotite, pyroxene, amphibole and variable chlorite, calcite and muscovite. Barker and Long (l969) also report minor to trace amounts of apatite, hematite, pyrite, sphene, and fluorite. Quartz is conspicuously absent. Most of this

hornfels corresponds to typical detrital cycles described by Van Houten (l965) particularly the dark gray carbonate-rich mudstone facies.

Benimoff et al. (1996, 1997 and 1998) concluded that the alkalic syenite associated with intrusive Stockton diabase at Brookville NJ is the crystallization product of a melt derived by fusion of the Na-rich nepheline normative Lockatong argillite in the thermal aureole of the intrusive Stockton diabase. They also determined that the syenite is a holocrystalline phanerite containing 15 modal % black euhedral amphibole prisms in a matrix matrix of mottled pink and white feldspar. Their electron microscopy reveals that the amphibole is zoned with a Mg -rich core and an Fe- rich rim. Based on the IMA classification of amphiboles the Mg -rich core is a sodian kaerusutite and the Fe rich rim is a sodian magnesium hastingite. Around the amphibole is an extremely fine intergrowth of oligoclase surrounded by K-feldspar,. The fine intergrowth of oligoclase surrounded by K-feldspar shows the reverse rapakivi texture. Furthermore, the presence of baddeleyite, the absence of quartz and zircon, the low tetrahedral site population of Si in the amphibole (5.824 vs. 8.00 tetrahedral sites/ formula unit), normative nepheline and no normative quartz indicate that the syenite represents a silica undersaturated melt.
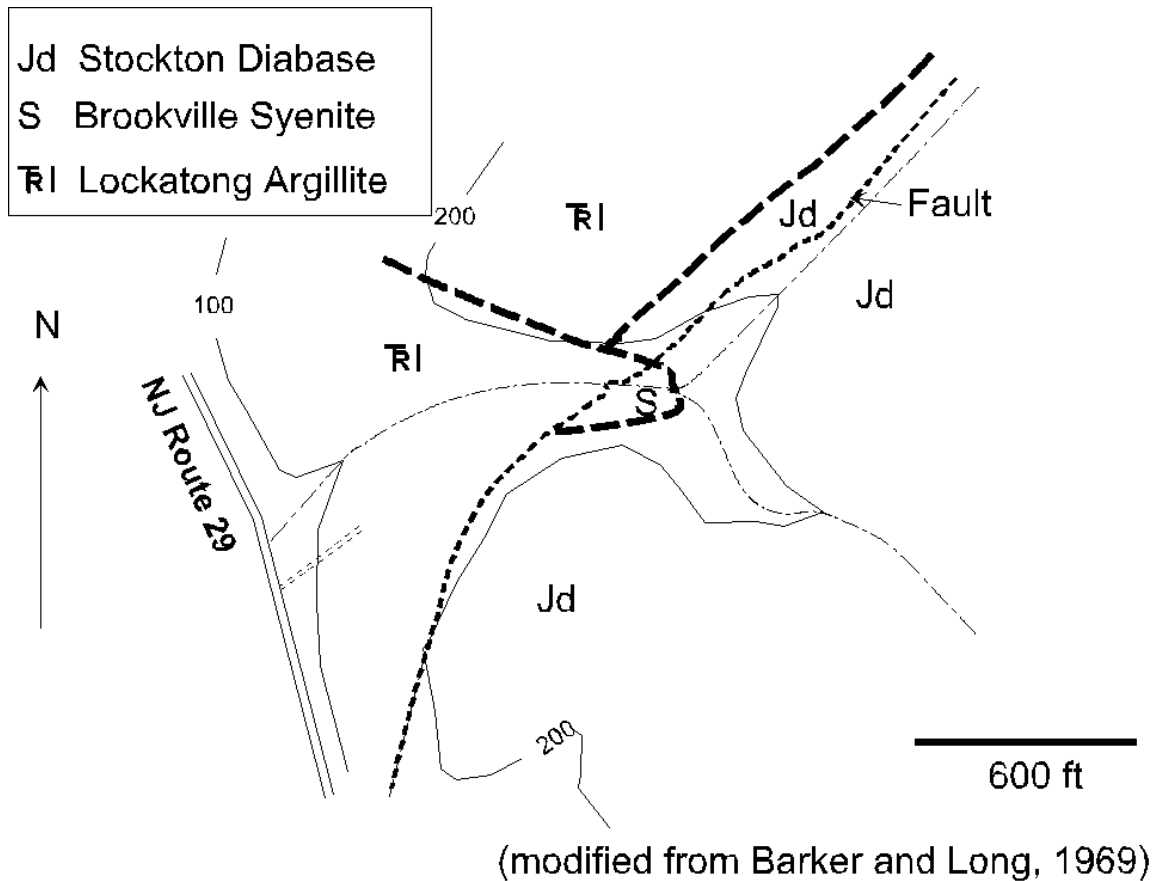
Figure 22. Geologic map from Barker and Long. 1969. Please note that this is private property and permission must be granted by, the owner of the property, Trap Rock Industries.

The chemical composition of the syenite includes about 54 percent SiO_2, 7 percent Na_2O, and 4 percent K_2O, about the same as the Lockatong hornfels, but contains less MgO and FeOt (2 and 5 vs. 5 and 7 percent). MgO and FeOt were partitioned into a black refractory residual hornfels exposed adjacent to and intergrown with the syenite resembling a migmatite. The MgO and FeOt content of the black biotite rich rock are 11 and 15 percent respectively. The build up of biotite in the black rock has displaced feldspar resulting in retention of only 0.5 percent Na_2O. Most elements in the syenite and argillite (including TiO_2 and Zr at 0.8 percent and 140 PPM) maintain approximately consistent levels indicating very high degrees of argillite fusion. The TiO_2 and Zr levels, however, differ from levels found in the Stockton Diabase and associated granophyre (about 1.4 and 120 PPM) suggesting that syenite magma mixing with diabase magma was no more than a minor factor. These data also indicate that the syenite could not be a fractionation product of Stockton Diabase in which case the TiO_2 and Zr contents would exceed Stockton Diabase levels instead of their actual lower levels.

In addition, chondrite normalized plots of the syenite, Lockatong argillite and Stockton Diabase were prepared . The syenite and Lockatong argillite plots(figure 23) are characterized by tightly grouped parallel trends and a negative europium anomaly (Eu= 20 times chondrites), LREE concentrations of about 100 times chondrites and HREE concentrations of 8 to 20 times chondrites. The similarity of REE trends for the Lockatong argillite and alkalic Brookville syenite is further evidence of a very high degree of partial melting of Lockatong argillite and the dissimilarity to the Stockton Diabase is further evidence of a low degree of mixing.
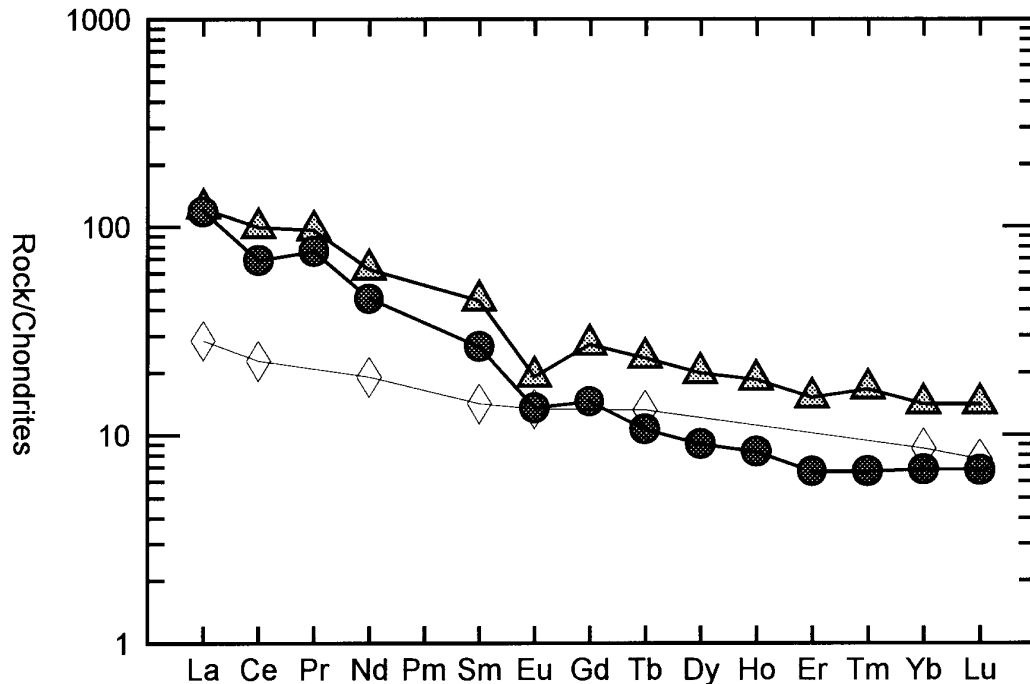
Figure 23. Chondrite normalized REE plot of Lockatong argillite(circles, Brookville Syenite(Triangles) and Stockton Diabase is represented as open diamonds(LQ1 from Husch, 1992).

Again, our complete chemical analyses of the trondhjemite when plotted on primitive mantle normalized spider diagrams(Sun and McDonough, 1989) provide compelling evidence that the syenite is genetically related to the Lockatong argillite and not genetically related to the Stockton Diabase(see Figure 24). The Brookville Syenite is an intrusion of fused Lockatong argillite. The general slope of the trondhjemite curve is negative. Furthermore, the range of the trondhjemite data plots within the range of the Lockatong argillite data and both display three very distinct negative anomalies: potassium, phosphorous and titanium. The Brookville Syenite data also plot very close to the North American Shale Composite(NASC). By comparison, all Stockton diabase analyses plot as a line with a different slope, and magnitude. This data rules out magmatic fractionation as a process capable of generating the Brookville Syenite of this study.
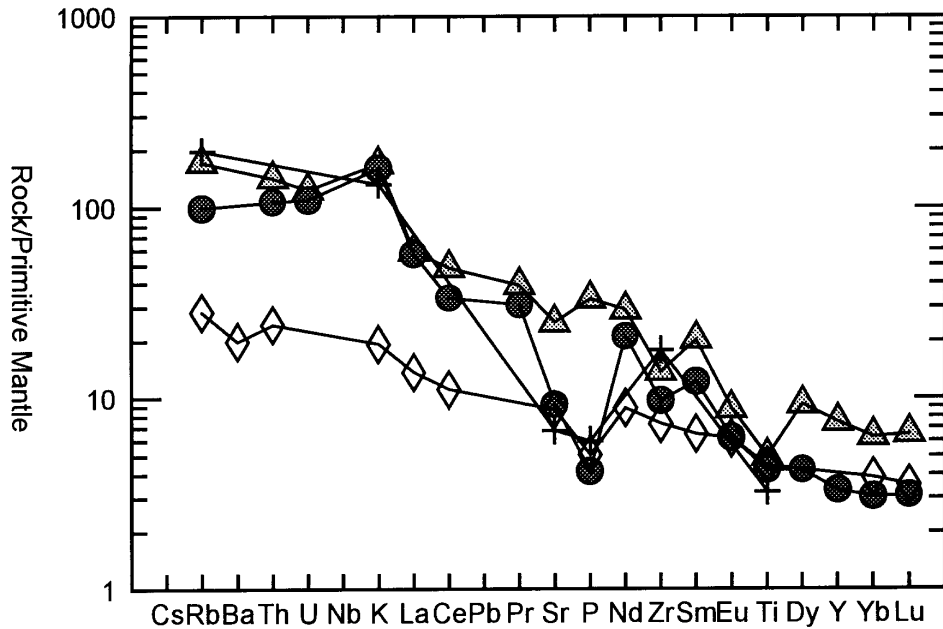
Figure 24. Sun and McDonough (1989) mantle normalized plot of Lockatong argillite (circles, Brookville Syenite (Triangles) and Stockton Diabase is represented as open diamonds (LQ1 from Husch, 1992).; + represents the North American Shale Composite (NASC)(Gromet et al., 1984). Note the similar chemical signatures of the NASC, the Brookville Syenite and the Lockatong Argillite.

CAMP

Table 8 shows average analyses of CAMP flood basalts. These data when plotted on a Sun and McDonough(1989) mantle normalized spider diagram(Figure 24) show amazing uniformity. The 200 Ma flood basalt event coincided with the extensional break-up of Pangaea and is classified as a reactivated arc-sourced, (A-Type) flood basalt, (Puffer, 2001) in contrast to a plume sourced flood basalt (P-type). The A-type

classification is based on : (1) its short duration of a few thousand years, (2) its uniform composition and (3) close resemblance to basalt and basaltic andesite from known arc-related sites. The uniform chemical composition, in particular is consistent with the rapid extrusion of a limited amount of eutectic magma. Rapid extrusion and a near absence of contamination is a result of the extensional tectonic activity, which allowed unobstructed egress to the surface in contrast to the ponding , contamination and fractionation typical of magmatism in compressional settings .   The reactivated arc source was enriched in water and large-ion-lithophile elements(LILE) typical of mantle metasomatic effects known to occur at subduction zones. However LIL and water enrichment into the CAMP source occurred during the Paleozoic assembly of Pangaea when subduction occurred in a compressional setting and calc-alkaline volcanism was common. When the vectors reversed from compression to extension, and Pangaea began to break up, this same arc-source underwent re-melting. Renewed melting , however, was limited by the amount of flux contained within the source and therefore, was of short duration.

The very minor role played by crustal contamination of CAMP basalt is seen in Table 8 and figure 25 with a virtual identical province-wide composition. Crustal contamination is largely limited to the margins of intrusive CAMP dikes and sills. In contrast to the flood basalts, the CAMP related dike swarms are chemically much more diverse. Table 9 lists some of the CAMP dike populations that range from mafic olivine normative(OLN) dikes common throughout the southeastern U.S. to high iron enriched quartz normative tholeiites(HFQ)(Weigand and Ragland, 1970) scattered throughout the CAMP province. The High-Titanium-Quartz-Normative population (HTQ) of dikes is chemically the same as the initial flood basalt population and is the most widespread dike population. The Low-Titanium-Quartz Normative population(LTQ) is confined to the southeastern U.S. The MgO content of the OLN population(Table 9) averages 10.52 wt. % in contrast to an average of only 5.53 wt. % for the HFQ population. In addition the TiO_2 content of the OLN population(table 9) average only 0.59 wt. % for the HFQ population. Weigand and Ragland(1970) also indicate that the mafic index for the ENA dikes range from 40 to 75.

The contrast between uniform flood basalt chemistry(table 8) and less uniform dike and sill chemistry(table 9) is probably due to a combination of factors. (1) Dikes are relatively susceptible to deuteric alteration and metasomatic effects compared with flows, (2) Dike chemistry is influenced by depth of emplacement; deep crustal dikes tend to be richer in dense phases, particularly olivine, then shallow dikes (3) Sills (such as the Palisades Sill) and even vertical intrusions (such as Snake Hill) are relatively susceptible to in-situ fractionation processes, and (4) dikes are relatively susceptible to crustal contamination and the mixing of fusion products near their outer contacts than basalt flows as this research makes clear. The kind of sediment fusion described in this study requires high sustained temperatures and insulated thermal energy that is absent in an extrusive environment. In addition, some sampling problems involving thin dikes(less than 10 m across) can add to the contrast in flood basalt vs. dike swarm chemistry. Hydrothermal alteration effects, particularly chloritization, are confined to the 10 m thick margins of Snake Hill(Puffer and Benimoff, 1997) and can generate olivine normative compositions. Any of the chloritized dikes of the southeastern U.S. OLN dike swarm that are less than 10 m thick should, therefore, be viewed with skepticism. This may, however, include the majority of the sample population. Although, mixing of the kind of

fusion products described in this study is even more confined that hydrothermal alteration effects, any resulting changes in magma chemistry would, again, be confined to the intrusive rock populations.

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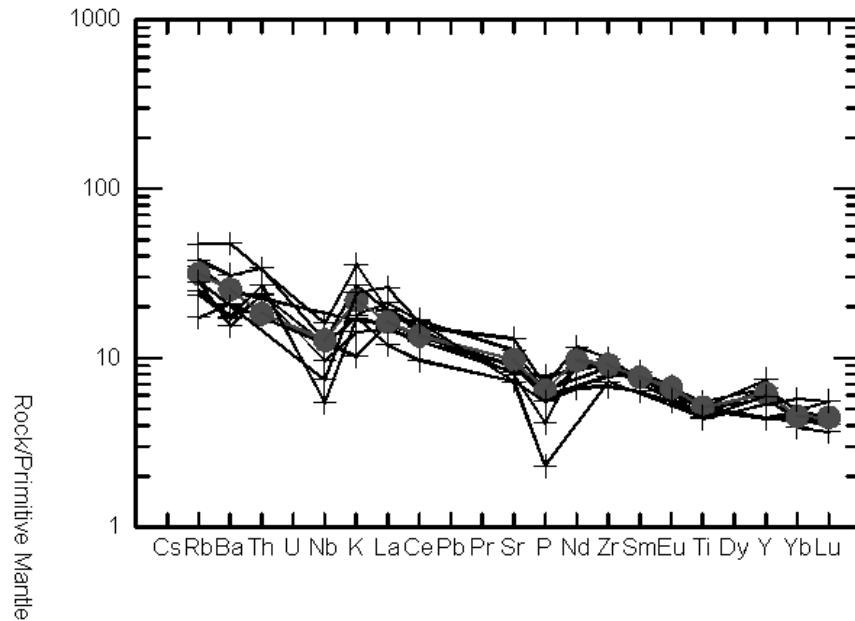
Figure 25 Sun and McDonough(1989) mantle normalized plot of CAMP extrusive rocks(table 8). The camp average is plotted as closed circles. Note the very tight clustering of CAMP extrusives in contrast to the diverse chemistry of CAMP intrusives(table 9).

TABLE 8. Average Analyses of CAMP Basalts

Name	A. Initial HTQ-type Flows								B. Secondary LTQ-type Flows		
	Orange Mt	Talcott	Mt.Zion	North Mt.	H. Atlas	Algarve	Maranhão	CAMP	Holyoke	Preakness	Sander
Location	NJ	CN	VA	N. Scotia	Morocco	Portugal	Brazil	average	CN	NJ	VA
n	11	7	7	6	15	2	16	64	28	31	16
SiO_2	52.68	51.79	52.65	53.81	52.80	51.90	52.98	52.41	53.65	52.09	52.69
TiO_2	1.12	1.07	1.09	1.08	1.19	1.01	1.10	1.11	0.97	0.95	1.09
Al_2O_3	14.25	14.25	14.62	13.79	14.38	14.44	14.87	14.50	14.67	14.33	14.22
FeO_t	10.15	10.84	9.97	9.73	9.57	10.36	9.77	10.00	11.74	12.66	12.43
MnO	0.18	0.16	0.17	0.16	0.16	0.16	0.17	0.17	0.20	0.21	0.22
MgO	7.81	7.97	7.68	8.09	8.13	7.91	7.26	7.80	5.97	6.55	5.76
CaO	10.80	11.23	10.69	10.38	10.98	11.23	10.43	10.84	9.40	9.49	9.40
Na_2O	2.45	2.06	2.68	2.06	2.10	2.31	2.21	2.37	2.61	3.11	3.44
K_2O	0.43	0.50	0.31	0.81	0.52	0.54	1.07	0.66	0.73	0.52	0.61
P_2O_5	0.13	0.13	0.14	0.09	0.17	0.14	0.15	0.14	0.05	0.12	0.14
Rb	15	22	11	24	18		30	20	18	16	
Ba	119	174	145	216	108		331	178	142	123	
Sr	192	186	191	169	173	235	275	207	153	153	
Th	2.00			2.88	2.04		0.00	1.55		2.29	
Zr	99	87	99	96	104	98	111	102	81	76	
Hf	2.40			2.90	2.64		0.00	1.97		2.02	
Nb	6.90			9.00	8.72		11.44	9.08	5.30	3.89	
Ni	99	86	79	64	89	87	76	88	36	52	
Cr	309	322	282	225	221	241	301	282	11	111	
La	10.2	11.1	10.8	13.0	10.4	14.6	13.3	11.2	18.0	8.2	
Ce	22.1	23.9	24.1	26.0	22.5	29.7	27.1	24.0	29.0	17.2	
Nd	11.8			12.8			15.8	13.1		9.0	
Sm	3.40	3.66	3.51	3.30	3.45		3.34	3.42		2.81	
Eu	1.10	1.15	1.13	1.03	1.11		1.11	1.12		0.93	
Tb	0.61	0.67	0.65	0.63	0.65		0.63	0.64		0.64	
Yb	2.10	2.35	2.30	2.13	2.41		1.91	2.22		2.81	
Lu	0.30	0.33	0.34	0.33	0.41		0.27	0.33		0.41	
Y	20			26	30		34	28	27	24	

Note all Fe is listed as FeO_t, major elements are in wt.% normalized to 100% anhydrous, trace elements are in ppm. Listed averages for Orange Mt. Basalt from *Tollo and Gottfried* [1992]; Talcott Basalt from *Puffer* [1992]; Mt Zion Church Basalt from *Puffer* [1992]; North Mt. Basalt from *Papezik et al.* [1988]; High Atlas Basalt from *Bertrand et al.* [1982]; Algarve basalt is new data; western Maranhão Basalt from *Fodor et al.* [1990]; Holyoke Basalt from *Philpotts et al.* [1996], Preakness Basalt from *Tollo and Gottfried* [1992]; and Sander Basalt from *Tollo* [1988].

Table 9. Major and minor element averages for ENA dolerites.

	HFQ	HTQ	LTQ	OLN
	(from Weigand and Ragland, 1970)			
SiO2	52.96	52.10	51.66	47.90
TiO2	1.14	1.12	0.76	0.59
Al2O3	14.21	14.22	14.95	15.26
FeOt	13.87	11.65	11.77	12.10
MnO	0.22	0.19	0.20	0.18
MgO	5.53	7.41	7.44	10.52
CaO	9.86	10.66	10.80	10.75
Na2O	2.51	2.12	2.23	2.00
K2O	0.64	0.66	0.48	0.29
Co	52	49	53	65
Cr	94	277	218	166
Cu	74	111	68	108
Li	18	19	16	12
Ni	34	81	48	308
Rb	22	21	15	8
Sr	178	186	127	115
Zn	99	84	86	84
Zr	94	92	60	50

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ROAD LOG
for
2001 NYSGA MEETING

The uniform composition of CAMP diabase types and the absence of wall rock contamination at Northern New Jersey and Staten Island, New York Locations

Total Mileage	Inc. Mileage	DESCRIPTION
0	0	Leave IBM Palisades Conference Center and Continue on US 9W south
11.7	11.7	Left Turn onto Main St.(Fort Lee, NJ)
13.6	1.8	Merge with County Rd. 505(River Road)

14.8	1.2	STOP 1 Caution- Dangerous Intersection! Park on left side of River Road Near Entrance to Henry Hudson Park

The Palisades diabase, exposed along its basal contact with the Lockatong Formation at Fort Lee NJ, is fine grained, massive chill-zone rock. The diabase is aphyric and subophitic and contains very few xenoliths. A few large xenoliths have been observed but they are typically spaced at least 100 meters apart. The lower contact is largely parallel to the bedding planes of the underlying metasediments but is locally discordant. In addition, there are anticlinal dome-like structures consisting of the Lockatong Formation that rise a few meters into overlying diabase. It is at these dome-like structures where most of the partial fusion of the Lockatong Formation has taken place. Three clearly exposed examples of these domes occur within 2 km of Ross Dock, where fusion has occurred resulting in syenitic rock intergrown with black laminated siltstone forming a migmatite and trondhjemite veins. The bedding at these domed structures is disrupted and may have involved movement of volatiles derived from brackish groundwater within the lacustrine Lockatong sediments. The high salt content of Lockatong Argillite may have helped flux the melting process. Both the syenite and the trondhjemite are sodic, typically containing 4 and 7.5% Na_2O respectively, but the K_2O and Rb is highly partitioned into the syenite typically containing 5 % and 125 ppm vs. only 0.5% and 25 ppm for the trondhjemite. Both the syenite and trondhjemite have similar REE contents that are comparable to the Lockatong Argillite.
Our complete chemical analyses of the syenite and trondhjemite when plotted on primitive mantle normalized spider diagrams (Sun and McDonough, 1989) provide compelling evidence that the igneous components of the migmatite are fused Lockatong argillite. For example, all three lithologies display distinctly negative Nb anomalies. However, the chemistry of these lithologies differs from that of the Palisades Diabase.

14.8	0	Head North on County Road 505
15	0.2	Bear Left at Y(Main St.)
15.2	0.2	right turn
15.4	0.2	left turn onto Bridge Plaza South
15.5	0.1	Right turn onto NJ 67
15.6	0.1	Right turn onto I-95 South, US 1 and 9 South
17.9	2.3	Bear Left onto US 1+9 South
18.2	0.3	Left turn - Follow US 1+9

		South(Broad Ave)
18.4	0.2	JCT 5 Follow US 1+9 South
18.8	0.4	JCT 93 - Follow US 1+9 South
18.9	0.1	Enter Traffic Circle Follow US 1+9 South
21.5	2.6	Pathmark supermarket on Right
22	0.5	Milepost 59
22.7	0.7	46th St.
23.6	0.9	JCT RT 3
25.5	1.9	Right Turn onto County Road(County Road 653)
26.6	1.1	Pass under I-95 NJTP
27.8	1.2	Left Turn onto New County Road (655)
28	0.2	Pass over RR tracks
28.4	0.4	Enter Hudson County Park
29.1	0.7	STOP 2 -Park car in lot

Laurel Hill(Snake Hill) is an elliptical exposure of early Jurassic diabase about 500 meters in diameter, located 2.5 km west of the underlying Palisades sill and 10 km east of the stratigraphically overlying Orange mountain Basalt. Fusion of Passaic siltstone at the southern contact has generated granitoid rocks. The granitoid rocks include trondhjemite and syenite. The potassic granitoids chemically contrast with the intrusive but closely resemble the wall rocks.

29.2	0.1	Exit on Park Road
29.8	0.6	Leave Hudson County Park
30.4	0.6	Turn Left onto County Ave.
30.7	0.3	Secaucus Diner on Right
30.9	0.2	Observe west slope of the Palisades Sill on right
32.2	1.3	Turn Right onto Paterson Plank Road
32.8	0.6	Enter NJ Turnpike South(Toll Road)
45.9	13.1	Exit at 13

46.6	0.7	Pay Toll -follow signs for Goethals Bridge -I-278 East
48.6	2	Pay Toll
48.8	0.2	Exit at Forest Avenue
48.9	0.1	Left onto Forest Ave.
50.3	1.4	STOP 3 Park on Right side between Van Name and Simonson Aves.

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

END OF FIELD TRIP