

## **Coexisting silicic and mafic melts resulting from marginal fusion of a xenolith of Lockatong Argillite in the Palisades Sill, Graniteville, Staten Island, New York**

ALAN I. BENIMOFF<sup>1</sup>

*Department of Applied Sciences  
The College of Staten Island, The City University of New York  
715 Ocean Terrace, Staten Island, New York 10301*

AND CHARLES B. SCLAR

*Department of Geological Sciences  
Lehigh University, Bethlehem, Pennsylvania 18015*

### **Abstract**

In the Palisades Sill on Staten Island, New York, is an extraordinary example of two coexisting chemically divergent 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 Lockatong argillite.

The xenolith is a vertical tabular body 30 m long and 0.5 m thick. The xenolith has a Na/K weight ratio of 75, a norm dominated by albite and quartz, and contains 0.5 wt.% each total iron oxide and MgO. The pyroxene trondhjemite contains 32 wt.% normative albite, 18 wt.% normative quartz, and 6–7 wt.% total iron oxide. The mineralogy and chemistry of the surrounding diabase, the mafic (67) and felsic (25) indices, and the position of the diabase on the AFM differentiation trend of the Palisades magma indicate that the xenolith is now 525±50 feet above the base of the Palisades sill if these data are normalized to the Englewood Cliff section of Walker (1969). The mafic index of the diabase indicates a magma temperature of 1160°C which is above the liquidus for a broad range of composition in the system albite–quartz. The high normative albite and quartz of the xenolith are manifested in the trondhjemite by relatively large euhedral albite crystals and an albite-quartz micrographic (granophyric) intergrowth which constitutes the groundmass of the trondhjemite. Chemical analyses of the xenolith, the trondhjemite, the contiguous diabase, and a diabase sample 13 m from the xenolith indicate that iron, magnesium, and calcium diffused into the coexisting trondhjemitic magma; correspondingly, sodium diffused from the trondhjemitic magma into the surrounding diabase magma. The diabase and the trondhjemite do not appear to have an immiscible relationship. The high viscosity of the dry silica-rich trondhjemitic magma may have prevented physical mixing of the two coexisting magmatic liquids.

### **Introduction**

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. In the extraordinary example described in this study (Benimoff

and Sclar, 1978, 1980), fusion of the margins of a xenolith of sodium-rich Lockatong argillite enclosed in the basaltic magma of the Palisades sill resulted in coexisting silicic and mafic melts.

Yoder (1973) in his investigation of contemporaneous basaltic and rhyolitic magmas, cited the field evidence of various workers, and noted that, in many cases, two magmas of greatly contrasting composition coexisted at the same locality and erupted from the same vent or were intruded into the same dike at the same time. He also showed that two magmas of highly contrasting composition may be generated successively from the same paren-

<sup>1</sup> This study began while Alan I. Benimoff was on sabbatical leave at Lehigh University, Bethlehem, Pennsylvania.

tal material by the mechanism of fractional melting. Other investigators (Roedder and Weiblen, 1970, 1971; De, 1974; Philpotts, 1976, 1978) described the occurrence of pairs of chemically diverse glasses intergrown as globules of one in the other which constitute the mesostasis of certain basalts, and suggested that silicate liquid immiscibility is a viable process for producing certain coexisting silicic and basic liquids. McBirney (1975) has shown experimentally that liquid immiscibility could have been responsible for the late-stage granophyres of the Skaergaard intrusion. Immiscibility in natural silicate systems is supported experimentally by the work of Roedder, 1951, 1978; Koster Van Groos and Wyllie, 1966; Rutherford et al., 1974; Irvine, 1976; Watson, 1976; Naslund, 1976; Cygan and Koster Van Groos, 1978; Visser and Koster Van Groos, 1978, 1979.

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

In rare occurrences, thermal metamorphism in the sanidinite facies may result in partial melting of hornfels

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

### Geologic setting and field relationships

Detailed studies of the Palisades Sill were made by Lewis, 1907, 1908a, 1908b; F. Walker, 1940; K. Walker, 1969a, 1969b; Pearce, 1970; and K. Walker et al., 1973. These studies were confined to those portions of the sill exposed in New Jersey and in Rockland County, New York. None of these studies covered the Staten Island portion of the Palisades Sill probably due to the poor exposures of the sill on Staten Island. There is general agreement that the sill is an intrusion of tholeiitic magma that differentiated through gravitational fractional crystallization. The boundaries of the sill on Staten Island are shown in Figure 1. Van Houten (1969), on the basis of

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

	XA	XB	TA	TB	D-1	D-2	W-R-60	W-N-60	W-J-60
SiO <sub>2</sub>	74.8	63.5	58.4	58.2	51.8	52.0	52.24	52.05	52.67
Al <sub>2</sub> O <sub>3</sub>	11.6	16.1	6.75	6.91	16.8	16.7	16.04	16.59	11.94
TiO <sub>2</sub>	.61	.75	1.63	1.48	1.17	1.13	1.15	1.24	2.76
MgO	.23	.30	4.89	5.14	4.91	4.74	5.80	5.08	3.94
FeO	.10	<0.1	4.35	5.60	6.70	7.85	7.69	7.70	11.08
Fe <sub>2</sub> O <sub>3</sub>	.31	.47	1.51	1.93	2.75	1.74	2.35	2.41	3.90
MnO	.02	.04	.14	.16	.16	.19	.16	.15	.19
CaO	2.07	5.60	13.1	11.5	8.79	10.2	10.61	9.80	8.06
Na <sub>2</sub> O	6.67	9.48	3.76	3.81	3.22	2.58	2.50	2.96	2.78
K <sub>2</sub> O	.07	.12	.12	.14	1.4	.76	.58	.81	1.29
P <sub>2</sub> O <sub>5</sub>	.09	.13	.30	.09	.14	.15	.15	.20	.31
LOI <sup>a</sup>	1.48	3.85	4.71	2.88	1.15	.23	1.29	1.52	1.22
TOTAL	98.99	100.34	99.66	97.84	98.99	98.27	100.54	100.51	100.14
Mafic Index <sup>b</sup>					65.81	66.92	63.38	66.55	79.17
Felsic Index <sup>c</sup>					34.45	24.6	22.49	27.78	33.55
Total Fe as FeO	.44	.47	5.71	7.21	9.17	9.42	9.81	9.87	14.59
CIPW Norms									

Table 1. (cont.)

	XA	XB	TA	TB	D-1	D-2	W-R-60	W-N-60	W-J-60
Q	35.41	7.00	19.32	16.27	1.42	4.63	4.41	2.63	8.09
Or	.39	.72	.72	.84	8.29	4.51	3.23	5.06	7.62
Ab	56.40	80.24	31.83	32.25	27.27	21.82	20.96	24.94	23.52
An			1.17	1.34	27.24	31.74	31.03	29.53	16.29
Wo			13.49	15.46	6.48	7.49	8.62	7.60	9.05
En	.57	.74	9.19	9.62	3.67	3.72	4.79	4.05	3.91
Di			3.25	4.92	2.53	3.62	3.48	3.30	5.14
Fs			2.99	3.18	8.53	8.08	9.71	8.65	5.91
En	.57	.74	1.06	1.62	5.87	7.85	7.07	7.07	7.78
Hy			2.20	2.80	3.98	2.52	3.37	3.50	5.65
mt									
hm	.34	.46							
il	.26	.09	3.10	2.81	2.22	2.14	2.21	2.34	5.24
tn		1.20							
ru		.22							
ap	.19	.28	.65	.19	.31	.34	.34	.34	.73
C	.20								
cc	3.36	8.76	10.71	6.65					
H <sub>2</sub> O					1.15	.23	1.29	1.52	1.22
TOTAL	97.59	100.49	99.68	97.85	98.96	98.69	100.52	100.53	100.16

<p><u>This Study</u></p> <p>D-1 Diabase: adjacent to trondhjemite (TA)</p> <p>D-2 Diabase: sample taken 47 meters S30W of D-1 (same height above base of sill as D-1)</p> <p>TA Trondhjemite: north end of xenolith</p> <p>TB Trondhjemite: south end of xenolith</p> <p>XA Lockatong xenolith (north end of outcrop)</p> <p>XB Lockatong xenolith (south end of outcrop)</p>	<p><u>From Walker (1969a)</u> (Specimens from Englewood Cliff Section):</p> <p>W-R-60 365 feet above the base of sill.</p> <p>W-N-60 560 feet above the base of sill.</p> <p>W-J-60 685 feet above the base of sill.</p> <p>a LOI for specimens XA, XB, TA and TB was considered as CO<sub>2</sub>; for D-1 and D-2, H<sub>2</sub>O; for W-R-60 to W-J-60 this is H<sub>2</sub>O<sup>+</sup> + H<sub>2</sub>O<sup>-</sup> combined as given by Walker (1969a).</p> <p>b, c determined only for tholeiitic magmatic rocks.</p>
---	---

drill-core data, showed that Lockatong argillite overlies and underlies the Palisades sill in this area.

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 (Fig. 2). 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.<sup>2</sup>

<sup>2</sup> 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<sub>99</sub> as the dominant feldspar is classified as a trondhjemite.

### Mineralogy and petrography

The diabase-trondhjemite interface and the trondhjemite-hornfels interface are sharp and irregular (Figs. 2 and 3). 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

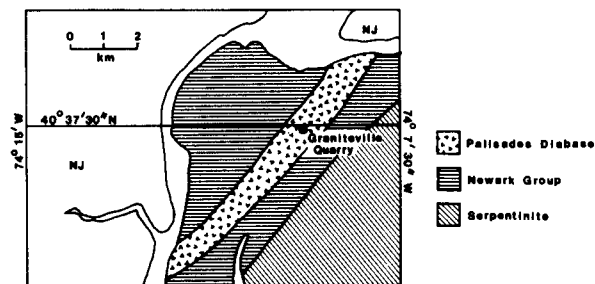


Fig. 1. Geological map of the northwestern part of Staten Island, N. Y. (modified from Fisher et al., 1970).

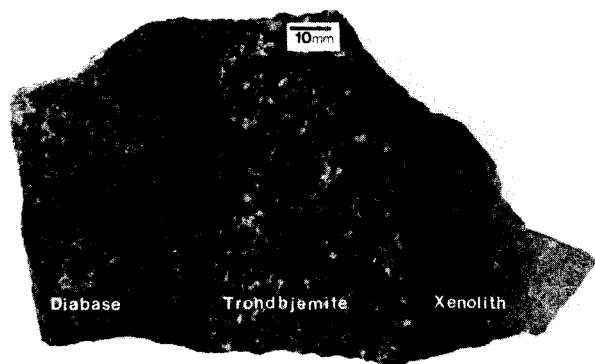


Fig. 2. Photograph of sawed surface of diabase, trondhjemite, and Lockatong xenolith. Note the sharp boundaries and absence of chilled contacts. Relic sedimentary bedding is present in the hornfels.

the Bence-Albee interactive routine. Natural and synthetic standards were utilized. The bulk chemical composition of whole-rock samples was obtained by X-ray fluorescence analysis; FeO was determined by wet chemical analysis.



Fig. 3. Photograph showing the sharp irregular boundary between the trondhjemite and the hornfels. Note that euhedral high-Ca clinopyroxene crystals are present in the trondhjemite. Although only cross-sections are shown in this figure, the clinopyroxene crystals range in length between 5 and 30 mm.

Table 2. Modal analyses (in volume %) of Palisades Diabase, Englewood Cliff section (from Walker, 1969a)

Specimen	Height*, ft.	Plag.	Pyroxenes	Opagues	Micropegmatite
W-889LC-60	1	39	1.5	5.0	
W-865-60	30	46	54.0	2.5	1.5
W-824-60	70	30	38.0	2.0	
W-804-60	90	43	51.0	1.5	2.5
W-U-60	215	49	47.0	1.3	1.4
W-R-60	365	59	33.0	2.0	3.0
W-N-60	560	66	24.5	3.0	3.8
W-J-60	685	47	34.3	5.0	10.0
W-E-60	805	35	23.0	6.2	23.0
W-F-60	790	40	tr.	3.0	24.5

Micrometric Analysis of Diabase, Graniteville Quarry, Staten Island, N.Y. (this paper)

D-1	500 ± 50	60.7	32.6	4.2	2.5
-----	----------	------	------	-----	-----

\*above the base of the sill.

### Diabase

The diabase is composed dominantly of plagioclase ( $An_{61}Ab_{38.8}Or_{0.2}$ ) and augite ( $En_{34.44}Fs_{17.31}Wo_{35.42}$ ) (see mode in Table 2). The augite contains exsolution lamellae of pigeonite on (001), and typically exhibits simple contact twinning on (100). A granophyric intergrowth of quartz and K-feldspar is present in minor amounts. Grains of titanomagnetite with oxidation lamellae of ilmenite and discrete grains of ilmenite are common. In view of the occurrence of oxidation lamellae of ilmenite in the titanomagnetite, no attempt was made to use the Buddington and Lindsley (1964) relationship to obtain an  $f_{O_2}$  and temperature of crystallization. However, an independent approach to determining the temperature of the diabase magma will be discussed below.

### Trondhjemite

The trondhjemite is composed dominantly of quartz-albite granophyre in which are enclosed 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.

### Pyroxene

Chemical variation among the pyroxenes is illustrated in Figure 4. 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; 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-

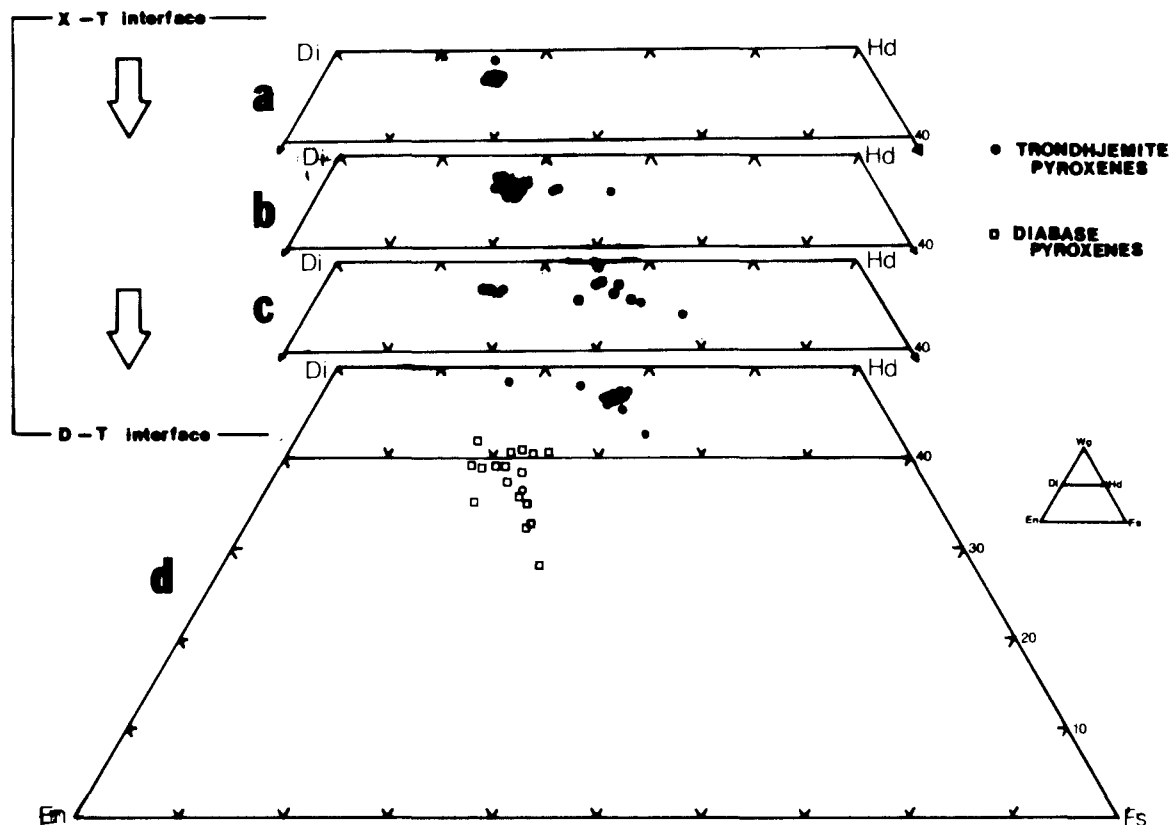


Fig. 4. Composition of pyroxenes in trondhjemite and in adjacent diabase. (a) 30–35 mm from the diabase–trondhjemite interface; (b) 19–20 mm from the diabase–trondhjemite interface; (c) 14–16 mm from the diabase–trondhjemite interface; (d) 3–12 mm from the diabase–trondhjemite interface.

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.

#### Minor minerals

The carbonate phase illustrated in Figure 5 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



Fig. 5. Photomicrograph showing the relationship of interstitial calcite ( $CO_3$ ), quartz (Q), albite (Ab), and high-Ca pyroxene (CPX) in the trondhjemite. Transmitted polarized light. Crossed nicols, scale bar = 250  $\mu m$ .



Fig. 6. Photomicrograph of euhedral sphalerite embedded in albite of the granophyre in the trondhjemite. Note the zoning in the sphalerite. Transmitted polarized light. Crossed nicols, scale bar = 50  $\mu\text{m}$ .

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.

Sphalerite is present as euhedral crystals embedded selectively in the albite of the granophyre. As seen in thin section (Fig. 6), 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.

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-quartz granophyre, and interstitial calcite. The crystallization sequence of the major phases (albite, quartz, and pyroxene) is in accord with the most pertinent ternary phase diagram of this system (diopside–nepheline–quartz) as determined by Schairer and Yoder (1960) (see dark region

of Fig. 7). 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, diopside 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 at one atmosphere (Schairer and Bowen, 1956). The composition of this eutectic is 31.5 quartz, 68.5 albite which is close to the normative quartz and albite content of part of the parental hornfels of the trondhjemite.

#### The xenolith

Petrographic examination shows that the xenolith is now a hornfels and exhibits a granoblastic texture (Fig. 8). The hornfels is composed dominantly of albite and quartz and subordinantly of calcite, titanite, apatite, ilmenite, and actinolite. The modal mineral percentages are albite 66, quartz 30, titanite 2.3, calcite 0.9, apatite 0.5, and actinolite 0.3. The bulk composition of the xenolith is variable, as shown in Table 1, which is not unexpected for a 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 Group of sedimentary rocks which is associated with the Palisades

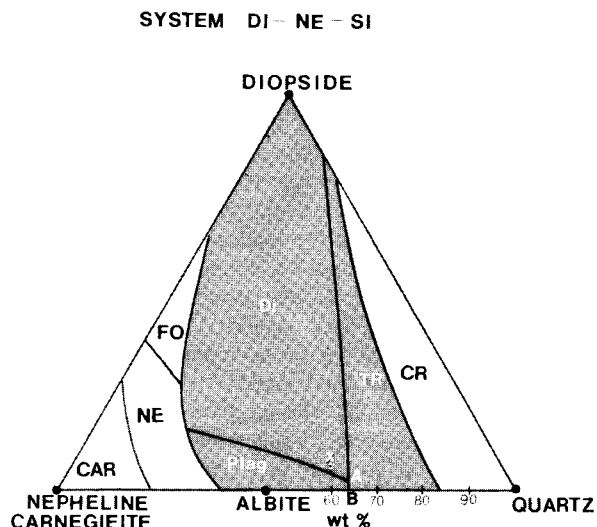


Fig. 7. The system diopside-nepheline-silica (Schairer and Yoder 1960). The deduced composition of trondhjemite magma is shown by x which lies at a temperature of approximately 1150°C. The crystallization sequence of major phases is: diopside, followed by diopside and albite, and lastly by quartz-albite granophyre. A is at 1073°C. B represents the dry minimum melting temperature (1062°C) in the quartz-albite system. The composition at B, is 68.5 albite and 31.5 quartz (in wt.%).

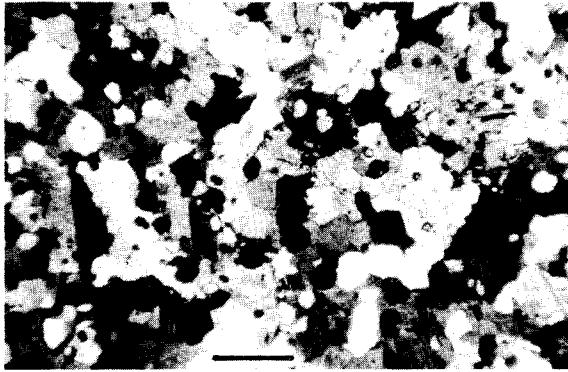


Fig. 8. Photomicrograph showing the granoblastic texture of the xenolith. Transmitted polarized light. Crossed nicols, scale bar = 250  $\mu\text{m}$ .

Sill. This group of rocks has been divided into the Stockton, Lockatong, and Brunswick formations (Van Houten, 1964, 1965, 1969). 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 of Schairer and Bowen (1956), the temperature of the diabase magma surrounding the hornfelsed xenolith must have been about 1160°C in order to have effected melting of a xenolith of the bulk composition shown in Table 1. Hess (1956) 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  $[(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)]$  in natural rocks. The iron-enrichment index of the chilled-zone of the Palisades diabase (Walker, 1969a) is 0.58 which correlates with a liquidus temperature of 1220°C. The iron-enrichment index of specimen D-2 is 0.67 which correlates with a liquidus temperature of approximately 1160°C. We have examined hornfelsed xenoliths of Lockatong argillite at the base of the Palisades Sill in New Jersey, but these xenoliths do not show any evidence of fusion. Sosman and Merwin (1913) found that arkosic xenoliths in the Palisades Sill in New Jersey did not show evidence of fusion, although this material was shown experimentally to be partly fused at a temperature of 1150°C dry. It appears that in some instances hornfelsed xenoliths which should have fused at the temperature to which they were subjected did not fuse, perhaps because of the relatively high rate of cooling which might be expected to prevail near the basal contact of the sill.

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

Several lines of evidence suggest that the location of this xenolith is approximately  $525 \pm 50$  feet above the base of the sill. Normalizing the diabase surrounding the xenolith to the Englewood Cliff section of Walker (1969a) shows that: (1) modal analysis of D-1 (Table 2) lies between W-N-60 and W-R-60 of Walker, thus placing upper and lower constraints of 560 feet and 365 feet above the base of the sill for the xenolith; (2) the composition of augite and plagioclase in D-1 is in accord with the above constraints and indicates the middle differentiation series of Walker; (3) the mafic fractionation indices  $[(\text{FeO} + \text{Fe}_2\text{O}_3)/(100\%)/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)]$  of W-N-60 and D-2 are respectively 66.55 and 66.92 (see footnotes, Table 1), and (4) D-2 plots directly on the differentiation trend for the Palisades Sill (Fig. 9). 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.

There are differences between the bulk chemical composition of the trondhjemite and that of the Lockatong hornfels (see Table 1), which are due to the paucity of the ferromagnesian component in the Lockatong hornfels.

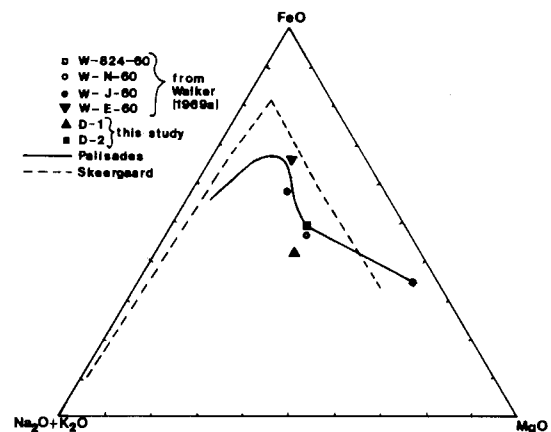


Fig. 9.  $(\text{Na}_2\text{O} + \text{K}_2\text{O})\text{-FeO-MgO}$  diagram which shows the composition of Palisades diabase specimens D-1 and D-2 from this study and the diabase from the Englewood Cliffs section of Walker (1969a). D-2 falls directly on the Palisades diabase differentiation trend of Walker (1969a). D-1 shows Fe-depletion and alkali enrichment. FeO represents total Fe expressed as FeO.

This suggests that  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$ , and perhaps some  $\text{Ca}^{2+}$  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 9, D-1 and D-2 differ in that D-1 is relatively enriched in sodium and relatively depleted in iron. This indicates that  $\text{Na}^+$  ions diffused out of the trondhjemitic liquid and into the diabase magma, whereas  $\text{Fe}^{2+}$  ions diffused from the diabase magma into the trondhjemitic 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.

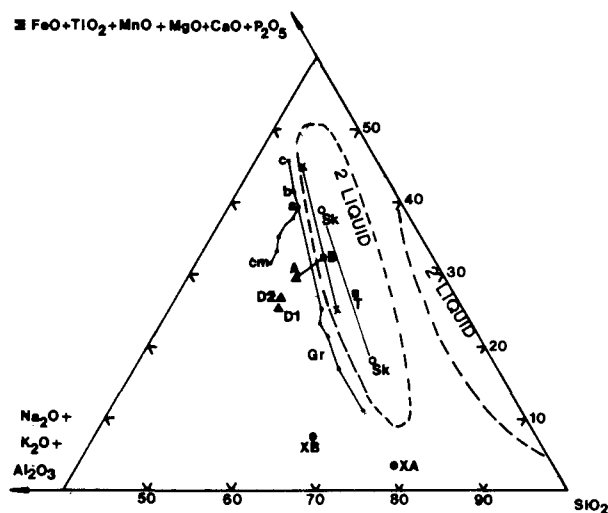


Fig. 10. Diabase, trondhjemite, and xenolith compositions plotted on the pseudoternary diagram  $(\text{SiO}_2) - (\text{K}_2\text{O} + \text{Na}_2\text{O} + \text{Al}_2\text{O}_3) - (\text{FeO} + \text{TiO}_2 + \text{MnO} + \text{MgO} + \text{CaO} + \text{P}_2\text{O}_5)$ . The high temperature and low-temperature immiscibility fields are marked by dashed lines (system fayalite-leucite-silica after Roedder, 1951). Also plotted are the compositions of (1) Rattlesnake Basalt (A) and its mesostasis (B) (Philpotts, 1979); and (2) a pair of conjugate liquids (SK) produced experimentally from mixtures of late-stage Skaergaard rocks (McBirney, 1975). The calculated Skaergaard differentiation trend is shown for comparison (cm = chilled margin; a, b, and c represent the upper zone, Gr = melanocratic granophyres). Inasmuch as both TA and TB coincide, their compositions are represented as T. As expected, Walker's (1969a) W-N-60 coincides with D2. The x's represent immiscible liquids in the Rattlesnake Hill Basalt (Philpotts, 1979).

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  $\Delta\bar{H}_{\text{mix}}$  (enthalpy of mixing), is greater than the entropy of mixing term  $T\Delta\bar{S}_{\text{mix}}$  so that  $\Delta\bar{G}_{\text{mix}}$  in equation (1) is positive

$$\Delta\bar{G}_{\text{mix}} = \Delta\bar{H}_{\text{mix}} - T\Delta\bar{S}_{\text{mix}} \quad (1)$$

(Ryerson and Hess, 1978). An upward convexity in the  $G-X$  surface of the liquid is produced such that the  $\Delta G$  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  $\text{FeO} - (\text{Al}_2\text{O}_3 + \text{K}_2\text{O}) - \text{SiO}_2$  diagram (Watson, 1976) were plotted. 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,  $[\text{SiO}_2] - [\text{Na}_2\text{O} - \text{K}_2\text{O} - \text{Al}_2\text{O}_3] - [\text{FeO} + \text{TiO}_2 + \text{MnO} + \text{MgO} + \text{P}_2\text{O}_5]$  (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 (Fig. 10). Therefore, the diabase and the trondhjemite do not appear to be in an immiscible relationship.

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. Viscosity of the silicic liquid appears to be the factor responsible for the lack of mixing.

## Conclusions

Petrographical, mineralogical, and chemical data, plus field evidence indicate that coexisting silicic and mafic melts resulted when the margins of a xenolith of Lockatong argillite 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 suggests that  $\text{Fe}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  diffused from the diabasic magma into the fusion zone of the xenolith, and that  $\text{Na}^+$  diffused from the fusion zone of the xenolith into the diabasic magma. Evidently, these two chemically divergent magmas did not physically mix.

A dry magma of the composition of the trondhjemite would have a very high viscosity compared with the diabase magma. This high viscosity apparently prevented disruption of the liquid-liquid interface and thereby minimized physical mixing of the diabase and trondhjemite magmas. We plan further studies on the distribution of trace elements between the two magmas.

### Acknowledgments

We wish to thank A. R. Philpotts of the University of Connecticut for discussion of his experimental results on Connecticut Valley diabase. Analytical costs for this study were defrayed through a grant from the Department of Geological Sciences at Lehigh University.

### References

- Benimoff, A. I. and Sclar, C. B. (1978) Pyroxene trondhjemite derived by partial fusion of a xenolith of Lockatong argillite in the Palisades sill, Staten Island, N. Y. (abstr.) Geological Society of American Abstracts with Programs, 10, 33.
- Benimoff, A. I. and Sclar, C. B. (1980) Partial fusion of a xenolith of Lockatong argillite in the Palisades diabase, Graniteville quarry, Staten Island: The petrochemistry of coexisting silicic and basic magmas (abstr.) Geological Society of American Abstracts with Programs, 12, 24.
- Buddington, A. F. and Lindsley, D. H. (1964) Iron-titanium oxide minerals and their synthetic equivalents. *Journal of Petrology*, 5, 310-357.
- Campbell, R., Day, T. C. and Stenhouse, A. G. (1932) The Braefoot outer sill, Fife Part I. *Transactions Geological Society of Edinburgh*, 12, 342-375.
- Campbell, R., Day, T. C. and Stenhouse, A. G. (1934) The Braefoot outer sill, Fife Part II. *Transactions Geological Society of Edinburgh*, 13, 148-172.
- Cygan, G. L. and Koster Van Groos, A. F. (1978) Effects of  $\text{Na}_2\text{O}$  and  $\text{MgO}$  on the liquid immiscibility field in  $\text{K}_2\text{O}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$  (abstr.) *American Geophysical Union, (EOS)*, 59, 401.
- De, A. (1974) Silicate liquid immiscibility in the Deccan traps and its petrogenetic significance. *Geological Society of America Bulletin*, 85, 471-474.
- Fisher, D. W., Isachsen, Y. W. and Rickard, L. V. (1970) Geologic map of New York, Lower Hudson Sheet. New York State Museum and Science Service. Map Chart Series No. 15.
- Grieg, J. W. (1927) Immiscibility in Silicate Melts. *American Journal of Science*, 13, 1-44, 133-154.
- Hess, H. H. (1956) The magnetic properties and differentiation of dolerite sills—A critical discussion. *American Journal of Science*, 254, 446-451.
- Hess, P. C. (1977) Structure of silicate melts. *Canadian Mineralogist*, 15, 162-178.
- Holgate, N. (1954) The role of liquid immiscibility in igneous petrogenesis. *Journal of Geology*, 62, 439-480.
- Holgate, N. (1956) The role of liquid immiscibility in igneous petrogenesis: A reply. *Journal of Geology*, 64, 89-93.
- Holmes, A. (1936) Transfusion of quartz xenoliths in alkali basic and ultrabasic lavas, south-west Uganda. *Mineralogical Magazine*, 24, 408-421.
- Irvine, T. N. (1976) Metastable liquid immiscibility and  $\text{MgO}-\text{FeO}-\text{SiO}_2$  fractionation patterns in the system  $\text{Mg}_2\text{SiO}_4-\text{Fe}_2\text{SiO}_4-\text{CaAl}_2\text{Si}_2\text{O}_8-\text{KAlSi}_3\text{O}_8-\text{SiO}_2$ . *Carnegie Institution of Washington Yearbook*, 75, 597-611.
- Kennedy, W. Q. and Read, H. H. (1936) The differentiated dyke of Newmans, Dumfriesshire, and its contact and contamination phenomena. *Quarterly Journal Geological Society*, 92, 116-144.
- Koster Van Groos, A. F. and Wyllie, P. S. (1966) Liquid immiscibility in the system  $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{CO}_2$  at pressures to 1 kilobar. *American Journal of Science*, 264, 234-255.
- Lewis, J. V. (1907) The origin and relations of the Newark rocks. *New Jersey Geological Survey Annual Report*, 1906, 99-129.
- Lewis, J. V. (1908a) Petrography of the Newark igneous rocks of New Jersey. *New Jersey Geological Survey Annual Report*, 1907, 99-167.
- Lewis, J. V. (1908b) The Palisades diabase of New Jersey. *American Journal of Science*, 26, 155-162.
- McBirney, A. R. (1975) Differentiation of the Skaergaard Intrusion. *Nature*, 253, 691-694.
- McSween, H. Y., Coish, R. A. and Norman, M. D. (1979) Coexisting acidic and basic melts: Geochemistry of a composite dike - A discussion. *Journal of Geology*, 87, 211-216.
- Naslund, H. R. (1976) Liquid immiscibility in the system  $\text{KAlSi}_3\text{O}_8-\text{NaAl}_3\text{O}_8-\text{FeO}-\text{Fe}_2\text{O}_3-\text{SiO}_2$  and its application to natural magmas. *Carnegie Institution of Washington Yearbook*, 75, 592-597.
- O'Connor, J. T. (1965) A classification of quartz-rich igneous rocks based on feldspar ratios. U. S. Geological Survey Professional Paper 525B.
- Pearce, T. H. (1970) Chemical variation in the Palisades Sill. *Journal of Petrology*, 11, 24-32.
- Philpotts, A. R. (1976) Silicate liquid immiscibility: its probable extent and petrogenetic significance. *American Journal of Science*, 276, 1147-1177.
- Philpotts, A. R. (1978) Textural evidence for liquid immiscibility in tholeiites. *Mineralogical Magazine*, 42, 417-425.
- Philpotts, A. R. (1979) Silicate liquid immiscibility in tholeiitic basalts. *Journal of Petrology*, 20, 99-118.
- Reynolds, D. L. (1938) Transfusion phenomenon in lamprophyre dykes. *Geological Magazine*, 75, 51-75.
- Roedder, E. (1951) Low-temperature liquid immiscibility in the system  $\text{K}_2\text{O}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ . *American Mineralogist*, 36, 282-286.
- Roedder, E. (1956) The role of liquid immiscibility in igneous petrogenesis: A discussion. *Journal of Geology*, 64, 84-88.
- Roedder, E. (1978) Silicate liquid immiscibility in magmas and in the system  $\text{K}_2\text{O}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ : An example of serendipity. *Geochimica et Cosmochimica Acta*, 42, 1597-1617.
- Roedder, E. and Weiblen, P. (1970) Lunar petrology of silicate melt inclusions, Apollo 11 rocks. *Proceedings Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1*, 801-837.
- Roedder, E. and Weiblen, P. (1971) Petrology of silicate melt inclusions Apollo 11 and Apollo 12 and terrestrial equivalents. *Proceedings Second Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 3*, 251-279.

- Rutherford, M. J., Hess, P. C. and Daniel, G. H. (1974) Experimental liquid line of descent and liquid immiscibility for basalt 70017. Proceedings Fifth Lunar Science Conference Geochimica et Cosmochimica Acta, Supplement 5, 569–583.
- Ryerson, F. J. and Hess, P. C. (1978) Implications of liquid-liquid distribution coefficients to mineral-liquid partitioning. Geochimica et Cosmochimica Acta, 42, 921–932.
- Schairer, J. F. and Bowen, N. L. (1956) The System  $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ . American Journal of Science, 254, 129–195.
- Schairer, J. F. and Yoder, H. S., Jr. (1960) The nature of residual liquids from crystallization, with data on the system nepheline-diopside-silica. American Journal of Science, 258-A, 273–283.
- Sosman, R. B. and Merwin, H. E. (1913) Data on the intrusion temperature of the Palisades diabase. Journal of the Washington Academy of Science, 3, 389–395.
- Spry, A. (1969) Metamorphic Textures. Pergamon Press Ltd., New York.
- Streckeisen, A., et al., (1973) Classification and nomenclature of plutonic rocks. (IUGS Subcommittee on Igneous Rocks) Geotimes, 18, 26–30.
- Taylor, T. R., Vogel, T. A. and Wilband, J. T. (1979) The origin of coexisting granitic and basaltic liquids at Mt. Desert Island Maine (abstr.). American Geophysical Union (EOS), 60, 411.
- Tilley, C. E., Yoder, H. S. and Schairer, J. F. (1964) New relations on melting of basalts. Carnegie Institution of Washington Yearbook, 63, 92–97.
- Van Houten, F. B. (1964) Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation Central New Jersey and adjacent Pennsylvania. Pennsylvania Geological Survey Bulletin, 169, 497–531.
- Van Houten, F. B. (1965) Composition of Triassic Lockatong and associated Formations of Newark Group Central New Jersey and adjacent Pennsylvania. American Journal of Science, 263, 825–863.
- Van Houten, F. B. (1969) Late Triassic Newark Group, north-central New Jersey and adjacent Pennsylvania. In S. Subitsky, Ed., Geology of Selected Areas in New Jersey and Adjacent Pennsylvania, p. 314–347. Rutgers University Press, New Brunswick, New Jersey.
- Visser, W. and Koster Van Groos, A. F. (1978) Effects of  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$  on the miscibility gap in  $\text{K}_2\text{O}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$  (abstr.). Transactions, American Geophysical Union (EOS), 59, 401.
- Visser, W. and Koster Van Groos, A. F. (1979) Phase relations in the system  $\text{K}_2\text{O}-\text{FeO}-\text{Al}_2\text{O}_3-\text{SiO}_2$  at 1 atmosphere with special emphasis on low-temperature liquid immiscibility. American Journal of Science, 279, 70–91.
- Vogel, V. A. and Wilband, J. T. (1978) Coexisting acidic and basic melts: Geochemistry of a composite dike. Journal of Geology, 86, 353–371.
- Walker, F. (1940) The differentiation of the Palisades diabase, New Jersey. Geological Society of America Bulletin, 51, 1059–1106.
- Walker, K. R. (1969a) The Palisades Sill, New Jersey: A Reinvestigation. Geological Society of America Special Paper, 111.
- Walker, K. R. (1969b) A mineralogical, petrological and geochemical investigation of the Palisades Sill, New Jersey. Geological Society of America Memoir, 115, 175–187.
- Walker, K. R., Ware, N. G. and Lovering, J. F. (1973) Compositional variations in the pyroxenes of the differentiated Palisades Sill, New Jersey. Geological Society of America Bulletin, 84, 89–110.
- Watson, E. B. (1976) Two liquid partition coefficients. Experimental data and geochemical implications. Contributions to Mineralogy and Petrology, 56, 119–134.
- Wright, W. B. (1911) In Geology of Colonsay. Memoir Geological Survey of Scotland.
- Yoder, H. S. (1973) Contemporaneous basaltic and rhyolitic magmas. American Mineralogist, 58, 153–171.

*Manuscript received, October 14, 1983;  
accepted for publication, June 21, 1984.*