



**New Jersey Geological Survey
Open-File Report OFR 92-1**



**The Palisades Sill and Watchung Basalt Flows,
Northern New Jersey and Southeastern New York:
A Geological Summary and Field Guide**



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Cover illustration: Palisades diabase along the Hudson River. The prominent vertical columns which give the Palisades its name formed as the result of tension when the molten diabase of the Palisades cooled and contracted. The contact between the Jurassic diabase and upper Triassic (older) sedimentary rocks is at the base of the cliffs, largely covered by a talus slope of fallen diabase blocks and rubble.

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Northern New Jersey and Southeastern New York:
A Geological Summary and Field Guide**

by

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THE PALISADES SILL AND WATCHUNG BASALT FLOWS, NORTHERN NEW JERSEY AND SOUTHEASTERN NEW YORK: A GEOLOGICAL SUMMARY AND FIELD GUIDE

INTRODUCTION

The early Jurassic igneous rocks of the northern Newark Basin are best examined at the seven stops detailed below and shown in figure 1. The narrative preceding the road log and site descriptions will focus on three aspects of the Jurassic igneous activity that are the subject of considerable ongoing research. Part one-The Palisades Sill introduces evidence suggesting that the sill may consist of as many as three distinct magma types: 1) At least two pulses of an Eastern North America (ENA) quartz-normative high titanium tholeiite (HTQ), both of which underwent some crystal fractionation; 2) A subsequent pulse of an ENA quartz-normative low titanium tholeiite (LTQ); 3) A late injection of a localized olivine-rich tholeiite to form the (in)famous

olivine zone. Part two - A Fused Xenolith of Lockatong Argillite describes a pyroxene trondhjemite occurrence in the Palisades sill that is interpreted as resulting from the fusion of a xenolith, producing an anatectic melt that failed to mix with the surrounding diabase magma. Petrological evidence suggests that the liquidus temperature of the trondhjemite was 1160°C. Part three - The Watchung Basalts is a review and discussion of some new geochemical data suggesting that the Preakness Basalt is far more complex than previously thought. Some speculations regarding the remarkable chemical resemblance of the Orange Mountain Basalt (an ENA-HTQ type) with the High Atlas basalts of Morocco and the Lesotho basalts of South Africa also are discussed.

NARRATIVE

The Newark Supergroup of the Newark Basin (New York, New Jersey, and Pennsylvania) is divided by Olsen (1980) into nine formations (from bottom to top): Stockton Formation (maximum 1800 m); Lockatong Formation (maximum 1150 m); Passaic Formation (maximum 6000 m); Orange Mountain Basalt (maximum 200 m); Feltville Formation (maximum 600 m); Preakness Basalt (maximum 300+m); Towaco Formation (maximum 340 m); Hook Mountain Basalt (maximum 110 m); and Boonton Formation (maximum 500+ m).

The Newark Basin contains the thickest preserved section of the Newark Supergroup. The sedimentary rocks and volcanic flows of the basin dip 5°-25° to the northwest, typically dipping 15° throughout most of northeastern New Jersey. Red siltstones and tholeiitic basalts are the dominant constituents of the basin. Mesozoic sediment deposition probably began during middle Carnian (early Late Triassic) time while the uppermost exposed deposits are Sinemurian (middle Early Jurassic) in age (Cornet, 1977).

PART 1: THE PALISADES SILL

The Palisades sill intruded approximately 200 million years ago (Sutter, 1988; Dunning and Hodych, 1990). Although the Palisades is conformable along most of its exposed length in northern New Jersey, it is clearly discordant north of Nyack, New York (fig. 1) and also at the southwestern ends of the Rocky Hill diabase and Lambertville sill in west-central New Jersey (fig. 2). Both of the two southerly diabase bodies are very similar chemically to the northern New Jersey portion of the Palisades sill and are, on the basis of

structural, geophysical, and well data, believed to be southern extensions of a single Palisades intrusion (Darton, 1890; Lewis, 1907; Bascom and others, 1909; Van Houten, 1969; Sandberg and others, in press). Thus, the Palisades sill is exposed over a strike length of approximately 150 km from southeastern New York to eastern Pennsylvania.

In northern New Jersey, the sill has been interpreted by Walker (1969) as having involved two pulses of magma, but Shirley (1987) suggested there were four separate magma pulses, each causing distinct reversals of geochemical crystal fractionation trends. Farther north, Puffer and others (1982) showed the sill near Nyack, New York to have resulted from the intrusion of at least two separate magma pulses; Steiner and others (1991) have observed numerous internal contracts in the Nyack section. Thus, the Palisades sill has been considered by many workers to be a composite body. On the other hand, the magma involved in the multiple pulses always has been assumed to be of a single type, an ENA-HTQ or its equivalent (Walker, 1969; Puffer and others, 1982; Froelich and Gottfried, 1985; Shirley, 1987). Recent geochemical data from lateral extensions of the Palisades sill in the central Newark Basin (Husch, 1988; Husch and Roth, 1988), together with a re-examination of the sill's classic olivine zone (Husch, 1990), suggest that multiple ENA magma types are involved.

Central Newark Basin Occurrences of the Palisades Sill

Lateral extensions of the Palisades sill in the central Newark Basin of New Jersey and Pennsylvania occur as at least eight distinct sheet-like intrusive bodies (fig. 2). Seven of these intrusions for which recent geochemical

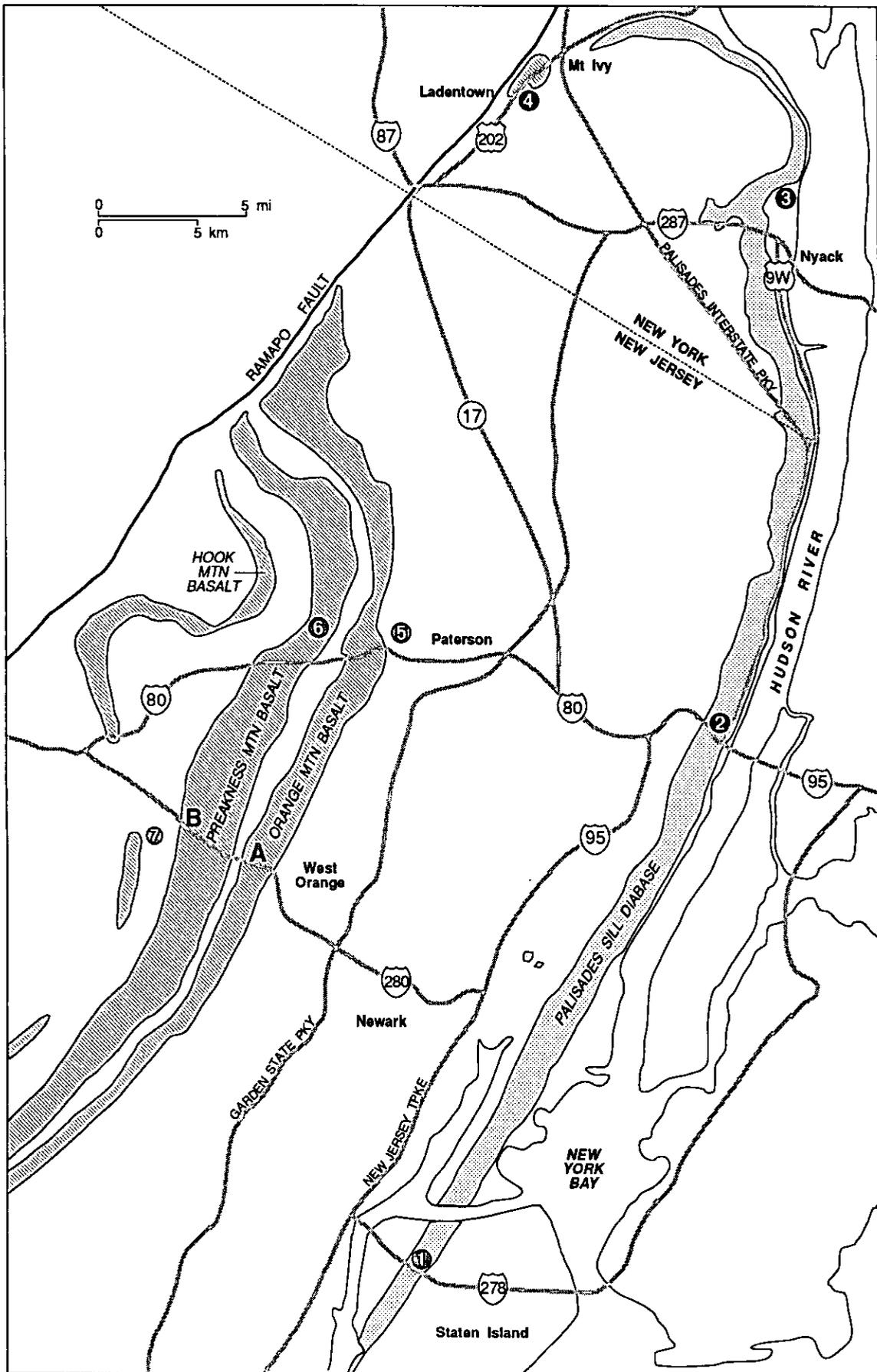


Figure 1. Map of the Jurassic igneous rocks of the northern Newark Basin. The seven field trip stop locations are shown. The type-sections of the Orange Mountain and Preakness Mountain Basalts are at A and B, respectively.

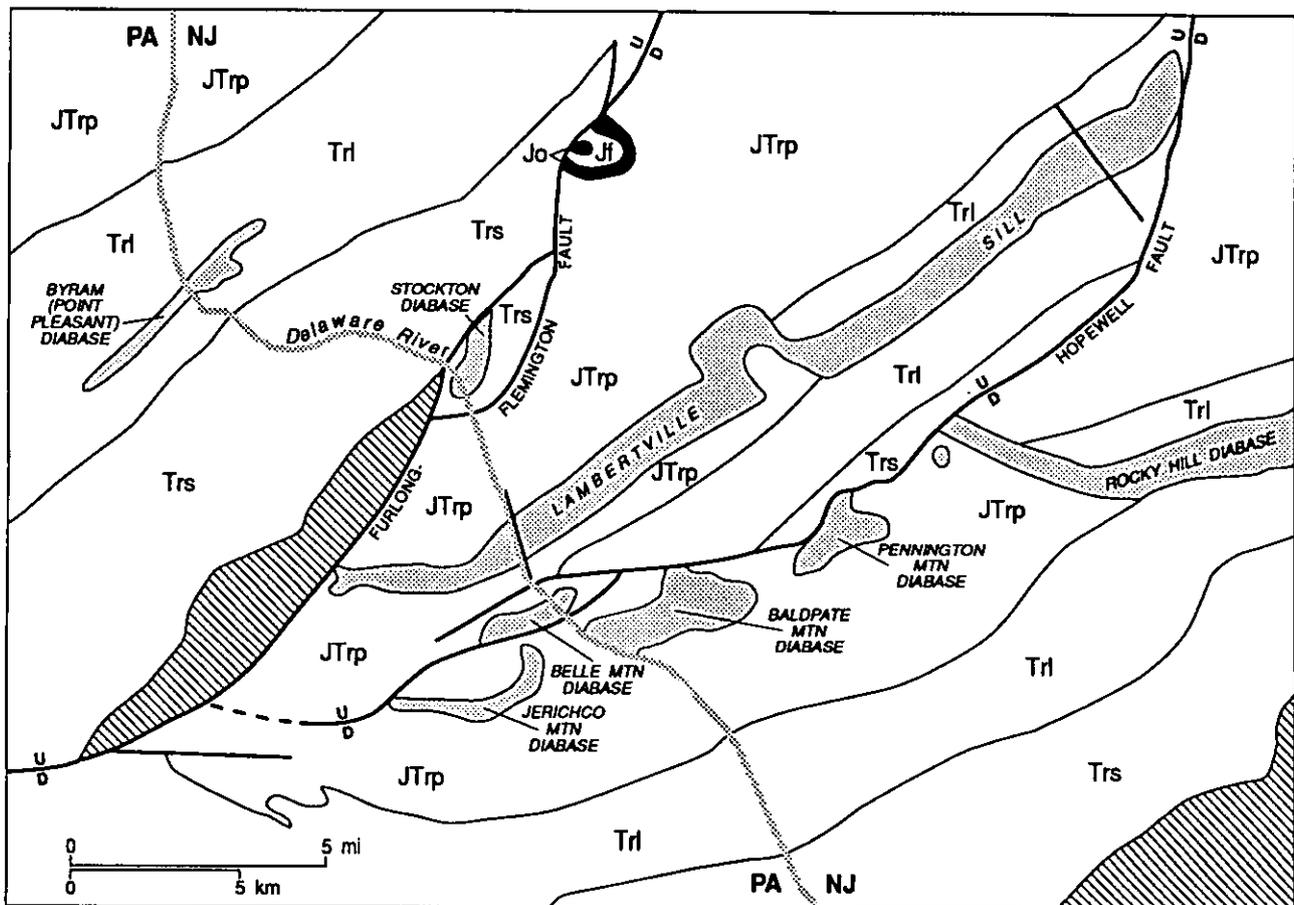


Figure 2. Geologic sketch map (after Lytle and Epstein, 1987) of the central Newark Basin. Shaded areas represent the intrusive diabase sheet(s), diagonally ruled regions represent pre-Triassic or post-Jurassic rock units, and black-filled areas represent Lower Jurassic Basalt flows. Two vertical sections through the Lambertville sill are located along solid black lines. Abbreviations used are: Trs, Stockton Fm.; Trl, Lockatong Fm.; JTrp, Passaic Fm.; Jf, Feltville Formation; Jo, Orange Mountain Basalt.

analyses are available are, from west to east, the Byram (Point Pleasant), Stockton, Lambertville (sill), Belle Mountain, Baldpate Mountain, Pennington Mountain, and Rocky Hill diabase bodies.

Selected major-element oxide and trace-element versus MgO diagrams are presented in figures 3A-H to illustrate important variation trends for diabases from the central Newark Basin portion of the Palisades sill. These trends, with very few exceptions, are extremely similar to those found for the Englewood Cliff (located near stop 2) and other sections of the sill in northern New Jersey (Walker, 1969). Whole-rock samples with MgO contents greater than 9 weight percent are not plotted in figures 3A-H. These samples are believed to be mafic enriched because of the accumulation of orthopyroxene and clinopyroxene.

In general, coarse-grained diabase compositions from the region are quite variable. However, all fine-grained chill margin samples exhibit an extremely restricted range of HTQ compositions (table 1) essentially identical to the chill margin composition for the Pali-

sades sill in northern New Jersey (stop 2; Walker, 1969). This is in contrast to the multiple ENA magma types represented by fine-grained samples from the Gettysburg, Hartford, and Culpeper Basins (Smith and others, 1975; Philpotts and Martello, 1986; Froelich and Gottfried, 1988). In addition, LTQ magmas now are recognized in the Preakness Basalt of the northern Newark Basin (Puffer, 1988; see Part 3).

Although no LTQ-related flows or chills are known from the central Newark Basin, there are four coarse-grained samples, collected in the middle of a stratigraphic section through the northeast end of the Lambertville sill, that do have whole-rock compositions with many LTQ-like characteristics (Husch and Roth, 1988). These include generally lower concentrations of Ba, Cr, Cu, Ni, Sr, Ti, and Zr and generally higher concentrations of Al, Ca, and Na than is typical for HTQ-related rocks with similar MgO contents (see fig. 3A-H). Because the LTQ-like rocks from the Lambertville sill are coarse grained, they may not represent actual magma compositions. However, the average

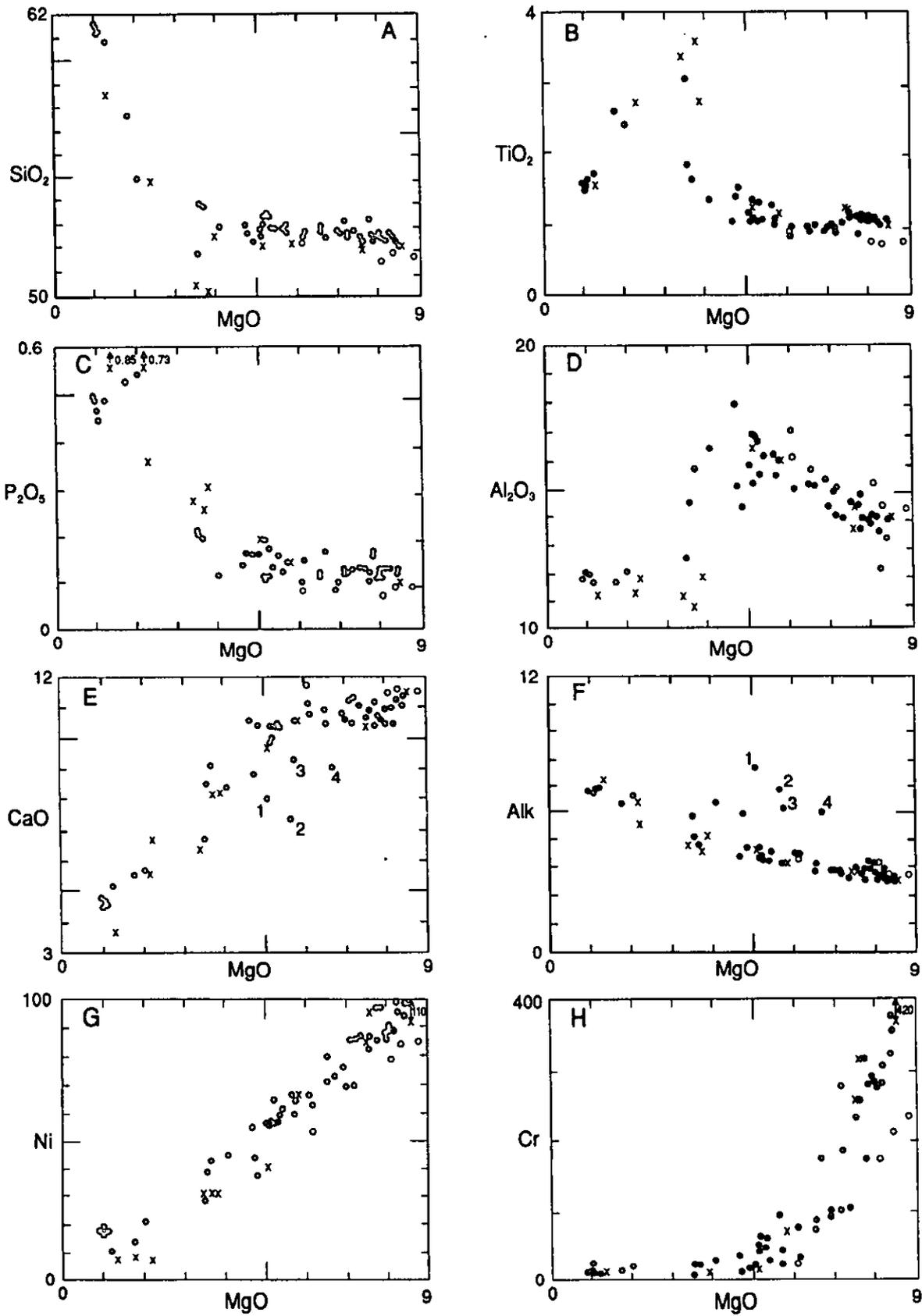


Figure 3. Selected whole-rock oxide and trace-element versus MgO variation trends for Mesozoic diabase from the central Newark Basin. HTQ-related samples are shown with filled circles; the four LTO-related samples are shown with open circles. For comparison, whole-rock samples (Walker, 1969) from the northern New Jersey portion of the Palisades sill (X) also are plotted. Oxide concentrations are given in weight percent and trace elements in parts per million. Alk is total alkali (Na₂O+K₂O). Contaminated samples with anomalously low calcium and high alkali contents are numbered 1 - 4 in E and F.

TABLE 1. Mesozoic Diabase Chill And Basalt Compositions

	1	2	3	4	5	6	7	8	9	10	
wt%	SiO ₂	52.88	52.52	52.47	52.57	53.18	52.55	51.61	51.86	52.69	52.65
	TiO ₂	1.13	1.11	1.17	1.15	1.13	1.22	1.09	1.07	1.11	1.13
	Al ₂ O ₃	14.26	14.22	14.69	14.16	13.73	14.64	14.34	14.27	14.57	14.37
	FeO _(tot.)	10.13	9.93	9.95	10.15	10.16	10.40	10.20	10.86	9.97	10.58
	MnO	0.16	0.16	0.18	0.17	0.19	0.16	0.15	0.16	0.20	0.19
	MgO	7.91	8.16	7.69	7.82	7.99	7.67	8.32	7.98	7.83	7.49
	CaO	10.26	11.02	10.93	10.66	10.48	10.44	11.41	11.24	10.90	10.78
	Na ₂ O	2.01	2.08	2.16	2.29	2.30	2.06	2.15	2.06	1.99	2.15
	K ₂ O	1.12	0.61	0.62	0.84	0.70	0.89	0.59	0.50	0.61	0.67
	P ₂ O ₅	0.13	0.14	0.14	0.18	0.14	0.14	0.13	0.12	0.12	--
ppm	Ba	156	147	154	149	166	195	182	174	160	--
	Cr	298	281	258	279	311	315	260	322	302	277
	Cu	99	105	107	113	122	110	127	123	121	111
	Ni	92	89	87	96	98	95	61	72	89	81
	Rb	37	16	15	33	32	--	37	22	25	21
	Sc	36	36	37	38	36	37	--	--	--	--
	Sr	189	169	208	229	170	175	183	186	187	186
	V	265	264	266	255	285	235	272	270	310	--
	Zr	101	94	104	102	102	120	116	87	115	92

Major elements normalized to 100 percent anhydrous.

DESCRIPTIONS OF SAMPLES

- 1.) Quarry dike chill (average of samples QD2, QD3, and QD14 of Husch and Schwimmer [1985]).
- 2.) Byram (Point Pleasant) diabase chill (sample PP2 of Husch and others [1984]).
- 3.) Lambertville Sill chill-Sourland Mountain region (sample LSR14 of Husch and Roth [1988]).
- 4.) Lambertville Sill chill-Delaware River area (average of samples EL55 and EL525 of Eliason [1986]).
- 5.) Baldpate Mountain chill (average of samples T4 and T5 of Trione [1985]).
- 6.) Palisades Sill chill (sample W-889LC-60 of Walker [1969]).
- 7.) Average Orange Mountain Basalt (Puffer and others, 1981).
- 8.) Average Talcott Basalt (Puffer and others, 1981).
- 9.) Average York Haven type basalt (Smith and others, 1975).
- 10.) Average HTQ diabase chill and basalt (Weigand and Ragland, 1970).

composition for the four samples shows marked similarity to various ENA-LTQ magma types and clear differences to typical ENA-HTQ and York Haven basalts (table 2). Although other coarse-grained rocks with relatively low Ti contents are found in the Lambertville sill and other sections through the Palisades sill (Shirley, 1987), many are mafic-rich and Ti-poor because of pyroxene accumulation in HTQ liquids. Although none of the low Ti samples analyzed by Shirley (1987) can be typed unequivocally as being derived from a LTQ magma, two samples from 327-329 m above the base of the sill near stop 2 (fig. 1) contain only 6.6 and 6.1 percent MgO, 78 and 90 ppm Cr, and 66 and 35 ppm Ni, respectively. Their respective TiO₂ contents of 0.9 and 0.8 percent contrast with the 1.1 to 1.9 percent TiO₂ content of the adjacent 18 samples within 20 m above or below them. Thus, it is possible that these two samples are derived from a LTQ magma. On the other hand, their rare-earth element (REE) distribution patterns (Shirley, 1987) are consistent with their being HTQ derived. Despite the uncertainty, the presence of LTQ-derived rocks in at least one section along the Palisades is indicated and, given the LTQ sample locations within the interior of the sill, a LTQ magma pulse must have been injected after the initial pulse(s) of HTQ magma found at all chill margins.

TABLE 2. LTQ and HTQ Magma Compositions

	1	2	3	4	5	6	
wt%	SiO ₂	51.93	51.32	51.51	51.27	52.69	52.65
	TiO ₂	0.81	0.83	0.76	0.75	1.11	1.13
	Al ₂ O ₃	15.08	14.94	14.91	16.79	14.57	14.27
	Fe ₂ O ₃	1.82	--	11.74	1.08	--	--
	FeO	7.75	11.12	--	9.15	9.97	10.58
	MnO	0.18	0.16	0.20	0.18	0.20	0.19
	MgO	7.81	8.08	7.42	6.89	7.83	7.49
	CaO	11.57	10.49	10.77	10.96	10.90	10.78
	Na ₂ O	2.43	2.52	2.22	1.98	1.99	2.15
	K ₂ O	0.52	0.36	0.48	0.40	0.61	0.67
	P ₂ O ₅	0.09	0.17	--	0.09	0.12	--
ppm	Ba	125	110	--	115	160	--
	Cr	186	250	218	205	302	277
	Cu	84	71	68	66	121	111
	Ni	75	56	48	63	89	81
	Rb	19	--	15	21	25	21
	Sc	36	--	--	--	--	--
	Sr	143	149	127	137	187	186
	V	269	225	--	--	310	--
	Zr	75	68	60	66	115	92

Major elements normalized to 100 percent anhydrous.

DESCRIPTIONS OF SAMPLES

- 1.) Average of four LTQ-like whole-rock compositions (samples LSR8, LSR9, LSR10, and LSR11 of Husch and Roth [1988]).
- 2.) LTQ-related third flow of Preakness basalt (Puffer, 1988).
- 3.) Average LTQ basalt (Weigand and Ragland, 1970).
- 4.) Average Rossville type basalt (Smith and others, 1975).
- 5.) Average York Haven type basalt (Smith and others, 1975).
- 6.) Average HTQ basalt (Weigand and Ragland, 1970).

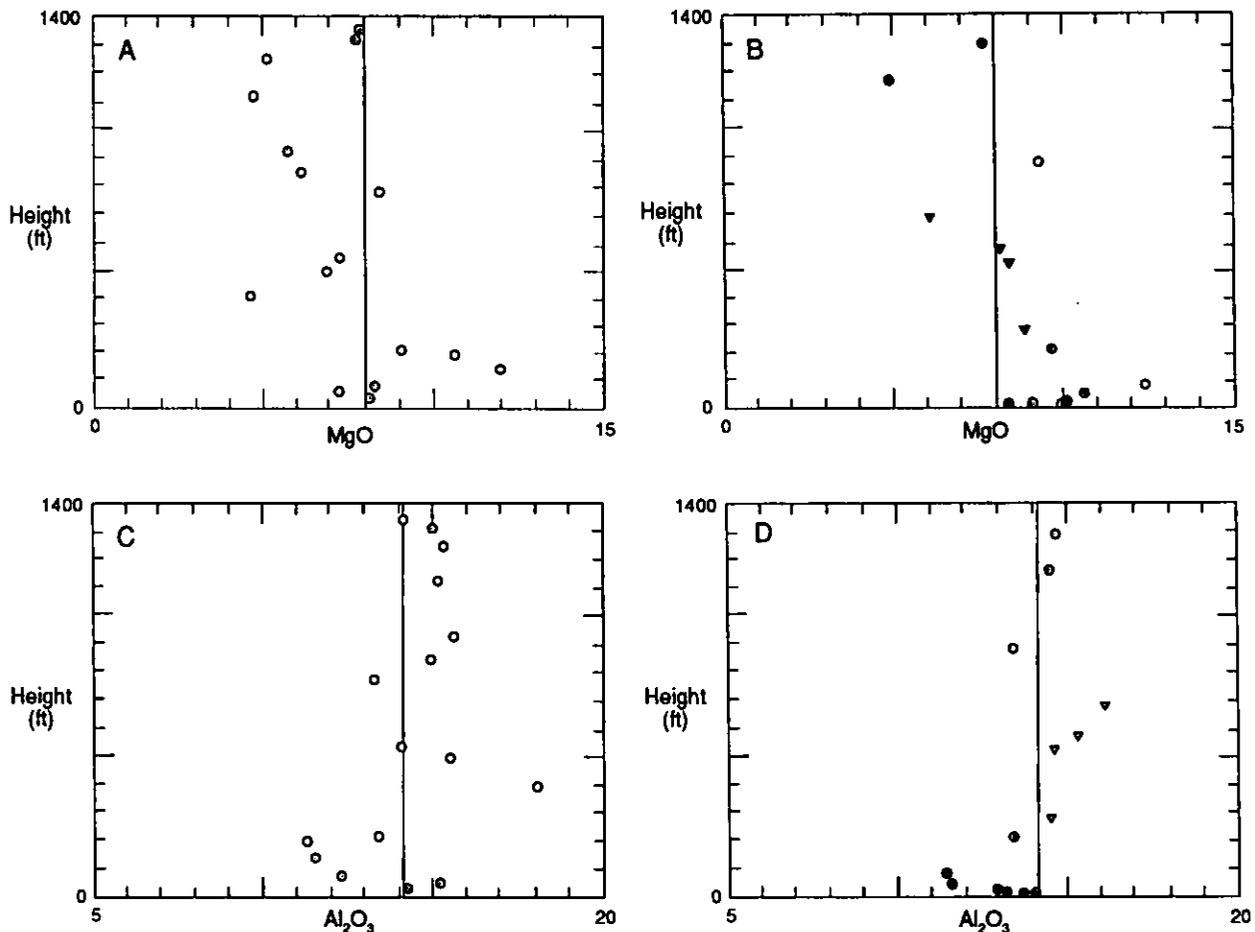


Figure 4. MgO and Al₂O₃ variations with height (in feet) through the Lambertville sill. A and C are for the southwest section and B and D are for the northeast section (see fig. 2). HTQ-related samples are shown with filled circles; the four LTQ-related samples from the northeast section are shown with inverted filled triangles. Vertical lines in all diagrams show chill margin values and provide a reference for estimating mass balance for the section.

Multiple HTQ Magma Pulses in the Central Newark Basin

In addition to the LTQ magma pulse, two sections through the Lambertville sill portion of the Palisades sill (fig. 2) contain whole-rock compositions that are consistent with the intrusion of at least two distinct pulses of HTQ magma (fig. 4A-D). MgO contents (fig. 4A-B), along with Ni and Cr abundances, rise initially from the lower chilled contact zone and peak in a lower pyroxene accumulation zone. They then fall as an overlying differentiated diabase zone is traversed (in the northeast section (fig. 4B) the LTQ zone is located at this level), rise again in a second, upper mafic-rich zone, fall again in a second, upper differentiated diabase zone, and rise a final time as the upper chilled contact zone is approached. Al₂O₃ (fig. 4C-D), acting incompatibly along with TiO₂, Na₂O, K₂O, P₂O₅, Ba, Cu, Rb, Sr, and Zr, exhibits a variation pattern which is a near mirror image of that found for MgO. Not surprisingly, pyroxene and plagioclase compositions are consistent with the available whole-rock data. Orthopyroxenes are most magnesian (~En₈₀) and plagioclases are most calcic (~An₇₀) in

both pyroxene-rich zones; orthopyroxenes are more iron-rich (~En₆₅) and plagioclases are more sodic (~An₅₅) in the two MgO-poor, differentiated zones.

The absolute timing of all pulses is not known. However, no internal chills have been observed in the central Newark basin region, suggesting the time between pulses was of short duration. Indeed, it is tempting to correlate the injection of the HTQ pulses in the central Newark Basin to the multiple magma injections documented for other sections of the Palisades sill located in northern New Jersey and adjacent New York (stops 2 and 3; Walker, 1969; Puffer and others, 1982; Shirley, 1987) and the multiple flows of the Orange Mountain Basalt (stop 5; Puffer, 1988; see Part 3). The LTQ pulse in the Lambertville sill section of the Palisades then would correlate with the extrusion of the younger Preakness Basalt, a LTQ flow (stop 6; Puffer, 1988; see Part 3). This would place an upward limit of approximately 250,000 years on the HTQ-LTQ multiple injection sequence (Olsen and Fedosh, 1988).

The Palisades Olivine Zone Revisited

Since the study of Walker (1969), the classic olivine accumulation zone located near the bottom of the Palisades sill in northern New Jersey (stop 2) usually has been considered to have formed by the *in situ* gravitational settling of olivine in a second, more fractionated HTQ magma than that found at the lower chill margin. However, various lines of evidence suggest that the zone may have been intruded into the partially crystallized lower portion of the sill as a separate olivine-rich magmatic pulse in which no extensive *in situ* olivine accumulation took place (Husch, 1990).

In the central Newark Basin portion of the Palisades sill, extensive olivine fractionation is not indicated by the variation trends presented in figures 3A-H, particularly those for SiO₂, CaO, and Ni. If olivine fractionated to any meaningful degree early in the crystallization sequence, residual liquid concentrations for SiO₂ and CaO would have increased while those for Ni would have decreased much more dramatically than observed. Although it is true that these compositional variations might be produced by fractionating a SiO₂- and CaO-rich and Ni-poor phase, such as plagioclase, along with olivine, the low abundances of modal olivine (even in high magnesium samples) and the complete lack of any olivine accumulation zones in the central Newark Basin portion of the sill or in the portion north and west of Nyack, New York (fig. 1) argue against the possibility. Also, the early incompatible behavior of Al₂O₃ (fig. 3D) and Sr and the absence of increasingly negative Eu anomalies with crystal fractionation in relatively high MgO rocks is not consistent with the early removal of plagioclase.

On the other hand, the early fractionation of high- and low-calcium pyroxenes is consistent with the observed petrography of the analyzed samples and with the more highly compatible behavior of Cr as compared to Ni; Cr pyroxene/basalt distribution coefficients are two to four times higher than those for Ni (Henderson, 1982). Furthermore, the slight early depletion of CaO (and Sc) and the lack of early SiO₂ enrichment agree with the early crystallization of both pyroxene phases. A CaO-MgO two-oxide mixing diagram (fig. 5) indicates that the early variation trend could have been produced by removing three times as much clinopyroxene as orthopyroxene from chill margin compositions, representing parental ENA-HTQ basalts. The pyroxene accumulated to form the mafic-rich samples (fig. 5) predominantly found near the base of the Palisades sill. Quantitative mass-balance models by Husch (1991) support these conclusions.

As shown in figure 3A-H, the close agreement between the variation trends for diabasic rocks from various sections of the Palisades sill suggests strongly that very similar differentiation processes were operating. The whole-rock geochemistry and the lack of olivine

accumulation zones anywhere but in the central portion of the sill in northern New Jersey (stop 2) and southeastern New York (stop 3) calls into question the necessity of having an extensive olivine fractionation event in order to produce very similar whole-rock compositions anywhere within the sill. This leads to the conclusion that the formation of the classic olivine zone of the Palisades sill was not central to the overall differentiation of the sill (Husch, 1990). Thus, whatever process formed the olivine zone did not play a direct role in the *in situ* geochemical evolution of the entire intrusion. The geochemical study of Pearce (1970) also showed that fractionation trends for the olivine-rich rocks of the Palisades sill were separate and distinct from those for the rest of the sill in the northern New Jersey area; other than in the olivine zone itself, fractionation was controlled dominantly by pyroxene and plagioclase (Husch, 1991).

The restricted lateral extent of the olivine zone within the Palisades sill (F. Walker, 1940; K. Walker, 1969), the zone's abrupt terminations, both upward and downward, the average high iron content of the olivine (Fo₆₅) and its small grain size (Walker, 1969), and the paucity of olivine in other coarse-grained rocks in the sill (Walker, 1969; Shirley, 1987) are consistent with this hypothesis. In fact, the Palisades sill is the only well-documented ENA-HTQ intrusion to contain a significant olivine zone; it is the exception rather than the rule!

The formation of the Palisades olivine zone may have been a separate event, resulting perhaps from the intrusion of a distinct olivine normative magma, possi-

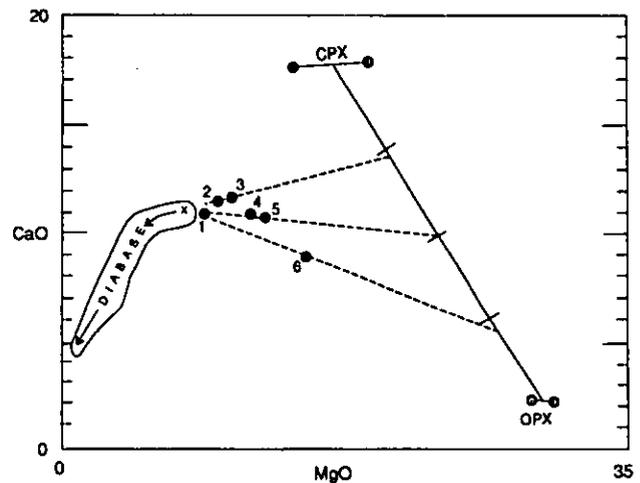


Figure 5. CaO versus MgO mixing diagram (in weight percent). Diabase field taken from figure 3E. Selected samples with greater than 9 weight percent MgO (number 1 - 6) are shown by filled circles. Three addition/removal lines with one end-member being the average regional HTQ chill margin composition (X) and the other end-member being a variable mixture of clinopyroxene (compositions from Walker [1969] and Philpotts and Reichenbach [1985]) and orthopyroxene (compositions from Smith [1973] and Philpotts and Reichenbach [1985]) are shown by the dashed lines. Arrows in diabase field show direction of variation due to crystal fractionation.

bly related to the high-lithophile element olivine normative (HLO; Ragland and Whittington, 1983) or Quarryville type (Smith and others, 1975) common farther south in the ENA magmatic province. However, based on the similar slopes for REE distribution patterns and constant Th/Hf values throughout the entire sill (Shirley, 1987), the olivine zone could represent the intrusion of a HTQ-related magma in which there had been a prior accumulation of olivine at depth (see Part 3).

Regardless of the exact petrogenetic relationship between the olivine zone magma and the multiple HTQ pulses of the Palisades sill, there appears to be little doubt that the olivine zone magma was emplaced after the initial pulse of HTQ magma found at the chills (Walker, 1969). The restriction of the olivine zone to the northern New Jersey portion of the Palisades sill (it has not been observed in the central and northernmost regions of the Basin) corresponds to where the sill intrudes near the bottom of the Triassic sedimentary section. This may be more than coincidental. An olivine-rich magma would be of relatively high density (~2.8 gm/cc) and would have a negative buoyancy as compared to the Triassic sedimentary rocks (~2.5 gm/cc), but an approximately neutral buoyancy relative to the underlying Precambrian basement rocks (Daly and others, 1966). As a result, the olivine zone magma would encounter a density barrier upon reaching the Triassic sedimentary section and, therefore, would tend to spread laterally at its base (the same may be true for the HTQ magmas). Thus, the density contrast between the olivine zone magma and the surrounding Triassic sedimentary rocks limits the formation of the olivine zone to where the Palisades sill is lowermost in the Triassic section (stop 2), and results in its absence where the sill is located structurally higher (north and west of stop 3). Similar density considerations might also explain why an olivine-rich magma has not been found in any of the Watchung flows (see Part 3).

Lateral compositional variations

As discussed by Husch and others (1988), most of the central Newark Basin intrusions do not appear to be in mass balance with their HTQ parental magma composition. Indeed, this appears to be a common feature of ENA-HTQ intrusions in general (Smith, 1973; Gottfried and Tollo, 1989). Thus, differentiated sheet-like intrusions with thick and extensive pyroxene accumulation zones, such as the Byram diabase and the Lambertville sill portions of the Palisades sill, lack large amounts of complementary residual, granophyric compositions, and those sections that do have significant volumes of granophyric rock, such as the Baldpate Mountain and Pennington Mountain diabbases, lack any significant amounts of pyroxene-rich compositions. However, when all section averages are combined, the regional average for the Palisades is in reasonably close agreement with the average chill margin (parental magma) composition.

The regional mass balance on the one hand, coupled with the lack of mass balance locally on the other, could have been produced by having residual liquids migrate laterally from where pyroxenes were accumulating. Because there is a consistent tendency for the more granophyre-rich portions of the Palisades sill to be located at higher stratigraphic levels than the mafic-rich portions (Puffer and others, 1982; Husch and others, 1988), the residual liquids appear to have migrated up-dip as well.

A possible mechanism for driving the lateral and upward migration of residual liquids is the apparent multiple injections of HTQ, LTQ, and olivine-rich magmas from below. As a new pulse intruded, space would be made for it by displacing or draining the relatively low density residual liquids of an earlier pulse to structurally higher and more distal (to the feeder dike) portions of the body. The areal extent of the Palisades sill may have been increasing with time as multiple magma injections and lateral differentiation continued.

Significant lateral variations in diabase composition and stratigraphic position also are common in other Mesozoic ENA basins where HTQ-derived, pyroxene-rich bodies often are located kilometers from their granophyric complements (Smith, 1973; Froelich and Gottfried, 1988; Gottfried and Tollo, 1989). Thus, the lateral and upward migration of residual liquids after pyroxene fractionation appears to be a common process in the petrogenesis of many Early Jurassic HTQ intrusive sheets from a number of separate basins. The classic view of these sills, particularly the Palisades, being differentiated by only vertically directed, olivine dominated fractionation mechanisms (see Carmichael and others, 1974; Hyndman, 1985) is not supported by the available geochemical, petrographic, and structural data. The Palisades sill also is a composite intrusion comprised of as many as three separate ENA magma types, two of which have extrusive equivalents (see Part 3).

PART 2: FUSED XENOLITH OF LOCKATONG ARGILLITE

At the Graniteville Quarry in Staten Island, N.Y. (stop 1), the margins of an argillaceous xenolith of Lockatong Formation enclosed in the diabase of the Palisades sill fused, cooled, and crystallized to yield a pyroxene trondhjemite melt (Benimoff and Sclar 1978, 1980, 1984, 1988). The sodium-rich, slab-like, and hornfelsed xenolith is 30 m long and 0.3-0.5 m thick; it strikes N30°E and has a vertical dip. Based on the relative densities of the xenolith (~2.6 gm/cc) and diabase magma (~2.7 gm/cc), it appears that the xenolith was derived from Lockatong Formation located below the sill. Completely surrounding the xenolith and in contact with the enveloping diabase is the coarse-grained pyroxene trondhjemite. The chemical compositions and CIPW norms of the three contiguous rocks are given in table 3.

Mineralogy and Geochemistry

The Palisades diabase at stop 1 (fig. 1) 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 parallel to (001). A late-stage granophyric intergrowth of K-feldspar and quartz is present in minor amounts. Opaque minerals are titanomagnetite and ilmenite.

Several lines of evidence suggest that the location of the xenolith is approximately 525 ft. (175 m) above the base of the 1000 ft. (300 m)-thick sill. Firstly, the mafic fractionation index ($[FeO+Fe_2O_3]/[MgO+FeO+Fe_2O_3]$) of Graniteville Quarry diabase sample D-2 corresponds closely to sample W-N-60 from the Englewood Cliff section of Walker (1969); their values are 66.5 and 66.92, respectively (fig. 6). Furthermore, D-2 plots directly on the AFM trend for the Palisades sill, closer to W-N-60 than to any other sample from the Englewood Cliff series. In addition, modal values of quarry sample D-1 are intermediate between samples W-N-60 and W-R-60 (Walker, 1969), placing upper and lower constraints of 560 ft and 365 ft, respectively, above the base of the sill for the xenolith. Finally, the compositions of augite and plagioclase in quarry sample D-1 are consistent with Walker's middle differentiation series, in accord with these constraints.

The xenolith exhibits the typical granoblastic texture of a hornfels. The modal percentages of the xenolith are albite 66, quartz 30, titanite 2.3, calcite 0.9,

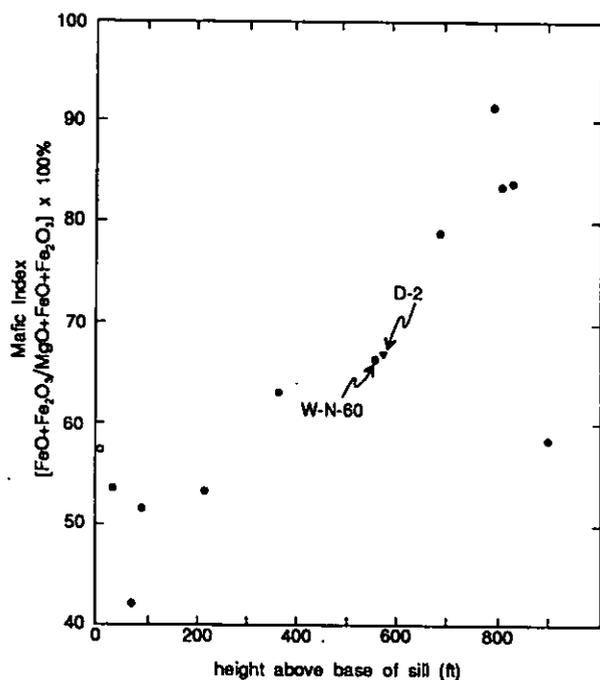


Figure 6. Plot of mafic index of Palisades diabase against height above the base of the sill. Note that Graniteville Quarry sample D-2 coincides with Palisades sill sample W-N-60 (Walker, 1969). From Benimoff and Sclar (1988).

apatite 0.5, and actinolite 0.3. Normative albite ranges from 56.4 to 80.2 weight percent. The protolith of the xenolith probably was a silty lacustrine sediment rich in sodium but low in potassium, characteristic of the chemical cycles found in the Lockatong Formation (Van Houten 1964, 1965, 1969, 1971).

The trondhjemite is composed dominantly of quartz-albite granophyre, which encloses large discrete crystals of albite ($Ab_{99}An_{0.52}Or_{0.44}$) and Ca-rich clinopyroxene ($En_{26.34}Fs_{14.37}Wo_{45.47}$), and subordinately of interstitial calcite, titanite, ilmenite, titanomagnetite, nickelian and cobaltian pyrrhotite, apatite, and sphalerite.

Sphalerite (ZnS) is present in the trondhjemite as microscopic euhedral crystals embedded selectively in the albite of the albite-quartz granophyre. The crystals are chemically zoned with iron-rich cores (13-16 mole % FeS) and iron-poor rims (0.2-2.0 mole % FeS). The source of the zinc and sulfur probably is the Lockatong sediment, but petrographic relationships show that the sphalerite in the trondhjemite is in equilibrium with the magmatic suite of minerals. Although sphalerite typically is interpreted as hydrothermal in origin, the great thermal stability of sphalerite (melting point $1500^{\circ}C$) allows for igneous crystallization. Desborough (1963) has reported other examples of magmatic sphalerite.

Also present in the trondhjemite are microscopic grains of nickel- and cobalt-bearing pyrrhotite and microscopic euhedral apatite. Euhedral inclusions of apatite also occur in the large high-Ca clinopyroxene crystals of the trondhjemite.

Phase Equilibria Considerations

It is apparent from the spatial relationships and geochemical data that the xenolith margins fused as a result of being immersed in the diabase magma. Based on the dry albite- SiO_2 phase diagram (fig. 7) of Schairer and Bowen (1956), the temperature of the diabase magma surrounding the xenolith must have been at least $1062^{\circ}C$ in order to have partially melted a xenolith of the bulk composition shown in table 3.

Tilley and others (1964) correlated experimental determinations of liquidus temperatures of natural rocks with an iron-enrichment index $[FeO+Fe_2O_3]/[MgO+FeO+Fe_2O_3]$; fig. 8). The iron-enrichment index of the Palisades chill (Walker, 1969), representing undifferentiated parental magma, is 0.58, indicating a liquidus temperature of about $1200^{\circ}C$. The iron-enrichment index of sample D-2 is 0.67, indicating a liquidus temperature of approximately $1160^{\circ}C$ (fig. 8), in close agreement with the $1200^{\circ}C$ and $1062^{\circ}C$ limiting values. Thus, there was more than enough heat to melt the xenolith.

The dry one-atmosphere albite- SiO_2 phase-equilibrium diagram (fig. 7) also may be used to demonstrate

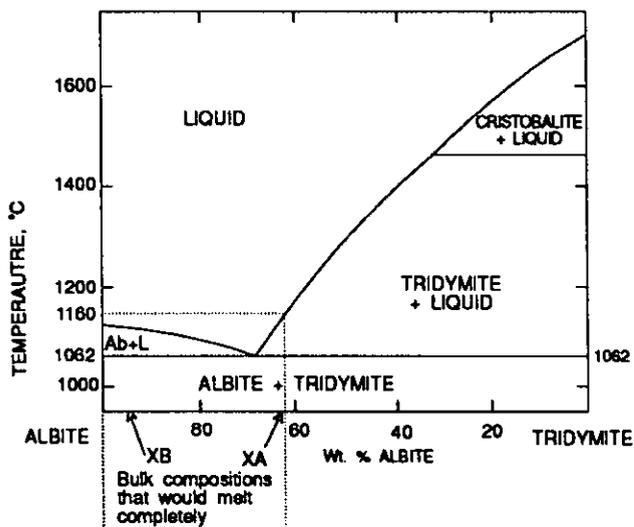


Figure 7. The dry one-atmosphere albite-SiO₂ system (Schairer and Bowen, 1956). Compositions within the dashed lines would be completely molten at 1160°C. From Benimoff and Sclar (1988).

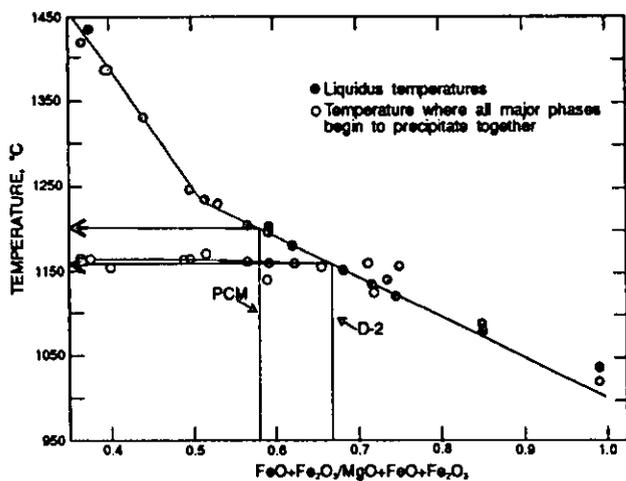


Figure 8. Plot of temperature versus iron enrichment (after Tilley and others, 1964) showing that Graniteville Quarry sample D2 correlates with a liquidus temperature of 1160°C and that the Palisades chill margin (PCM; Walker, 1969) correlates with a liquidus temperature of 1200°C. From Benimoff and Sclar (1988).

TABLE 3. Chemical Analyses and CIPW Norms of Graniteville Rocks

Chemical Analyses						
	XA	XB	TA	TB	D-1	D-2
SiO ₂	74.8	63.5	58.4	58.2	51.8	52.0
Al ₂ O ₃	11.6	16.1	6.75	6.91	16.8	16.7
TiO ₂	.61	.75	1.63	1.48	1.17	1.13
MgO	.23	.30	4.89	5.14	4.91	4.74
FeO	.10	<.1	4.35	5.60	6.70	7.85
Fe ₂ O ₃	.31	.47	1.51	1.93	2.75	1.74
MnO	.02	.04	.14	.16	.16	.19
CaO	2.07	5.60	13.1	11.5	8.79	10.2
Na ₂ O	6.67	9.48	3.76	3.81	3.22	2.58
K ₂ O	.07	.12	.12	.14	1.4	.76
P ₂ O ₅	.09	.13	.30	.09	.14	.15
LOI	1.48	3.85	4.71	2.88	1.15	.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	7.00	19.32	16.27	1.42	4.63
Or	.39	.72	.84	8.29	4.51	3.23
Ab	56.40	80.24	31.83	32.25	27.27	21.82
An			1.17	1.34	27.24	31.74
Wo			13.49	15.46	6.48	7.49
En	.57	.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			2.20	2.80	3.98	2.52
hm	.34	.46				
il	.26	.09	3.10	2.81	2.22	2.14
tn		1.20				
ru		.22				
ap	.19	.28	.65	.19	.31	.34
C	.20					
cc	3.36	8.76	10.71	6.65		
H ₂ O					1.15	.23
TOTAL	97.59	100.49	99.68	97.85	98.96	98.69

D-1 Diabase: Adjacent to trondhjemite (TA)
D-2 Diabase: Sample taken 47 meters S 30 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

that xenoliths with compositions ranging from 62% to 100% normative albite would melt completely if immersed in a diabase magma with a temperature of 1160°C. Both analyzed xenolith samples, XA (56.4% normative albite) and XB (80.2% normative albite), fall within these limits. In addition, the normative composition of trondhjemite sample TB is nearly identical to the eutectic value in figure 7. This is not surprising, given the proposed anatectic origin of the trondhjemite.

The crystallization sequence of the trondhjemitic magma can be obtained by utilizing the phase diagram of Schairer and Yoder (1960) for the system diopside-nepheline-silica (fig. 9). The composition of the trondhjemitic magma is shown by the X in figure 9. The liquidus temperature at this point is approximately 1150°C. If crystallization commenced at this point, diopsidic clinopyroxene would be the first major phase to crystallize. Upon cooling, when the diopside-plagioclase cotectic boundary was reached, albite and diopside would crystallize. With further cooling, the diopside-plagioclase-SiO₂ eutectic would be reached at 1073°C and interstitial quartz-albite granophyre would crystallize. This sequence is in accord with the crystallization sequence deduced petrographically.

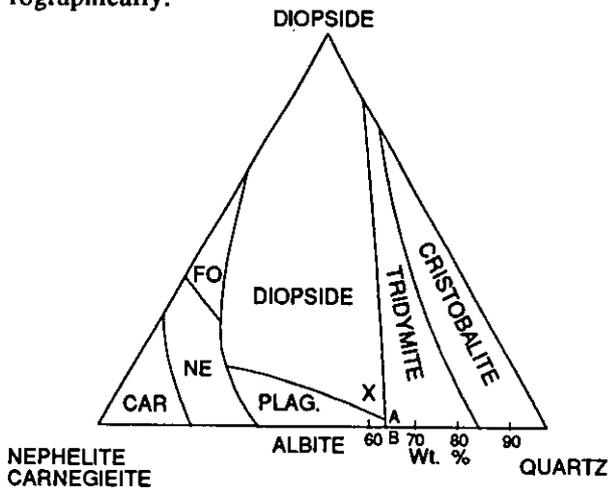


Figure 9. The system diopside-nepheline-silica (Schairer and Yoder, 1960). The deduced trondhjemite magma composition is shown (X) and has a liquidus temperature of approximately 1150°C. The crystallization sequence of major phases is: diopside, followed by diopside and albite, and lastly by quartz-albite granophyre. A is at 1073°C. B represents the dry minimum (eutectic) melting temperature (1062°C) in the quartz-albite system. The composition at B, is 68.5 albite and 31.5 quartz (in weight percent). From Benimoff and Sclar (1984).

Melt Relationships and Processes

Petrographic, mineralogic, chemical, phase equilibria, and field evidence indicate, therefore, that silicic (trondhjemitic) and mafic (diabasic) silicate magmas coexisted when the margins of the Lockatong Formation xenolith fused within the middle of the Palisades sill. However, there are large chemical differences between the trondhjemite and the xenolith (table 1). This indicates that Fe²⁺, Mg²⁺, and Ca²⁺ diffused from the dia-

base magma across the liquid-liquid interface into the trondhjemite magma, and upon crystallization, into the large euhedral high-Ca clinopyroxenes now present in the trondhjemite. Diffusion thus gave rise to a more complex chemistry for the trondhjemitic liquid than that which would have been obtained solely by simple fusion of the xenolith. As seen in figure 10, samples D-1 and D-2 differ chemically in that D-1 (adjacent to trondhjemite) is enriched in alkali and depleted in iron relative to D-2 (47 m from the trondhjemite). This is consistent with the diffusion of sodium ions out of the trondhjemitic liquid and into the diabase magma, whereas Fe²⁺ diffused from the diabase magma into the trondhjemitic liquid. This is shown schematically in figure 11. The diffusion paths of all the ions involved apparently followed concentration gradients. A similar diffusion mechanism has been proposed by Husch and Schwimmer (1985) and Husch (1991) to account for the geochemistry of a small diabase dike in eastern Pennsylvania and several whole-rock samples from the Palisades sill of the central Newark Basin. In these instances, contamination was marked by enrichments in alkalis (resulting in elevated Sr isotopic ratios) and a de-

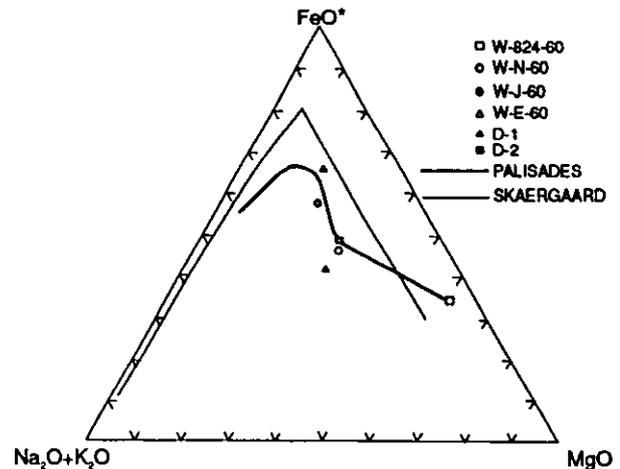


Figure 10. AFM ([Na₂O+K₂O]-FeO*-MgO) diagram showing the Palisades and Skaergaard fractionation trends. Selected Palisades samples from the Englewood Cliff section (Walker, 1969) are shown for comparison. Graniteville Quarry sample D-2 plots directly on the Palisades trend, whereas sample D-1 shows Fe depletion and alkali enrichment. From Benimoff and Sclar (1984).

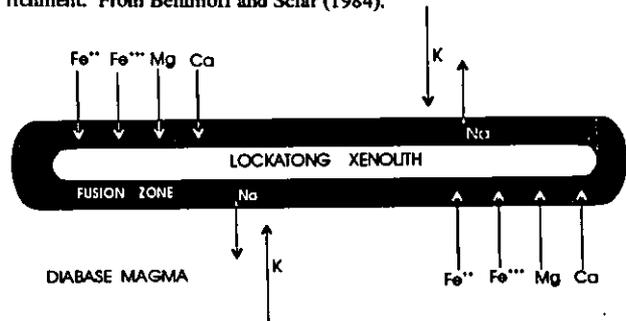


Figure 11. Schematic diagram of fused xenolith (not to scale) immersed in Palisades diabase magma showing proposed diffusion directions for several ions. From Benimoff and Sclar (1988).

pletion in Ca (see fig. 3E-F). All other elements show little or no contamination effects.

Although the simultaneous diffusion of ions across the liquid-liquid interface occurred in both directions, the coexisting diabase and trondhjemitic liquids did not physically mix. One possibility for this is that the magmas were in an immiscible relationship with one another. In order to test this hypothesis, their respective chemical compositions can be plotted on an FeO-[Al₂O₃+K₂O]-SiO₂ ternary diagram. Figure 12 shows that the trondhjemite and the diabase plot outside of the liquid-immiscible field proposed by Watson (1976). It also is evident from figure 12 that any attempt to draw conjugate tie lines between the diabase and trondhjemite compositions results in an orientation approximately perpendicular to tie lines connecting experimentally determined coexisting compositions across the liquid-immiscible field. In addition, in figure 13, the chemical compositions of the diabase, trondhjemite, and xenolith are plotted on the pseudoternary diagram SiO₂-[Na₂O+K₂O+Al₂O₃]-[FeO+TiO₂+MnO+MgO+CaO+P₂O₅] (Greig, 1927; McBirney, 1975; Roedder, 1978). Again, any tie lines drawn between the diabase and trondhjemite compositions would be perpendicular to the equilibrium tie lines in the field of liquid immiscibility. Therefore, it is concluded that the trondhjemite and diabase were not in a chemically immiscible relationship.

Why then, did the magmas fail to mix? It is well established for silicate melts that their viscosity is a strong function of their silica content (for example, see Hyndman (1985)). It is possible, therefore, that the relatively high silica content (58%) of the trondhjemitic liquid, as compared with that of the diabase magma (52%), resulted in a sufficiently high enough viscosity contrast to prevent the disruption of the liquid-liquid interface and thereby make it impossible for the physical mixing of the coexisting diabase and trondhjemitic magmas.

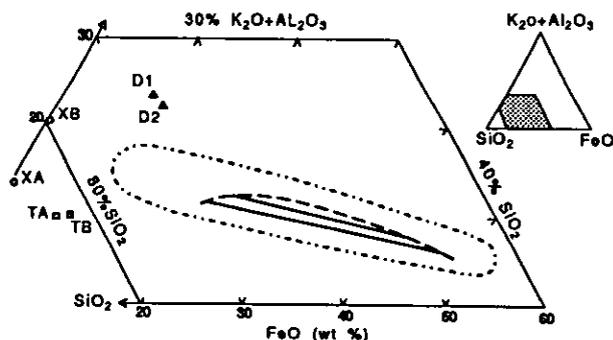


Figure 12. Diabase, xenolith, and trondhjemite compositions plotted in the system [K₂O+Al₂O₃]-SiO₂-FeO (Watson, 1976) showing that the diabase and trondhjemite are not in an immiscible relationship. The high-temperature and low-temperature immiscibility fields are marked by the dashed and dot-dashed curves, respectively.

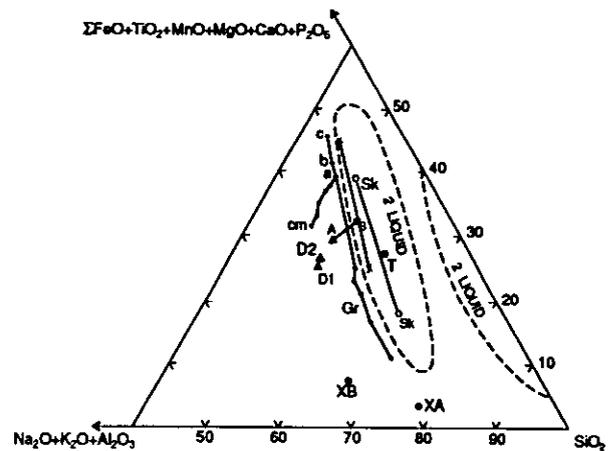


Figure 13. Diabase, trondhjemite, and xenolith compositions plotted on the pseudoternary diagram (SiO₂+K₂O+Na₂O+Al₂O₃)-(FeO+TiO₂-MnO+MgO+CaO+P₂O₅). The areas enclosed within the dashed curves are the fields of immiscibility (from system fayalite-leucite-silica after Roedder [1978]). Also plotted are the compositions of: 1) Rattlesnake Hill basalt (A) and its mesostasis (B) (Philpotts, 1979); 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). Since Graniteville Quarry samples TA and TB coincide in this diagram, their compositions are represented at T. Palisades sill sample W-N-60 (Walker, 1969) coincides with D-2. X's represent immiscible liquids in the Rattlesnake Hill basalt (Philpotts, 1979). From Benimoff and Sclar (1984; 1988).

PART 3: THE WATCHUNG BASALTS

Paleontological, stratigraphic, and geochemical evidence (Olsen and Fedosh, 1988; Puffer and others, 1981) indicate that the three Watchung Basalts extruded in rapid succession during the Hettangian age of the early Jurassic period. Olsen and Fedosh (1988) suggest that the time interval separating the Watchung Basalts, and the stratigraphically equivalent flows of the Hartford Basin, Connecticut, was only 550,000 years.

Most exposures of the Watchung Basalts display closely spaced columnar joints, but a few, particularly of the uppermost flow of the Orange Mountain Basalt, are pillowed. One of the best exposures of columnar jointing is found at the type section of the Watchung Basalts (Olsen, 1980) along Route 280, West Orange, New Jersey (fig. 1). The structural sequence is comparable to that of the chemically similar Giants Causeway of northern Ireland as described by Tomkeieff (1940), the Columbia River basalt flows (Long and Wood, 1986), and several other flows of the western United States (DeGraff and Aydin, 1987).

The basalt flows, together with the entire Newark Basin, have been subjected to some burial metamorphism. The vesicles of the basalt and the spaces between any pillows were partially filled with gypsum and glauberite, presumably precipitated by volcanic vapors and solutions released during the cooling of the basalt lava. The vesicles and vugs were filled further with carbonates and clay, as typically is the case with flows

subjected to prolonged groundwater alteration. Then, during zeolite facies burial metamorphism, the clay and carbonates were recrystallized into a complex assemblage of zeolites (including stilbite, heulandite, chabazite, pectolite, analcime, and datolite) and prehnite (Puffer and Laskovich, 1984; Laskovich and Puffer, 1989).

In addition, copper minerals probably were recrystallized, along with the mobilization of copper-bearing fluids, during zeolite facies mineralization. The base of the Orange Mountain Basalt coincides with over 20 copper deposits that were mined during the Civil War (Puffer, 1987).

Petrology and Geochemistry of the Orange Mountain Basalt

The Orange Mountain Basalt (stop 5) averages 183 m thick (Faust, 1975) and consists of three flow units. The upper flow unit characteristically is fine grained, pillowed, and amygdaloidal, whereas the lower two flows typically display well-developed columnar joints (lower colonnade and entablature).

The Orange Mountain Basalt is a quartz-normative tholeiite composed of plagioclase and augite with minor orthopyroxene and altered olivine in a glassy mesostasis containing quench dendrites of Fe-Ti oxides. Augite phenocrysts, glomeroporphyritic aggregates of augite, orthopyroxene, olivine, and a few plagioclase phenocrysts are characteristic of the basalt. Typical modes average 35 percent plagioclase (An₆₅), 35 percent pyroxene (augite (Wo₃₄En₅₅Fs₁₀), pigeonite, and minor

hypersthene), 28 percent glassy mesostasis, and 3 percent opaque Fe-Ti oxides. Accessory and trace minerals include apatite, biotite, alkali feldspar, and pyrite.

The Orange Mountain Basalt fits into the HTQ type of ENA tholeiites as proposed by Weigand and Ragland (1970). The chemistry of the basalt is rather uniform throughout (table 4; figure 15) and virtually is equivalent in all respects to samples of Palisades chill analyzed by Walker (1969), Shirley (1987), and Husch (1988). The REE content of the Orange Mountain Basalt plots close to and parallel with the REE-distribution pattern of the lower chill margin of the Palisades sill (fig. 16A).

The chemistry, mineralogy, and texture of the Orange Mountain Basalt also is equivalent to the first Early Jurassic basalts in the other basins of the Newark Supergroup, such as the Talcott Basalt of the Hartford Basin, Connecticut, and the Mount Zion Church Basalt of the Culpeper Basin, Virginia (Puffer and others, 1981; Puffer, 1984).

Petrology and Geochemistry of the Preakness Basalt

The Preakness Basalt (stop 6) consists of at least three flows locally separated by thin layers of red siltstone. The combined thickness of the Preakness flows averages 215 m (Olsen, 1980).

The very coarse-grained appearance of the first or lowermost flow of the Preakness, resembling a diabase, may be related to the unusual flow thickness that may have included intrusive pulses similar to those proposed by Philpotts and Burkett (1988). The lower flow is well

TABLE 4. Chemical Composition of Watchung Basalts (typical samples)

	Orange Mt. Basalt			Preakness Basalt			Hook Mt. Basalt		
	1st flow	2nd flow	3rd flow	1st flow	2nd flow	3rd flow	1st flow	2nd flow	
	012	06	09	P5b	P18	P6	H1	H9	
wt%	SiO ₂	51.44	51.88	51.31	51.65	51.20	50.83	49.89	49.51
	TiO ₂	1.19	1.09	1.12	1.05	1.21	0.83	1.44	1.40
	Al ₂ O ₃	14.75	14.70	14.31	14.19	15.30	15.65	13.26	13.94
	FeO	10.54	10.40	10.60	11.41	12.45	10.15	14.89	14.59
	MnO	0.16	0.15	0.17	0.19	0.21	0.17	0.19	0.21
	MgO	7.77	7.32	7.61	6.48	5.41	7.60	5.65	5.58
	CaO	10.61	9.75	10.15	9.48	9.55	10.31	9.88	10.23
	Na ₂ O	2.35	2.40	2.98	3.05	3.21	2.49	2.53	2.23
	K ₂ O	0.32	0.47	0.52	0.63	0.59	0.36	0.32	0.44
	P ₂ O ₅	0.11	0.12	0.12	0.12	0.12	0.08	0.14	0.17
	H ₂ O+	0.42	0.69	0.91	0.76	0.48	0.61	0.69	1.03
	TOTAL	99.66	98.97	99.60	99.01	99.73	99.08	98.88	99.33
ppm	Ba	162	165	153	142	135	88	110	119
	Co	37	39	39	38	39	38	43	49
	Cr	374	330	435	76	53	251	122	72
	Cu	120	205	137	78	80	70	167	183
	Ni	84	77	69	38	25	55	50	55
	Sr	206	191	194	136	151	141	118	128
	V	250	250	257	315	340	248	324	351
	Zn	72	82	82	84	95	72	115	129
	Zr	78	100	97	88	91	56	98	77
ppm	La	10.1	10.0	--	9	11	7.4	8.1	--
	Ce	22.5	22.0	--	19	26	15	19	--
	Nd	13.5	13.0	--	14	16	9	12	--
	Sm	3.8	4.0	--	2.8	3.0	2.5	2.9	--
	Eu	1.11	1.00	--	1.02	1.25	0.90	1.00	--
	Gd	3.6	3.5	--	3.25	3.8	4.0	4.0	--
	Dy	3.8	3.9	--	5.0	5.0	4.2	5.5	--
	Er	2.3	2.3	--	3.5	3.8	2.5	4.0	--
	Yb	2.3	2.35	--	3.1	3.2	2.2	3.1	--

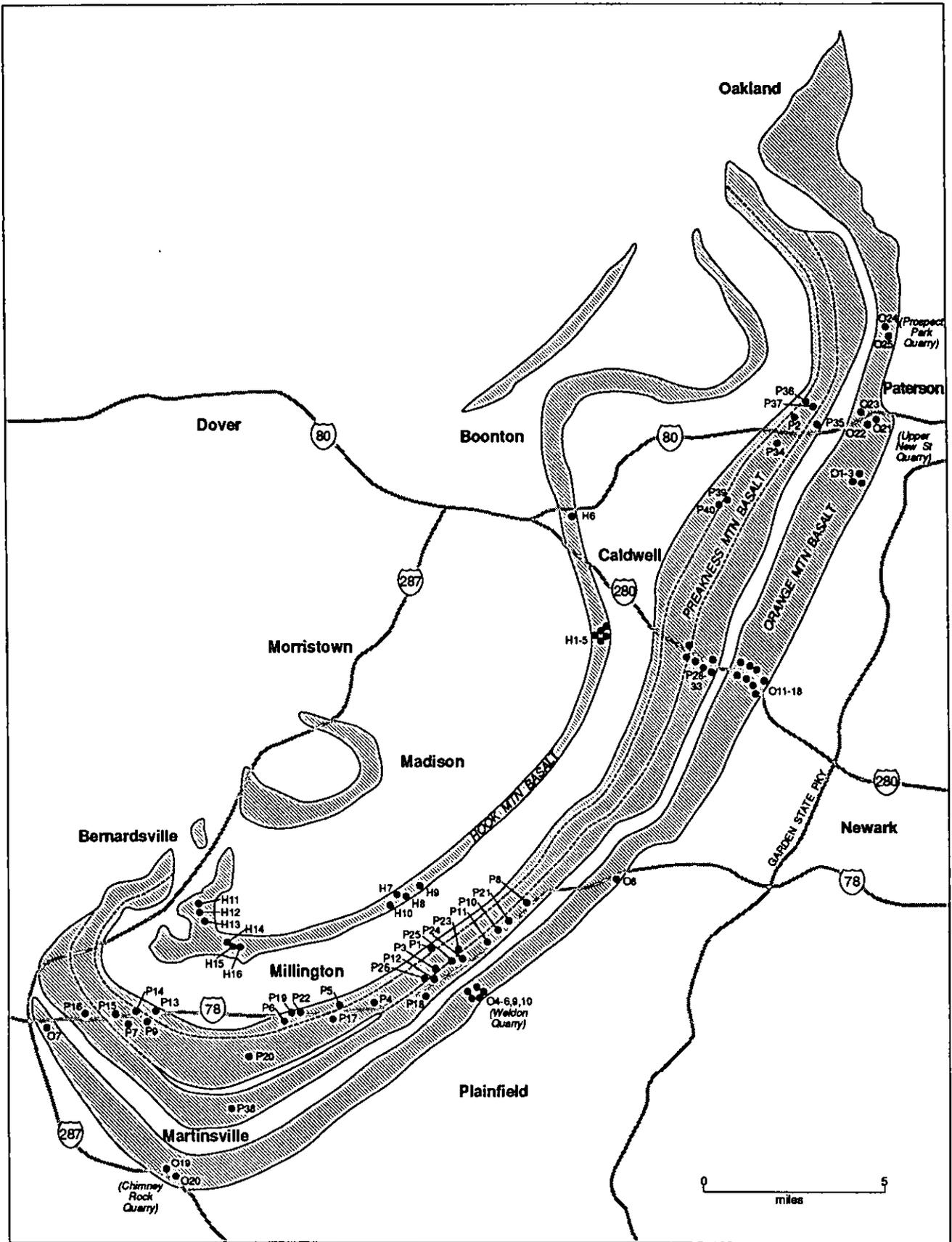


Figure 14. Map of Watchung Basalts with locations of samples chosen for chemical analysis (see fig. 15 and representative analyses in table 4) and approximate contacts (dashed lines) of the three Preakness Basalt flows.

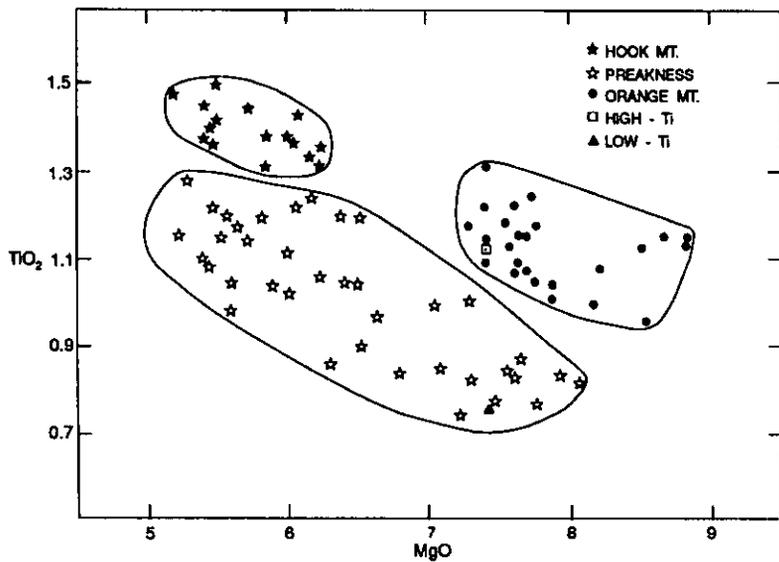
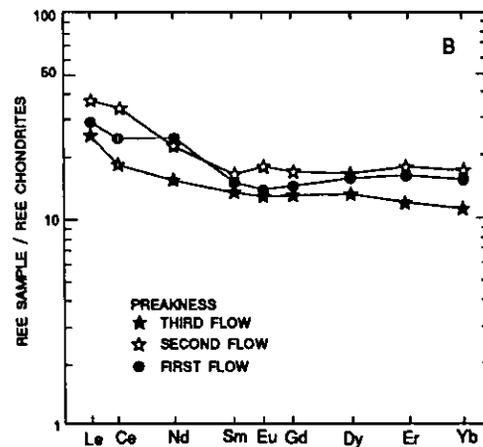
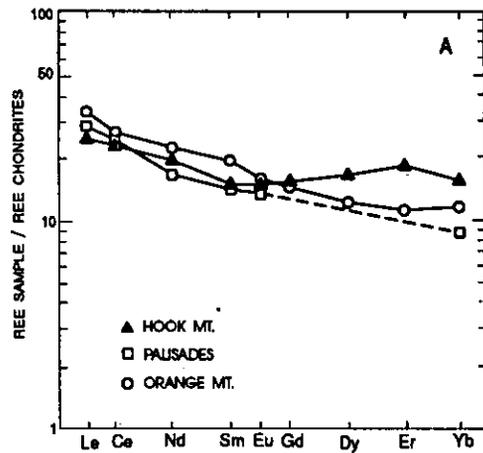


Figure 15. Plot of TiO_2 versus MgO showing distribution of Watchung basalt samples located on figure 14. High-Ti (HTQ) and Low-Ti (LTQ) values after Weigand and Ragland (1970).

Figure 16. Chondrite normalized (after Masuda and others, 1973) REE distributions of five typical Watchung basalt samples and the Palisades sill lower chill (sample 80B1 of Shirley [1987]).



exposed at several locations along the length of the Second Watchung ridge, including the type locality of the Preakness Basalt on Interstate 280 (figs. 1 and 14).

Thin sections of basalt sampled at the base and throughout the lower columnade of the lowermost Preakness flow are fine to medium grained and porphyritic. Typical unaltered lower columnade samples consist of about 50 percent pyroxene and 43 percent plagioclase as an intergranular mixture with about 3 percent plagioclase phenocrysts and 5 percent dark, fine-grained glassy mesostasis enriched in quench oxides. Typical unaltered entablature samples consist of a coarse intergranular mixture of about 45 percent pyroxene, 50 percent plagioclase, 3 percent opaque oxides, with only about 2 percent brown devitrified glass. Samples affected by only slight degrees of apparent alteration, however, are found to contain considerable albite. Despite this, the plagioclase composition of the least altered samples averages about An57 (table 5), on the basis of 40 microprobe analyses, with a range from An50 to An60, excluding albite determinations. On the basis of 35 microprobe analyses, about two-thirds of the pyroxene of the entablature samples is pigeonite with about one-third augite ($Wo_{35}En_{45}Fs_{20}$). On the basis of 20 microprobe analyses, the magnetite composition typically is Usp_{60} , and, on the basis of 12 microprobe analyses, the ilmenite composition is Hem_8 .

The chemical composition of the first flow of the Preakness Basalt (table 4) averages approximately 1.2 percent TiO_2 , 6.1 percent MgO , 40 ppm Cr, and 95 ppm Zr. The chemical composition and texture virtually are identical to the Holyoke Basalt of Connecticut exposed along Rt. 66, and to typical Sander Basalt of the Culpeper Basin, Virginia.

Mapping of the middle flow, or flows, of the Preakness Basalt still is incomplete and has been difficult. Flow contacts rarely are exposed and are difficult to recognize. Although abandoned copper mines and several very large trap-rock quarries are found along the length of the Orange Mountain Basalt ridge, there are no such quarries expos-

TABLE 5. Watchung Basalt Mineral Compositions

Plagioclase					
	Hook Mountain	Preak. Third	Preak. Second	Preak. First	Orange Mountain
SiO ₂	52.03	51.49	55.94	54.59	53.28
wt % Al ₂ O ₃	30.40	30.92	28.48	29.14	29.23
FeO	0.75	0.65	0.75	0.59	1.06
CaO	13.21	14.11	8.71	11.02	11.85
Na ₂ O	3.50	2.85	6.29	4.54	3.66
TOTAL	99.89	100.02	100.17	99.88	99.08
An%	An ₆₈	An ₇₃	An ₄₃	An ₅₇	An ₆₄

Augite					
	Hook Mountain	Preak. Third	Preak. Second	Preak. First	Orange Mountain
SiO ₂	52.49	52.45	49.52	52.45	52.63
TiO ₂	0.44	0.28	0.75	0.32	0.29
wt % Al ₂ O ₃	3.64	2.05	1.45	1.69	3.36
FeO	11.63	12.91	19.83	12.65	6.67
MgO	17.51	19.92	11.73	15.76	19.34
CaO	14.73	11.89	15.96	16.85	17.13
Na ₂ O	0.22	0.11	0.27	0.17	0.22

ing Preakness Basalt. The best exposures of the lower contact of the middle flow are found at sample location P36 (stop 6) and along the sedimentary bed between samples P38 and P20 (fig. 14). The upper contact of the middle flow is exposed along another sedimentary bed at sample locations P39-40 (Greenbrook) and along I-78 near locations P17 and P15 (fig. 14).

A high degree of textural and chemical variation further complicates the mapping of the middle flow, but some preliminary generalizations may be warranted. Most samples from the middle flow are medium-grained, intergranular mixtures of 35 percent pyroxene (both pigeonite and augite), 59 percent plagioclase, 4 percent opaque oxides, and 2 percent brown devitrified glass. Some samples are aphyric, but large plagioclase phenocrysts make up as much as 7 percent of other middle flow samples. The low pyroxene content and high plagioclase content are responsible for the low magnesium and high aluminum content of the rock (table 1). The high modal content of Fe-Ti oxides is responsible for the high TiO₂ content. Loss of pyroxene and accumulation of plagioclase also seem to be responsible for a slightly positive Eu anomaly (fig. 16B). The plagioclase-rich samples plot at the fractionated end of the Preakness field on a TiO₂ versus MgO diagram (fig. 15).

The uppermost flow of the Preakness Basalt is exposed best along Interstate 78 (fig. 14); elsewhere exposures typically are altered. The somewhat vuggy nature of the flow seems to have accelerated alteration. The flow typically is medium grained and slightly porphyritic, consisting of glomeroporphyritic clots of pyroxene (largely augite) and plagioclase in a dark mesostasis enriched in quench oxides. The mesostasis makes up 30 to

50 percent of the rock. The pyroxene and plagioclase content of the rock is approximately equal. Large euhedral phenocrysts of plagioclase and pyroxene are not uncommon.

The chemical composition of the uppermost flow (table 4) is characterized by a consistently low TiO₂ content ranging from 0.7 to 0.9 and averaging 0.8 percent (fig. 15). The basalt qualifies in all respects as a typical ENA-LTQ basalt as defined by Ragland and Whittington (1983). The occurrence of LTQ basalt within the Newark Basin is not surprising in light of its occurrence in the Gettysburg Basin to the south (Smith and others, 1975) and in the Hartford Basin to the north (Philpotts and Martello, 1986).

The overlapping compositions of the three Preakness Basalt flows in figure 15 and other variation diagrams support interpretations that all three Preakness flows are genetically related to each other. Apparently, the two lower Preakness flows fractionated out of a LTQ magma, as also seems to have been the case in the Buttress-Ware dike to Holyoke Basalt fractionation trend found in the Hartford Basin (Philpotts and Martello, 1986). The fractionated, more felsic upper portion of a differentiated LTQ magma chamber apparently extruded as the first two Preakness flows before a more mafic, parental pulse of LTQ magma finally was extruded as the uppermost flow.

The REE content of the third flow of the Preakness Basalt is within the "low-Ti" range of Ragland and others (1971) but the first and second flows contain distinctly higher REE concentrations. The distribution patterns (fig. 16B), however, are close to each other and are reasonably parallel, supporting a genetic relationship controlled by fractionation. The slightly positive Eu anomaly displayed by the second flow (fig. 16B) is consistent with a plagioclase enrichment that approximately is balanced by the relatively low plagioclase content of the first Preakness flow.

Petrology and Geochemistry of the Hook Mountain Basalt

The Hook Mountain Basalt (stop 7) extruded about 550,000 years after the extrusion of the Orange Mountain Basalt and the intrusion of the Palisades sill (Olsen and Fedosh, 1988). The Hook Mountain Basalt, which chemically is equivalent to the Hampden Basalt of the Hartford Basin, extruded onto a 340-m-thick section of the underlying Towaco Formation. The basalt flowed toward the southwest, unlike the northeast flow directions of the Orange Mountain and Preakness Basalts (Manspeizer, 1969). The Hook Mountain Basalt averages 91 m in thickness (Faust, 1975) and consists of at least two amygdaloidal and deeply altered flows. The basalt is composed of plagioclase, clinopyroxene, and Fe-Ti oxides in a fine-grained to glassy and typically vesicular mesostasis. Phenocrysts of plagioclase and pyroxene are common.

The SiO₂, Na₂O, Cr, Ni, Rb, and Sr contents of the Hook Mountain Basalt (table 4) are intermediate between those of the Orange Mountain and Preakness Basalts. Puffer and others (1981), therefore, point out that the Hook Mountain Basalt could not have developed as the result of continuing the same fractionation trend (from an initial Orange Mountain magma) that yielded the Preakness Basalt. Philpotts and Reichenbach (1985) have suggested that the chemically equivalent Hampden Basalt, the uppermost flow unit of the Hartford Basin, may have developed out of HTQ magma via an independent parallel fractionation route. They suggest that a 31 percent fractional crystallization of Talcott magma (a HTQ type chemically equivalent to the Orange Mountain Basalt), forming plagioclase (An₇₂), augite (Ca₃₇Mg₅₈Fe₅), orthopyroxene (En₈₇), and olivine (Fo₉₀), would produce a residual liquid of Hampden composition. The fractionating magma was ponded, at least temporarily, in a shallow crustal environment (Palisades sill?).

The REE distribution pattern of the Hook Mountain Basalt (fig. 16A) plots close to that of the Orange Mountain Basalt and is within the "high-Ti" range of Ragland and others (1971). The Hook Mountain Basalt, however, contains less light REEs than the Orange Mountain Basalt despite its more highly evolved major-element concentrations (including iron and titanium). These new REE data (table 4) are consistent with the previously published data of Kay and Hubbard (1978) and Ragland and others (1971). For all three data sets, the fractionated "high-Fe" samples contain less light REE than the more mafic "high-Ti" samples. Further, there also is a distinct "cross-over" in the distribution patterns (fig. 16A), resulting in a higher heavy REE content for the "high-Fe" (Hook Mountain) samples than for the "high-Ti" (Orange Mountain) samples. This cross-over pattern, however, need not be inconsistent with interpretations that include the fractionation of Hook Mountain Basalt from a parental Orange Mountain magma. If assimilation of a light REE-depleted phase or removal of a light REE-enriched phase occurred during fractionation, the observed REE distribution patterns could have been produced. Assimilation of OPX has been proposed by Philpotts and Martello (1986) and by Smith and others (1975), but the light REE versus heavy REE content of the assimilated OPX has not been determined. Alternatively, the Hook Mountain Basalt may have fractionated from a parental LTQ magma along a fractionation path that differs from the one that led to the first flow of the Preakness Basalt. A second alternative, that none of the three Watchungs are related to each other by fractionation, also must be considered. Swanson and Wright (1981) were unable to relate any of the Columbia River lava types to each other by fractionation processes on the basis of major- and trace-element mixing calculations. Similar problems seem to be developing with the new Watchung data.

COMPARISONS TO OTHER CONTINENTAL BASALT PROVINCES

The Watchung Basalts, in comparison with other continental basalts, are, in general, somewhat lower in their TiO₂ and Zr content. These lower values prevent the Watchung Basalts from plotting within the "within-plate" or continental basalt fields on several tectonic discrimination diagrams such as those of Pearce and Cann (1973). In addition, it is much easier to compare the chemistry of the Orange Mountain Basalt with other basalt provinces than either the Preakness or Hook Mountain Basalts. The Orange Mountain Basalt is characterized by its rather uniform composition and, given its close compositional and stratigraphic similarity to the Mount Zion Church and Talcott Basalts, its widespread occurrence. The Preakness Basalt, however, is much more diverse chemically and difficult to characterize, while the Hook Mountain Basalt is a relatively minor basalt occurrence.

When compared with other basalts, including most of the major terrestrial continental flood basalt provinces, the Orange Mountain Basalt clearly resembles the basalts of the High Atlas of Morocco and the Lesotho basalts (part of the Karoo province) of South Africa more closely than others (table 6). This close resemblance was first noted by Manspeizer and Puffer (1974) on the basis of much less data than currently is available. As the quantity of chemical data has increased over the past ten years, the similarity with the High Atlas and Lesotho basalts has become even more striking.

A good measure of the degree of chemical similarity among basalts has been devised by Marsh (1987). Figure 17 is a Lesotho normalized diagram that demonstrates convincingly the high degree of chemical similarity between the Lesotho and High Atlas basalts. When the Orange and Hook Mountain Basalts data are plotted on the same type of diagram an equally good or perhaps even better geochemical match is obtained (fig. 18), particularly for the Orange Mountain Basalt. Note that the third flow of the Preakness Basalt (an ENA-LTQ type) plots below the 1/1 line in figure 18 and is distinctly unlike the Lesotho basalts.

A conservative interpretation of this geochemical data would be that it simply is coincidental that of all the major continental basalt provinces listed in table 6, the three that most closely resemble each other also are each early Jurassic in age and developed under similar tectonic conditions (continental rifting). But it probably is safe to conclude that the sources and/or parent magmas of the Lesotho basalts were about the same chemically as those for the High Atlas and Orange Mountains basalts. The degree of similarity between the entire Mesozoic Karoo and ENA igneous provinces even extends into the Cretaceous when alkalic magmas were being intruded in both areas.

**TABLE 6. Continental Flood Basalt
(Average Composition)**

PROVINCE	MgO (wt%)	TiO ₂ (wt%)	Zr (PPM)	⁸⁷ Sr/ ⁸⁶ Sr	AGE	REFERENCE
ENA-HTQ Orange Mt/Palisades	7.9	1.08	105	0.7045	Early Jurassic	Puffer (1988) Gast (1967)
Morocco High Atlas	7.9	1.16	103	--	Early Jurassic	Bertrand and others (1982)
Karoo Lesotho	7.5	1.0	110	0.7059	Early Jurassic	Cox and Homung (1967); Compston and others (1968)
Columbia River Grande Ronde	5.3	1.8	90	0.705	Tertiary	McDougall (1976) Nelson (1980)
Brazil Parana	4.8	3.0	250	0.7057	Early Cretaceous	Ruegg (1976) Compston and others (1968)
L. Superior Keweenawan	8.3	1.2	100	0.7046	Late Precambrian	Green (1972) Van Schmus and others (1981)
India Deccan	5.3	2.2	--	0.706	Early Tertiary	Alexander and Paul (1977)
Antarctic Ferrar	4.5	1.0	94	0.712	Late Jurassic	Compston and others (1968)
Siberia Nadezhdinsk Fm.	7.4	1.1	180	--	Permo/ Triassic	Nesterenko and others (1964)

Several South African petrologists recently have offered some interpretations of the Karoo data that, due to the high degree of chemical similarity, may be applied equally well to the Orange Mountain Basalt. Marsh (1987), for example, suggests that Lesotho-type continental flood basalts are a primary magma type that is derived from an old and enriched subcontinental lithosphere. If the high ⁸⁷Sr/⁸⁶Sr ratios reported for the Lesotho and Orange Mountain basalts (table 6) are not a product of crustal contamination, as seems plausible considering the high degree of compositional uniformity of the basalts across a wide geographic area, then a Rb enriched source seems likely. Sr and Nd isotopic data have been interpreted by Bristow and others (1981) and by Hawkesworth and Van Calsteren (1984) as indicating subcontinental enrichment events beneath southern Africa between approximately 1 and 2 b.y.

However, the suggestion that Lesotho-type magma may be primary is not supported by Mg' values. The Mg' value of the Orange Mountain Basalt is only 0.51, much lower than the 0.68 to 0.75 range indicative of primary mantle melts as discussed by O'Hara and others (1975) and Frey and others (1978). As they noted, if a magma is primary the forsterite content of its liquidus olivine should be the same as that of olivine in the magma's residual source. Only melts with an Mg' range of 0.68 to 0.75 would be in equilibrium with the Fo90 olivines typically found in harzburgite and lherzolite inclusions interpreted as mantle xenoliths. The currently popular view that only picritic basalts or komatiites qualify as primary basaltic magmas supports the interpretation that the ENA quartz tholeiites are derived from more primitive olivine normative magmas (perhaps the HLO or LLO (low-lithophile element olivine normative) types of Ragland and Whittington (1983)) that underwent extensive deep olivine fractionation. If Lesotho-type or HTQ magmas are primary, they must have been derived from more iron-rich mantle rocks than typical lherzolite or some special combination of conditions must have been met during the early Jurassic.

Attempts at searching for a plausible combination of special conditions that could have generated a Lesotho-type primary magma are stimulated by the observation of Carmichael and others (1974) that "Continental tholeiitic flood basalts and related diabases, more than any other class of volcanic rocks, satisfy the two criteria postulated for magmas generated directly by fusion - great volume of and compositional homogeneity within each province... To derive this magma from picritic basalt of deep-seated origin by low pressure fractionation ... requires that again and again each successive draught of magma must rid itself cleanly, while still largely liquid, of the same fraction of crystalline olivine along some identical course of ascent. This seems highly improbable." If the Lesotho province together with the High Atlas of Morocco and the ENA-HTQ province (that was adjacent to the High Atlas during the early Jurassic) forms some superprovince or matching set of provinces, the great volume and compositional homogeneity arguments are clearly strengthened.

In addition to high-iron mantle compositions, other conditions that have been proposed (Kushiro, 1975; Mysen, 1977; Wilkinson and Binns, 1977; Elthon and Scarfe, 1984) to favor the development of primary quartz normative tholeiitic magmas are low pressure (lithospheric mantle), high lithospheric temperatures (extended insulation of the source under a thick continental crust), and monovalent cation source enrichment (H₂O, K₂O, and Na₂O from lithospheric kaersutite and phlogopite). Although it is difficult to prove that most of these conditions applied during the early Jurassic, future modeling efforts might consider these factors. The model proposed by Marsh (1987) calls for the anorogenic development of Lesotho-type magma from an old and enriched subcontinental lithosphere. Later, during the early Cretaceous, following lithospheric attenuation and rifting, alkalic and MORB-like melts were generated. If Marsh (1987) is correct, similar conditions may have applied during the petrogenesis of ENA-HTQ magmas.

Figure 17. Lesotho normalized diagrams (Marsh, 1987) comparing composition of average Karoo (Lesotho) basalt with other continental tholeiites. Data from Reidel (1983), Bertrand and others (1982), and Thompson and others (1980).

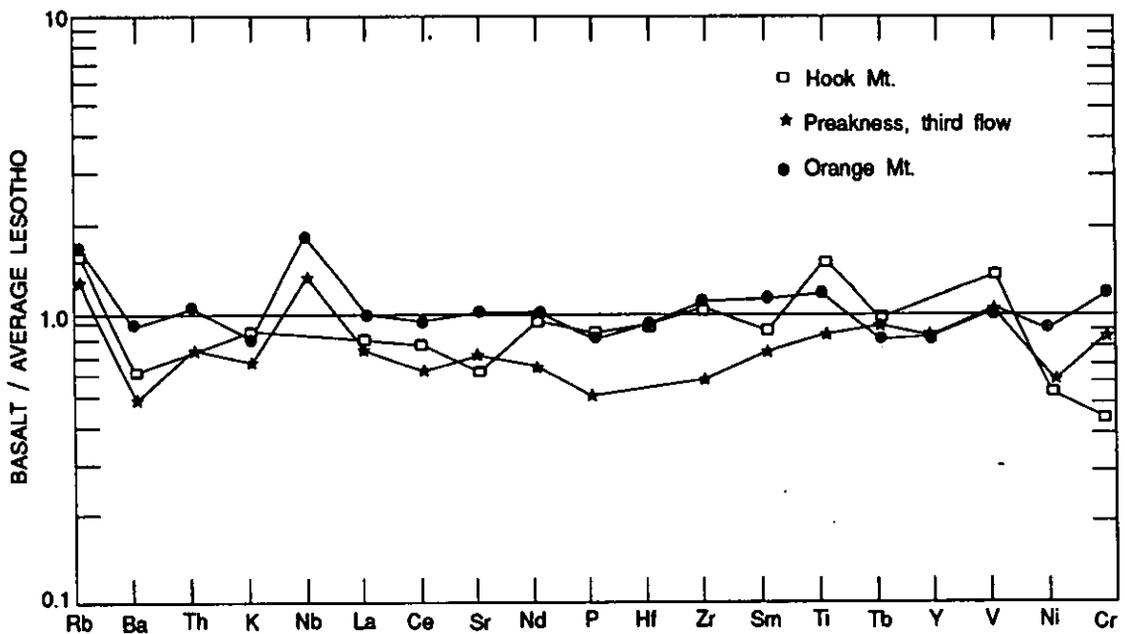
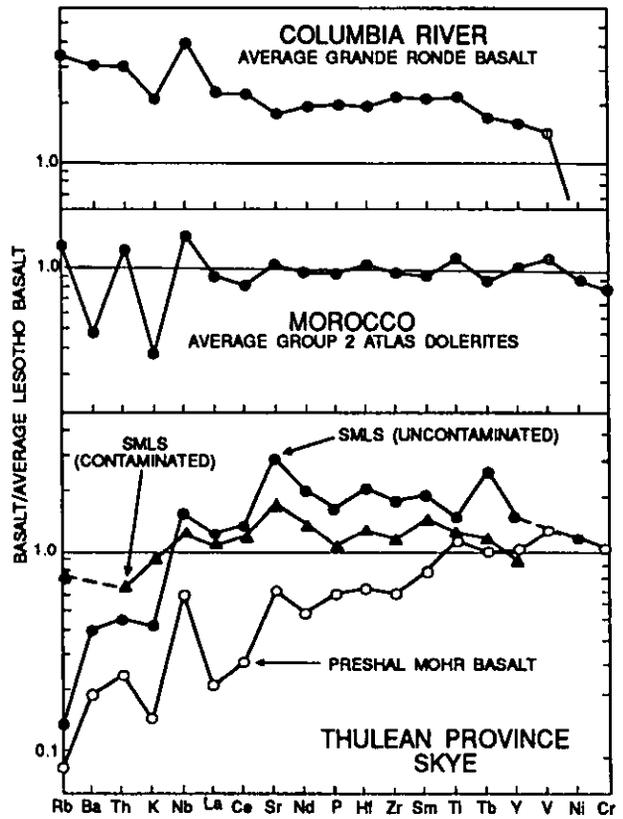


Figure 18. Lesotho normalized diagram (Marsh, 1987) comparing average Lesotho (Karoo) basalt with Watchung Basalts.

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ROAD LOG AND STOP DESCRIPTIONS

Mileage

- 0.0 From Neilson Street in front of the Hyatt Hotel in New Brunswick, NJ turn right onto Albany Street (NJ 27 north).
- 0.1 Turn right onto Burnet Street (NJ 18 south).
- 2.6 Enter New Jersey Turnpike (northbound).
- 18.4 Take exit 13 (Verazzano Bridge - Goethals Bridge) and proceed east on I-278, over the Goethals Bridge towards Staten Island.
- 23.2 Take "Bayonne Bridge" exit (NY 440 north).
- 24.2 Exit onto Forest Avenue west (turn left).
- 24.7 Near top of small rise, turn left onto Eunice Road. Park at end of road. The Graniteville Quarry is 100 yds to your right (west) through field.
- 24.8 Stop 1.

Fused Lockatong Xenolith in Palisades Sill

At this locality, the margins of an argillaceous xenolith of Lockatong Formation enclosed in the diabase of the Palisades sill fused, cooled, and crystallized to yield a trondhjemitic melt (Benimoff and Sclar, 1978, 1980, 1984, 1988). The sodium-rich, hornfelsed, and slab-like xenolith of argillite is 30 m long and 0.3-0.5 m thick and strikes N30°E with a vertical dip. It appears that the xenolith was derived from Lockatong Formation located below the Palisades sill at this stop. Completely surrounding the xenolith and in contact with the enveloping diabase is a coarse-grained pyroxene trondhjemite. Whole-rock chemical analyses (Benimoff and Sclar, 1988) reveal that there was diffusion of ions across the liquid/liquid interface between the diabase and trondhjemite magmas. Fe, Mg, and Ca diffused into the trondhjemite, whereas Na, and perhaps other alkalis (Rb, K, and Ba), diffused into the diabase. A similar situation is seen at other localities in the Newark Basin, although not with the contaminating material exposed (Husch and Schwimmer, 1985). However, in most instances alkali enrichment and Ca depletion of the diabase are found (Husch, 1991).

- 25.0 From Eunice Road turn left (west) onto Forest Avenue.
- 26.3 Turn right onto I-278 west and follow signs to Goethals Bridge.
- 28.3 Exit onto New Jersey Turnpike (I-95) northbound.
- 35.2 Follow signs to George Washington Bridge.
- 39.2 Snake Hill, a Jurassic volcanic plug related to the Palisades sill is exposed across the tidal marsh to the right (east). The huge landfills of Secaucus, New Jersey are exposed on the left (west).
- 46.7 At the end of the NJ Turnpike continue north on I-95.
- 47.4 Take express lane of I-95 to George Washing-

- ton Bridge.
- 50.2 The upper contact and associated chill zone of the Palisades sill is exposed on the left (north).
- 50.5 Two narrow vertical trondhjemite dikes (less than six feet thick) composed of white albite, quartz, and minor opaque oxides cut through the Palisades sill and are exposed on both sides of the highway. The dikes have been described by Germine and Puffer (1981) and Benimoff and others (1989), and are similar to the Staten Island occurrence just visited (stop 1). Several vertical calcite veins less than two feet thick also are exposed in these roadcuts
- 51.5 Just before the George Washington Bridge toll booth exit the highway at Fort Lee (exit 67).
- 51.6 Turn left (east) at stop sign onto Bridge Plaza Square.
- 51.8 Turn right (south) at stop sign onto River Road. Begin descent down steep hill.
- 52.1 Before bottom of hill turn left (east) into Palisades Interstate Park and continue around curve. Follow the road north back toward the George Washington Bridge.
- 52.2 The olivine zone of the Palisades sill is exposed on the left.
- 52.6 A xenolith of Lockatong hornfels is exposed on the left.
- 52.7 Pass under the George Washington Bridge
- 52.8 The lower contact of the Palisades sill is exposed on the left.
- 53.1 Turn right at Ross Dock, continue down hill, and park in parking lot at river level.
- 53.3 Stop 2.

Lower Contact of Palisades Sill with Lockatong Hornfels at Ross Dock

After admiring the view, walk south from the parking lot along the road to the boat launch, then up the stone steps, through the tunnel under the road, and out onto road level. Walk north along the contact of the lower chill zone with hornfels of the Lockatong Formation. The fine-grained diabase chill zone consists of about 1 percent olivine (Fo80), 49 percent plagioclase (An64), and 50 percent pyroxene (augite and hypersthene). Pyroxene-dominated, tholeiitic-trend fractionation of the parental magma culminated in the development of a granophyre layer about 33 m thick near the upper contact of the 330 m-thick sill. Some thin white veins of late quartzofeldspathic granophyre cut the diabase along the road at this locality.

A 10 to 13 ft (3 to 4 m) thick olivine-enriched zone is exposed 52 ft (16 m) above the road level and is exposed at road level 0.1 mile (0.2 km) east of the entrance to the park (mile 52.2). The olivine zone historically has been assigned an important part in the Palisades fractionation se-

ries and has been attributed by some to be the result of *in situ* gravitational crystal settling. Walker (1969), however, has shown that most of the olivine in the olivine zone is too iron-rich (Fo₆₅) to have formed as an early cumulate phase and too fine-grained to have settled very far through the viscous magma. In addition, Husch (1991) has shown that extensive olivine fractionation is inconsistent with geochemical trends within the sill. Instead, the olivine zone may have crystallized late as part of a pulse of olivine-rich magma that intruded into a composite Palisades sill after its initial formation from an ENA-HTQ magma (see Part I).

While walking north along the road from the stone path, observe metamorphosed buff-colored arkose exposed 0 to 250 ft (0 to 75 m) and 600 to 800 ft (180 to 250 m) north of the chill zone contact. In the intervening zone, from 250 to 600 ft (75 to 180 m) north of the contact, are metamorphosed platy and laminated siltstones. These metasediments have been described by Olsen (1980) and correlate with other Lockatong Formation exposures to the south. The pelitic layers, particularly, have been affected by contact metamorphism and have been converted into black hornfels consisting of biotite and albite with minor analcime, diopside, and calcite, or to green hornfels consisting of diopside, grossularite, chlorite, and calcite with minor biotite, feldspar, amphibole, and prehnite (Van Houten, 1969).

Porphyroblasts of pinitite after cordierite commonly occur as small green spots in the black biotite-albite hornfels (Miller and Puffer, 1972). Large tourmaline porphyroblasts and even larger green spherical structures up to 1.5 in (4 cm) across, composed largely of clinozoisite, are less common in the hornfels, but have been found in several contact metamorphosed rocks located throughout the Newark and Culpeper Basins.

- 53.5 From circle at top of road to Ross Dock, take road back south under George Washington Bridge to park entrance. Turn right (north) onto River Road and proceed up hill. Continue north on county road under highway (entrance to GWB). Follow signs to Palisades Interstate Parkway; enter Parkway and continue north.
- 64.5 Take exit 4 onto US 9W (north).
- 64.7 Pass entrance to Lamont-Doherty Geological Observatory (Columbia University).
- 70.0 Bear right onto Broadway, continue north through Nyack, New York.
- 73.2 Turn into Nyack Beach State Park, continue down hill to the right, and park in lot along the Hudson River.
- 73.4 Stop 3.

Palisades Sill at Nyack Beach State Park

From the parking lot next to the snack bar walk north on the trail along the river. The Palisades diabase at this locality intruded the Passaic Formation which

overlies the Lockatong Formation examined at the previous stop. The contact here is approximately parallel to the Hudson River escarpment and is exposed about 30 ft (10 m) above the level of the trail. Bright reddish-brown fluvial deposits of micaceous mudstone interbedded with arkose displaying cross-bedding, channels, and burrows are well exposed along the trail at the base of the spectacular escarpment formed by the Palisades sill. The Palisades diabase along the southern part of the trail can be examined by climbing the lower slope of the escarpment. At 1.1 mi (1850 m) north of the parking lot the lower contact is exposed at path level. Still farther north, the contact rises again through the uppermost Triassic section of the Passaic Formation.

The sedimentary rocks of the Passaic Formation have not been metamorphosed beyond a few meters from the sill. The arkosic sandstones of the Passaic Formation are particularly resistant to contact metamorphic effects, unlike the shales of the Lockatong Formation (see stops 1 and 2) that have been metamorphosed pervasively by the heat of the Palisades diabase. The olivine zone seen at the previous stop is not exposed north of the Nyack Beach escarpment; even here it is less than 1 m thick. This observation led Sanders (1974) to suggest that the olivine zone had been displaced below the present erosion surface by a nearly vertical normal fault along the base of the sill. Upon close examination of the diabase near the contact, however, a distinctly finegrain size is observed, suggesting the presence of a chill zone. In addition, there is an absence of any clear evidence for a fault. Thus, it appears that the olivine zone never formed north and west of this location.

- 73.5 Return south along Broadway to the center of Nyack.
- 75.5 Turn right (west) onto Main Street.
- 77.2 Exit right onto NY 303 north.
- 77.9 Turn left onto I-287 (New York State Thruway) west.
- 79.7 Take exit 13 N onto Palisades Parkway northbound.
- 86.0 Take exit 13 and follow signs to US 202.
- 86.3 Turn right onto US 202 westbound. Continue on US 202 for 2.5 miles and park opposite the outcrop.
- 88.8 Stop 4.

Ladentown Basalt at Ladentown, New York

The closely-spaced curved cooling columns displayed by the Ladentown basalt along US 202 contrast with the thick massive columns typical of the Palisades sill (stops 2 and 3) that underlies the basalt and probably was its source of magma. The basalt exposed at this locality is fine grained, contains large plagioclase phenocrysts, and is slightly vesicular. Chemical analyses of the Ladentown Basalt (Puffer and others, 1982) compare closely (particularly the Cu and Sr contents) with

the fractionated interior (Walker's (1969) second magma pulse) of the Palisades sill. The Ladentown Basalt, therefore, appears to have extruded onto sediments of the Passaic Formation, perhaps forced to the surface by the injection of a second HTQ magma pulse within the Palisades sill. This occurred before the Felville Formation was deposited, and before the Preakness basalt (stop 6) was extruded. A physical connection between the Ladentown flow and the western end of the Palisades sill at Mount Ivy is indicated by magnetic and gravity data (Koutsomititis, 1980; Kodama 1983). However, this connection is not seen at the surface.

Good exposures of coarse boulder conglomerates are located another 0.4 mi south along US 202. The coarse clast size of the sediment coincides with its close proximity to the western border fault in the valley running parallel to US 202. Note the distinct change in topography on the opposite side of the border fault where Precambrian gneisses are the dominant lithology.

- 89.1 Continuing south on US 202, observe the coarse-grain conglomerates exposed on the left and the Precambrian highlands of the Reading Prong exposed along the Ramapo fault valley on the right.
- 94.6 Turn left at stop sign and continue on US 202 south.
- 95.4 Turn right (west) at stop sign and pass under railroad tracks.
- 96.5 Turn left onto NJ 17 south.
- 109.3 Exit right onto the Garden State Parkway south.
- 112.3 Take exit 159 onto I-80 west.
- 115.9 Take exit 57.
- 116.0 Turn left onto Grand Street
- 116.3 Turn right onto Spruce Street
- 116.8 Turn right onto Market Street and immediately turn right into the Paterson Museum parking lot.
- 116.9 Stop 5.

The Orange Mountain Basalt at Great Falls, Paterson, New Jersey

The basalt flows of the Newark Basin are exposed as three northeast/southwest trending ridges. The three basalt units dip to the west at about 15 degrees and were known as the First, Second, and Third Watchungs (Darton, 1890; Faust, 1975); Olsen (1980) renamed them the Orange Mountain (stop 5), Preakness (stop 6), and Hook Mountain (stop 7) Basalts, respectively. One deeply altered exposure of basalt near the Ramapo fault may represent a basaltic flow younger than the Hook Mountain Basalt. However, preliminary chemical analyses suggest it probably is a displaced fault slice of Hook Mountain or Preakness Basalt.

At the exposure along the north edge of the parking lot near the statue of Alexander Hamilton, the lower contact of the Orange Mountain Basalt with the underlying Passaic Formation is seen. Southwest-plunging

pipe-amygdules and vesicles are exposed in the basalt near the contact. However, these vesicles occur entirely within the basalt above the basal contact.

From the statue of Alexander Hamilton observe the vertical strike-slip fault planes through the lower flow unit of the Orange Mountain Basalt and the contact between the lower colonnade and the overlying entablature. Pleistocene glacial activity has removed the overlying, friable, pillowed flow unit. The "S.U.M." over the door of the historic building near the river at the base of the view area stands for "Society of Useful Manufactures," an organization founded in 1789 to promote local trade. The hydroelectric plant operated from 1914 through 1968 and was closed in 1969 because of flood damage, and then re-opened in 1990.

From the statue of Alexander Hamilton, walk north up Spruce Street to the path leading to the footbridge over the falls. Cross the footbridge to the park and observe the columnar jointing in the basalt and some large convex-upward amygdules. Climb into the narrow notches in the basalt eroded along the strike-slip faults for a closer inspection of the basalt.

From the falls, walk south along Spruce Street, cross McBride Avenue and continue one-half block to the Paterson Museum. Some of the best examples of the secondary minerals found in the Paterson area trap rock quarries are on display at the museum. Specimens of prehnite, heulandite, datolite, chabazite, stilbite, and amethyst crystal clusters are particularly outstanding.

- 117.0 Turn right (north) onto Spruce Street.
- 117.1 Turn left (west) onto McBride Avenue.
- 118.6 Turn right (northwest) onto the Hiliery Street Bridge and cross the Passaic River.
- 118.7 Proceed west (left) on Totowa Road.
- 119.7 Turn right onto Green Avenue.
- 119.7 Turn left onto Claremont Avenue, proceed northwest to a sharp right curve in the road, and park along outcrop.
- 119.9 Stop 6.

Preakness Pillow Basalt, Totowa, New Jersey

The lower portion of a Preakness Mountain Basalt flow unit, the second of three, is exposed along the west side of Claremont Avenue. The base of the flow is a subaqueous flow lobe containing ellipsoidal pillows and pahoehoe toes. Secondary mineralization includes calcite, quartz, and minor heulandite in small stretch amygdules. The pillowed base of the flow rests on a previously undescribed thin layer of red siltstone exposed (depending on the amount of refuse present) at road level. The flow grades upward into massive columnar basalt. Further north on Claremont Avenue the upper part of the flow, in contrast to the bottom, is not pillowed and contains large spherical amygdules mineralized with prehnite and pectolite.

- 120.1 Return southeast on Claremont Avenue to Green Avenue and turn right.
- 120.2 Turn left on Totowa Road.
- 120.7 Turn right (southwest) onto Union Blvd.
- 121.4 Turn right at "I-80 West" sign.
- 121.9 Turn right onto Fuller Avenue.
- 122.2 Turn left at I-80 west entrance.
- 129.1 Exit I-80 at Hook Mt. Road (Exit 48) and proceed south on Hook Mt. Road.
- 129.3 Turn right (west) onto Bloomfield Avenue. Hook Mountain Basalt is exposed along the road.
- 129.8 Turn left (south) onto New Road.
- 130.7 Turn right at entrance to I-280 east.
- 133.0 Exit I-280 at Eisenhower Parkway (Exit 4A) and proceed south on Eisenhower Parkway.
- 133.9 Turn right into parking lot.
- 133.9 Stop 7.

Hook Mountain Basalt, Roseland, New Jersey

An extensively weathered volcanoclastic layer is exposed near the base of the Hook Mountain Basalt. In addition, some bleaching and evidence of low-grade thermal metamorphism is seen at the lower contact.

In contrast to the Orange Mountain (stop 5) and Preakness (stop 6) Basalts, the Hook Mountain Basalt is relatively enriched in amygdules and vesicles. The

higher stratigraphic position of the Hook Mountain Basalt, relative to the two underlying basalts, has resulted in a less pervasive zeolite-facies mineralization, although prehnite is abundant at this locality and is easily collected, particularly near the north end of the exposure.

Pipe vesicles are common near the base of the flow and have been interpreted by Manspeizer (1969) as indicating southerly flow for the Hook Mountain Basalt, in contrast to the apparent northeasterly flow of the Orange Mountain and Preakness basalts. This particular Hook Mountain exposure displays columnar joints, but a well-defined Tomkeieff (1940) sequence is not apparent.

- 134.6 Proceed north on Eisenhower Parkway and turn right onto I-280 east.
- 137.6 Type section of Preakness Basalt on both sides of highway.
- 139.1 Type section of Orange Mountain Basalt on both sides of highway.
- 142.5 Exit onto Garden State Parkway south.
- 160.0 Exit onto New Jersey Turnpike south.
- 167.5 Take Exit 9 onto NJ 18 north towards New Brunswick.

THE PALISADES SILL AND WATCHUNG BASALT FLOWS, NORTHERN NEW JERSEY AND SOUTHEASTERN NEW YORK
(New Jersey Geological Survey Open-File Report 92-1)