EARLY JURASSIC DIABASE SHEETS AND BASALT FLOWS, NEWARK BASIN, NEW JERSEY: AN UPDATED GEOLOGICAL SUMMARY AND FIELD GUIDE

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INTRODUCTION

Many important features of the early Jurassic igneous rocks exposed in the northern and central Newark Basin can be examined at the stops detailed below and located in Figures 1 and 2. The narrative preceding the road log and site descriptions is an update of one presented by Puffer and others (1992) and focuses on two aspects of the igneous activity that are the subject of considerable ongoing research. **Part One - The PRHL and Other Diabase Sheets** reviews the petrogenetic processes responsible for producing the rock compositions found within the sheets. In particular, evidence is presented that low density, late-stage granophyric magmas, produced by the olivine-absent crystal fractionation of an Eastern North America (ENA) quartz-normative high-titanium tholeiite (HTQ) magma, migrated laterally and vertically to the highest structural levels within any given sheet. In addition, each sheet apparently differentiated as a relatively closed system with little, if any, of the residual magmas reaching the surface flows of the Watchung Basalts. **Part Two - The Watchung Basalts** is a review and discussion of the geochemical data showing that the youngest of the three basalts formations, the Orange Mountain Basalt, is part of a huge chemically uniform HTQ igneous province and appears to be largely unchanged by fractionation from its mantle source, either an undepleted subcontinental lithosphere or a slightly enriched lithosphere produced by previous subduction events throughout the Paleozoic. The overlying basalt formations, the Preakness and Hook Mountain Basalts, are much more chemically diverse and contain high-iron (HFQ) and low-titanium (LTQ) quartz-normative ENA magma types derived from mantle sources chemically modified or distinct from the HTQ source.

NARRATIVE

The Newark Supergroup of the Newark Basin ranges in age from Carnian (Late Triassic) to Sinemurian-Pliensbachian (Early Jurassic) and is divided by Olsen (1980) into nine formations with a total thickness of over 7,700 m. From bottom to top these formations are: Stockton Formation (maximum 1800 m); Lockatong Formation (maximum 1150 m); Passaic Formation (maximum 6000 m); Orange Mountain Basalt (OMB; maximum 200 m); Feltville Formation (maximum 600 m); Preakness Basalt (PB; maximum 300 m); Towaco Formation (maximum 340 m); Hook Mountain Basalt (HMB; maximum 110 m); and Boonton Formation (maximum 500+ m).

The Newark Basin is a deeply eroded half graben containing the thickest preserved section of the Newark Supergroup and encompassing an area of approximately 129,500 km^2 (50,000 mi^2) in southeastern New York, northern and central New Jersey, and eastern Pennsylvania (Fig. 1). The sedimentary rocks and volcanic flows of the basin dip 5°-25° to the northwest, typically dipping $\cong 15^\circ$ throughout most of central and northern New Jersey. Red siltstones, dark gray mudstones, and tholeiitic basalts are the dominant lithologies of the basin. Intrusive into the three lowermost formations of the Newark Supergroup are numerous sills, sheets, and dikes of diabasic and related igneous rocks.

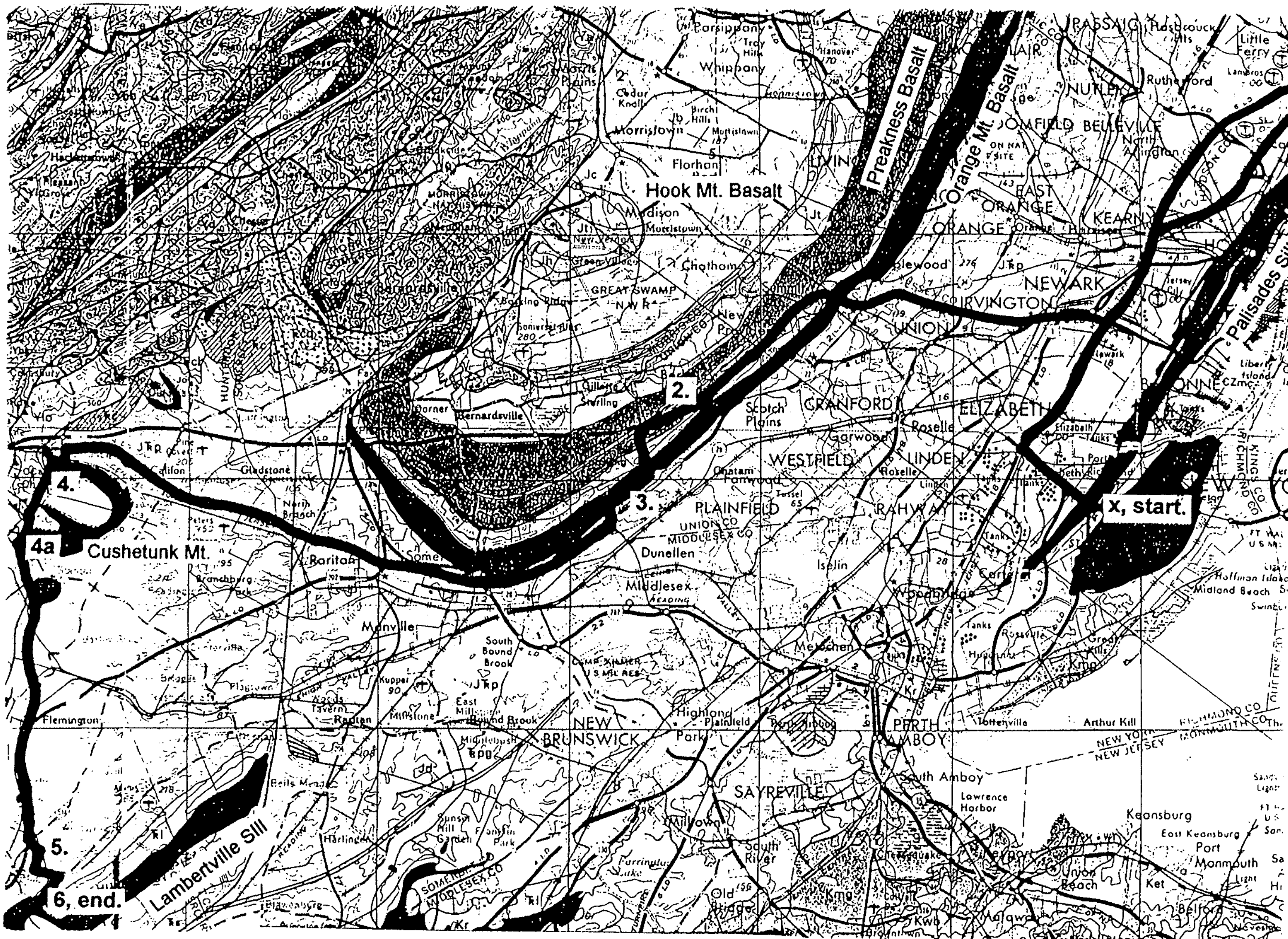


Figure 1. A portion of the Newark 1° x 2° quadrangle by Little and Epstein (1987) with field trip route and numbered stops.

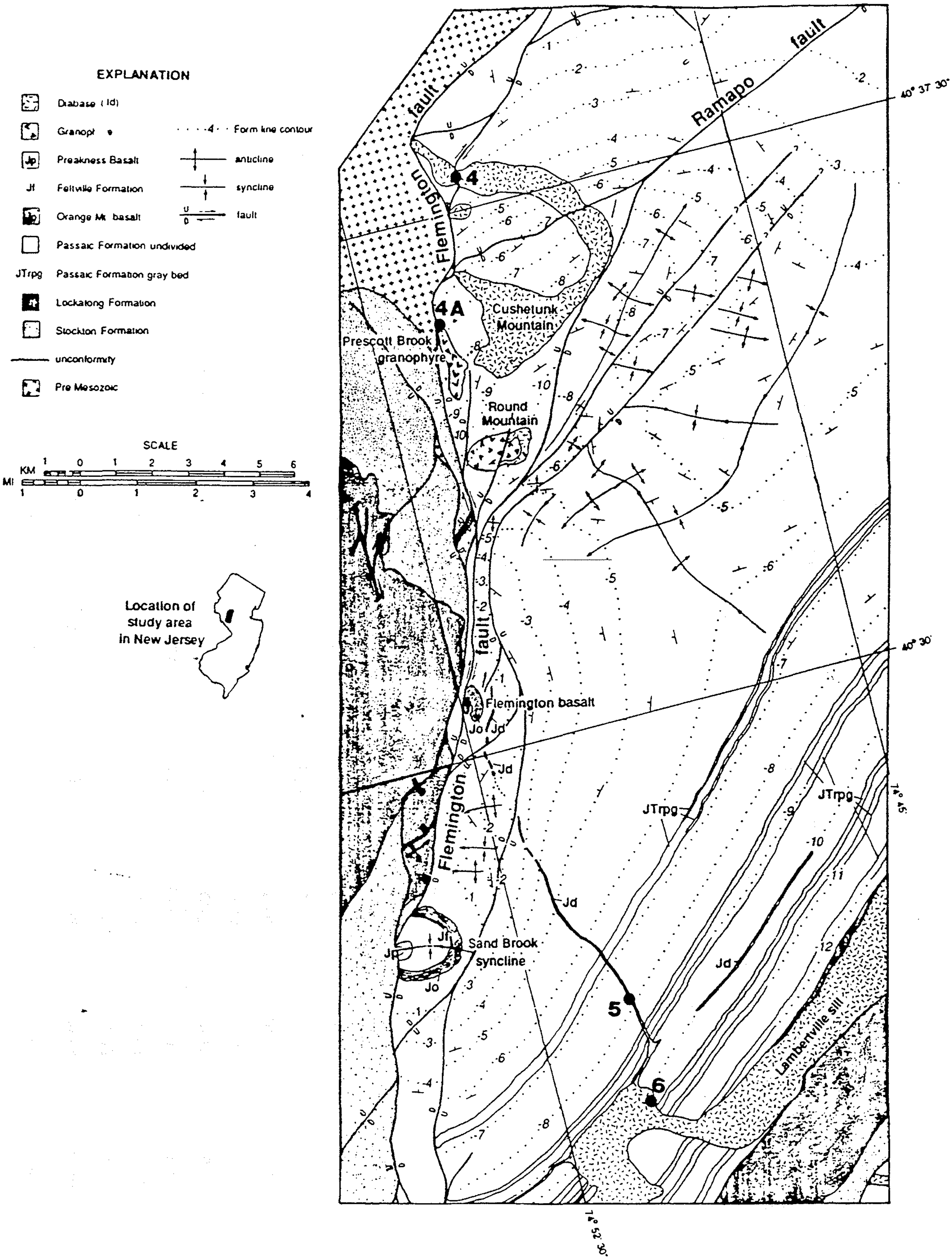


Figure 2. Geologic map (from Houghton and others, 1992) for stops 4-6, central Newark basin, New Jersey. Dotted lines are stratigraphic thickness contours of distance below the OMB. Numbered dots are stop locations.

TABLE 1. NEWARK BASIN DIABASE CHILL AND ENA-HTQ TYPE BASALT COMPOSITIONS

	1	2	3	4	5	6	7	8	9
SiO_2	52.88	52.52	52.47	52.57	53.18	52.88	52.55	52.69	52.65
TiO_2	1.13	1.11	1.17	1.15	1.13	1.17	1.22	1.11	1.13
Al_2O_3	14.26	14.22	14.69	14.16	13.73	14.29	14.64	14.57	14.37
FeO*	10.13	9.98	9.95	10.15	10.16	10.30	10.40	9.97	10.58
MnO	0.16	0.16	0.18	0.17	0.19	0.17	0.16	0.20	0.19
MgO	7.91	8.16	7.69	7.82	7.99	7.49	7.67	7.83	7.49
CaO	10.26	11.02	10.93	10.66	10.48	10.56	10.44	10.90	10.78
Na_2O	2.01	2.08	2.16	2.29	2.30	2.19	2.06	1.99	2.15
K_2O	1.12	0.61	0.62	0.84	0.70	0.82	0.89	0.61	0.67
P2O5	0.13	0.14	0.14	0.18	0.14	0.13	0.14	0.12	--.--
Ba	156	147	154	149	166	158	195	160	---
Cr	298	281	258	279	311	240	315	302	277
Cu	99	105	107	113	122	124	110	121	111
Ni	92	89	87	96	98	81	95	89	81
Rb	37	16	15	33	32	32	---	25	21
Sc	36	36	37	38	36	37	37	---	---
Sr	189	169	208	229	170	195	175	187	186
V	265	264	266	255	285	273	235	310	---
Zr	101	94	104	102	102	115	120	115	92

Major elements normalized to 100 weight percent anhydrous. Trace elements in ppm.
*All iron as FeO. 1=average Quarry dike chill (Husch and Schwimmer, 1995); 2=Byram (Point Pleasant) diabase chill (Husch and others, 1984); 3=Lambertville sill chill-northeast section (Husch and Roth, 1988); 4=average Lambertville sill chill-Delaware River section (Eliason, 1986); 5=average Baldpate Mountain diabase chill (Trione, 1985); 6=Cushetunk Mountain diabase chill (Keely and Husch, 1993); 7=Palisades sill chill (Walker, 1969); 8=average York Haven type basalt (Smith and others, 1975); 9=average ENA-HTQ basalt (Weigand and Ragland, 1970)

TABLE 2. FRACTIONATION MASS-BALANCE MODELS (continued)

3.5–2 Weight Percent MGO Interval

Model 1

Parent: L_3 Daughter: L_4

	Solution	% Cumulate
3.5%	1.000	
CPX	-0.118	29.194
OPX	0.016	4.083
PLAG1	-0.251	62.157
MAG	-0.018	4.402
ILM	-0.001	0.164
2%	0.597	

R^2 = 0413

		Daughter	Calc.	Resid.
SiO_2		56.40	56.87	-0.47
TiO_2		2.51	2.53	-0.02
Al_2O_3		11.94	12.03	-0.09
FeO*		15.36	15.48	-0.12
MnO		0.23	0.24	-0.01
MgO		1.91	1.87	0.04
CaO		5.62	5.62	0.00
Na_2O		3.50	3.28	0.22
K_2O		2.00	1.71	0.29
P_2O_5		0.54	0.35	0.19
				$\bar{K}_D$§
Ba	445	395	50	0.244
Cr	16	4	12	3.891
Cu	241	298	-57	0.289
Ni	18	18	0	2.487
Rb	67	54	13	0.065
Sc	31	36	-5	0.878
Sr	169	173	-4	1.338
V	104	309	-205	1.089
Zr	255	248	7	0.146
La	31.5	24.8	6.7	0.242
Sm	9.20	7.33	1.87	0.250
Eu	2.45	1.04	1.41	1.246
Lu	0.73	0.53	0.20	0.260

Model 2

Parent: L_3 Daughter: L_4

	Solution	% Cumulate†
3.5%	1.000	
CPX	-0.104	21.409
OPX	-0.149	30.824
PLAG1	-0.282	58.297
MAG	-0.029	6.092
ILM	-0.002	0.367
OL	0.082	-16.988
2%	0.516	

R^2 = 0.032

		Daughter	Calc.	Resid.
SiO_2		56.40	56.48	-0.08
TiO_2		2.51	2.51	0.00
Al_2O_3		11.94	11.95	-0.01
FeO*		15.36	15.39	-0.03
MnO		0.23	0.21	0.02
MgO		1.91	1.91	0.00
CaO		5.62	5.62	0.00
Na_2O		3.50	3.57	-0.07
K_2O		2.00	1.95	0.05
P_2O_5		0.54	0.41	0.13
				$\bar{K}_D$
Ba	445	442	3	0.238
Cr	16	1	15	5.803
Cu	241	329	-88	0.292
Ni	18	17	1	2.256
Rb	67	62	5	0.057
Sc	31	35	-4	0.977
Sr	169	175	-6	1.246
V	104	244	-140	1.427
Zr	255	281	-26	0.141
La	31.5	27.4	4.1	0.253
Sm	9.20	8.24	0.96	0.233
Eu	2.45	1.06	1.39	1.161
Lu	0.73	0.58	0.15	0.276

2–1 Weight Percent MGO Interval

Parent: L_4 Daughter: L_5

	Solution	% Cumulate
2%	1.000	
CPX	-0.039	21.056
OPX	-0.013	6.715
PLAG2	-0.072	38.537
MAG	-0.044	23.477
ILM	-0.015	7.890
AP	-0.004	2.325
1%	0.814	

R^2 = 0.331

		Daughter	Calc.	Resid.
SiO_2		61.56	61.26	0.30
TiO_2		1.56	1.56	0.00
Al_2O_3		12.06	11.96	0.10
FeO*		12.63	12.57	0.06
MnO		0.22	0.21	0.01
MgO		1.03	1.07	-0.04
CaO		4.66	4.67	-0.01
Na_2O		3.39	3.86	-0.47
K_2O		2.41	2.41	0.00
P_2O_5		0.48	0.44	0.04
				$\bar{K}_D$
Ba	489	530	41	0.154
Cr	14	10	4	3.331
Cu	278	272	6	0.404
Ni	18	3	15	9.974
Rb	72	82	-10	0.041
Sc	20	31	-11	1.026
Sr	145	175	-30	0.833
V	25	46	-21	5.019
Zr	301	300	1	0.213
La	43.0	35.0	8.0	0.486
Sm	11.8	10.3	1.5	0.445
Eu	2.82	2.46	0.36	0.978
Lu	0.92	0.81	0.11	0.492

*All iron reported as FeO.

†Cumulate values are weight percents of the minerals in the fractionated mineral assemblage removed from the parent composition.

§Trace-element bulk distribution coefficients and abundances calculated on the basis of perfect fractional crystallization and the mineral abundances from the major-element solutions.

TABLE 2. MINERAL FRACTIONATION MASS-BALANCE MODELS

8–5 Weight Percent MGO Interval

Model 1

Parent: L_1 Daughter: L_2

	Solution	% Cumulate†
Chill	1.000	
CPX	-0.107	63.960
OPX	-0.060	36.040
5%	0.833	

$R^2 = 0.264$

	Daughter	Calc.	Resid.
SiO_2	53.15	52.82	0.33
TiO_2	1.30	1.30	0.00
Al_2O_3	16.25	16.49	-0.24
FeO*	10.03	9.97	0.06
MnO	0.17	0.16	0.01
MgO	5.11	5.32	-0.21
CaO	10.33	10.42	-0.09
Na_2O	2.71	2.51	0.20
K_2O	0.80	0.83	-0.03
P_2O_5	0.15	0.17	-0.02

				$\bar{K}_D$§
Ba	182	186	-4	0.031
Cr	41	42	-1	11.572
Cu	122	121	1	0.407
Ni	55	47	8	4.747
Rb	28	30	-2	0.021
Sc	33	29	4	2.144
Sr	214	217	-3	0.071
V	269	264	5	1.048
Zr	114	113	1	0.204
La	12.1	12.6	-0.5	0.053
Sm	3.71	3.80	-0.09	0.320
Eu	1.17	1.18	-0.01	0.321
Lu	0.33	0.33	0.00	0.416

Model 2

Parent: L_1 Daughter: L_2

	Solution	% Cumulate†
Chill	1.000	
CPX	-0.117	49.962
OPX	-0.071	30.372
PLAG1	-0.042	17.819
MAG	-0.003	1.487
ILM	-0.001	0.360
5%	0.766	

$R^2 = 0.040$

	Daughter	Calc.	Resid.
SiO_2	53.15	53.18	-0.03
TiO_2	1.30	1.30	0.00
Al_2O_3	16.25	16.27	-0.02
FeO*	10.03	10.03	0.00
MnO	0.17	0.17	0.00
MgO	5.11	5.11	0.00
CaO	10.33	10.33	0.00
Na_2O	2.71	2.53	0.17
K_2O	0.80	0.88	-0.08
P_2O_5	0.15	0.18	-0.03

				$\bar{K}_D$
Ba	182	199	-17	0.093
Cr	41	31	10	9.316
Cu	122	192	-7	0.364
Ni	55	37	17	4.415
Rb	28	32	-4	0.033
Sc	33	30	3	1.726
Sr	214	213	1	0.403
V	269	258	11	1.109
Zr	114	122	-8	0.182
La	12.1	13.5	-1.4	0.108
Sm	3.71	4.07	-0.36	0.284
Eu	1.17	1.17	0.00	0.569
Lu	0.33	0.36	-0.03	0.358

5–3.5 Weight Percent MGO Interval

Parent: L_2 Daughter: L_3

	Solution	% Cumulate†
5%	1.000	
CPX	-0.090	28.545
OPX	-0.037	11.775
PLAG1	-0.188	59.389
ILM	-0.001	0.385
3.5%	0.683	

$R^2 = 0.012$

	Daughter	Calc.	Resid.
SiO_2	53.84	53.78	0.07
TiO_2	1.77	1.77	0.00
Al_2O_3	15.09	15.07	0.02
FeO*	12.42	12.41	0.01
MnO	0.18	0.21	-0.03
MgO	3.61	3.61	0.00
CaO	8.90	8.90	0.00
Na_2O	2.88	2.95	-0.07
K_2O	1.09	1.09	0.00
P_2O_5	0.21	0.22	-0.01

				K_D
Ba	267	243	23	0.237
Cr	18	10	8	4.696
Cu	206	160	46	0.280
Ni	39	40	-1	1.853
Rb	33	40	-7	0.063
Sc	34	34	0	0.933
Sr	206	192	14	1.279
V	324	327	-3	0.485
Zr	159	158	1	0.138
La	16.7	16.6	0.1	0.165
Sm	4.96	5.05	-0.09	0.189
Eu	1.18	1.10	0.08	1.157
Lu	0.36	0.45	-0.09	0.201

PART ONE: THE PRHL AND OTHER DIABASE SHEETS

The Palisades sill intruded approximately 201 million years ago (Sutter, 1988; Dunning and Hodych, 1990). Although the Palisades is largely conformable along most of its exposed strike length in northern New Jersey (Stop 1), it clearly is discordant north of Nyack, New York, eventually reaching the Jurassic paleosurface near Suffern, New York (Kodama, 1983; Ratcliffe, 1988). Also highly discordant are the central sections and southwestern ends of the Rocky Hill diabase and Lambertville sill (Figs. 1 and 2) Stop 6; two-dimensional gravity and magnetic models by Pappano and others (1990) confirm the crosscutting nature of these intrusions in the subsurface as well. Husch and others (1988) and Husch (1992) have shown that both the Rocky Hill diabase and Lambertville sill are extremely similar chemically and mineralogically to the Palisades sill (sensu stricto) of the northern Newark Basin. In addition to compositional similarities, structural, geophysical, and well-log data (Darton 1890; Bascom and others, 1909; Sandberg and others, 1996; Klewsaat and Gates, 1994) show the Lambertville sill and Rocky Hill diabase to be southwestern continuations of a single Palisades-Rocky Hill-Lambertville (PRHL) "megasheet," extending ~150 km from southeastern New York to eastern Pennsylvania (Husch, 1992). Thus, the PRHL megasheet is exposed at various structural levels, ranging upward from just above the angular unconformity with the underlying basement to just below the Jurassic paleosurface over which the OMB flowed. A separate, presumably contemporaneous HTQ-derived intrusion, the Cushetunk Mountain diabase (CMD; Stop 4), also exhibits similar structural relief (Houghton and others, 1992; Keely and Husch, 1993; Jakubicki and Husch, 1995).

There appears little question that the PRHL megasheet is a composite body, involving as many as four separate magma pulses, with each causing distinct reversals of whole-rock and mineral variation trends (Walker, 1969; Puffer and others, 1982; Shirley, 1987; Husch, 1992; Steiner and others, 1992; Gorring and Naslund, 1995). The dominant (and perhaps only) magma type involved appears to be the HTQ type, although LTQ-related rocks may be present at sporadic localities (Husch, 1992). Furthermore, the genetic relationship between the HTQ magma type and the apparent magma pulse that formed the (in)famous olivine zone (OZ) of the Palisades sill section of the PRHL (Stop 1) is ambiguous (Husch, 1990, 1992;Gorring and Naslund, 1995). Regardless, what is certain is that the OZ does not represent the gravity driven, in-situ accumulation of olivine derived from the overlying magma of the PRHL megasheet. Rather, it appears to be a distinct and slightly later injection of olivine-rich magma that may (Gorring and Naslund, 1995) or may not (Husch, 1990; 1992) be comagmatic with the HTQ magma found at all chilled margins.

Petrography

As reported by Walker (1969), Shirley (1987), Houghton and others (1992), Husch (1992), Steiner and Others (1992), and Gorring and Naslund (1995), textures within the PRHL megasheet and other diabase intrusions vary from partly glassy, fine-grained basalts to coarsely crystalline gabbros. Subophitic intergrowths of plagioclase and clinopyroxene are common, except in the OZ where the texture can be strongly poikolitic (Gorring and Naslund, 1995). Other than in the OZ, where olivine may be as abundant as 28 modal percent (Gorring and Naslund, 1995), olivine is conspicuously rare or absent. Most diabase samples are composed predominantly of plagioclase (An_{45-70}), clinopyroxene (augite and pigeonite), orthopyroxene (En_{65-80}), and Fe-Ti oxides. Accessory minerals include biotite, apatite, quartz, alkali feldspar, sphene, and various opaque sulfides. In granophyric samples, clinopyroxene may be replaced by hornblende and biotite, plagioclase typically is much more sodic, and quartz and alkali feldspar occur in graphic micropegmatitic intergrowths. Most coarse-grained rocks, especially granophyric compositions, exhibit at least some amount of deuteric alteration, as evidenced by the saussuritization of plagioclase and the uralitization, epidotization, and/or chloritization of pyroxene and olivine.

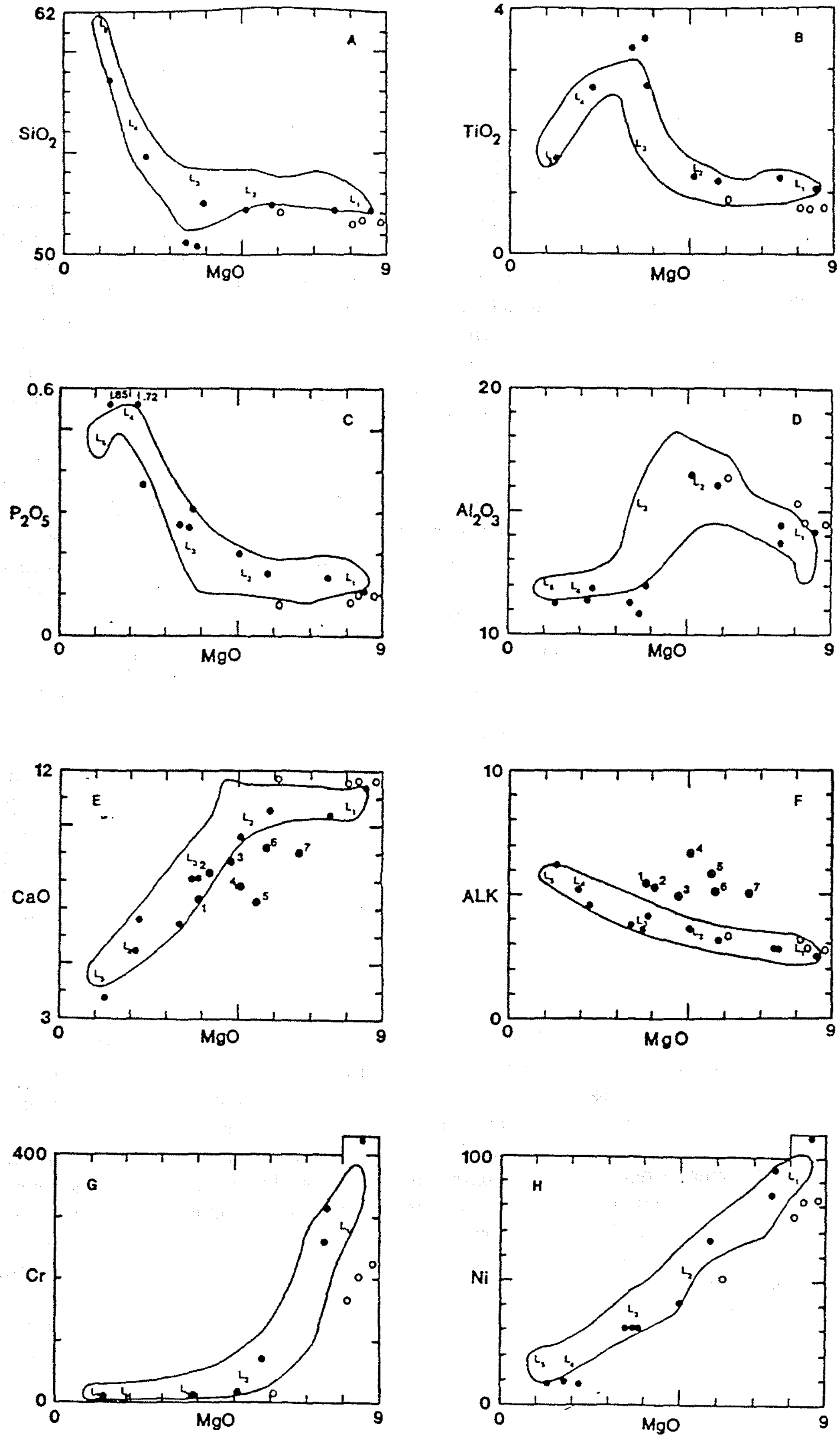


Figure 3. Selected whole-rock oxide and trace-element vs. MgO variation trend fields (from Husch, 1992) for diabase from the PRHL of the central Newark basin and associated sheets. Olivine-free samples from the Palisades section of the PRHL (solid circles, Walker, 1969) and possible LTQ-related samples from central New Jersey (open circles) also are shown. L_1 L_5 give positions of average compositions used in mass-balance models (see Tables 2 and 3). Samples numbered in E and F exhibit geochemical evidence (anomalously low calcium and high alkali contents) of contamination. Alk is total alkali ($Na_2O + K_2O$). Oxide concentrations have been normalized to 100 weight percent anhydrous and trace elements are given in ppm.

Whole-Rock Geochemistry

Whole-rock geochemical data for the PRHL and other diabase sheets have been presented by numerous workers (e.g. F. Walker, 1940; K. Walker, 1969; Puffer and others, 1982; Shirley, 1987; Husch and others, 1988; Houghton and others, 1992; Husch, 1992; Steiner and others, 1992, Gorring and Naslund, 1995). Selected major- and trace-element versus MgO variation trends from Husch (1992) are presented in Figures 3A-H. Although the fields shown are constructed largely from data for the central Newark Basin portion of the PRHL megasheet, the trends are extremely similar to those found for the northern Newark basin (Palisades) section. The trends shown do not include samples with greater than 9 wt% MgO or any samples from the OZ. The former are believed to be mafic enriched because of the accumulation of orthopyroxene and clinopyroxene, while the latter are greatly enriched in modal olivine (see below).

Although coarse-grained whole-rock compositions are quite variable, all fine-grained chilled margin samples are extremely similar, exhibiting a very restricted range of HTQ compositions (Table 1). This is in contrast to the multiple ENA magma types represented by fine-grained diabase and basalt samples from the Gettysburg, Hartford, and Culpeper Basins (Smith and others, 1975; Philpotts and Martello, 1986; Froelich and Gottfried, 1988) and the northern Newark basin (Puffer, 1988, 1992; see Part Two). The compositions of the fine-grained chilled margin samples are assumed to give the best available approximation of the HTQ magma parental to the PRHL and other diabase sheets and is labelled L1 in Figures 3A-H.

A number of the PRHL variation trend fields shown in Figures 3A-H have major inflection points, occurring at MgO contents of approximately 5, 3.5, and 2 wt%. Average whole-rock compositions approximating the points of inflection are labelled L2, L3, and L4, respectively. The point labelled L5 is the average composition of four granophyre-rich samples and is believed to approximate the final end-product of magma differentiation.

Crystal Fraction Models

In an attempt to quantify earlier differentiation models, Husch (1992) completed a series of major-element mass-balance calculations, utilizing the least-squares matrix inversion routine and the trace-element crystal-liquid distribution coefficients of Geist and others (1985). Results for compositions L1-L5 are summarized here and shown in Table 2, including the trace-element abundances produced by the major-element models. The agreement of calculated trace-element abundances with measured abundances provides an independent measure of the validity of the models.

Between 8 and 5 wt% MgO, two models are preferred. One produces the lowest calculated trace-element residuals while the other minimizes major-element residuals. Both models indicate that the early fractionation of the PRHL megasheet was dominated by pyroxene, with clinopyroxene being removed preferentially over orthopyroxene; plagioclase and Fe-Ti oxides may or may not have been involved. The removal (or addition) of olivine is not required and only increases trace-element residuals. For the 5 to 3.5 wt% MgO interval, the most significant change found is the dramatic increase in the required amount of fractionated plagioclase, averaging about 60% in all models run. Including olivine in the models improves major-element residuals only slightly, while increasing trace-element residuals significantly. For the 3.5 to 2 wt% MgO interval two models are preferred. One, with no olivine involvement, results in a fractionation assemblage similar to the one for the previous MgO interval. A second, where olivine is added (or resorbed), substantially reduces the major-element residuals. The preferred model for the 2 to 1 wt% MgO interval contains two significant changes. First, Fe-Ti oxide fractionation increases dramatically, and second, a small amount of apatite removal is required.

If the preferred interval models are combined, the total amount of crystallization needed to produce the most fractionated composition is 70-80%. The preferred models also show that the early fractionation assemblage is dominated by pyroxene, particularly clinopyroxene. Subsequent assemblages are dominated by plagioclase with Fe-Ti oxide and apatite fractionation becoming important only for the lowest MgO rocks. Although there are obvious uncertainties and simplifications inherent in these models, there are independent lines of geochemical evidence that support these conclusions. For example, Rayleigh fractionation models for

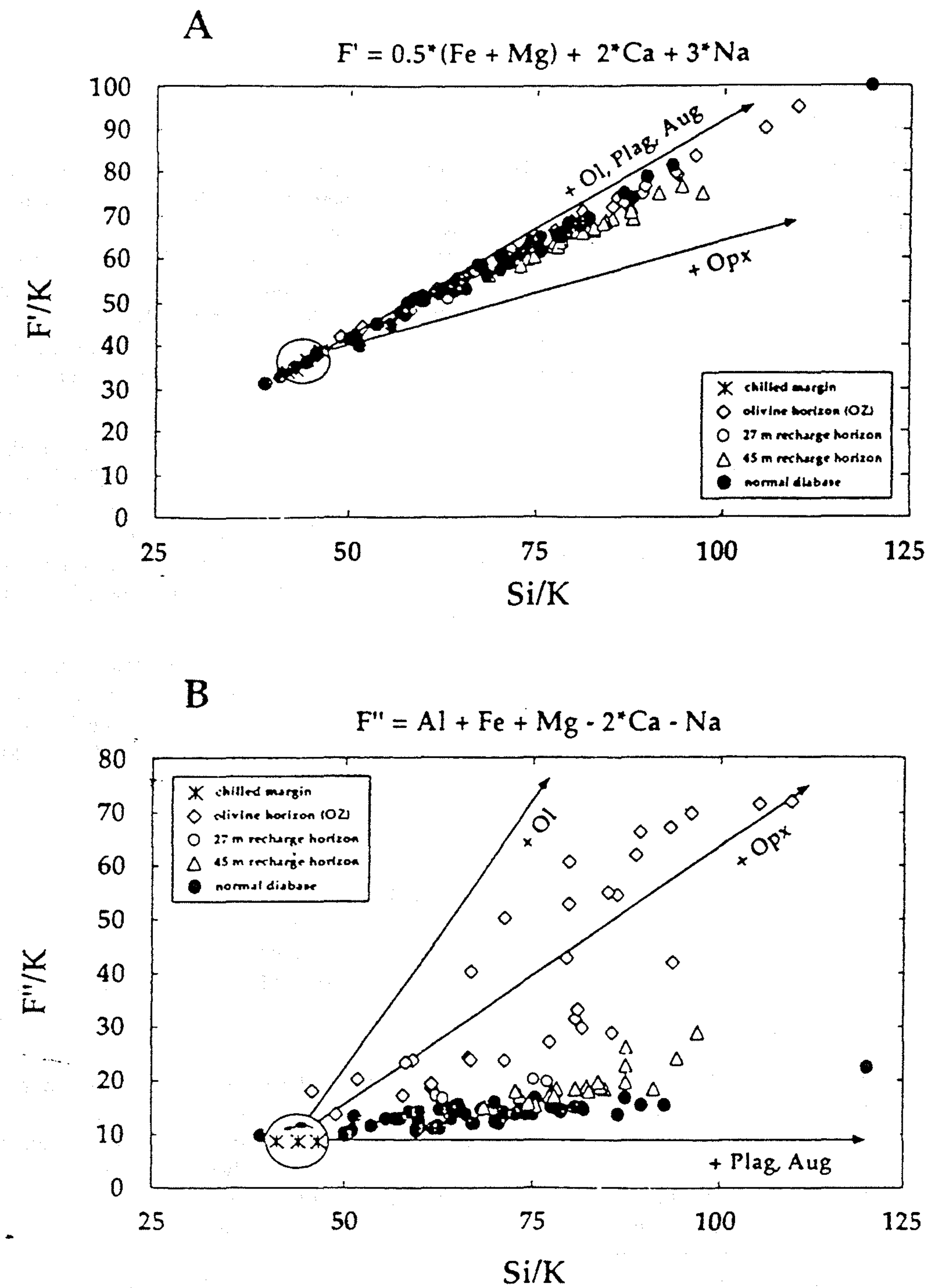


Figure 4. Pearce Element Plots (from Gorring and Naslund, 1995) for the Fort Lee, NJ section of the Palisades. Although olivine control can not be determined in **A**, most, if not all, OZ rocks (open diamonds) in **B** require the addition of olivine in order to produce the fractionation trends observed. All non-OZ rock compositions can be produced by the addition or removal of clinopyroxene, orthopyroxene, and plagioclase without the participation of olivine.

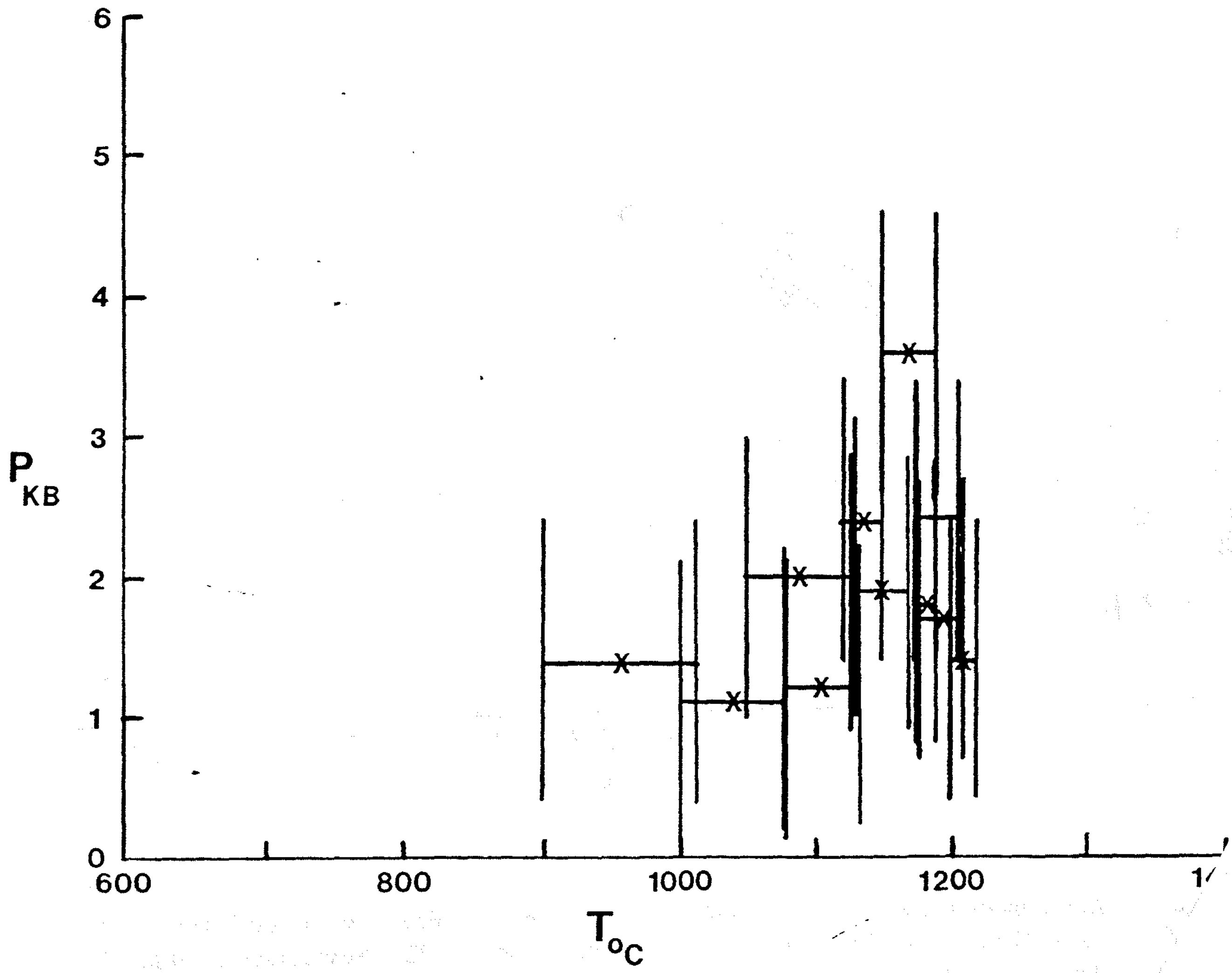


Figure 5. P-T determinations (with uncertainty estimates) for clinopyroxenes from c
Newark basin diabase (from Husch, 1991). Median pressure value of 1.7 Kb is ap'
for a depth of approximately 5 km.

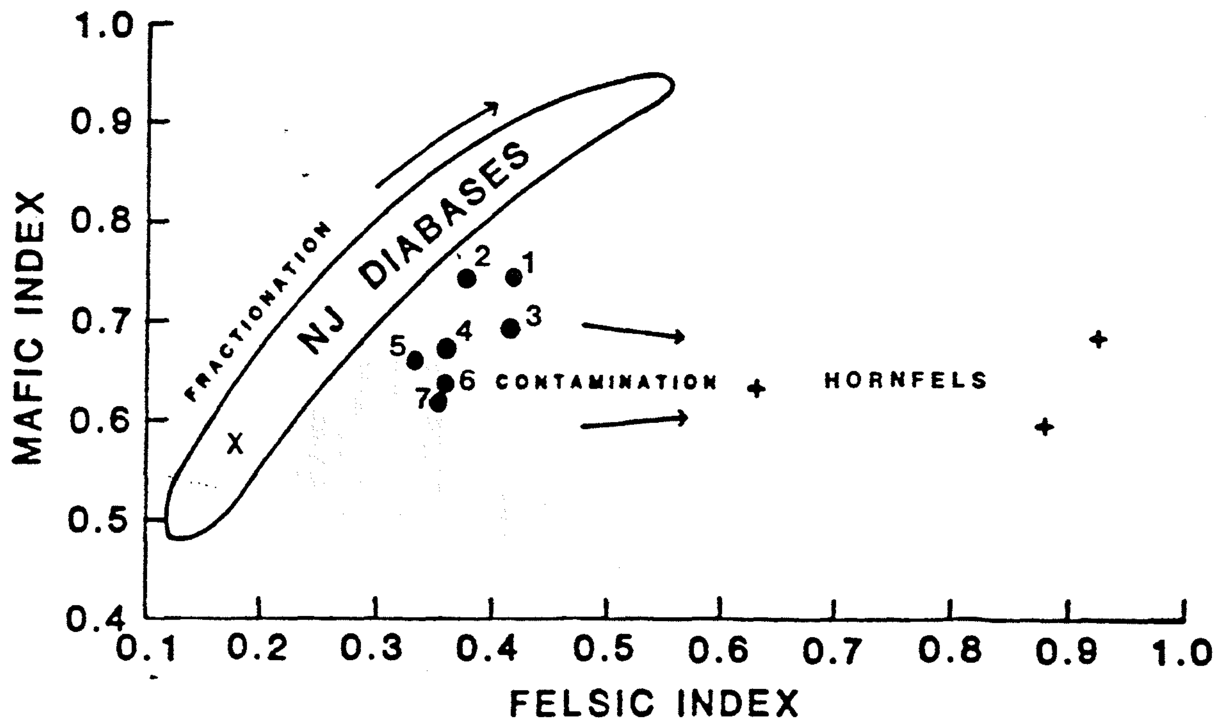


Figure 6. Mafic index (Fe_2O_3*/Fe_2O_3*+MgO: all iron reported as Fe_2O_3) vs. felsic index ($Na_2O+K_2O/Na_2O+K_2O+CaO$) variation diagram (from Husch, 1992). New Jersey diabase field includes data for Palisades from Walker (1969). Numbered samples exhibit evidence of contamination and are the same as in Fig. 3E-F.

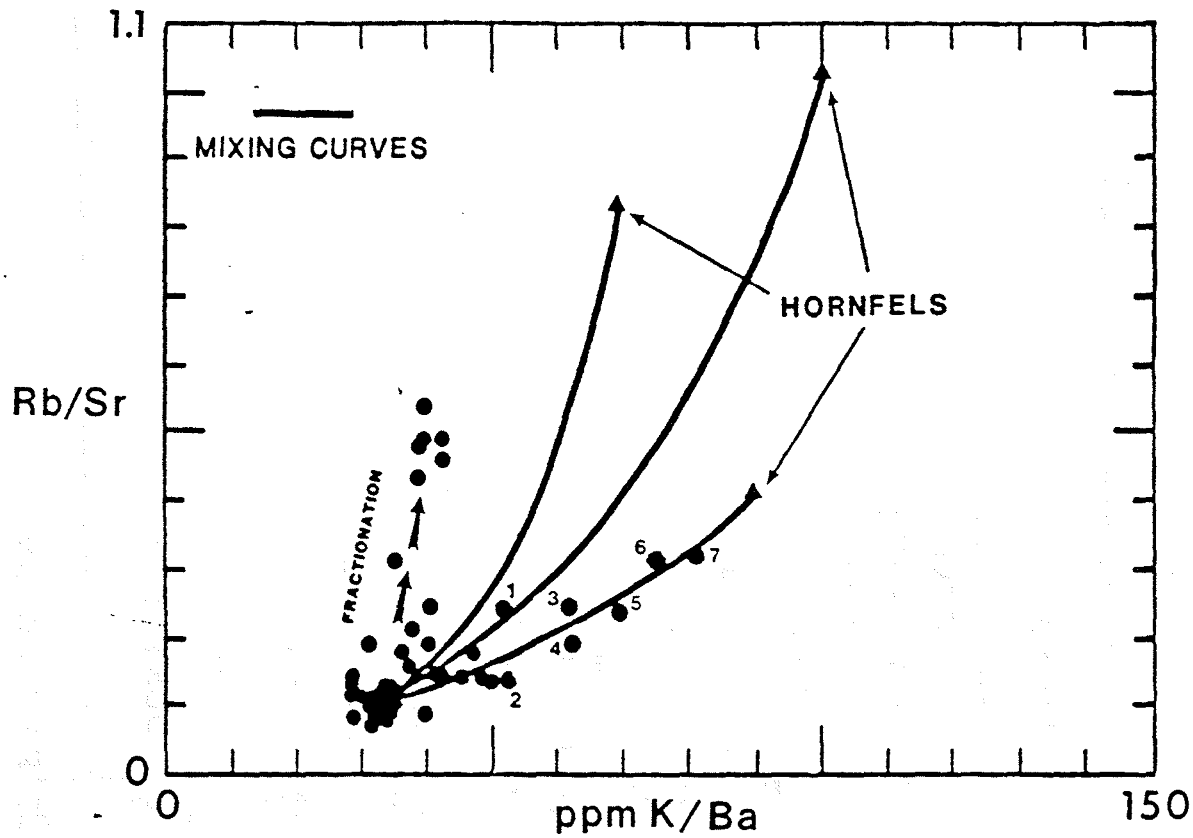


Figure 7. Rb/Sr vs. K/Ba variation diagram (from Husch, 1992). Three mixing curves, extending from average chill composition to each of three analyzed hornfels compositions, calculated using the general equations of Langmuir and others (1978). Numbered samples exhibit evidence of contamination and are the same as in Fig. 3E-F.

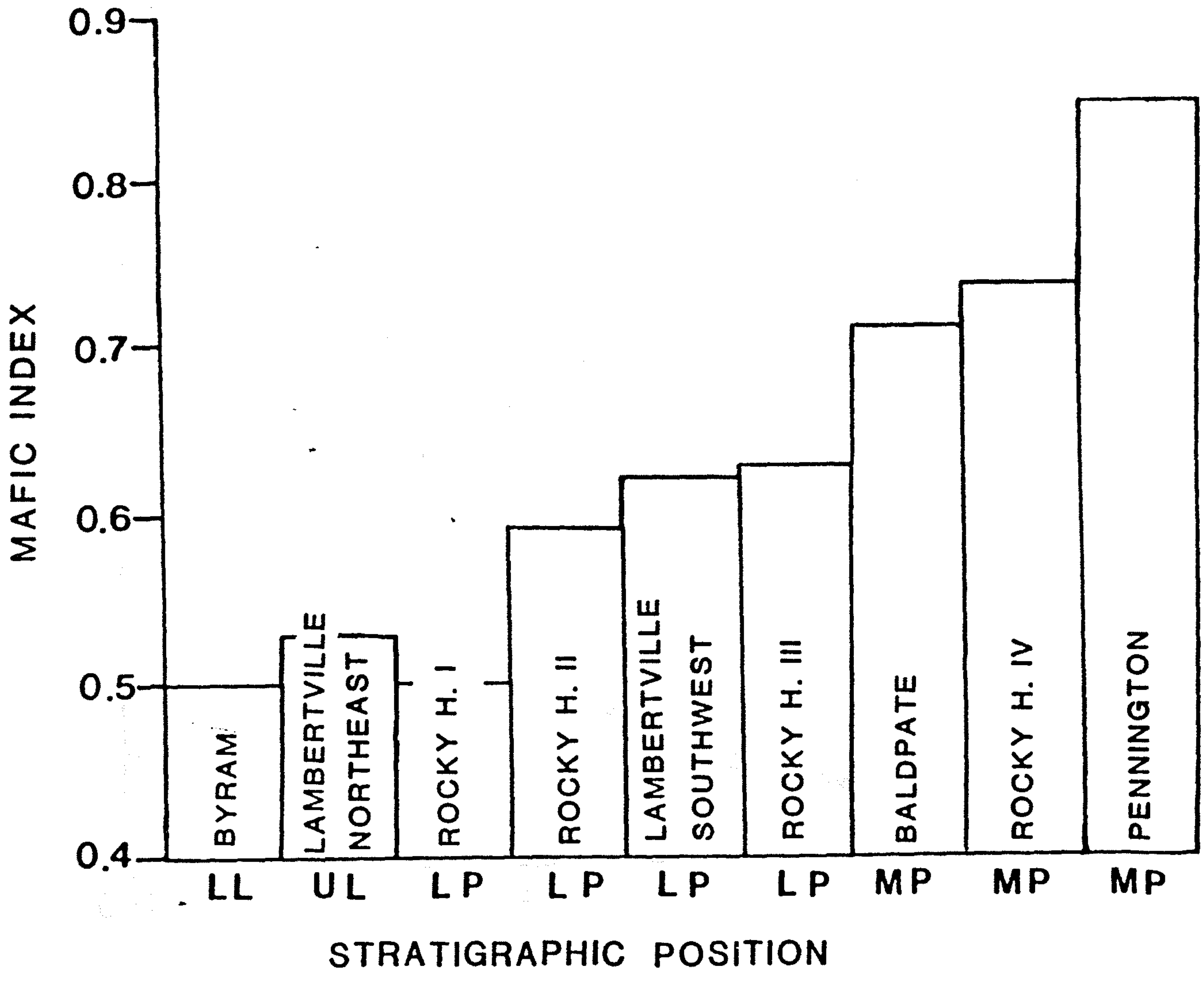


Figure 8. Average mafic index (Fe_2O_3*/Fe_2O_3*+MgO: all iron reported as Fe_2O_3) vs approximate stratigraphic level of emplacement for various exposures of central Newark basin diabase. Rocky H. I-IV averages represent separate sampling areas through the Rocky Hill diabase as it cuts up section. LL=Lower Lockatong Formation; UL=Upper Lockatong Formation; LP=Lower Passaic Formation; MP=Middle Passaic Formation.

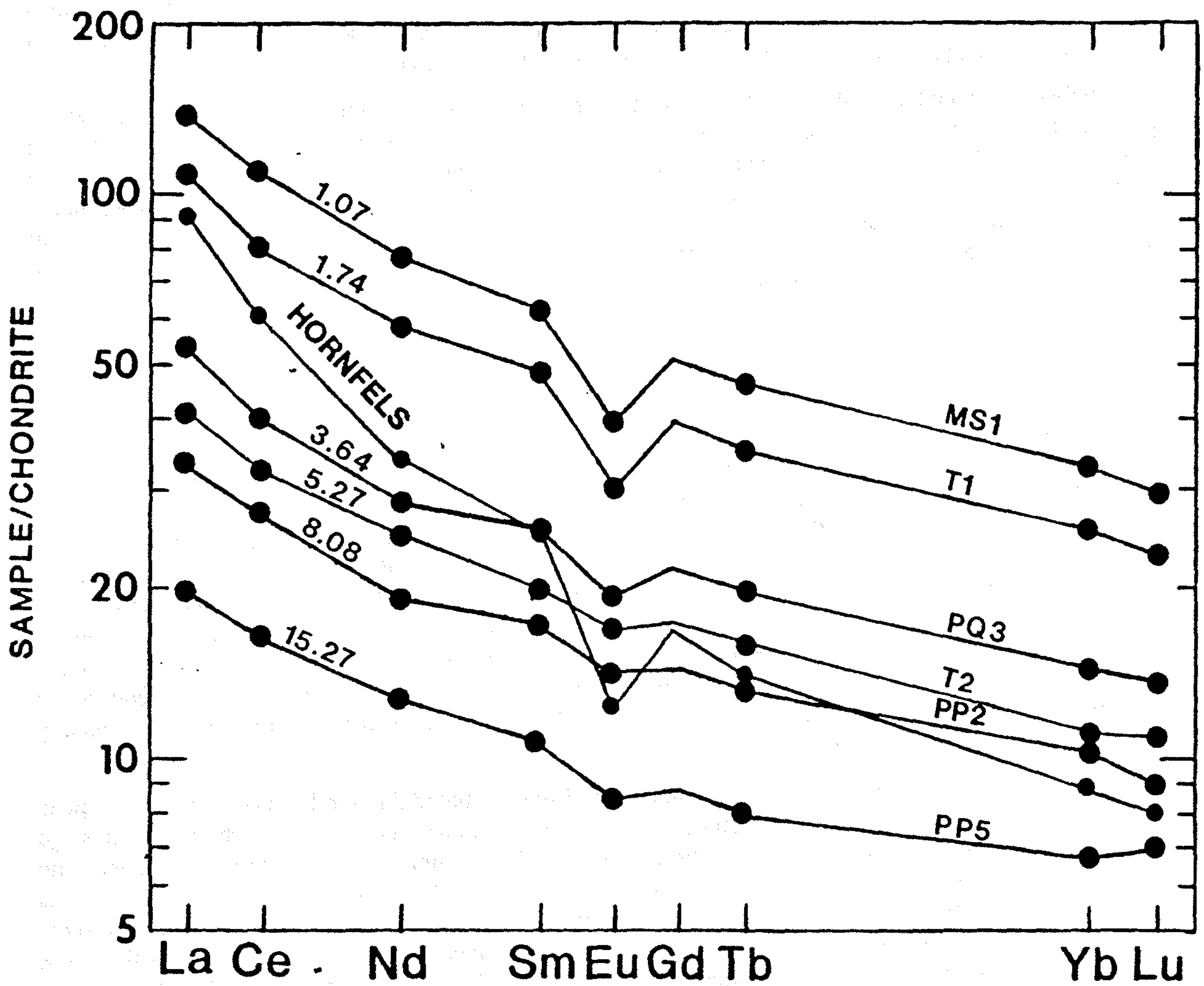


Figure 9. Chondrite-normalized REE distribution patterns for selected diabase samples from the central Newark basin and one hornfels sample (after Husch, 1992). MgO contents in weight percent of the diabase samples are shown at the left of each pattern. Note distinctly higher slope for the hornfels sample compared to diabase, particularly granophyric ones (low MgO rocks).

Ba, Rb, and Zr also require about 75% crystallization in order to produce the most fractionated compositions (Husch and others, 1988). Furthermore, Husch (1992) showed that a number of the important features of measured REE distributions patterns can be reproduced by the combined preferred models. Finally, the combined fractionation scheme generally agrees with other HTQ-related diabase fractionation models proposed by Steiner and others (1992), Gorring and Naslund (1995), and Woodruff and others (1995).

Mafic-Rich Samples

Mass-balance calculations (Table 3) also show that many high-MgO (>9 wt%) samples result form the accumulation of variable amounts of clinopyroxene and orthopyroxene in the average PRHL chilled margin composition (Husch, 1992). For one sample, LS2, the added cumulate minerals are almost identical in their proportions to one of the preferred fractionation models for the 8 to 5 wt% MgO interval (cf. Tables 2 and 3), suggesting they may be complementary compositions. A rare olivine-rich rock, sample CH2, from the Rocky Hill diabase segment of the PRHL does require olivine to be added in an amount that matches its modal abundance. Gorring and Naslund (1995) also show that OZ rocks require the addition of olivine (along with clinopyroxene, orthopyroxene, and plagioclase), whereas non-OZ mafic-rich rocks do not (Fig. 4).

Whether the modelled crystal fractionation and mineral accumulations took place at the present level of exposure, at depth, or as a combination of the two has not been determined unambiguously. Gorring and Naslund (1995) believe the mineral accumulations required to produce the rocks of the OZ took place in a differentiating sub-PRHL, HTQ-derived magma chamber and did not occur in situ. On the other hand, pyroxene thermobarometry studies by Husch (1991) on non-OZ rocks from central New Jersey suggest that diabase differentiation took place within the PRHL megasheet at a pressure of 1-2 kb (Fig. 5), consistent with the sheet's typical stratigraphic level of emplacement beneath approximately 5 km of Triassic sediments.

Localized Contamination and Origin of Cross-Cutting Leucocratic Dikes

A number of samples from the PRHL and other diabase sheets contain anomalously high alkali and low Ca for a given value of MgO (Benimoff and Sclar, 1984, 1988; Husch and Schwimmer, 1985; Husch and others, 1988; Husch, 1992); seven of these are labelled in Figures 3A-H. These samples also plot consistently to the right of the main diabase variation trend on a mafic index vs. felsic index variation diagram (Fig. 6) and along one of the calculated mixing curves on a Rb/Sr vs K/Ba variation diagram (Fig. 7). As detailed by Benimoff and Sclar (1984, 1988) and further documented by Husch (1992), the anomalous compositions apparently were produced by the selective diffusion of alkalis from a contaminant, best approximated by hornfels of Passaic or Lockatong Formation, and of calcium from the enveloping diabase magma into a leucocratic anatectic melt derived from the contaminating material. Although Sr isotopic ratios are increased by this contamination process, many elements, including Al, Cr, Mg, Ni, Ti, and the REEs, appear completely unaffected (Husch and Schwimmer, 1985; Husch, 1992).

Benimoff and others (1989) and Benimoff and Sclar (1990) proposed that the leucocratic anatectic melts produced by the partial fusion of contaminating xenoliths were intruded into cooling fractures as late-stage dikes that cross-cut the sheets at numerous localities. The very similar compositions of the dikes and anatectic melts, particularly their extremely low K_2O/Na_2O values (typically <0.05) and REE distribution patterns (Benimoff and Sclar, 1992), support this model. F. Walker (1940), on the other hand, believed the late-stage dikes (or "white veins") were derived from residual granophyric magmas produced by crystal fractionation, whereas K. Walker (1969) concluded they were hydrothermal in origin. Laney and others (1995) sampled a number of sodic dikes and veins from the northeastern end of the Lambertville section of the PRHL megasheet and discovered at least three distinct compositional groups. One (low-K_2O) group appears derived from anatectic melts of xenolithic origin, a second (high-K_2O) group appears to be produced by intruding magmas residual to diabase crystal fractionation, and a third group has transitional characteristics and may be hybrid in origin. Evidently, as with cats, there is more than one way to derive a dike!

TABLE 3. MASS-BALANCE MODELS FOR MGO-RICH ROCKS

Parent: L_1 Daughter: LSR5

	Solution	% Cumulate
Chill	1.000	
CPX	0.237	62.963
OPX	0.094	24.817
PLAG1	0.039	10.269
MAG	0.007	1.813
ILM	0.001	0.138
LSR5	1.377	

$R^2 = 0.062$

	Daughter	Calc.	Resid.
SiO_2	52.22	52.33	-0.12
TiO_2	0.95	0.95	0.00
Al_2O_3	11.64	11.68	-0.04
FeO*	10.32	10.35	-0.03
MnO	0.19	0.18	0.01
MgO	10.69	10.69	0.00
CaO	11.50	11.51	-0.01
Na_2O	1.91	1.70	0.21
K_2O	0.50	0.51	-0.01
P_2O_5	0.08	0.10	-0.02

Parent: L_1 Daughter: LS2

	Solution	% Cumulate
Chill	1.000	
CPX	0.293	44.429
OPX	0.231	34.945
PLAG1	0.127	19.183
MAG	0.006	0.975
ILM	0.003	0.469
LS2	1.660	

$R^2 = 0.006$

	Daughter	Calc.	Resid.
SiO_2	52.34	52.35	-0.01
TiO_2	0.89	0.89	0.00
Al_2O_3	11.45	11.45	0.00
FeO*	10.00	10.00	0.00
MnO	0.17	0.17-	0.00
MgO	11.91	11.91	0.00
CaO	11.08	11.08	0.00
Na_2O	1.67	1.62	0.05
K_2O	0.46	0.44	0.02
P_2O_5	0.03	0.08	-0.05

Parent: L_1 Daughter: PP5

	Solution	% Cumulate†
Chill	1.000	
CPX	0.263	18.881
OPX	0.819	58.672
PLAG1	0.305	21.831
ILM	0.008	0.599
PP5	2.395	

$R^2 = 0.058$

	Daughter	Calc.	Resid.
SiO_2	52.61	52.77	0.16
TiO_2	0.75	0.75	0.00
Al_2O_3	10.31	10.35	-0.04
FeO*	9.65	9.68	-0.03
MnO	0.18	0.17	0.01
MgO	15.42	15.44	-0.02
CaO	9.05	9.06	-0.01
Na_2O	1.57	1.40	0.17
K_2O	0.35	0.33	0.02
P_2O_5	0.11	0.06	0.05

Parent: L_1 Daughter: ELS11

	Solution	% Cumulate†
Chill	1.000	
CPX	0.278	73.714
OPX	0.071	18.827
PLAG1	0.028	7.505
MAG	-0.002	-0.538
ILM	0.002	0.493
ELS11	1.378	

$R^2 = 0.027$

	Daughter	Calc.	Resid.
SiO_2	52.47	52.57	-0.10
TiO_2	0.94	0.94	0.00
Al_2O_3	11.49	11.52	-0.03
FeO*	9.89	9.91	-0.02
MnO	0.18	0.18	0.00
MgO	10.68	10.69	-0.01
CaO	11.89	11.91	-0.02
Na_2O	1.80	1.68	0.12
K_2O	0.53	0.51	0.02
P_2O_5	0.12	0.10	0.02

Parent: L_1 Daughter: CH2

	Solution	% Cumulate†
Chill	1.000	
OL	0.108	23.279
CPX	0.164	35.289
OPX	0.099	21.179
PLAG1	0.087	18.725
MAG	0.009	1.877
ILM	-0.002	-0.348
3.5%	1.466	

$R^2 = 0.047$

	Daughter	Calc.	Resid.
SiO_2	51.46	41.46	0.00
TiO_2	0.82	0.82	0.00
Al_2O_3	11.84	11.82	0.02
FeO*	10.48	10.49	-0.01
MnO	0.18	0.15	0.03
MgO	12.58	12.58	0.00
CaO	10.38	10.39	-0.01
Na_2O	1.54	1.70	-0.16
K_2O	0.63	0.49	0.14
P_2O_5	0.08	0.10	-0.02

*All iron reported as FeO.

†Cumulate values are the relative weight percents of the minerals added to L_1.

TABLE 4. FLEMINGTON DIKE AND FLEMINGTON BASALT COMPOSITIONS

	1	2	3	4	5
SiO_2	52.65	53.09	52.11	52.34	50.42
TiO_2	1.13	1.13	1.11	1.13	1.26
Al_2O_3	14.37	13.96	14.17	14.38	14.91
FeO*	10.58	10.06	9.89	9.90	11.27
MnO	0.19	0.16	0.16	0.17	0.20
MgO	7.49	7.94	8.14	7.94	7.98
CaO	10.78	10.29	10.41	9.53	8.08
Na_2O	2.15	2.00	1.86	2.36	5.08
K_2O	0.67	0.86	0.68	1.53	0.65
P2O5	--.--	0.16	0.14	0.12	0.14
Ba	---	146	143	182	300
Cr	277	300	303	316	292
Ni*	81	83	79	83	70
Sr	186	201	191	188	188
Zr	92	102	97	109	99

Major elements normalized to 100 weight percent anhydrous. Trace elements in ppm. *All iron as FeO. 1=average ENA-HTQ basalt (Weigand and Ragland, 1970); 2, 3, and 4=Flemington dike samples FD2, FD5, and FD8, respectively (Crohe, 1996). 5=Flemington basalt (Houghton and others, 1992).

Table 5 **Pangean Flood Basalts**

	HTQ Large Igneous Province							Other Pangean	
	Orange Mt. NJ	Talcott Conn	Mt.Zion VA	North Mt Nova Scoti	H Atlas Morocco	Algarve Portugal	S.Parana Brazil	Norilsk Siberia	Lesotho S. Africa
samples	7	7	18	3	14	2	12	58	49
Wt %									
SiO_2	50.93	51.16	51.89	50.86	51.51	50.71	51.91	50.28	51.5
TiO_2	1.15	1.06	1.15	1.14	1.16	0.99	0.94	1.12	0.95
Al_2O_3	14.25	14.08	14.42	13.78	14.03	14.11	15.82	15.17	15.69
FeOt	9.8	10.71	10.03	8.6	9.34	10.12	9.81	9.8	9.86
MnO	0.16	0.16	0.18	0.12	0.16	0.16	0.16	0.17	0.16
MgO	7.75	7.87	7.7	7.94	7.93	7.73	7.39	7.2	7.01
CaO	10.68	11.09	10.34	9.92	10.71	10.97	10.75	10.13	10.69
Na_2O	2.43	2.03	2.78	2.23	2.05	2.26	2.18	2.17	2.17
K_2O	0.48	0.49	0.27	1.01	0.51	0.53	0.76	0.89	0.7
P_2O_5	0.14	0.13	0.13	0.18	0.17	0.14	0.15	0.06	0.16
LOI*	1.16	1.38		2.3	1.31	1.79		2.86	
Total	98.93	100.16	98.89	98.08	98.88	99.51	99.87	99.85	98.89
ppm									
Ba	182	174	145	143	109	386	272	370	177
Cr	337	322	282	224	240	241		130	283
Ni	85	86	79	73	87	87		120	94
Rb	27	22	11	17	20	20	34		12
Sr	192	186	191	201	187	235	236	240	192
Zr	101	87	99	102	103	98	96		94
La	10.9	11.1	10.8	12.4	10.6	14.6	14	16.5	9.9
Ce	25.1	23.9	24.1	26.1	22.5	29.7		36	23.7
Sm	1.09	3.66	3.51	3.65	3.3	4.11		4.3	3.25
Eu	1.2	1.15	1.13	1.16	1.11	1.23		1.2	
Yb	2.3	2.35	2.3	2.23	2.19	2.29		2.4	
Lu	0.39	0.33	0.34	0.35	0.33	0.37		0.6	

Non-Pangean Flood Basalts

	Imnaha Wash	Lolo Wash	loSnakeR Idaho	upSnakeR Idaho	loDeccan India	upDeccan India	loEast Rift Ethiopa	upEast Rift Ethiopa	lKeeween L.Superior	uKeeween L.Superior
samples	21	29	1	1	1	1	81	5	1	1
wt. %										
SiO_2	51.11	50.04	46.18	45.89	50.56	47.93	50.5	47.8	48.55	49.54
TiO_2	2.04	3.2	2.06	3.33	2.57	3.05	3	2.7	1.86	2.14
Al_2O_3	14.92	14.37	14.47	14.63	13.83	14.96	14.2	15.4	9.02	15.05
FeOt	13.16	14.04	12.17	14.81	12.41	11.78	11.89	11.54	12.57	12.28
MnO	0.23	0.24	0.19	0.21	0.17	0.17	0.2	0.19	0.24	0.17
MgO	5.08	5.25	9.99	6.46	5.12	4.53	5.5	6.6	11.69	5.05
CaO	9.55	8.91	9.68	9.37	9.62	9.73	9.6	10.5	11.29	8.38
Na_2O	2.76	2.29	2.63	2.84	2.65	2.89	3	2.9	1.62	2.67
K_2O	0.68	1.03	0.61	0.65	0.93	1.49	1	0.6	0.71	1.29
P_2O_5	0.28	0.67	0.44	0.69	0.22	0.34	0.5	0.46	0.25	0.29
LOI*						2.47	1.2	0.96	1.77	2.54
Total	99.81	100.04	98.42	98.88	98.08	99.34	100.59	99.65	99.57	99.4
ppm										
Ba	277	477	298	464	239		537	201		
Cr	78	78	256	107	44		107		890	207
Ni	28	40	193	44	44		31	5.6	240	90
Rb	15	28	13.7	10.4	15		22	248	46	50
Sr	238	298	285	370	219		521		389	235
Zr	193	195	167	295	203		264	28	207	
La	14.4	27	18.3	32.3	19.3	36.4	28	55	29.4	19.4
Ce	33.8	56	41.2	74	43	69.8			77	44.4
Sm	5.72	8	5.6	9.4	7.6	6.53		1.8	8.66	6.74
Eu	1.88	2.55	1.94	3.35	2.47	2.49	3.2		2.29	1.91
Yb	4.06	3.88	2.78	4.06	3.63	2.58			2.36	3.6
Lu	0.61	0.59	0.42	0.61	0.53	0.37			0.26	0.54

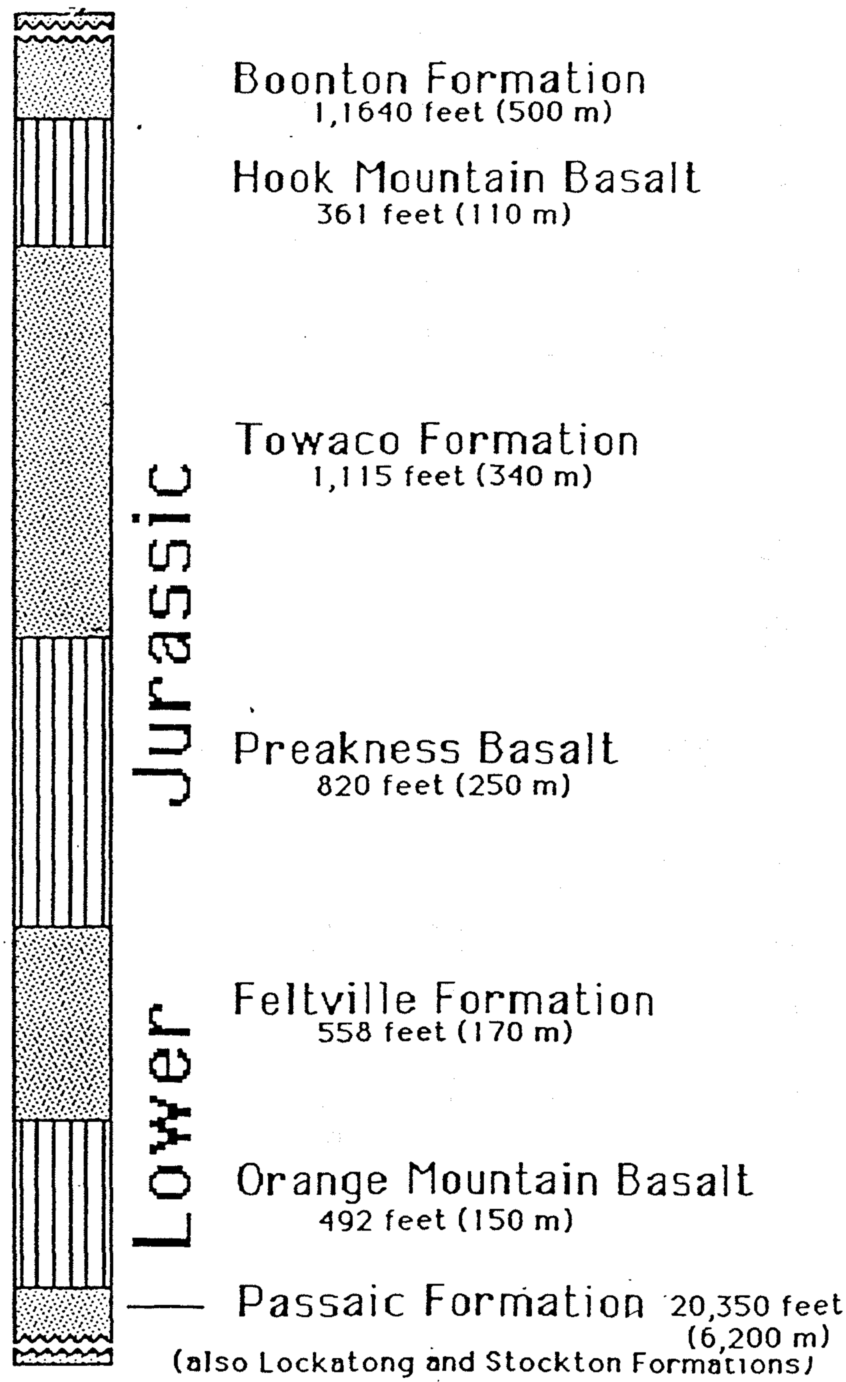


Figure 10. Stratigraphic column for the Newark basin after Tollo and Gottfried (1992). Thickness data are from Olsen and others (1989).

Lateral Compositional Variations and Migration of Residual Magmas

It now is widely accepted that many sections through the diabase sheets (including the PRHL) of the Newark, Gettysburg, and Culpeper Basins are not in mass balance with their HTQ or LTQ parent (Smith, 1973; Froelich and Gottfried, 1985, 1988; Husch and others, 1988; Husch, 1992; Mangan and others, 1993; Woodruff and others, 1995) and that significant lateral and up-dip migrations of residual magmas must have occurred. The calculated average compositions for these sections across individual diabase exposures support what is obvious in the field; those sections with significant pyroxene-rich zones lack complementary residual, granophyric compositions, and those that do have large volumes of granophyric rock lack significant, if any, amounts of pyroxene-rich rocks.

Murphy and Husch (1990) and Husch (1992) further showed that the lateral variations in average PRHL diabase composition could be correlated with the emplacement level of the megasheet within the surrounding Triassic sedimentary rocks; the higher in the stratigraphy the exposed section is located, the more fractionated its average composition (Fig. 8). Three localities where this relationship has been documented in detail are: 1) along the continuously exposed discordant western end of the Rocky Hill diabase section of the PRHL megasheet (Murphy and Husch, 1990); 2) at three separate sections across the Lambertville sill section of the PRHL megasheet, particularly as found at a centrally located stope-like structure (Szemple, 1996; Stop 6); 3) along the highly discordant and continuously exposed northeastern arm of the CMD (Stop 4), a dike-like structure that traverses over 6000 ft of the Triassic sedimentary section (Keely and Husch, 1993). For all three cases, true granophyric rocks are found only at the highest exposed structural levels of each sheet.

A similar situation appears to be the case for the Palisades section of the PRHL, where the mildly fractionated northern dike-like extension in southeastern New York is emplaced relatively high up in the Late Triassic section (Puffer and others, 1982; Ratcliffe, 1988). This contrasts with the northern New Jersey segment (Stop 1), where the sheet is much more conformable and emplaced at its lowest level in the Basin (Stockton Formation). In this region, mafic-rich rocks, including those of the geographically restricted OZ (Husch, 1990), are much more common and lateral variations in composition are much reduced (Shirley, 1988).

As discussed by Husch (1992), there is no evidence to suggest that the observed lateral compositional variations and their consistent relationship with structural or stratigraphic level of emplacement were produced by the intrusion of variable parental magma compositions, the in-situ large-scale anatexis of surrounding country rock, the localized fractionation of varying mineral assemblages, or the large-scale contamination of sections of the sheets. For example, chilled margin compositions are extremely constant (Table 1) and all of the HTQ type, granophyric rocks have REE distribution patterns similar in slope to those for all other diabase compositions and distinctly different than those for the country rock (Fig. 9). Furthermore, differentiation trends are similar from throughout the region, as are the proposed crystal fractionation models that produce them, and recognized country-rock contamination and associated anatexis appears volumetrically minor and restricted to a limited number of localities.

There also is no evidence to suggest that significant amounts of late-stage, fractionated granophyric magmas were erupted onto the surface as part of the OMB, PB, or HMB (see Part Two). Rather, it appears that once the PRHL and other diabase sheets were intruded contemporaneously with the OMB, they remained relatively closed systems with little, if any, residual magmas being ejected. An excellent example of this relationship is found at the stope-like structure of the Lambertville sill section of the PRHL (Stop 6) and its associated Flemington dike (Fig. 5); the dike cross-cuts over 9000 ft of the Late Triassic sedimentary section, feeding the Flemington basalt, an OMB equivalent. Crohe (1996) documents that the composition of the Flemington dike is resonably constant except for increasing signs of contamination with decreasing depth, and is essentially the same as the HTQ-type magma found at all sampled PRHL chilled margins and the Flemington basalt (Table 4); no fractionated compositions are seen anywhere in the dike-basalt system. This is despite the fact that the dike emerges from the sheet at the same general location where significant amounts of granophyric compositions are found (Szemple, 1996). So, although it appears that while the PRHL sheet internally differentiated for some period of time (hundreds to a few thousand years; Shirley, 1987; Husch, 1992; Gorring and Naslund, 1995), the feeder system to the surface flows shut down almost immediately upon the contemporaneous intrusion of the parental HTQ magma. Residual granophyric magmas could then only migrate to the highest structural levels within the sheet in which they were generated. Thus, the picture that is now emerging is one of a very short-lived, though multiple, sheet injection event of a regionally constant HTQ magma, followed by the dynamic, but self-contained, differentiation of the individual sheets.

PART 2: THE WATCHUNG FLOOD BASALTS

Stratigraphy

The Watchung basalt flows are grouped into three units (Orange Mountain, Preakness, and Hook Mountain) separated by Lower Jurassic red-bed siltstone formations (Figure 10).

The Orange Mountain unit consists of three flows (Puffer and Student, 1992), a very thick lower flow and two relatively thin upper flows, totaling 150 m (Olsen and others 1989, 96). The flow contacts are defined by scoriaceous flow tops beneath overlying massive to vesicular flow bottoms and the common presence of discontinuous layers of red-bed sediment between flows.

The Preakness unit consists of five flows defined on the same basis, and in the case of the lowest two flows by a 2 to 4 m thick layer of siltstone. The combined thickness of the five flows totals 250 m (Olsen and others, 1989). The lowest of the five flows is the thickest (about 150 m) overlain by a second flow 80 to 100 m thick and three relatively thin upper flows that total about 40 to 65 m thick (Puffer and Student, 1992).

The Hook Mountain unit consists of three flows separated by thin discontinuous layers of red-bed sediment (Puffer and Student, 1992) for a combined thickness of 110 m (Olsen and others, 1989).

Most of the Watchung flows are subaerial, but pillowed basalt, (particularly within the upper Orange Mountain and portions of the second Preakness flow) is found in the Paterson, New Jersey area where early Jurassic lake waters were deepest.

The three early Jurassic Watchung units correlate with early Jurassic basalt units exposed north and south of New Jersey on the basis of virtually indistinguishable petrography and chemical compositions (Puffer and Philpotts, 1988), and the paleontology of interbedded sedimentary units.

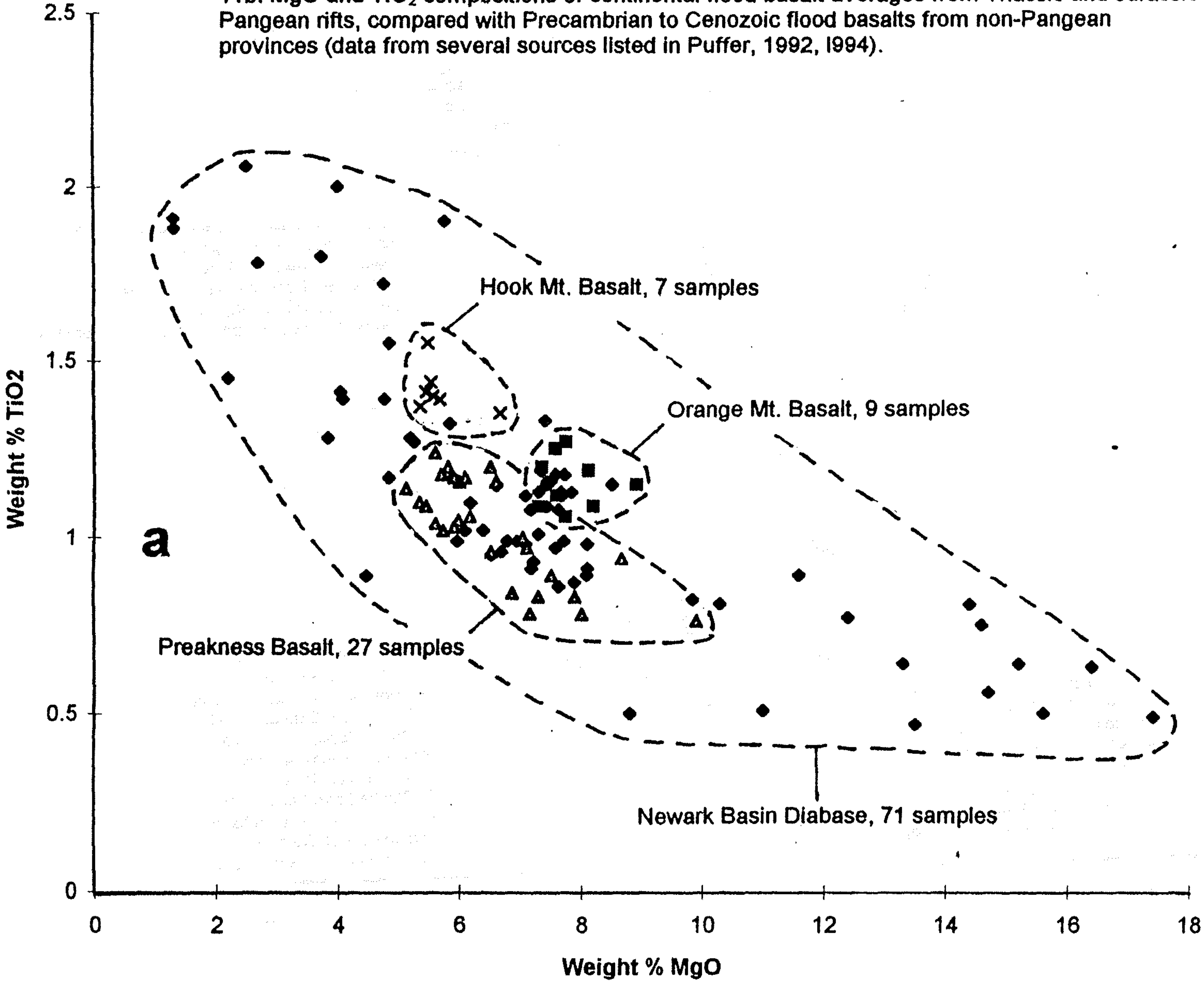
Petrography

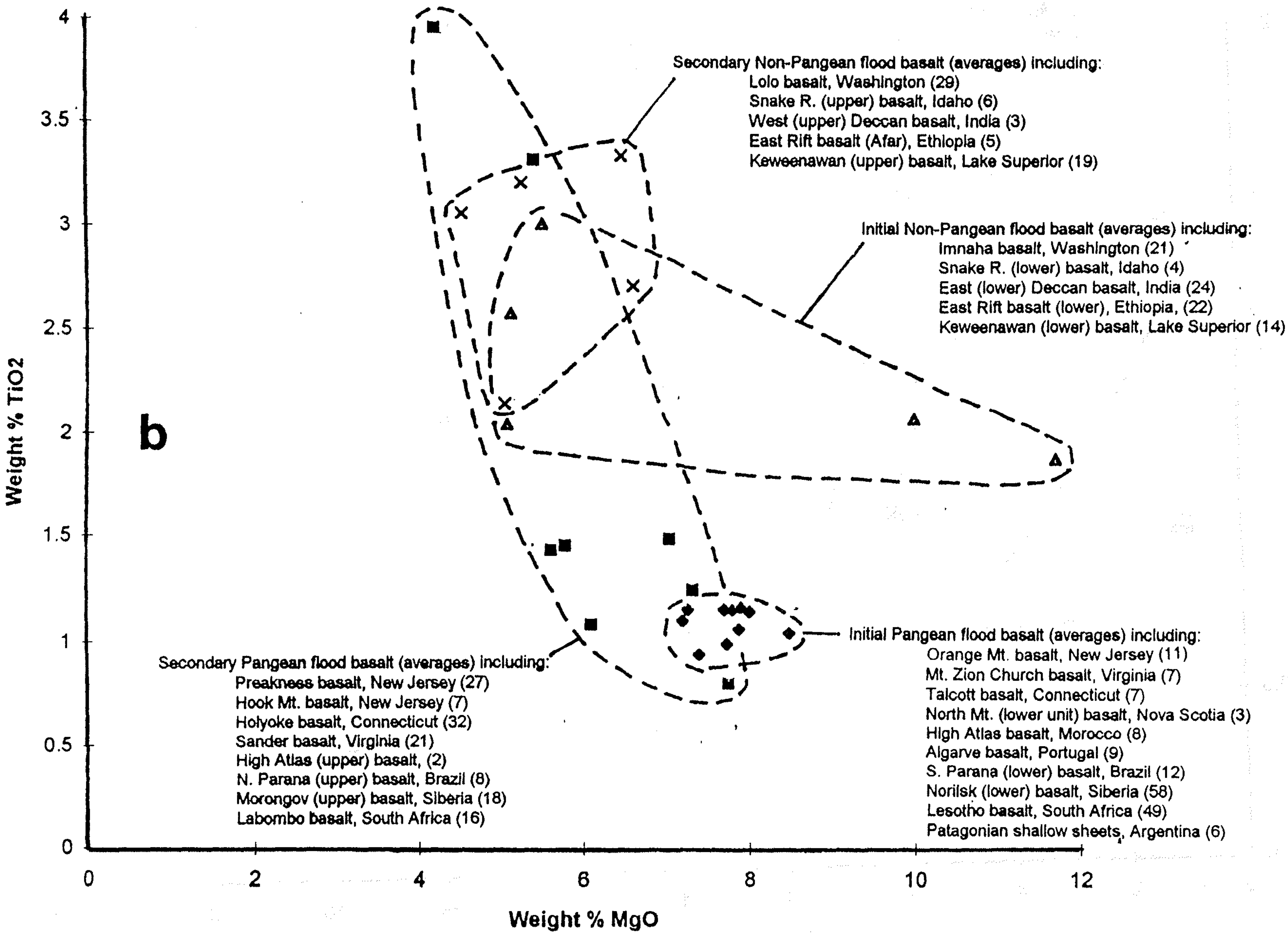
Orange Mountain basalt is petrographically indistinguishable from the Talcott basalt of Connecticut and the Mount Zion Church basalt of Virginia. Most Orange Mountain basalt consists of glomeroporphyritic clusters and intergrowths of subhedral augite and subhedral plagioclase plus common dispersed grains of plagioclase and pyroxene in a dark brown, fine grained to glassy mesostasis. The mesostasis comprises about 5 to 20 percent of the rock and contains abundant skeletal grains of ilmeno-magnetite.

Preakness basalt is typically aphyric to porphyritic and coarser grained than Orange Mountain basalt, but there is a wide variation in textures among the five Preakness flows. The lower two flows are particularly coarse and contain more plagioclase and much less mesostasis than Orange Mountain basalt or the upper three Preakness flows.

Hook Mt. basalt is also coarser grained than Orange Mountain basalt and there is much less textural variation than present in the Preakness. The Hook Mountain is typically aphyric but is locally porphyritic.

Figure 11a. MgO and TiO_2 compositions of diabase from the Newark Basin (Gottfried and others, l991) compared with Orange Mt, Preakness, and Hook Mt. basalts (Puffer, l992);
11b. MgO and TiO_2 compositions of continental flood basalt averages from Triassic and Jurassic Pangean rifts, compared with Precambrian to Cenozoic flood basalts from non-Pangean provinces (data from several sources listed in Puffer, 1992, l994).




b
Weight % TiO2
Weight % MgO
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
Secondary Non-Pangean flood basalt (averages) including:
Lolo basalt, Washington (29)
Snake R. (upper) basalt, Idaho (6)
West (upper) Deccan basalt, India (3)
East Rift basalt (Afar), Ethiopia (5)
Keweenawan (upper) basalt, Lake Superior (19)
Initial Non-Pangean flood basalt (averages) including:
Imnaha basalt, Washington (21)
Snake R. (lower) basalt, Idaho (4)
East (lower) Deccan basalt, India (24)
East Rift basalt (lower), Ethiopia, (22)
Keweenawan (lower) basalt, Lake Superior (14)
Secondary Pangean flood basalt (averages) including:
Preakness basalt, New Jersey (27)
Hook Mt. basalt, New Jersey (7)
Holyoke basalt, Connecticut (32)
Sander basalt, Virginia (21)
High Atlas (upper) basalt, (2)
N. Parana (upper) basalt, Brazil (8)
Morongov (upper) basalt, Siberia (18)
Labombo basalt, South Africa (16)
Initial Pangean flood basalt (averages) including:
Orange Mt. basalt, New Jersey (11)
Mt. Zion Church basalt, Virginia (7)
Talcott basalt, Connecticut (7)
North Mt. (lower unit) basalt, Nova Scotia (3)
High Atlas basalt, Morocco (8)
Algarve basalt, Portugal (9)
S. Parana (lower) basalt, Brazil (12)
Norilsk (lower) basalt, Siberia (58)
Lesotho basalt, South Africa (49)
Patagonian shallow sheets, Argentina (6)

Some unusual items found in the Watchungs:

a. Pegmatitic Segregation veins

In addition to the Watchungs, pegmatitic rock has been found in other ENA flood basalts including the North Mountain basalt of Nova Scotia (Greenough and Dostal, (1992), and the Holyoke basalt of Connecticut (Philpotts and Carroll, 1996). It is also found in the Columbia River Basalts, particularly the LoLo (Puffer and Horter, 1993), and in thick lava lake accumulation in Hawaii (Helz and others, (1989).

There are two modes of occurrence of pegmatitic veins, each with a different mode of emplacement. Some pegmatitic rock consistently occurs in the entablature of thick flows at a level about one-third of the way through the flow from the top. These pegmatites are vesicular, and have sharp upper contacts but gradational lower contacts. They are fractionation products of their host basalt consistent with about 20 percent crystallization. They were probably accumulated beneath the upper flow contact as it advanced downward into still molten basalt below. The pegmatitic rock was probably carried by volatiles rising out of the lower crystallization front according to models proposed by Helz and others, (1989); Greenough and Dostal, (1992); and Puffer and Horter, (1993). The coarse grains that they contain presumably grew large in a melt with a viscosity reduced by the volatile content. Most crystal nuclei may have been fused during transport through the hot interior of the flow adding to the likelihood of coarse grains.

Other pegmatitic rock occurs in the lower colonnade of thick flows. These pegmatites are not vesicular, and have sharp upper and lower contacts. They are also fractionation products of their host basalt but represent about 30 percent crystallization. They were probably squeezed (filter pressed) out of a lower colonnade crystal mush and flowed into overlying subhorizontal cracks that opened up during floundering of thick slabs of basalt. Since most crystal nuclei were consumed during partial crystallization at their source, the grain size of the residual pegmatitic rock is increased. This mode of pegmatite (segregation vein) occurs in the Hambden basalt of Connecticut and has been described by Philpotts and Carroll in a series of GSA abstracts, (particularly Philpotts and Carroll, 1996).

b. Platy prismatic joints.

In addition to the columnar shrinkage joints that develop in most subarial basalt flows according to a process described by Degraff and Aydin (1987), a much more closely spaced set of joints is commonly found at exposures of Preakness basalt and less commonly at exposures of Orange Mountain and Hook Mountain basalt. These closely spaced platy prismatic joints have been described by Faust (1978) and Puffer and Student (1992) and may have been generated by transform shearing forces acting on the basalt during crystallization.

c. Secondary Prehnite and Zeolite mineralization.

Laskowich and Puffer (1990) and Puffer and Student (1992) have described a complex set of hydrothermal alteration and metamorphic processes that have led to the precipitation of abundant zeolites, prehnite, carbonates, amethyst, and sulfides in gas vesicles and between basalt pillows. Most such secondary mineralization is confined to the Orange Mountain basalt and Hook Mountain basalts. Gas vesicles were probably partially filled with hydrothermal sulfates, carbonates, chlorite and clays during the cooling of the flows. Subsequent zeolite facies metamorphism during burial recrystallized this mineral assemblage into an assemblage dominated by prehnite and zeolites.

d. Copper Mineralization

Puffer and Proctor (1994) have described copper mineralization that is concentrated in basalt vugs and shallow lake sediments near the base of the Orange Mountain basalt. A copper bearing mineral assemblage similar to that found in the Keeweenawan basalts of the Lake Superior province was mined at several sites of historic importance in a linear district extending from North Arlington to Chimney Rock, New Jersey. The copper values correlate with magnesium mineralization, particularly chlorite that may have precipitated out of heated brackish groundwater during and just before Orange Mountain extrusion. The model proposed by Puffer and Proctor (1994) depends on heated brine circulation and, therefore, extrapolates the classic submarine black-smoker model to shallow brackish ponds.

Geochemistry

Whole-rock geochemical analyses of Watchung Basalts (Puffer, 1992) are compared with the major ENA magma types of Weigand and Ragland (1970). The Orange Mountain is consistently HTQ-type basalt and is compositionally uniform. However, the upper Orange Mountain flow is slightly more mafic than the lower flows. The composition of the Orange Mountain basalt (Table 5) closely resembles the chill zones of the PRHL and most other sheets in the Newark basin (see Part 1).

The Preakness basalt is chemically diverse. The lower flows of the Preakness are generally much more highly fractionated than the upper flows. The compositions of the upper flows, typically 0.8 percent TiO_2 and 8.0 percent MgO (Puffer, 1992) are within the LTQ-type range. The lower flows, however, are the product of plagioclase and pyroxene fractionation of LTQ magma and typically contain about 1.1 percent TiO_2 and 6.0 percent MgO (Puffer, 1992).

The Hook Mountain basalt is chemically uniform and is classified as an HFQ-type largely on the basis of its TiO_2 content and mafic index (Puffer, 1992).

The Watchung Flood Basalts as part of the ENA rift related Large Igneous Province

The Jurassic Watchung basalts of New Jersey meet each of the criteria needed to assign them to the category of continental flood basalts (Puffer and Student, 1992). The extreme thickness of most of the flows, their quartz tholeiitic composition, their probable extrusion out of fissures, and the very large aerial extent of the basalt outpourings are some of these criteria. The Orange Mountain basalt is part of an HTQ province (Table 5) that extends from at least as far south as the Culpepper Basin of Virginia (the Mount Zion Church basalt, Puffer and Philpotts, 1988) through New England and eastern Canada to as far north as northern Newfoundland (the Avalon Dike, Papezik and Hodych, 1980). HTQ rocks are not common south of Virginia but a few HTQ dikes may occur as far south as South Carolina (Ragland and others, 1992). The HTQ province probably also includes portions of Morocco (the early Jurassic basalts of the High Atlas mountains; Manspeizer and others, 1976) and Portugal (the early Jurassic basalts of the Algarve basin, Puffer, unpublished data).

The Preakness basalt is part of an LTQ province that extends at least as far north as the Hartford basin of Connecticut (the Holyoke basalt, Puffer and Philpotts, 1988) and into the southeastern US states, as the Sander basalt of Virginia, (Puffer and Philpotts, 1988) and as a major dike swarm in the Carolinas where is closely associated with olivine normative tholeiitic dikes (Ragland and others, 1992). The LTQ province may also extend into Florida and the Blake Plateau off the coast of Florida.

The only well known correlative to the Hook Mountain basalt is the Hampden basalt of Connecticut (Puffer and Philpotts, 1988). The Hook Mountain/Hampdan province, therefore, is much more restricted than the huge HTQ and somewhat smaller LTQ provinces. After Hook Mountain/Hampden magmatism very little ENA activity occurred until the Middle Jurassic to Lower Cretaceous with the intrusion of distinctly alkalic rocks including lamprophyric rocks in New England and Atlantic Canada (McHone, 1992). These alkalic rocks, unlike the flood basalt magmatism below appear to be controlled by either hot-spot tracks or long transform faults that may have tapped a magma source unrelated to early Jurassic magma. Presumably while this alkalic magmatism was occurring in New England, some of the first true Atlantic MORB activity was beginning and has continued without much compositional change to the present.

The aerial extent of the HTQ and LTQ provinces as they occurred during the early Jurassic is uncertain but McHone (1996) and McHone and Puffer (1996) have made a first approximation. McHone (1996) has shown that the status of the ENA basalts should be elevated to that of a world class Large Igneous Province (LIP) and should no longer be ignored by assemblers and modelers of LIPs such as Coffin and Eldholm (1994).

The Origin of Orange Mountain Basalt (First Watchung): From Extremely Uniform HTQ-type Magma Melted During Pangean Rifting

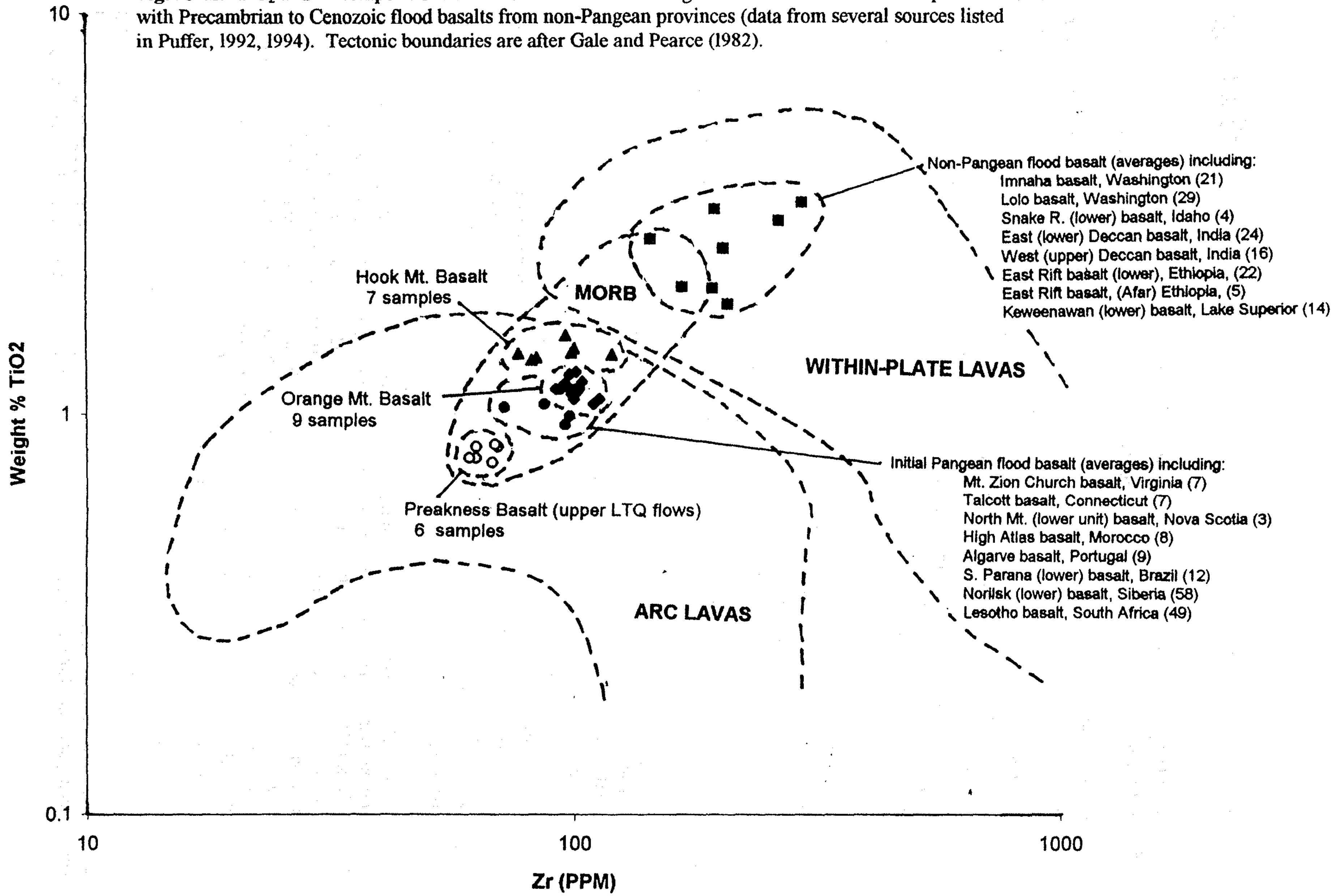
One outstanding characteristic of the HTQ LIP is the extremely uniform composition of each of the basalt flow components (Table 5) and the chill-zones of the feeder dikes. Although most intrusive HTQ sheets (such as the PRHL) have undergone in-situ fractionation or lateral fractionation (see Part-1) and (Figure 11a), there is abundant evidence that the HTQ magma that intruded into these sheets and extruded as flood basalt was chemically too uniform to be the product of fractionation of any more primitive magma (Puffer, 1992, 1994). Although there is no apparent way to prove that some deep fractionation did not occur, perhaps in the mantle or in a magma chamber ponded at the base of the crust, there is no evidence of any mafic cumulate that could account for the huge volume of HTQ magma as a fractionation product. However, the choice of processes that might have generated HTQ magma is highly constrained by its uniform composition on a regional (eastern North America) to perhaps global scale.

The chemical composition of HTQ magma is unlike that of most flood basalts (Table 5) and does not even plot in the continental basalt field of most Pearce-type discriminant diagrams. For example, the Zr/TiO_2 ratios of the HTQ basalts plot within the MORB field of Figure 12. In addition, the MgO/TiO_2 ratios of most if not all Cenozoic, Paleozoic, and Precambrian flood basalts are much different than the HTQ basalt group (Figure 11b). However, there is one group of flood basalts (initial Pangean basalts) that closely resembles HTQ basalts (Figures 11b amd 12), and it is probably not a random coincidence that each member of this group was also extruded out of fissures that opened during the initial break-up of Pangea. There seems to be a uniform set of initial conditions that controlled the melting of each of the similar Pangean magmas in Table 5. Those conditions were clearly subcontinental and extensional and very unlike the subduction related conditions associated with andesites, or the mid-oceanic and depleted source conditions associated with MORB, or the hot-spot conditions associated with alkalic basalts. It is less clear just how the sub-Pangean conditions differ from those associated with non-Pangean flood basalts, but the break-up of Pangea was a rapid and unique event. The threshold strength of the Pangean lithosphere during the initial break-up was probably a function of the minimum thickness and maximum mantle heat content requirements that may have been unique to Pangean rift zones. The magnitude of the forces needed to initiate movement of the large pieces of the Pangean super-plate also may have been unique to Pangea. These unique threshold conditions, therefore, may have controlled the rate of assent of mantle source material under the Pangean rifts and the degree of decompression melting related to the prevailing extensional tectonism.

Although HTQ magma probably intruded quickly (Philpotts, 1992) and avoided much crustal contamination, some assimilation of crustal rock such as described by Puffer and Benimoff (in press) has locally affected HTQ rocks (see also Part -1). As might be expected of crustal contamination, the most highly mobile elements are those that display the most variation among HTQ rocks. Ba, Rb, and K show the most variation among HTQ rocks (Table 5) and could at least partially be the result of late hydrothermal alteration (sericite) and may not have involved much crustal assimilation. Dostal and Dupy (1984) interpret the negative Nb anomaly that is a characteristic of HTQ rocks as evidence of considerable crustal contamination, but careful examination of the Nb data-base that is commonly used to interpret spider diagrams and discrimination diagrams is suspiciously lacking in credibility (Puffer, unpublished data).

Sr and Nd isotopic data (Puffer, 1992) are somewhat ambiguous and are consistent with either: 1.) some crustal contamination, 2.) an enriched subcontinental mantle source, with enrichment presumably occurring during an earlier subduction cycle (Pegram 1990), or 3.) an undepleted subcontinental mantle source of uniform composition. Of the three choices, Puffer (1992) favors choice 3, again largely on the basis of the uniform composition (including isotopic composition) of Pangean flood basalts that would tend to rule out various

Figure 12. TiO_2 and Zr compositions of Triassic and Jurassic Pangean flood basalt districts compared with Precambrian to Cenozoic flood basalts from non-Pangean provinces (data from several sources listed in Puffer, 1992, 1994). Tectonic boundaries are after Gale and Pearce (1982).



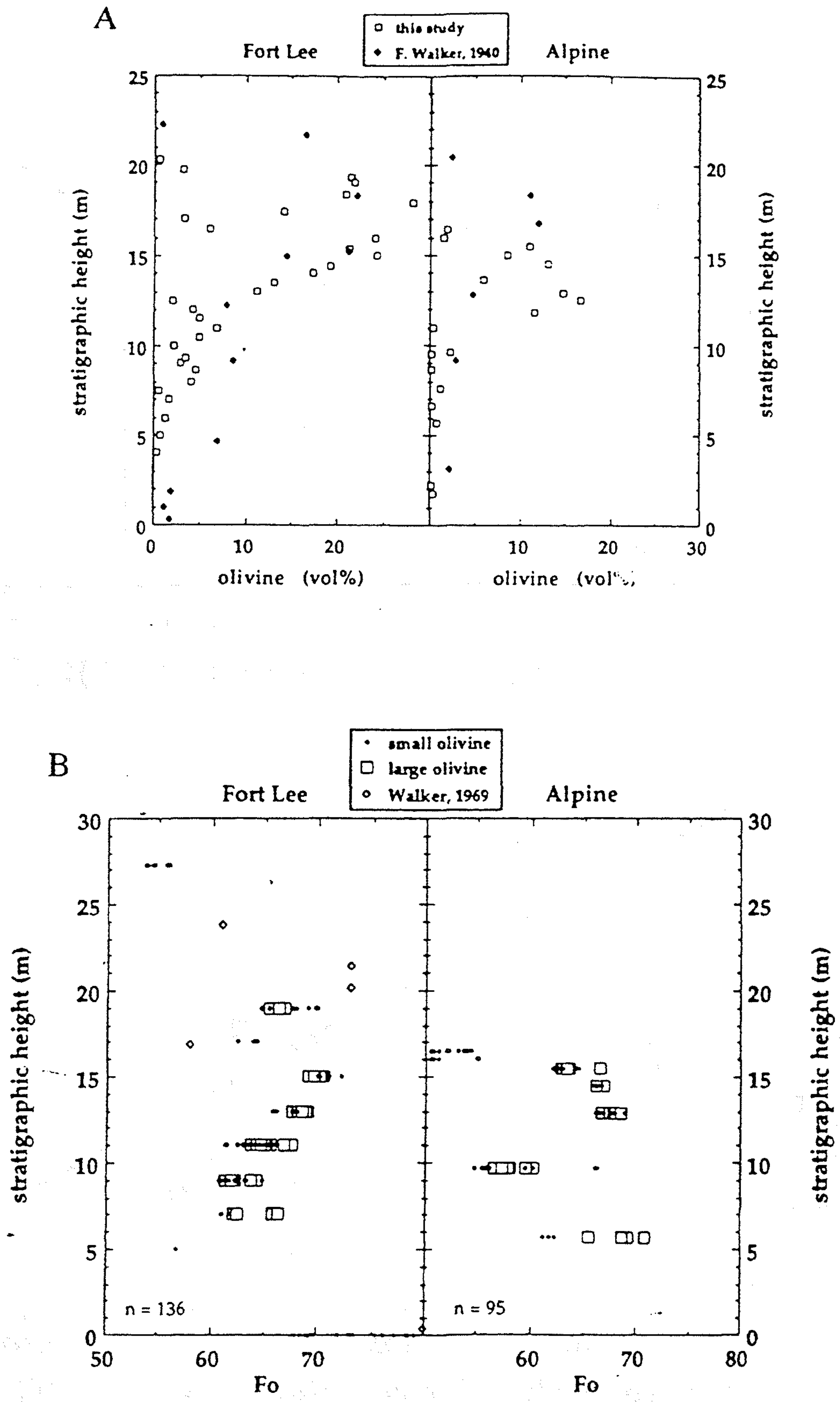


Figure 13. Modal abundance (A) and Fo content (B) of olivine vs. stratigraphic position above lower contact from the Fort Lee and Alpine, New Jersey sections of the Palisades (from Gorring and Naslund, L995). Note the presence of two maxims in both A and B, suggesting a double pulse of OZ magma with early formed olivines concentrated near the core of each pulse.

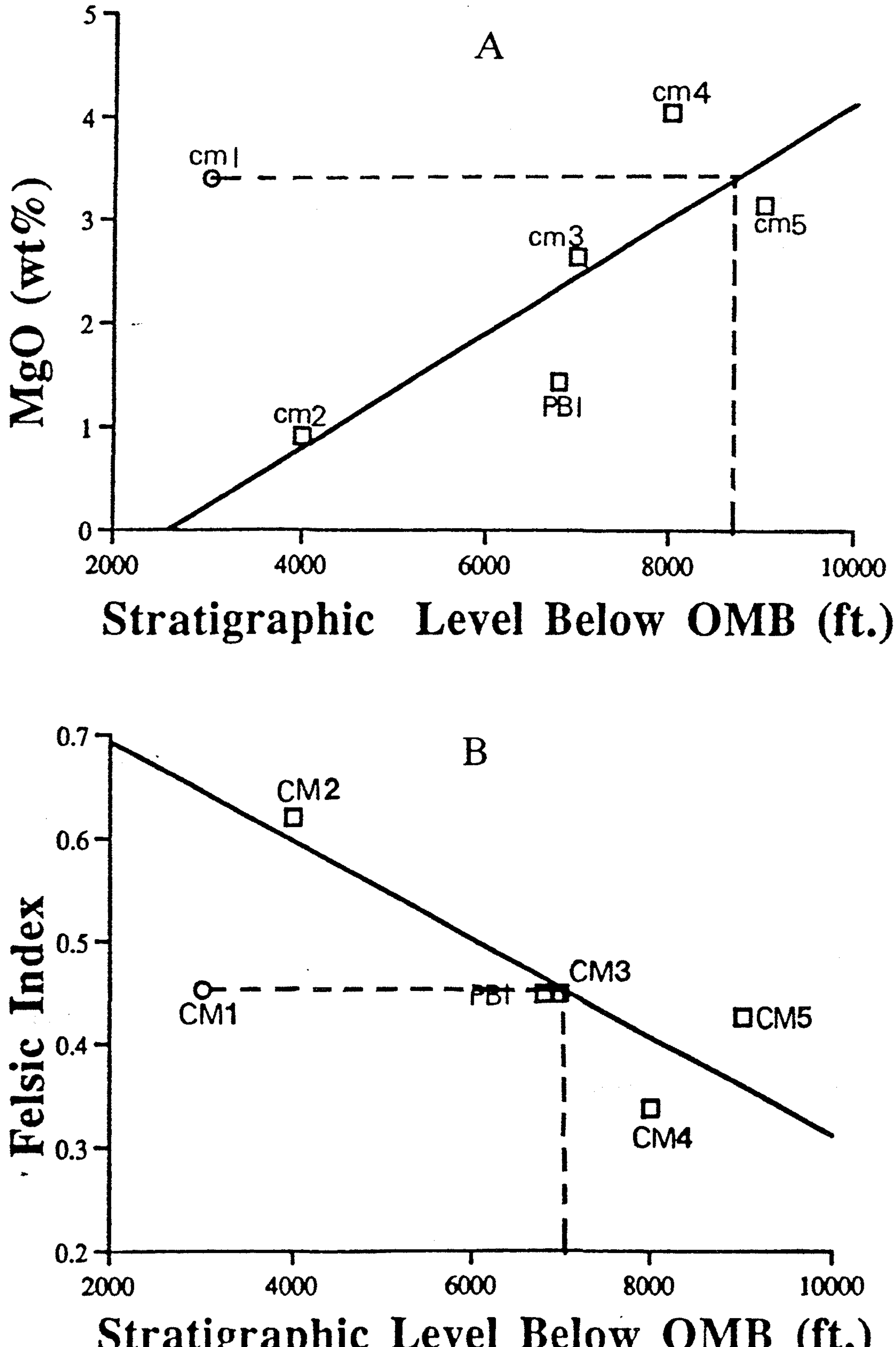


Figure 14. MgO (A) and felsic index ($Na_2O+K_2O/Na_2O-K_2O+CaO$; B) vs. stratigraphic level below the OMB (Orange Mountain Basalt) for the northeastern arm of the CMD (from Keely and Husch, 1993). Solid diagonal lines are least-squared regression of all samples except CM1 (Stop 4). Dashed lines represent estimates of actual stratigraphic position of CM1 prior to post-intrusion normal faulting; an offset of approximately 5000 ft is indicated. Note also the consistency of the position of the Prescott Brook sample (PB1, Stop 4A), suggesting the presence of a subsurface connection of the PBD with the CMD.

degrees of contamination or enrichment. Still another complicating factor is the role that mantle metasomatism may have played as suggested by the isotopic data of Dunn and Stringer (1990).

The Origin of Preakness Basalt (Second Watchung): Four Ways to Generate Diverse LTQ-type Magmas

The Preakness basalt flows clearly consist of LTQ-type rock (upper flows) and fractionated LTQ-type rock (lower flows), however, there are at least four ways to generate LTQ or LTQ-like magma:

1. An independent magma batch.

The chief difference between the HTQ and the LTQ batches is the relatively incompatible element depleted nature of the LTQ batch. Most LTQ-type diabase, basalt, and related fraction products, therefore, are probably the result of a magma batch that was melted from a relatively depleted mantle source compared to the HTQ batch that preceded it, or from a magma batch that represents a higher degree of partial melting than the HTQ batch. On Sun and McDonough mantle normalized spider diagrams where elements are arranged according to their relative incompatibility in the mantle, the Preakness basalt and other LTQ basalts such as the Holyoke of Connecticut and the Sander of Virginia consistently plot well below HTQ levels (Puffer, 1992, 1994). One reasonably likely scenario is that the LTQ magma was generated by renewed decompression melting of the same rising mantle diapier or ridge-like structure that had been previously depleted by earlier HTQ magma generation.

2. Fractionated OLN-type Magma.

Ragland and others (1992) have found several cases of LTQ intrusions that are differentiates of a parent olivine normative type (OLN-type, Weigand and Ragland, 1970) magma that may qualify as a primary melt. Evidence of a genetic link between some LTQ intrusions and OLN màgma at some southeastern US locations includes the occurrence of olivine phenocrysts in LTQ diabase and rocks that plot along continuous uninterrupted fractionation trends. Apparently there are two types (batches?) of OLN magma. However, there is a distinct gap in fractionation trends that separates one type of OLN rock from most LTQ rock.

3. Plagioclase and Pyroxene Accumulation and Hydrothermal Alteration of HTQ Magma.

Puffer and Benimoff (in press) have described the geochemistry and petrology of the Laurel Hill diabase intrusion near Secaucus, New Jersey. They have found that plagioclase and pyroxene separated from an HTQ magma have accumulated near the outer margin and have reduced TiO2 levels to LTQ levels. The TiO2 levels were reduced still further by hydrothermal precipitation of sericite in the outer margin. The major element chemistry of the resulting rock closely resembles LTQ diabase.

4. Mafic residue remaining after escape of late melt phase during in-situ fractionation.

Philpotts and Carroll (1996) have shown that plagioclase and pyroxene can also become concentrated in HTQ rock without involving movement or accumulation of phenocrysts. They have shown that collapse of increasingly dense partially crystallized rock can occur after about 30 percent crystallization and force the remaining incompatible element enriched melt to become filter pressed out. The resulting enrichment of early pyroxene and plagioclase phases results in a rock containing less TiO2 and other incompatibles than the expelled liquid phase and would presumably be comparable to LTQ rock.

Of the four ways to form LTQ magma, the preferred application to the Preakness basalt is method 1. There is no evidence of a large supply of OLN magma in New Jersey that could have fractionated into Preakness basalt (method 2), and there is no textural evidence of any accumulation of plagioclase and pyroxene

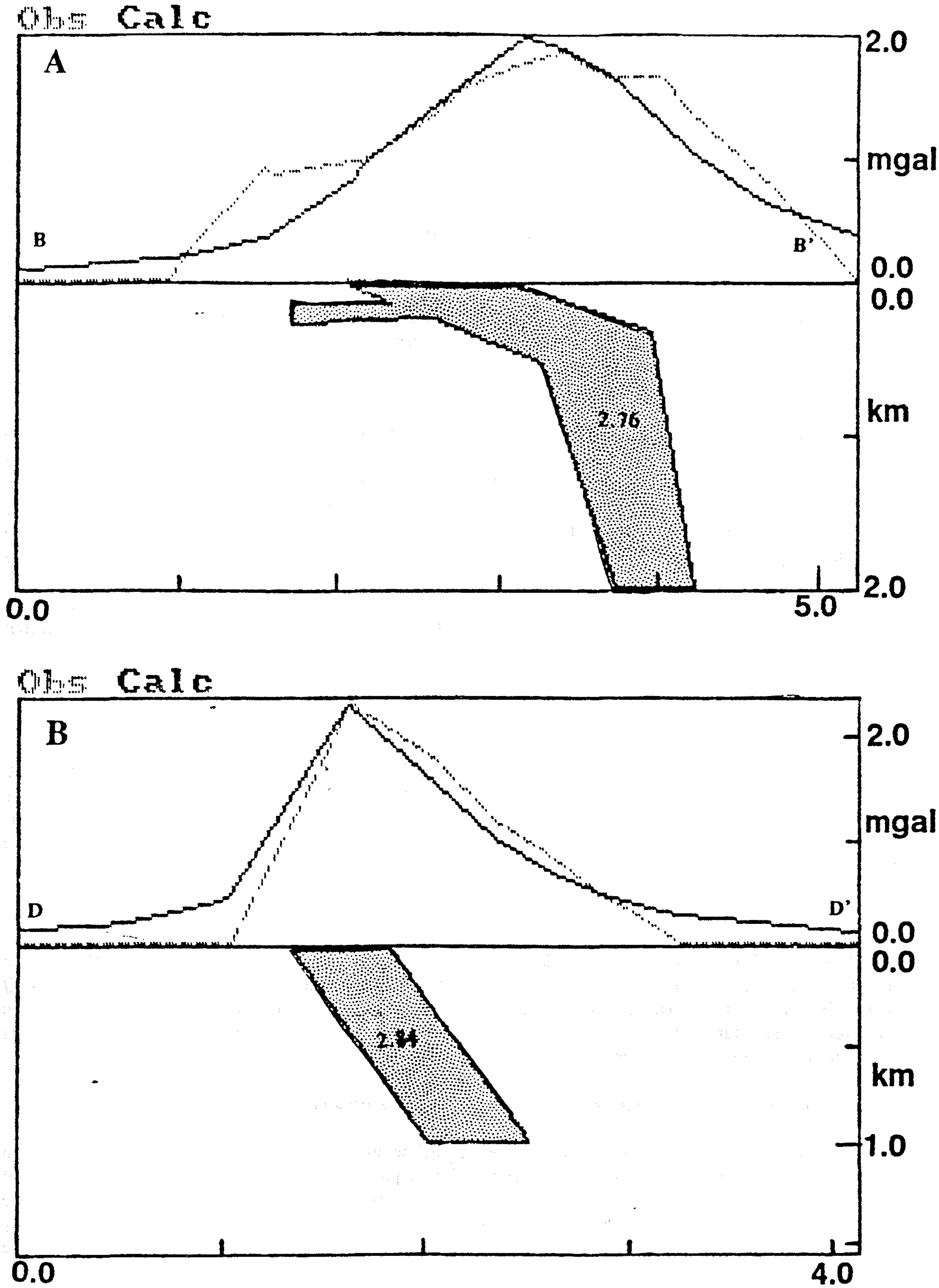
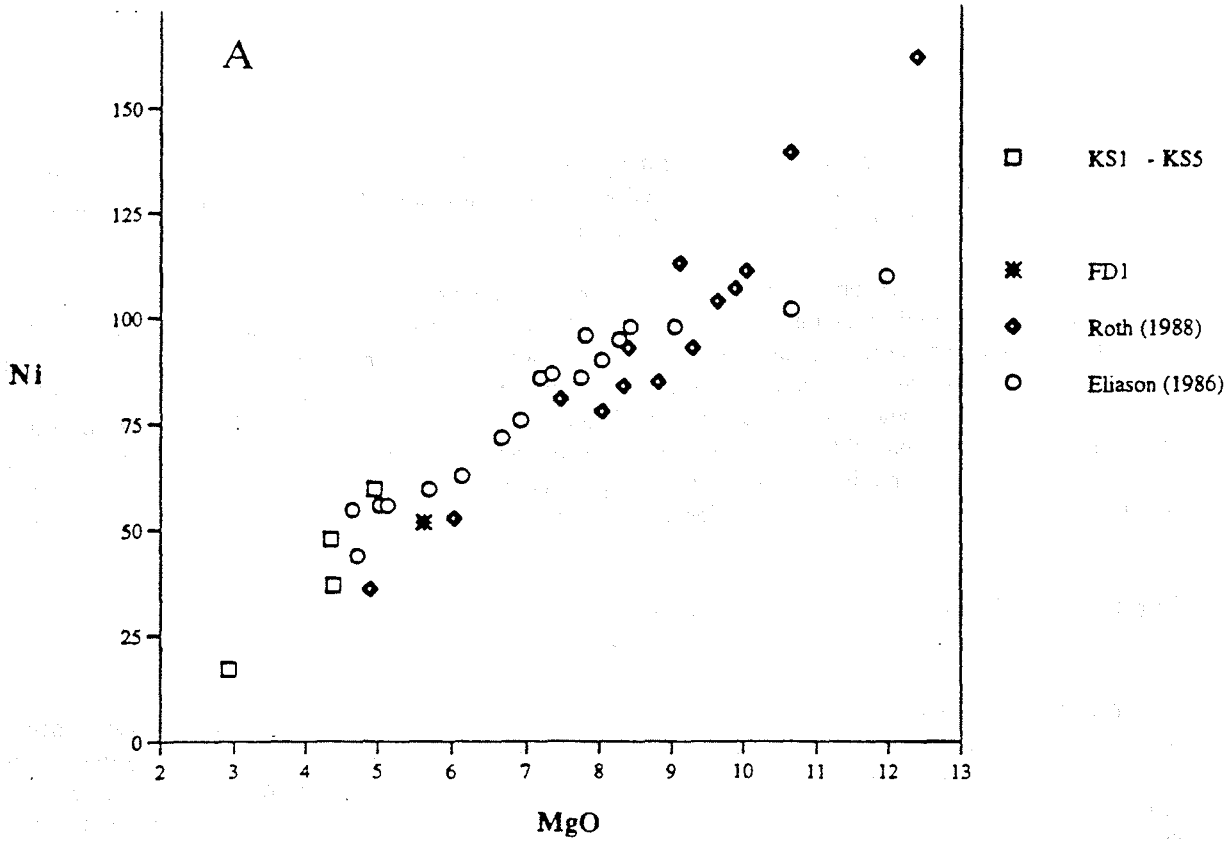


Figure 15. Two-dimensional Bouguer Anomaly models across the northeastern arm of the CMD (from Jakubicki and Husch, 1995) indicating that the intrusion is a ring dike. Center of the CMD is to the left for both profiles. The diabase density required in A (2.76 gm/cc) is less than for B (2.84 gm/cc), consistent with the lower stratigraphic position and more mafic chemistry of the profile location modeled in B. Obs=observed Bouguer Anomaly (light line); Calc=calculated Bouguer Anomaly (dark line) using a reference density of 2.67 gm/cc.



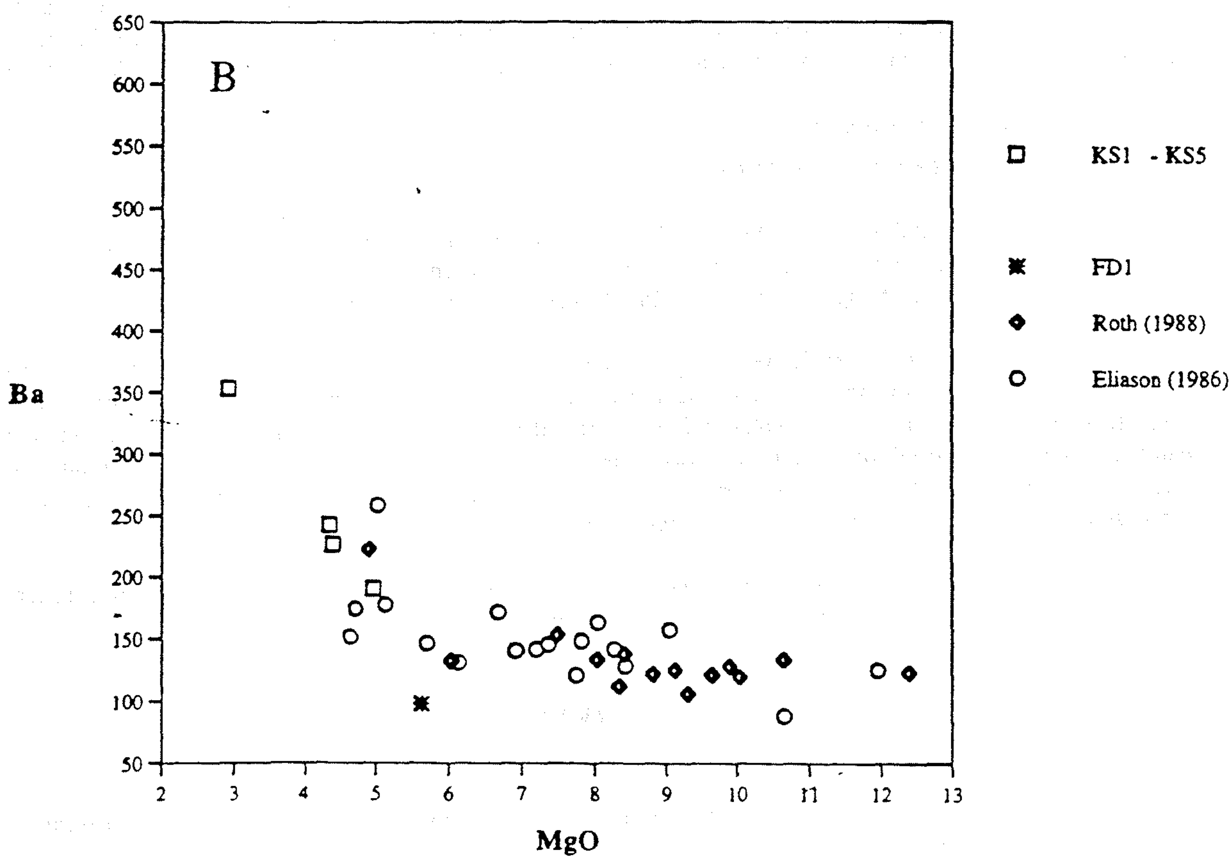


Figure 16. Ni (A) and Ba (B) vs. MgO diagrams for the Lambertville sill (from Szemple, 1996). KS1-5 and FD1 samples are from the stope-like structure (Stop 6). Samples from Roth (1988) and Eliason (1988) are from the northeastern and southwestern ends of the sheet, respectively. Note how only low-MgO, granophyric compositions are found in stop|e-like structures; northeastern and southwestern sections are dominated by high-MgO rocks with no true granophyre

phenocrysts (method 3). If enriched melt was filter pressed out of a partially crystallized HTQ source (method 4) the depleted solid residue would be contained as a layer within an HTQ source (in this case the Orange Mountain flows or the PRHL sheet) but the Preakness clearly is not.

Method 2 is a close second choice. OLN rocks are not common in New Jersey but become increasingly common toward the south beginning with the Quarryville dike swarm in Pennsylvania. Some of this olivine normative rock may be mafic cumulates from the fractionation of an LTQ parent magma batch (method 1) and plots on a long, continuos fractionation trend that balances with some highly evolved rocks such as the lower flows of the Preakness and some dike interiors (Figure 11a). But as erosion depths increase toward the southeast into the Carolinas, OLN dikes become abundant and lead to the impression that they are the parent magma, and not simply a mafic cumulate. The LTQ population lacks the compositional uniformity of the HTQ population and there is less compelling evidence that it is a parent magma instead of a fractionation product.

The Origin of Hook Mountain Basalt (Third Watchung): A Third Magma Batch or a Fractionation Product?

The Hook Mountain flows and the Hampden flows of Connecticut are the only two known occurrences of late HFQ magmatism. Although most HFQ rocks are probably fractionation products of HTQ magma, the Hook Mountain and Hampden are not (Puffer and others, 1981). They are instead localized, rather unique outpourings of basalt that do not compare to the widespread dimensions of the underlying flow units. Their chemistry was probably controlled by renewed melting under the complex and highly dynamic tectonic conditions that accompanied the opening of the Atlantic. These rapidly changing conditions are difficult to model and may not have any bearing on the more important magmatism that preceded them and followed them.

Another Unsolved Problem: Where did the Watchungs Come From?

It is quite likely that the Orange Mountain flows extruded out of rifts fed by the same magma that intruded as the underlying PRHL sheet, but before the sheet underwent dynamic but self contained fractionation. All evidence suggests that the Orange Mountain and PRHL sheet are largely co-magmatic HTQ rocks.

The source of the Preakness, however, is less well understood. None of the dikes and sheets exposed in New Jersey are LTQ intrusions that could have supplied the massive quantities of magma required of the Preakness. One possibility is that Preakness flows were fed by conduits that were never exposed by erosion. Another is that the exposed intrusive source was covered by Cenozoic coastal plain sediments. Flow direction studies by Manspeizer (1980) based on curved pipe amygdules found at the base of the Preakness, suggest that the source was to the east, but so far nothing to east has been found.

The source of the Hook Mountain is even more perplexing because flow direction studies suggest a western source. Erosion has penetrated deeply into everything to the west but again, there is no clue.

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EARLY JURASSIC DIABASE AND BASALT OF THE NEWARK BASIN ROAD LOG

Miles From Start	Miles Between Points	
0.0	0.5	Start at the College of Staten Island parking lot near the outcrop of Palisades diabase, proceed to the exit.
0.7	0.2	Cross over Victory Blvd., proceed north then turn right into the entrance of I-278-west.
4.2	3.5	Proceed west on I-278, cross the Goethals Bridge and follow signs around complex clover-leaf to I-95 north (NJ Turnpike).
5.5	1.3	Take toll card at booth
12.5	7.0	I-95 devides, take east fork toward Lincon Tunnel (but dont enter the Tunnel).
17.3	4.8	Observe Laurel Hill Diabase on both sides of I-95.

View Site: Laurel Hill

Due to the realities of traffic congestion and aggressively enforced trespassing laws throughout the New York City area, Laurel Hill is one of several excellent sites that we will not be able to stop at. But this exposure is at least clear enough to see through the bus windows.

Laurel Hill is an almost completely exposed early Jurassic volcanic neck, consisting of three concentric zones (Puffer and Benimoff, in press). The diverse chemical composition of Laurel Hill diabase overlaps each of the major eastern North American (ENA) Jurassic diabase types. Zone 1 is an irregular, heterogeneous, border-zone characterized by chemistry resembling the low-Ti-quartz-normative type (LTQ) ENA diabase but is interpreted as an alteration product of high-Ti-quartz-normative type (HTQ) diabase. Dilution of HTQ magma with hydrothermal sericite, and with plagioclase and pyroxene that accumulated during fractionation, has reduced the TiO_2 content of Zone 1 from HTQ (1.1 percent) to LTQ levels (<0.9 percent). Localized assimilation of Passaic Formation siltstone is recognized by an enrichment of Zr in some Zone 1 samples. Zone 2, the intermediate zone, is characterized by chemistry typical of HTQ-type diabase. Zone 3, the interior zone, resembles the HFQ-type (High-Fe-quartz-normative) ENA diabase and is interpreted as an HTQ fractionation product.

19.4	2.1	Pay toll at Exit 18 "George Washington Bridge" but don't worry you don't have to go over the bridge.
23.9	4.5	I-95 merges with I-80, follow signs to George Washington Bridge.
25.9	2.0	Consistently take local lanes on I-95 toward "Last Exit in NJ".
26.5	0.6	Continue north on I-95; observe the Palisades sill on the east exposed as the north-south ridge in the background.

28.4	1.9	Observe upper portions of the Palisades sill on the left. The upper contact is hidden behind vegetation and retaining walls.
29.5	1.1	Observe the vertical leucocratic dikes cutting through black Palisades diabase. The relatively thick dikes are composed of trondhjemite while the relatively thin dikes are albatite and calcite. They are described by Benimoff and others (1989) and are interpreted as fusion products of sodic Lockatong argillite host rock. They have a chemical composition similar to the host rock.
29.8	0.3	Exit I-95 on right onto Lemoine Ave.; avoid going across George Washington Bridge!!!
30.1	0.3	Turn right onto Lemoine Ave.
30.3	0.2	From Lemoine turn left onto Main Street, Fort Lee.
30.6	0.3	From Main Street turn right onto River Road.
30.8	0.2	From River Road turn left into entrance for Palisades Interstate Park.
30.9	0.1	Follow park road to the north; observe olivine zone of Palisades Sill on left recognized as an eroded out deeply altered cut at the base of the diabase slope. Stopping on the park road is strictly forbidden, but if you park at the entrance to the park the olivine zone is only a short walk.
31.3	0.4	Observe irregular lower contact of the Palisades Sill with the Lockatong Formation.
31.4	0.1	Pass under George Washington Bridge.
31.5	0.1	Observe additional exposures of the conformable Lockatong/Palisades contact on the left.
31.8	0.3	At the circle in the park road at the base of the Palisades Sill take the road which veers off on the right towards Ross Dock.
32.1	0.3	Take road down to parking lot at Ross Dock.

STOP 1. Lower Contact Of Palisades Sill With Lockatong Hornfels At Ross Dock, Fort Lee, NJ.

Permission From The Palisades Interstate Park Commission To Stop And Collect Along The Road Is Required.

After admiring the view of the Hudson River and Manhattan Island, 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 chilled zone with hornfels of the Lockatong Formation. According to Gorring and Naslund (1995), the fine-grained diabase chilled zone in the Fort Lee area consists of about 1-2 percent olivine (Fo_{68-78}), 35-55 percent augite, 1-2 percent orthopyroxene (En_{75-80}), and 35-55 percent plagioclase (An_{65-70}; Walker, 1969). The pyroxene-dominated (along with plagioclase), tholeiitic-trend fractionation of this HTQ-type parental magma culminated in the development of a 33 m-thick granophyre layer, or sandwich horizon (Shirley, 1987), 50-100 m below the upper contact of the 330 m-thick sheet. Because this section of the PRHL megasheet is quite conformable, there appears to be little in the way of density driven lateral migrations of residual magmas and nearby sections through the Palisades contain very similar distributions of rock types (Husch, 1990). Some thin leucocratic veins and dikes of quartzofeldspathic material cut the diabase along the road at this locality. As discussed in Part I, these may have multiple origins.

The 3-4 m-thick OZ is exposed approximately 15 m above the road level and is exposed at road level 0.1 mile east of the entrance to the park (mile 30.8). At this locality the lower contact of the OZ is somewhat gradational, although the upper contact is quite abrupt, with olivine modes falling from over 20 percent to zero within less than one meter (Gorring and Naslund, 1995). At other localities along the Hudson river, both the upper and lower contacts of the OZ can be equally sharp (Walker, 1940; Gorring and Naslund, 1995).

Although originally thought by Walker (1969) to be the result of in situ gravitational crystal settling from a second pulse of Palisades magma that produced most (if not all) of the residual, granophyric compositions found higher up in the sheet, recent studies by Husch (1990, 1992) and Gorring and Naslund (1995) indicate that this interpretation is incorrect. Husch (1990, 1992) showed that olivine removal is inconsistent with the geochemical fractionation trends observed for the PRHL megasheet (see Part I) and that there are large-scale features of the OZ that suggest it was a separate olivine-rich intrusion into an already formed, although still largely molten, PRHL sheet. Gorring and Naslund (1995), on the other hand, believe the OZ to have formed as part of the initial injection of the HTQ parent (or at least within 5 years of that event) and that the olivine accumulation took place prior to or during the injection sequence. Based upon the distribution of olivine within the OZ and its composition (Fig. 13), Gorring and Naslund (1995) propose a mechanical sorting of olivine by a flow differentiation mechanism, a process also suggested by Husch (1990).

Beneath the lower contact of the Palisades are contact metamorphosed buff-colored arkoses and 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, in particular, have been affected by thermal 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 green diopside, grossularite, chlorite, and calcite with minor biotite, feldspar, amphibole, and prehnite (Van Houten, 1969).

Porphyroblasts of pinite 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 4 cm across, composed largely of clinozoisite, are less common in the hornfels, but are known from several other hornfels localities in the Newark and Culpeper Basins.

32.4	0.3	Proceed to park exit and turn right around circle to the south.
33.4	1.0	Return south to the park exit and turn right onto River Road.
33.6	0.2	From River Road turn left onto Main Street (Rt.11).
33.9	0.3	From Main Street turn right on Lemoine Ave. and continue north over I-95.
34.1	0.2	From Lemoine Ave. turn left onto Cross Street and stay in left lane.
34.3	0.2	From Cross Street turn onto the entrance ramp for I-95, proceed south.
35.6	1.3	Directions to Stop 1A (optional). Follow signs for Interstate 95 Local Lanes. Proceed down the dip slope of the top of the Palisades and pass under the Jones Road viaduct (prominent arch support bridge). Stop on shoulder at western end of outcrop.

STOP 1A (Optional). Upper Contact Of Palisades Sill Along Westbound Interstate 95 (Local Lanes).

Stopping Along The Highway Other Than For Emergencies Is Illegal In New Jersey. The Police Will Ask You To Leave Immediately (If You Haven't Been Arrested Already).

This rare exposure of the upper contact of the Palisades is visible on both sides of the highway. The chilled margin is almost identical in composition, mineralogy, and texture to that found at the lower contact (Stop 1). Of course, no upper analog to the OZ is seen. Overlying the upper contact are hornfels of the

Lockatong Formation, again similar to those found beneath the lower contact. The contact is highly conformable at this locality with only minor cross cutting "steps" visible; a few minor faults also have offset the contact. In at least one instance, apparent cooling cracks have been filled in with overlying sediments, producing a sedimentary dike structure. Other fractures in the upper contact zone contain copper mineralization and calcite fillings.

As one walks east towards the viaduct, more interior portions of the sheet are exposed and grain size increases, as does the amount of granophyric material. Eventually, pods of pegmatitic granophyre are found within a finer-grained, less differentiated diabase. Looking south across the highway at the opposite cliff (now sheathed in metal netting to keep loose boulders from falling onto the highway) it is possible to see a number of leucocratic dikes running vertically across the face. Benimoff and others (1989) described these dikes as being trondhjemitic in character and concluded, on the basis of geochemical data, that they represented the late-stage injection of anatectic melts, derived from country rock xenoliths, into cooling fractures.

37.5	1.9	Bear left under sign for I-95 "The Ridgefields"; stay on I-95 south.
44.0	6.5	Pick up toll card at booth and stay in local lanes.
52.2	8.2	Take exit 14 and follow signs for I-78 west.
52.6	0.4	Pay toll at booth and enter express lanes for I-78 west
62.8	10.2	Continue west across valley underlain by Jurassic red-beds of the Passaic Formation. Exposure of Orange Mountain Basalt is on the left with a well defined flow contact identified by an undulating erosion surface, and the contrasting textures of the vesicular upper entablature of the lower flow and the relatively massive lower colonnade of the upper flow.
65.2	2.4	Lower contact of Preakness Basalt on the right. Most of the actual contact has been recently hidden by a new retaining wall and some landscaping but Feltville Formation siltstones exposed here have been thermally metamorphosed by the extrusion of one of the thickest flows of flood basalt anywhere on earth. The contact metamorphism has converted the otherwise consistently red siltstone into a gray layer within 5 meter of the contact and a dark gray hornfels within 1 meter of the contact. The thickness of the lower flow is about 150 m, comparable to the thickness of the Grand Ronde flow of the Columbia River Basalt and thicker than almost any flood basalt.
65.7	0.5	Note vertical strike-slip faults through the Preakness Basalt defined by eroded fault gouge. The fault planes curve below the Preakness flow and do not seem to penetrate into the underlying Feltville Formation. Apparently shearing stresses were absorbed by plastic flow of unlithified Feltville sediments. Similar strike-slip faults are exposed at each of the several trap-rock quarries cut into Orange Mt., Preakness and Hook Mt. basalts in New Jersey.
65.8	0.1	Note the very closely spaced vertical jointing of the lowest of the five Preakness flows. A set of tectonically generated vertical platy-prismatic joints have been superimposed onto the vertical polygonal cooling joints, probably along incipient planes of weakness opened during cooling. The joint patterns have been described and their origin has been discussed by Puffer and Student (1992) and by Faust (1978).
65.9	0.1	The discontinuous exposure of the lower flow of the Preakness Basalt on the right was a virtually uninterrupted exposure 6 miles long during highway construction in 1987, and afforded close inspection and sampling (Puffer, 1992). The chemistry and texture is uniform although there is a slight change in composition across the lower

colonnade / entablature contact. The upper contact of the flow is clearly defined by a layer of feruginous siltstone. The chemistry of the lower flow is the most highly fractionated of the 5 Preakness flows. The least fractionated flows are the thin upper flows (flows 3,4 and 5) which have typical LTQ compositions.

67.1	1.2	Observe the variations in jointing of Preakness basalt exposures on the right and the strike slip fault plains.
67.7	0.6	Take I-78 exit-43 (the first Berkeley Heights exit).
68.4	0.7	Turn left immediately upon exiting onto the unnamed road marked "DEAD END" that leads to the microwave tower on top of the ridge. The bus can unload along the exposure and turn around at the tower.

STOP 2. Preakness Basalt

The view to the south includes the Orange Mountain basalt of the First Watchung Mountain in the background and the valley eroded into Early Jurassic Feltville Formation red beds in the foreground. While examining the Preakness note:

1. The very uniform medium grained texture consisting largely of plagioclase and pyroxene with only minor glass or mesostasis.
2. The large flat widely spaced joint plains in strong contrast to the very closely spaced platy prismatic joints exposed along I-78.
3. The long curved but subhorizontal step-like parallel structure on the joint surfaces. They are interpreted as the kind of boundaries that join crack segments described by DeGraff and Aydin (1987). The cracks propagate downward through layers of freshly hardened basalt in the entablature as the upper crystallization front of the flow advances down into the largely liquid crystal mush below.
4. The strike-slip fault plain eroded into the Preakness. Note the horizontal striations on the slickenside surfaces.
5. The occurrence of a few rare and small shapeless basaltic pegmatites located between crack segment boundaries, and the occurrence of discontinuous, very thin, vesicular, basaltic pegmatite layers at the crack segment boundaries as described by Puffer and Horter (1993). Although the crack segment boundaries are well defined at this exposure, the pegmatites are not particularly well developed. The size and occurrence of basaltic pegmatite is rather unpredictable but seems to be restricted to unusually thick lava flows. Probably the largest pegmatite layer found in any ENA basalt, as of 1996, was recently mapped by Richard Volkert of the New Jersey Geological Survey at a construction site in the Preakness basalt located near the Chimney Rock quarry. The pegmatite in addition to being huge is highly fractionated with only 2 % MgO and as much as 3 % TiO_2. It also contains considerable glass, but for more details we will wait for Volkert's report.

68.8	0.4	Return to I-78 west.
69.4	0.6	The Weldon Trap Rock Quarry cut into Orange Mountain basalt is on the left. The basalt here is mineralized with zeolites and prehnite that lines huge vugs over 2 m across. The quality of the zeolites and prehnite is easily of museum grade but access to the quarry was denied. Chemical analyses of several basalt samples collected here are reported by Puffer (1992). Each of the three Orange Mountain flows are exposed in the quarry.
71.8	2.4	Proceed on I-78 to exit 40 and turn south (left) onto Rt. 531 (Hillcrest Rd.).
73.2	1.4	Proceed south on Rt. 531 and turn right onto Rt. 527 south.

73.3	0.1	Stay on Rt. 527 south (Mountain Blvd.) through the traffic circle.
74.9	1.6	From Rt. 527 turn left (south) onto Washington Rock Rd. at the sign "Washington Rock"
75.5	0.6	Avoid "Dead End" at sharp right turn.
76.1	0.6	Proceed south on Washington Rock Road to Washington Rock State Park; park in the lot on the right.

STOP 3. Orange Mountain Basalt

Walk to the monument to General George Washington at the flag pole. The view to the south-east is largely a valley eroded into Triassic red-beds. This entire view area was once occupied by Orange Mountain flood basalt. The Atlantic Ocean (Raritan Bay) is 15 miles to the south/east and can be seen on a clear day. Picnic tables and drinking fountains are available but the rest-room facilities have been closed as a cost cutting measure in defiance of the laws of nature.

The Orange Mountain Basalt exposed near the flag poll is much finer-grained than typical of the Preakness. The basalt here contains common amygdules composed of chlorite and less commonly by quartz. The columnar joint pattern is reasonably clear but lacks the sharp flat surfaces typical of Preakness exposures or the greater degree of clarity at greater depths into Orange Mountain entablatures. The irregular columnar joint pattern and amygdule content are evidence of close proximity to a flow top.

76.1	0.0	Exit parking lot and proceed down hill on Washington Avenue. Be careful around sharp curves.
77.0	0.9	At light at bottom of hill make right onto Route 22 West. Please keep sophomoric jokes about Texas Wieners (at corner on right) to a minimum.
82.3	5.3	Chimney Rock Quarry in OMB on right. This is probably the largest active trap-rock quarry in the Watchung basalts. In addition to a spectacular array of beautiful prehnite and zeolites, particularly heulandite and some of the best natrolite anywhere on earth, there is abundant native copper mineralization in the first Orange Mountain basalt flow and in the Passaic red-beds within a meter of the contact. Sheets of native copper mesuring as much as a foot across are easily collected; however, permission for us to collect today was denied. Basalt flow contacts are clearly displayed with very thin layers of red-bed rock between the flows. A description of the mineral collecting here was written by Sassen (1978).
82.6	0.4	Intersection with Interstate 287. Stay on 22 West.
85.7	2.9	Intersection with Routes 202-206. Stay on 22 West.
88.9	3.3	Cross North Branch of the Raritan River.
93.8	4.9	Good view to the southwest (left) of the forested ridge, rising approximately 500 feet above the surrounding plain of the Newark Basin, formed by the northeastern arm of the Cushetunk Mountain diabase (CMD).
97.4	3.6	Exit left at sign for Lebanon Business Center. Proceed along East Main Street.
98.6	1.2	Make left onto Cherry Street (Route 629).

98.9	0.3	Pass under railroad bridge. Continue up hill with view of Round Valley North Dam to the left.
99.3	0.4	Park on left in small pulloff at west end of dam directly across road from exposure of CMD on right.

STOP 4. Fault Zone In Granophyric Rock of the Cushetunk Mountain Diabase, West End of Round Valley North Dam, Lebanon, NJ.

Round Valley Reservoir was filled in the late 1960's and is an important source of water for many municipalities in northern and central New Jersey. It is surrounded on three sides by the arcuate ridge of the CMD. The northwest quadrant of the reservoir is bounded by Precambrian metamorphic rocks, presumably of Grenville age.

Initial geochemical data by Puffer and Lecher (1979) indicated that the CMD chilled margin composition was a quartz normative, high-iron (HFQ) ENA type. However, more recent analyses by Keely and Husch (1993) show that the CMD chilled margin composition is very similar to all other Newark Basin HTQ chills and flows. Keely and Husch (1993) also show that the composition of the interior of the CMD generally becomes more fractionated and granophyre rich as one progresses northward along the intrusion's northeastern arm (Fig. 14). This arm cross-cuts over 5000 feet of the Triassic sedimentary section, rising to within 3000 feet of the OMB, the presumed Early Jurassic paleosurface (Houghton and others, 1992). Reversals in the general fractionation trend, as is found for this stop location (Fig. 14), are believed to be due to post-intrusion normal faulting exposing deeper, less fractionated structural levels of the CMD within the footwall block (Keely and Husch, 1993).

The diabase at this locality is quite granophyric, although less so than the diabase found at the east end of the dam, and contains abundant pink alkali feldspar. Equally obvious at this exposure are numerous fracture surfaces on which well-developed slickensides are observed. Most surfaces indicate a nearly horizontal right-lateral motion, although a few surfaces suggest a normal oblique, right-lateral motion. Houghton and others (1992) map this fault zone as a normal oblique splay fault of the Flemington Fault Zone (Fig. 2). Based upon the geochemical data of Keely and Husch (1993), as much as 5000 ft of vertical offset may have occurred along the fault zone seen here between the footwall block to the west and the headwall block exposed on the opposite side of the dam to the east (see sample CM1, Fig. 14). Jakubicki and Husch (1995), utilizing two-dimensional Bouguer Anomaly modelling, confirmed the normal sense of the vertical offset, but suggested the throw was less, on the order of 1500-2000 feet. The gravity modelling of Jakubicki and Husch (1995) also confirmed the initial findings of Wofford (1962) that the CMD dips outward (Fig. 15) and has the general shape of a ring dike.

100.5	1.2	After continuing south around reservoir on Route 629, make left at stop sign onto Stanton-Lebanon Road (still Route 629).
101.3	0.8	Entrance on left to Round Valley Recreation Area.
102.9	1.6	Crossing Prescott Brook. Round Valley South Dam on left.
103.7	0.8	Make left at Stanton Mountain Road. Park along side of road immediately across from white house. Climb to top of hill on right.

STOP 4A (optional). Outcrops of Granophyre At Northern End Of The Prescott Brook Diabase, Stanton, NJ.

The diabase at this locality is quite coarse grained and granophyre rich, with MgO concentrations as low as 1.5 weight percent (Keely and Husch, 1993). Approximately 1 km farther south (and structurally lower by approximately 1500 ft) the diabase composition is not quite as fractionated with an MgO content of approximately 3.0 weight percent (Houghton and others, 1992). Again, the chilled margin (not exposed here) composition for the Prescott Brook diabase (PBD) is typical ENA-HTQ type (Houghton and others, 1992). Keely and Husch (1993) proposed that the PBD was connected at depth to the adjacent CMD to the east, based upon their similar relationships between stratigraphic level of emplacement and composition (Fig. 14). This however, could neither be confirmed nor refuted by the Bouguer Anomaly modelling of Jakubicki and Husch (1995).

Running diagonally across the north-facing slope of the hill is an enigmatic 3 to 5 ft-thick layer that weathers more readily than the surrounding rocks, forming a prominent recess in the hillside. Two of the layer's more noticeable features are its broken, brecciated character and the presence of chevron-like fractures or folds across it. A number of origins have been suggested for this unit, none with any great conviction or certainty. Thus, its origins are unknown at this time and any and all suggestions or ideas, no matter how far-fetched, will be entertained.

103.6	0.1	Return back to intersection with Stanton-Lebanon Road (Route 629) and make left
104.4	0.6	Make right at Payne Road and cross bridge over Prescott Brook.
100.7	0.2	Bear left and remain on Payne Road
105.2	0.6	Make left at light onto Route 31 south towards Flemington.
107.6	2.4	Hill to left is western slope of the Round Mountain diabase (RMD), a HTQ-derived, granophyre-rich intrusion located approximately one mile to the south of the CMD and PBD (Houghton and others, 1992). Gravity data suggests that it is connected at depth to the CMD (Jakubicki and Husch, 1995).
108.7	1.1	Cross over South Branch of the Raritan River.
112.4	3.6	Flemington Circle (don't you just love driving in New Jersey). Go half-way around and continue south on Routes 31-202.
115.5	3.2	Family Golf Center on right. A fairly complete cross section of the Flemington dike (FD) was exposed for a few weeks in the foundation pit during the construction of the center's main building. Samples collected at that time were analyzed by Crohe (1996) for major- and trace-element compositions. Significant contamination affects (see Part I), particularly adjacent to the eastern contact zone of the dike, were found.
115.7	0.3	Road crosses over the FD (now on left) which continues to strike almost due south towards the upper contact zone of the Lambertville sill.
117.2	1.4	Exit right for Reaville and go around jughandle onto Route 514 east. Cross over highway.
117.5	0.3	Make right onto Dutch Lane.
118.3	0.8	Make left onto Back Brook Road.
118.7	0.4	Sharp left turn with float of FD on both sides of road. Park along straight section of road just beyond turn.

STOP 5. Float Boulders of Flemington Dike, Ringoes, NJ.

All Boulders At This Location Are On Private Property. Many Are In Yards Or Gardens. Please Ask For and Get Permission Before Examining Or Collecting.

Walk across road (west side) to wooded area just to the left of the gray house (Janet and George Holt, 39 Back Brook Road, Ringoes, NJ 08552). There are numerous pieces of FD float lying along the road; there are no known outcrops of the dike exposed at the present time. Please disturb the pieces on the property as little as possible and leave those in the yard and garden alone. Hand samples may be collected from float in the bushes on the east side of the road opposite the house.

All float pieces contain the same fine-grained diabase found along the entire strike length (approximately 7 miles) of the FD. The dike, which is approximately 50-100 feet wide, exhibits little textural or mineralogic variation. Although all samples of the FD have compositions very typical of the ENA-HTQ type (Crohe, 1996), probable wall rock contamination affects, such as elevated concentrations of Na_2O, K2O, and Ba, and decreased concentrations of CaO, generally become more pronounced as the dike strikes northward towards shallower structural levels. This is not surprising given the fact that the FD traverses over 9000 feet of the Triassic sedimentary section between the Lambertville sill (the dike's source; Stop 6) and the Flemington basalt (Houghton and others, 1992), the OMB equivalent flow that the FD presumably feeds. According to Houghton and others (1992), the Flemington Basalt exhibits striking geochemical signs of contamination, with as much as 5 weight percent Na_2O and 300 ppm Ba.

118.8	0.1	Turn around at entrance to Forthcoming Farm and proceed south and west on Back Brook Road.
119.3	0.6	At stop sign make left onto Dutch Lane.
119.5	0.2	At stop sign make left onto Wertzville Road (Route 602 east).
119.8	0.3	Cross over Flemington Dike. Small pieces of float have been collected from south side of road. Dike strikes south up the hill to the right and intersects the stope-like structure of the Lambertville sill at crest.
120.0	0.2	Make right at Losey Road and proceed up hill.
120.3	0.3	Just beyond gray ranch house (23 Losey Road) on right a dirt road heads west along the crest of the hill. Approximately 0.3 miles up from Losey Road, float from the approximate intersection of the Flemington dike and the Lambertville sill contact zone can be collected. Compositions and textures are very similar to what can be found at Stop 5.
120.5	0.2	Turn right at stop sign onto Rocktown Road.
121.3	0.8	Just after entering trees, stop at outcrop on right.

STOP 6. Diabase With Pegmatitic Granophyre In The Stope-Like Structure Of The Lambertville Sill, Rocktown, NJ.

This stop is located along the eastern limb of the stope-like structure found in the central portion of the Lambertville sill (Fig. 2). The top of this structure is emplaced approximately 3000 feet higher in the stratigraphy than the adjoining northeastward striking arm of the sill. Consistent with the dynamic fractionation model where residual, fractionated magmas migrate to the highest structural levels within a sheet, Szemple (1996) found that all diabase samples collected from the stop-like structure are differentiated to some degree, containing between 2.9 and 5.6 weight percent MgO; no MgO-rich samples with elevated pyroxene modes are known. This makes the stope-like structure compositions complimentary to the mafic- (and pyroxene-) rich compositions found in sections at the Lambertville sill's southwestern and northeastern ends by Eliason (1986) and Roth (1988), respectively (Fig. 16). By combining these sections, a regional or sheet-wide mass balance is attained, although at any individual section a local mass balance is lacking.

At this particular locality, the diabase is fairly feldspathic with as much as 19 weight percent Al_2O_3 (Crohe, 1996). However, pods of pegmatitic granophyre, reminiscent of those seen at Stop 1A, are quite common within the host diabase. A more granophyric diabase can be seen in some of the float pieces located across the road and in float located on the other side of Route 31, approximately one mile to the west.

Finally, it should be reinterated here, that it does not appear that any of the residual, granophyric material, so common in this section of the Lambertville sill, was transported into the immediately adjoining Flemington dike or erupted onto the surface as part of the Flemington basalt. This indicates that the emplacement of the HTQ magma into the Flemington dike and its eruption as the Flemington basalt was completed prior to the internal differentiation of the PRHL sheet (as represented locally by the Lambertville sill). Otherwise, granophyric compositions resulting from that differentiation would be more common within the dike and flow.

121.4	0.1	Continue west on Rocktown Road and cross one-lane bridge.
122.2	0.8	Make right at stop sign onto Route 31 and head north back to Staten Island via. Routes 31, 202, and 287.