Late Proterozoic Diabase Dikes of the New Jersey Highlands—A Remnant of Iapetan Rifting in the North-Central Appalachians

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By Richard A. Volkert and John H. Puffer

GEOLOGIC STUDIES IN NEW JERSEY AND EASTERN PENNSYLVANIA

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A study of the field relations, geochemistry, and petrogenesis of diabase dikes that intrude Middle Proterozoic rocks of the New Jersey Highlands

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.039 37	inch
centimeter (cm)	0.393 7	inch
meter (m)	3.281	foot
kilometer (km)	0.621 4	mile

Late Proterozoic Diabase Dikes of the New Jersey Highlands—A Remnant of Iapetan Rifting in the North-Central Appalachians

By Richard A. Volkert[1] and John H. Puffer[2]

ABSTRACT

Middle Proterozoic rocks in the New Jersey Highlands are intruded by abundant, widely distributed diabase dikes. These dikes postdate the regional granulite-grade Grenville metamorphism and are absent in continental margin cover-sequence rocks of Cambrian or younger age. They are characterized by dominant northeast linear trends, thin chill margins, and sharp, mainly conformable contacts with the enclosing Middle Proterozoic rocks.

New Jersey Highlands diabase dikes have compositions that are hypersthene normative and are enriched in TiO_2, P_2O_5, Zr, and light rare earth elements. P_2O_5 contents define two distinct groups, one low (0.28–0.81 percent) and one high (1.19–1.60 percent). Major and trace elements suggest that both groups have undergone plagioclase and clinopyroxene fractionation but may have fractionated from separate magmas tapping different mantle sources. Low P_2O_5 dikes possess compositions typical of quartz tholeiites, whereas high P_2O_5 dikes are transitional to slightly alkalic. The latter probably were generated by small amounts of partial melting of an enriched mantle source. The low P_2O_5 dikes may have been derived through increased amounts of partial melting of a mantle source that was slightly more depleted in composition, possibly by removal of the enriched, high P_2O_5 magma. Both groups have major- and trace-element characteristics consistent with their emplacement in a rift-related, within-plate tectonic setting.

Chemically, New Jersey Highlands diabase dikes are dissimilar to Late Ordovician to Early Silurian(?) alkaline intrusive rocks and dikes of the Beemerville Intrusive Suite or to Early Jurassic basalt and diabase in the Newark basin. Major-oxide and trace-element compositions of New Jersey Highlands diabase dikes are remarkably similar to those of occurrences of Late Proterozoic basaltic magmatism from throughout the Appalachians. They are probably the same age and were emplaced during Iapetan rifting of the eastern North American craton.

INTRODUCTION

The occurrence of diabase dikes that intrude Middle Proterozoic rocks in the New Jersey Highlands has long been recognized (Westgate, 1895; Darton and others, 1908; Bayley and others, 1914). Because of the composition and geographic occurrence of the dikes, previous workers assigned a Mesozoic age to most and correlated them with basalt and diabase in the Newark basin to the east (for example, Milton, 1947; Hague and others, 1956; Sims, 1958; Baker and Buddington, 1970; Maxey, 1973). A recent exception is the study of Hull and others (1988) in which some of the New Jersey Highlands diabase dikes were considered to be early Paleozoic in age and part of the Beemerville alkaline complex (renamed the Beemerville Intrusive Suite by Drake and Monteverde, 1992) in northern New Jersey. On the basis of field relations and geochemical data, Ratcliffe (1987) argued compellingly for a Late Proterozoic age for diabase dikes occurring in the New York Hudson Highlands. Geochemical analyses of a few tholeiitic diabase dikes from the New Jersey Highlands published by Milton (1947) and Maxey (1973) led Ratcliffe (1987) to conclude that these dikes may be Late Proterozoic in age also and possibly correlative with the diabase dikes he studied in the Hudson Highlands.

The current study is an outgrowth of a cooperative geologic mapping effort between the New Jersey Geological Survey and the U.S. Geological Survey to update the New Jersey State geologic map. Detailed geologic mapping of the northern and central Highlands at a scale of 1:24,000 by Volkert from 1986 to 1991 has revealed numerous previously unrecognized diabase dikes and permitted a critical examination of the orientation, structure, and field relations of previously mapped dikes. A geochemical study was subsequently undertaken from which reasonable constraints on the petrogenesis and age of the New Jersey Highlands diabase dikes could be established.

Our conclusion is that most of the post-Grenvillian diabase dikes in the New Jersey Highlands are of Late Proterozoic age, but some mafic dikes are part of the Late Ordovician to Early Silurian(?) Beemerville Intrusive Suite. Mesozoic dikes are present but rare. In order to avoid confusion, we will use the term New Jersey Highlands diabase for

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those dikes thought to be of Late Proterozoic age, Beemerville dikes for the Beemerville Intrusive Suite, and Mesozoic dikes.

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GEOLOGIC SETTING

The New Jersey Highlands and the physically continuous New York Hudson Highlands constitute the largest of the Middle Proterozoic (Grenville) massifs in the north-central Appalachians, extending southwest from southeastern New York to near Reading, Pa. The New Jersey Highlands is underlain by plagioclase-rich gneiss and granofels, amphibolite, metadiorite, and quartz-rich charnockitic gneiss, which are unconformably overlain by a variety of metasedimentary and metavolcanic gneisses and intruded by three suites of granitoid rocks (Drake, 1984; Volkert and Drake, 1991). All of these rocks are of Middle Proterozoic age. In New Jersey, the Highlands is divided into two subequal parts by unmetamorphosed sedimentary rocks of Cambrian through Devonian age in the Green Pond Mountain region (fig. 1). On the southeast, the New Jersey Highlands is in fault contact with sedimentary and igneous rocks of Mesozoic age in the Newark basin. On the northwest, the Middle Proterozoic rocks are unconformably overlain by, or in fault contact with, unmetamorphosed continental margin clastic and carbonate rocks of Cambrian age.

Diabase dikes are widely distributed throughout the New Jersey Highlands where they intrude virtually all Middle Proterozoic lithologies. They occur in about equal abundance along the regional strike length of the New Jersey Highlands, as well as southeast and northwest of the Green Pond Mountain region. Dikes are somewhat less abundant in the central Highlands, perhaps due to poorer bedrock exposure within and to the south of the Wisconsinan terminal moraine. Dike concentrations appear to be greatest in the Wanaque, Blairstown, and High Bridge quadrangles and to a lesser extent, the Boonton quadrangle (fig. 1).

Beemerville dikes and related alkaline rocks, which are generally nepheline normative, intrude rocks in northern New Jersey ranging in age from Middle Proterozoic through Middle Ordovician. They are abundant in the northwestern Highlands, near the lower Paleozoic unconformity, but are absent to sparse further to the east within the Highlands. They are especially abundant northwest of the Highlands near Beemerville. Beemerville dikes typically trend northwest and are chemically distinct from the hypersthene-normative New Jersey Highlands diabase dikes. Specifically, the former are marked by an enrichment in light rare earth elements (LREE), particularly La and Ce, and are also enriched in K_2O, Ba, Rb, Sr, and Zr compared to the diabase dikes. In addition, Beemerville dikes may be distinguished in the field from New Jersey Highlands diabase dikes in that the former often contain biotite, phenocrysts of pyroxene, and ocelli of feldspar and (or) nepheline, in places, effervesce in the presence of HCl, and are a lighter color on a fresh surface. Although the Beemerville dikes overlap the geographic occurrence of the New Jersey Highlands diabase dikes, the latter are confined exclusively to the Middle Proterozoic rocks. Nowhere in New Jersey are hypersthene normative diabase dikes observed intruding Cambrian or younger rocks. This suggests that the Beemerville dikes and related rocks are younger than the diabase dikes. No crosscutting relations between Beemerville dikes and diabase dikes were observed in the New Jersey Highlands.

New Jersey Highlands diabase dikes are also dissimilar to Early Jurassic basalt and diabase of the Eastern North American province from the Newark basin. The latter are physically distinct in lacking the retrograde alteration common in the Highlands diabase. New Jersey Highlands diabase is also chemically unlike Early Jurassic basalt and diabase, particularly in its enrichment in TiO_2, P_2O_5, Zr, and LREE. Intrusive activity of early Mesozoic age may have occurred in the Highlands, and one objective of this study was to scrutinize dike occurrences for the presence of Mesozoic dikes, especially in areas of the Highlands adjacent to the border fault. Volkert (unpub. data) mapped a single dike from a gas pipeline trench a few kilometers west of the Ramapo fault and considered it a possible candidate for a Mesozoic dike. Its composition (table 1, sample 364) is markedly different from that of the other Highlands diabase and confirms that it probably is Jurassic. Chemically, it closely resembles the oldest of the flows in the Newark basin, the Orange Mountain Basalt (Puffer, 1989), and also the chill margins of some Early Jurassic diabase from the west-central Newark basin in New Jersey (Houghton and others, 1992). Other possible Jurassic candidates were recognized from within the border fault zone (Costas, 1991), but these rocks appear too highly deformed and altered for their compositions to be useful in this study. No other candidates for correlation with Jurassic basalt and diabase were recognized in either the New Jersey Highlands or further to the west in the Valley and Ridge.

DESCRIPTION OF THE DIKES

FIELD RELATIONS

The diabase dikes in the New Jersey Highlands range in width from a few centimeters to about 18.5 m and have strike lengths of up to several kilometers where traceable by

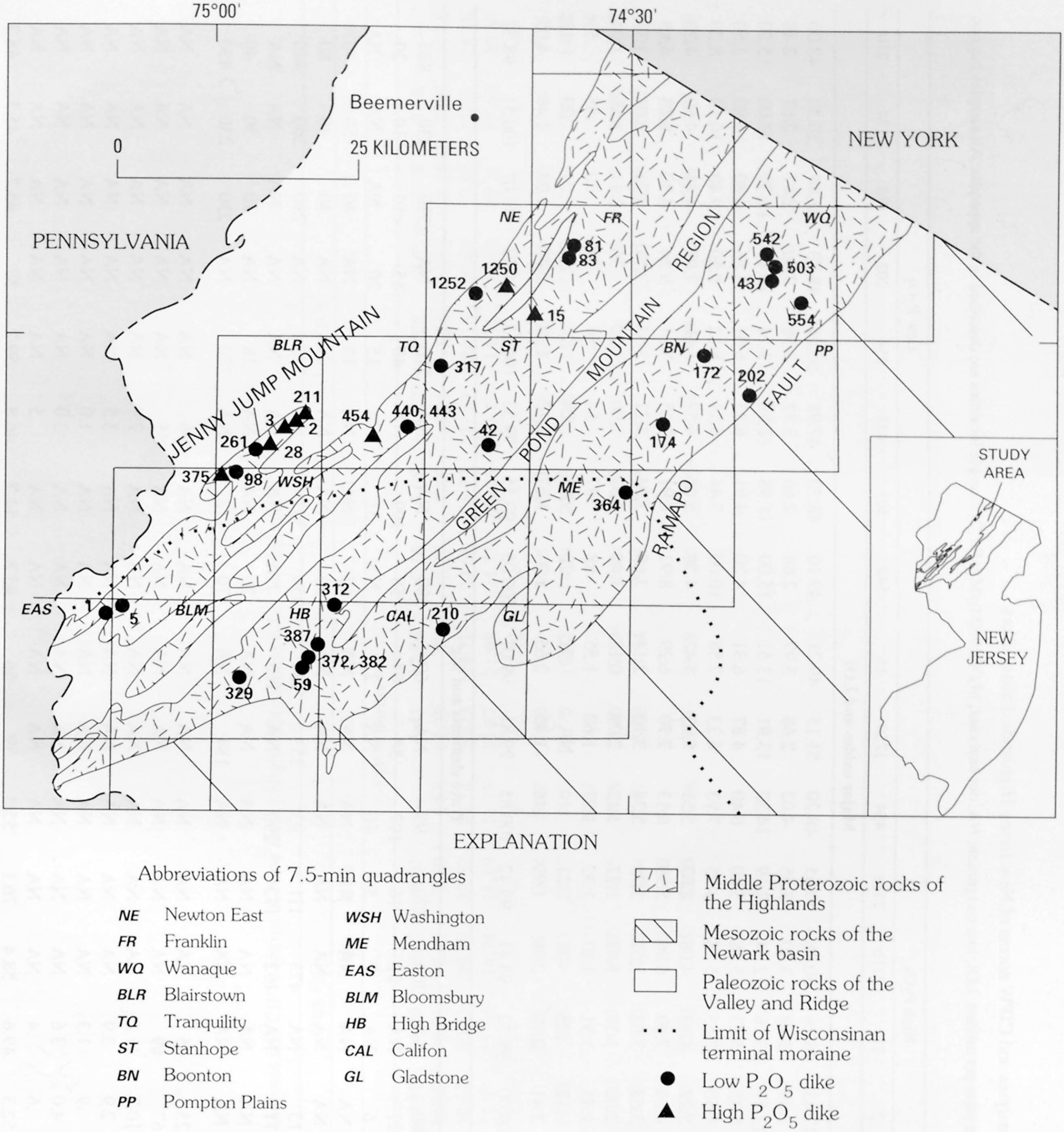

Figure 1. Generalized geologic map of northern New Jersey showing Middle Proterozoic rocks of the Highlands (patterned), Mesozoic rocks of the Newark basin (diagonal ruled), and Paleozoic rocks of the Valley and Ridge (unpatterned). Dotted line marks limit of Wisconsinan terminal moraine. Small inset map locates study area shown in geologic map. Symbols indicate geochemical sample locations for this study; circles, low P_2O_5 dikes; triangles, high P_2O_5 dikes. Samples are numbered as in tables 1 and 2 and the appendix.

outcrop and float. The majority of dikes are solitary, but where multiple dikes intrude the same general area, they occur in en echelon or closely parallel sets. Most dikes are remarkably linear, although a few are locally arcuate along their strike length.

On a regional scale, the dikes are largely conformable to the Grenville age foliation in the Middle Proterozoic rocks. However, at outcrop scale, contacts range from conformable to nearly orthogonal to the foliation. Of the more than 60 diabase dikes mapped in the New Jersey Highlands,

Table 1. Major-oxide and trace-element analyses and CIPW norms of New Jersey Highlands diabase dikes.

[Major oxides in weight percent; trace elements in parts per million. LOI, loss on ignition; NA, not analyzed; Mg'=[100(Mg/Mg+Fe^{2+})]. Sample localities are described in the appendix. All samples but one are Late Proterozoic]

	High P_2O_5										Low P_2O_5							
Sample no.	375	28	3	2	211	211b	211c	454	1250	15	542	503	437	554	202	172	174	210
Major oxides and LOI																		
SiO_2	50.00	49.80	47.54	47.43	48.28	50.48	50.65	48.20	51.15	49.21	49.10	48.50	47.98	50.01	48.73	51.40	50.50	48.00
TiO_2	2.87	2.95	3.32	3.89	3.49	3.80	3.55	4.02	2.68	3.97	2.66	2.66	3.72	3.56	2.60	2.47	2.67	2.48
Al_2O_3	13.00	13.30	13.59	13.57	13.16	12.74	12.19	14.32	13.91	13.51	15.00	15.98	12.98	12.14	10.98	12.70	13.00	15.20
Fe_2O_3	5.90	5.30	5.76	6.35	5.83	5.88	5.60	6.40	4.87	6.31	4.20	4.61	6.25	6.01	5.16	4.80	4.80	3.50
FeO	7.20	8.60	8.45	8.60	7.55	5.18	4.95	7.93	6.23	7.58	10.00	7.44	9.24	8.12	9.50	9.40	10.10	8.20
MgO	3.85	4.57	5.31	5.29	4.17	4.08	8.87	5.51	5.03	5.42	4.38	5.04	4.57	6.60	7.07	4.44	4.69	4.30
CaO	7.14	7.38	6.43	4.24	7.59	6.90	5.99	6.13	7.70	6.29	8.92	8.91	7.65	7.31	9.34	8.30	8.23	6.83
Na_2O	2.56	2.52	2.80	3.62	3.62	3.52	2.78	5.34	3.10	2.14	2.68	3.04	3.27	3.33	3.17	2.71	3.04	3.33
K_2O	2.88	2.20	2.24	2.00	1.39	1.43	1.32	1.13	2.09	0.13	1.40	1.33	1.00	1.22	.36	1.11	1.50	1.94
P_2O_5	1.23	1.19	1.48	1.48	1.31	1.23	1.32	1.27	1.60	1.55	.28	.37	.51	.81	.38	.30	.35	.51
MnO	.23	.28	.24	.12	.23	.21	.21	.14	NA	.31	.20	NA	.24	.23	.16	.21	.23	.18
LOI	1.45	2.00	2.74	3.41	2.70	2.96	1.99	.46	1.45	2.65	1.23	1.67	2.12	1.28	2.48	1.23	1.40	4.05
Total	98.31	100.09	99.90	100.00	99.32	98.41	99.42	100.85	99.81	99.07	100.05	99.55	99.53	100.62	99.93	99.07	100.51	98.52
Trace elements and Mg'																		
Ba	1100	890	1040	580	NA	300	270	95	NA	60	380	NA	NA	270	NA	290	330	880
Cr	<10	14	30	27	NA	25	16	102	58	63	58	109	NA	40	85	<10	10	20
Ni	NA	NA	12	6	NA	7	5	46	NA	27	NA	31	NA	15	20	NA	NA	NA
Nb	40	30	NA	NA	NA	NA	NA	NA	NA	NA	40	NA	NA	15	NA	40	50	40
Rb	60	40	NA	NA	NA	NA	NA	NA	NA	NA	60	NA	NA	NA	NA	40	40	80
Sr	460	400	330	213	NA	473	111	93	353	154	350	301	NA	370	NA	290	260	440
V	NA	NA	155	171	NA	192	172	290	NA	168	NA	NA	NA	NA	NA	NA	NA	NA
Y	60	50	NA	NA	NA	NA	NA	NA	NA	NA	20	NA	NA	18	NA	30	30	40
Zr	300	290	NA	NA	NA	NA	NA	NA	184	NA	170	112	NA	220	NA	230	230	450
La	NA	NA	28	25	45	NA	NA	NA	NA	NA	NA	NA	36	NA	NA	NA	NA	NA
Ce	NA	NA	68	67	69	NA	NA	NA	NA	NA	NA	NA	55	NA	NA	NA	NA	NA
Sm	NA	NA	11.1	10.7	11.2	NA	NA	NA	NA	NA	NA	NA	7.9	NA	NA	NA	NA	NA
Eu	NA	NA	3.8	2.9	3.9	NA	NA	NA	NA	NA	NA	NA	3.5	NA	NA	NA	NA	NA
Tb	NA	NA	.7	.9	1.3	NA	NA	NA	NA	NA	NA	NA	1.0	NA	NA	NA	NA	NA
Yb	NA	NA	4.2	4.0	3.6	NA	NA	NA	NA	NA	NA	NA	3.0	NA	NA	NA	NA	NA
Lu	NA	NA	.8	.6	.4	NA	NA	NA	NA	NA	NA	NA	.5	NA	NA	NA	NA	NA
Mg'	48.8	48.6	52.8	52.3	49.6	58.4	76.1	55.3	59	56	43.8	54.7	46.8	59.2	57	45.7	45.3	48.3

Table 1. Major-oxide and trace-element analyses and CIPW norms of New Jersey Highlands diabase dikes—Continued.

	High P_2O_5										Low P_2O_5							
Sample no......	375	28	3	2	211	211b	211c	454	1250	15	542	503	437	554	202	172	174	210
									CIPW norms									
Q................	7.25	6.47	3.49	3.95	4.35	9.61	8.01	—	6.41	17.84	2.16	1.08	4.22	4.25	1.55	7.78	3.18	—
Or...............	17.02	13.00	13.24	11.82	8.21	8.45	7.80	6.68	12.35	.77	8.27	7.86	5.91	7.21	2.13	6.56	8.86	11.46
Ab..............	21.66	21.32	23.69	30.63	30.63	29.79	23.52	44.34	26.23	18.11	22.68	25.72	27.67	28.18	26.82	22.93	25.72	28.18
An..............	15.48	18.48	17.90	11.37	15.56	14.74	16.89	11.77	17.87	21.08	24.77	26.03	17.79	14.58	14.67	19.21	17.40	20.80
C................	—	—	—	1.29	—	—	—	—	—	2.12	—	—	—	—	—	—	—	—
Di................	9.60	8.44	3.49	—	10.87	8.92	3.28	8.22	7.86	—	14.61	12.71	13.66	13.09	23.66	16.48	17.44	8.01
Hy..............	9.00	14.33	17.26	17.52	8.88	6.03	20.57	—	11.78	16.22	14.54	11.88	10.86	14.69	15.32	12.54	13.67	14.72
Ol...............	—	—	—	—	—	—	—	9.07	—	—	—	—	—	—	—	—	—	.34
Mt..............	8.55	7.68	8.35	9.21	8.45	6.37	6.35	9.28	7.06	9.15	6.09	6.68	9.06	8.71	7.48	6.96	6.96	5.07
Il.................	5.45	5.60	6.31	7.39	6.63	7.22	6.74	7.63	5.09	7.54	5.05	5.05	7.07	6.76	4.94	4.69	5.07	4.71
Hem...........	—	—	—	—	—	1.49	1.22	—	—	—	—	—	—	—	—	—	—	—
Ap..............	2.85	2.76	3.43	3.43	3.04	2.85	3.06	2.94	3.71	3.59	.65	.86	1.18	1.88	.88	.70	.81	1.18

Table 1. Major-oxide and trace-element analyses and CIPW norms of New Jersey Highlands diabase dikes—Continued.

	Low P_2O_5																	Jurassic
Sample no.	312	387	382	372	59	329	1	5	98	261	440	443	42	317	1252	83	81	364
Major oxides and LOI																		
SiO_2	50.70	50.49	49.63	51.74	49.80	50.10	48.20	49.00	47.60	49.00	48.90	48.46	48.88	48.40	47.60	46.74	45.85	47.40
TiO_2	2.79	2.64	2.54	2.68	2.74	3.21	3.54	3.30	3.32	3.10	2.52	2.34	3.46	3.43	2.99	2.65	2.78	.84
Al_2O_3	13.20	11.69	13.07	12.07	12.70	13.10	12.90	12.60	12.70	13.10	13.70	14.51	13.23	12.40	13.00	14.00	13.88	15.80
Fe_2O_3	5.40	5.17	4.90	5.21	5.00	5.60	7.00	6.90	5.60	6.80	6.30	4.58	5.96	6.20	6.70	5.17	5.28	3.30
FeO	8.80	9.18	7.71	9.26	10.80	9.30	8.60	7.50	9.70	7.70	7.60	6.68	8.98	8.70	8.50	9.16	8.92	7.80
MgO	4.11	3.99	4.74	4.24	4.40	4.70	5.18	4.95	5.11	4.76	5.57	7.34	4.51	5.00	5.43	6.18	6.14	8.15
CaO	7.20	8.97	8.55	9.37	8.57	7.22	5.48	6.69	7.87	7.55	10.10	9.68	7.21	7.96	8.33	9.84	9.22	10.30
Na_2O	3.69	2.63	2.88	2.61	2.57	2.94	3.28	2.70	2.63	2.89	2.19	2.38	3.96	3.27	2.26	2.83	2.40	2.08
K_2O	1.91	1.39	1.22	1.32	1.06	1.98	1.66	1.90	1.71	1.69	1.30	1.18	1.22	.51	1.77	1.05	2.36	.50
P_2O_5	.62	.41	.48	.46	.29	.42	.56	.59	.48	.62	.47	.57	.44	.57	.74	.58	.57	.07
MnO	.24	.18	.20	.18	.23	.20	.18	.21	.22	.22	.16	NA	.19	.19	.21	.22	.20	.17
LOI	1.23	NA	1.66	1.22	.70	1.39	2.50	2.00	2.31	1.95	1.54	1.25	2.02	1.54	1.95	1.74	2.52	2.85
Total	99.89	96.74	97.58	100.36	98.86	100.16	99.08	98.34	99.25	99.38	100.35	98.97	100.06	98.17	99.48	100.16	100.12	99.26
Trace elements and Mg'																		
Ba	550	NA	NA	NA	310	320	480	410	440	510	430	NA	330	210	520	590	1080	80
Cr	33	42	102	41	20	20	30	10	45	20	66	99	40	40	10	92	103	300
Ni	NA	2	47	1	NA	NA	NA	NA	NA	NA	NA	23	NA	NA	NA	42	42	NA
Nb	30	NA	NA	NA	30	30	50	30	40	70	10	NA	30	30	30	NA	NA	<10
Rb	40	NA	NA	NA	30	30	60	80	40	50	40	NA	30	30	50	NA	NA	30
Sr	360	NA	286	NA	240	310	410	360	380	390	330	283	320	310	290	398	592	210
V	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	275	289	NA
Y	30	NA	NA	NA	20	30	30	30	30	20	30	NA	20	30	30	NA	NA	<10
Zr	290	NA	154	NA	250	250	250	250	230	260	220	147	240	220	270	NA	NA	30
La	34	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	34	NA	NA	15	14	NA
Ce	54	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	55	NA	NA	38	38	NA
Sm	8.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.5	NA	NA	6.0	6.0	NA
Eu	3.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.3	NA	NA	1.6	1.8	NA
Tb	1.5	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	1.5	NA	NA	.7	.7	NA
Yb	3.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.1	NA	NA	3.1	2.8	NA
Lu	.6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	.5	NA	NA	.5	.5	NA
Mg'	45.4	43.6	52.3	44.9	42.1	47.4	51.8	54	48.4	52.4	56.6	66.2	47.2	50.6	53.2	54.6	55.1	65

Table 1. Major-oxide and trace-element analyses and CIPW norms of New Jersey Highlands diabase dikes—Continued.

	Low P_2O_5																	Jurassic
Sample no.	312	387	382	372	59	329	1	5	98	261	440	443	42	317	1252	83	81	364
CIPW norms																		
Q	2.54	7.54	5.66	8.13	5.86	4.24	4.55	7.34	2.85	5.84	5.38	2.00	1.34	5.91	4.85	—	—	—
Or	11.29	8.21	7.21	7.80	6.26	11.70	9.81	11.23	10.11	9.99	7.68	6.97	7.21	3.01	10.46	6.21	13.95	2.95
Ab	31.22	22.25	24.37	22.09	21.75	24.88	27.75	22.85	22.25	24.45	18.53	20.14	33.51	27.67	19.12	23.95	20.31	17.60
An	13.81	15.99	19.13	17.32	19.99	16.70	15.57	16.65	17.80	17.78	23.71	25.43	14.72	17.65	20.10	22.40	20.13	32.30
C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Di	14.63	21.27	16.34	21.50	17.11	13.36	6.38	10.10	14.77	12.51	18.71	15.04	14.76	14.62	13.20	18.38	17.73	14.87
Hy	10.60	8.01	10.16	8.59	14.07	12.71	14.34	10.54	13.63	9.68	9.78	15.74	10.27	10.94	12.69	9.84	2.61	18.28
Ol	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3.78	8.61	3.87
Mt	7.83	7.50	7.10	7.55	7.25	8.12	10.15	10.00	8.12	9.86	9.13	6.64	8.64	8.99	9.71	7.50	7.66	4.78
Il	5.30	5.01	4.82	5.09	5.20	6.10	6.72	6.27	6.31	5.89	4.79	4.44	6.57	6.51	5.68	5.03	5.28	1.60
Hem	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Ap	1.44	.95	1.11	1.07	.67	.97	1.30	1.37	1.11	1.44	1.09	1.32	1.02	1.32	1.71	1.34	1.32	.16

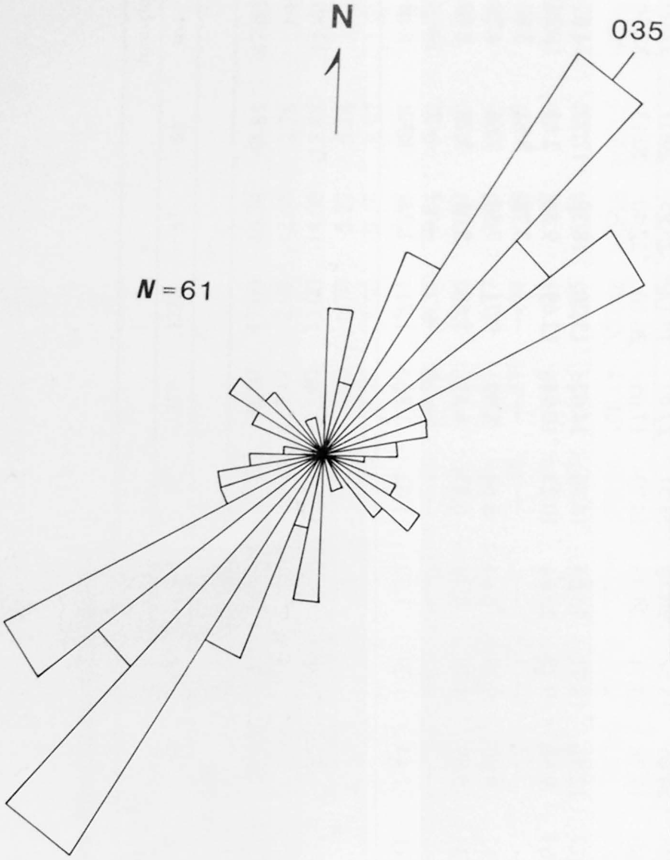

Figure 2. Rose diagram of strikes of 61 diabase dikes mapped in the New Jersey Highlands.

Figure 3. Xenolith of fractured and undigested Middle Proterozoic country rock immediately left of hammer. Xenolith has same mineralogy as granite at right of photograph. Its orientation is coincident with that of the dike, suggesting that it was dislodged and dragged along parallel to the contact during dike emplacement. Hammer for scale is 28 cm in length.

9 (included here in the Late Proterozoic population) are northwest trending and transect the foliation at a high angle. These appear to have intruded along the dominant joint set. The remainder of the dikes are northeast trending, and dike orientations plotted on a rose diagram (fig. 2) show a dominant N.35°E. trend. Most of the dikes have steep dips of between 70° and 90°, but some have much gentler dips and are oriented parallel to the dips of the foliation in the enclosing Middle Proterozoic rocks. Preexisting fault zones, as well as synrift shearing, may have helped to localize some dike emplacement, but currently fewer than 5 percent of the dikes occur along or close to a fault.

New Jersey Highlands diabase dikes typically have chilled margins and sharp contacts against Middle Proterozoic rocks. Aphanitic dike margins argue strongly for dike emplacement into relatively cold country rock, as does the lack of any thermal alteration along the dike-country rock contact. Scattered small, undigested xenoliths of country rock occur along the margins of some dikes (fig. 3). Many of the xenoliths were probably detached through magmatic stoping; others are commonly fractured and probably were dislodged through forceful injection during dike emplacement. Thin apophyses of fine-grained diabase locally intrude the country rock adjacent to the main body of thicker dikes.

Closely spaced columnar jointing was observed in several dikes from widely separated areas, supporting the conclusion that some of the dikes were emplaced at fairly shallow, cold crustal levels, perhaps even locally breaking the surface. The columns in the chilled margin of one dike from the Tranquility quadrangle are particularly well developed (fig. 4).

The diabase dikes characteristically are hard and massive textured, fine grained to aphanitic, weathering light olive gray (5*Y* 6/1) to grayish brown (5*YR* 3/2) to dark gray (*N* 3) and on a fresh surface are dark greenish gray (5*G* 4/1) or greenish black (5*GY* 2/1; rock-color terms from Goddard and others, 1948). The groundmass is typically felty and contains small, conspicuous laths of plagioclase up to a few millimeters in length and ubiquitous, small anhedral masses of pyrite. Phenocrysts of plagioclase, although present in some dikes, are relatively uncommon overall.

The high-grade granulite-facies metamorphism so evident in the Middle Proterozoic rocks is altogether absent in the diabase dikes, which are largely unmetamorphosed. A

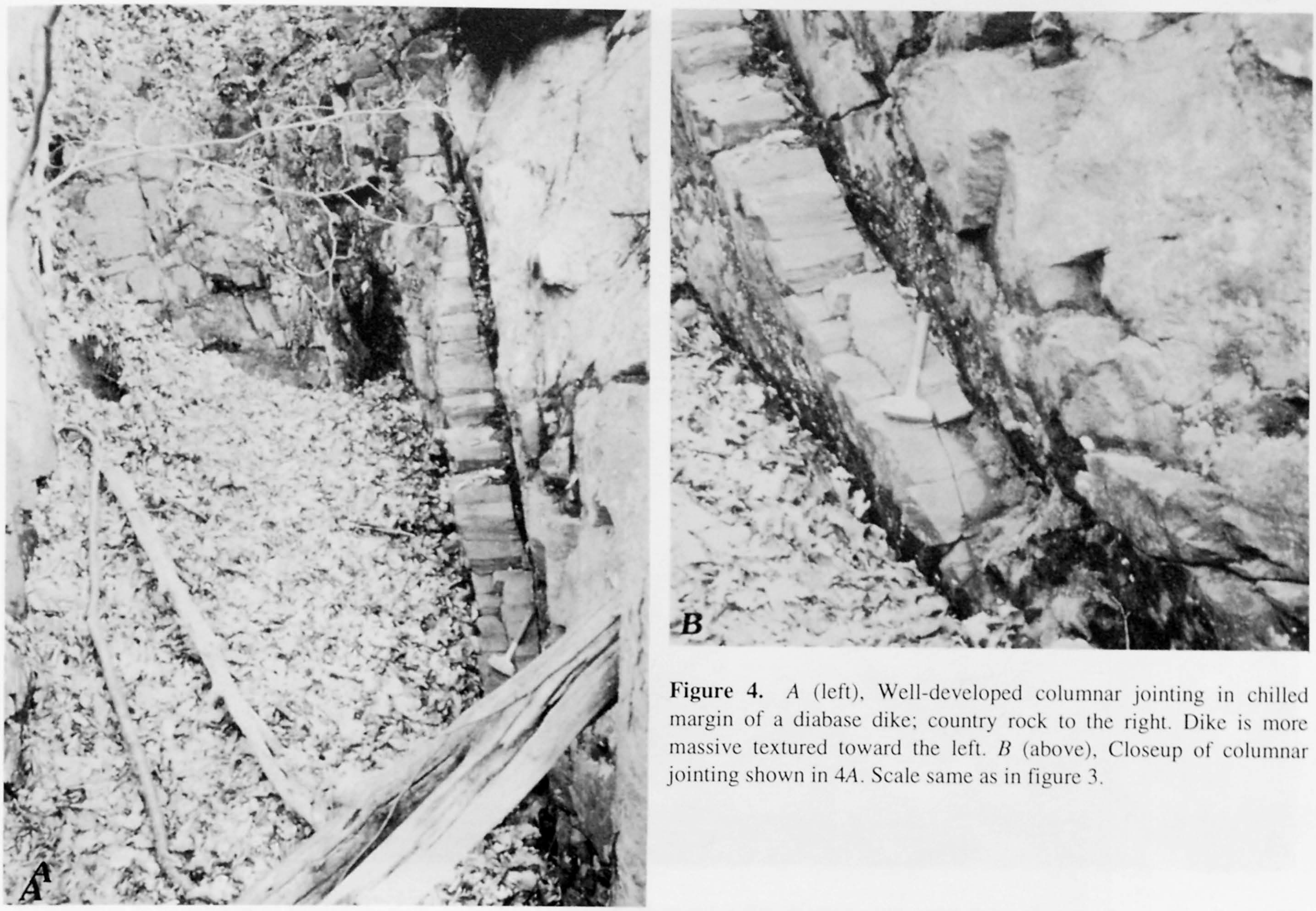

Figure 4. *A* (left), Well-developed columnar jointing in chilled margin of a diabase dike; country rock to the right. Dike is more massive textured toward the left. *B* (above), Closeup of columnar jointing shown in 4*A*. Scale same as in figure 3.

few are very weakly foliated and a few more display what may be a crude flow structure.

PETROGRAPHY

Most of the New Jersey Highlands diabase dikes studied appear to be at least somewhat altered in hand sample. Alteration effects in even the freshest samples have largely obscured the primary igneous mineralogy in thin section. Where dikes have been tectonized, alteration commonly is severe.

In thin section (fig. 5), the dikes are uniformly holocrystalline, hypidiomorphic to subophitic diabase. The principal igneous phases are plagioclase (labradorite to andesine), augite, ilmeno-magnetite, and ilmenite with trace amounts of titanite and largely altered olivine. Principal alteration effects observed are (1) abundant, secondary albite occurring as fine-grained laths and rimming partially replaced plagioclase phenocrysts; (2) partial sericitic replacement of plagioclase; (3) secondary blue-green amphibole occurring as fine, anhedral grains and rimming relict pink titano-augite phenocrysts; (4) partial replacement of augite by chlorite; (5) partial oxidation of relict ilmeno-magnetite grains; (6) quench dendrites of magnetite altered to hematite and skeletal ilmenite altered to pseudorutile; and (7) precipitation of disseminated, subhedral grains or clusters of small grains of pyrite. Trace amounts of quartz, calcite, chalcopyrite, epidote, and serpentine are also present in thin section.

GEOCHEMISTRY

ALTERATION

Alteration processes have resulted in varying degrees of modification of the primary composition of the dikes. The degree of modification is recognized by comparing the composition of the samples displaying the most secondary mineralization as viewed in thin section with samples displaying the least altered mineralogy. Samples containing the most secondary albite and sericite correlate with the highest Na_2O (3.5–5.3 percent) and K_2O (2–2.3 percent) values. Secondary albitization and sericitization also correlate directly with elevated SiO_2, Sr, and Ba and with depletion of CaO. Alteration is also reflected in elevated LOI (loss on ignition) values. Fifteen of the diabase dikes analyzed have LOI ranging from 2.0 to 4.05 weight percent (table 1).

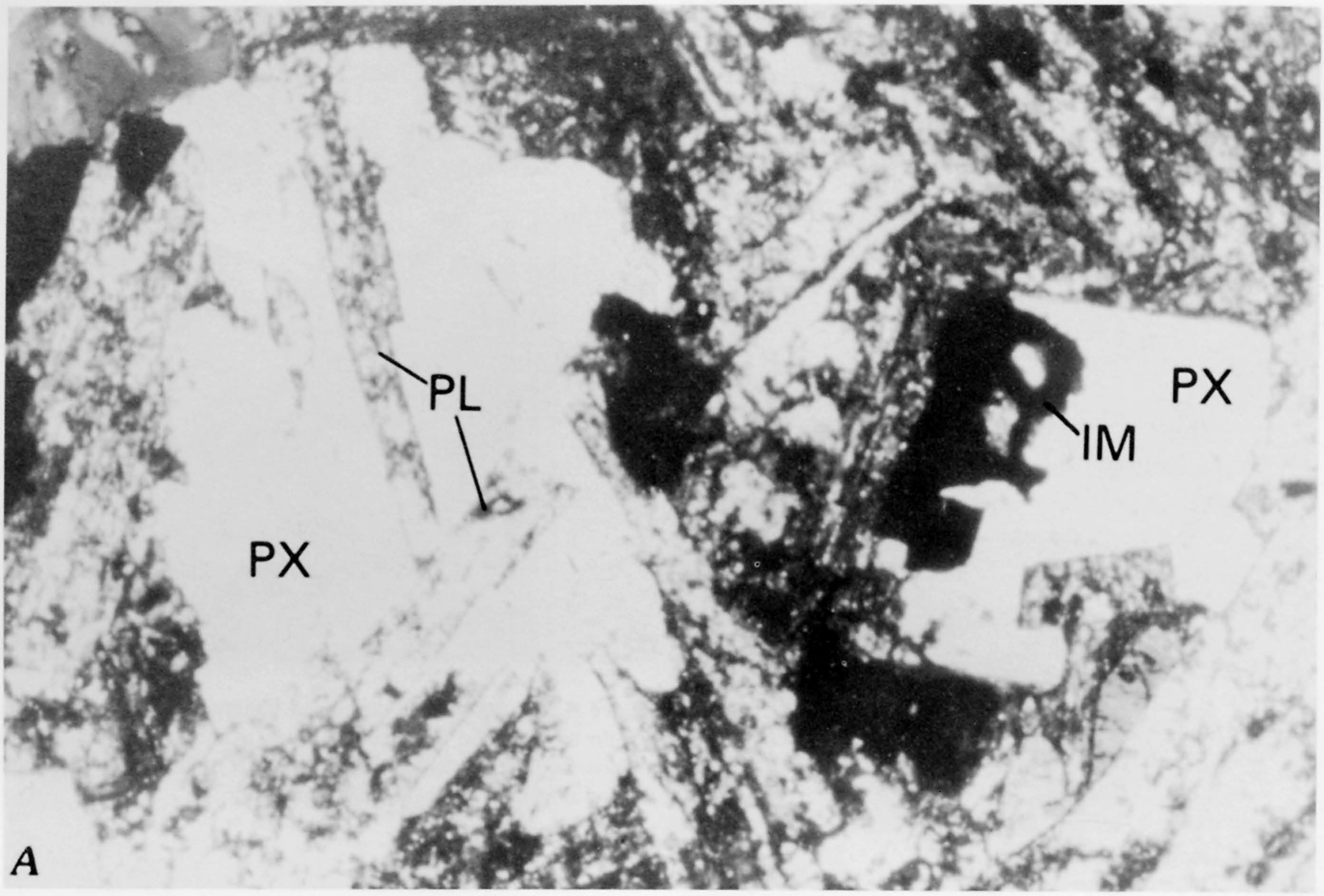

Figure 5. Photomicrographs of diabase dikes from the New Jersey Highlands. *A*, Medium-grained diabase from interior of sample 81 showing sericitized plagioclase laths (PL), subhedral clinopyroxene (PX), and skeletal ilmeno-magnetite (IM).

The enrichment of Na, K, Si, Sr, and Ba and depletion of Ca may be attributed to reactions involving the assimilation of Na- and K-rich Middle Proterozoic rocks during dike emplacement, retrograde reactions involving hydrothermal solutions generated during Taconian, Alleghanian, and (or) Mesozoic orogenesis, or a combination of both. Because xenoliths of Middle Proterozoic rock are uncommon and undigested, hydrothermal solutions are probably the principal enrichment process. Additional support comes from the fact that calculated viscosities of New Jersey Highlands dike magma are relatively low, ranging from 1.83 to 2.92 poises, suggesting fairly rapid dike emplacement and minimal reaction with the country rock. The most highly altered samples are from diabase dikes that are relatively thin, dikes that are tectonized, or are from the margins of thicker dikes.

MAJOR AND TRACE ELEMENTS

Major-oxide and trace-element analyses and CIPW normative compositions of the 36 dikes sampled for this study are given in table 1. All samples were analyzed at XRAL Activation Services, Ann Arbor, Mich. Major-oxide and trace-element contents, except FeO, were obtained by X-ray fluorescence; FeO content was obtained by wet chemistry. Rare earth elements (REE) were obtained by instrumental neutron activation analysis. The low total of a few samples in table 1 correlates mainly with the abundance of a sulfide phase and to a lesser extent with a carbonate phase. Major-oxide contents were normalized to 100 percent anhydrous, and these values are reported in table 2. All but one of the dikes are hypersthene normative; of these, 31 are quartz normative and 5 are olivine normative. The olivine normative dikes (samples 454, 210, 83, 81, and 364 in table 1) are from widely separated areas of the New Jersey Highlands. Of these, sample 364 is interpreted to be Early Jurassic and not part of the Late Proterozoic population.

New Jersey Highlands diabase dikes have major-oxide and trace-element compositions quite similar to those of typical continental quartz tholeiites from the Columbia River and Deccan provinces (Basaltic Volcanism Study Project, 1981) and dikes of the Keweenawan Supergroup (Green and others, 1987). There is a general trend toward TiO_2, P_2O_5, and LREE enrichment in some of the New Jersey Highlands diabase dikes that appear to have an alkalic

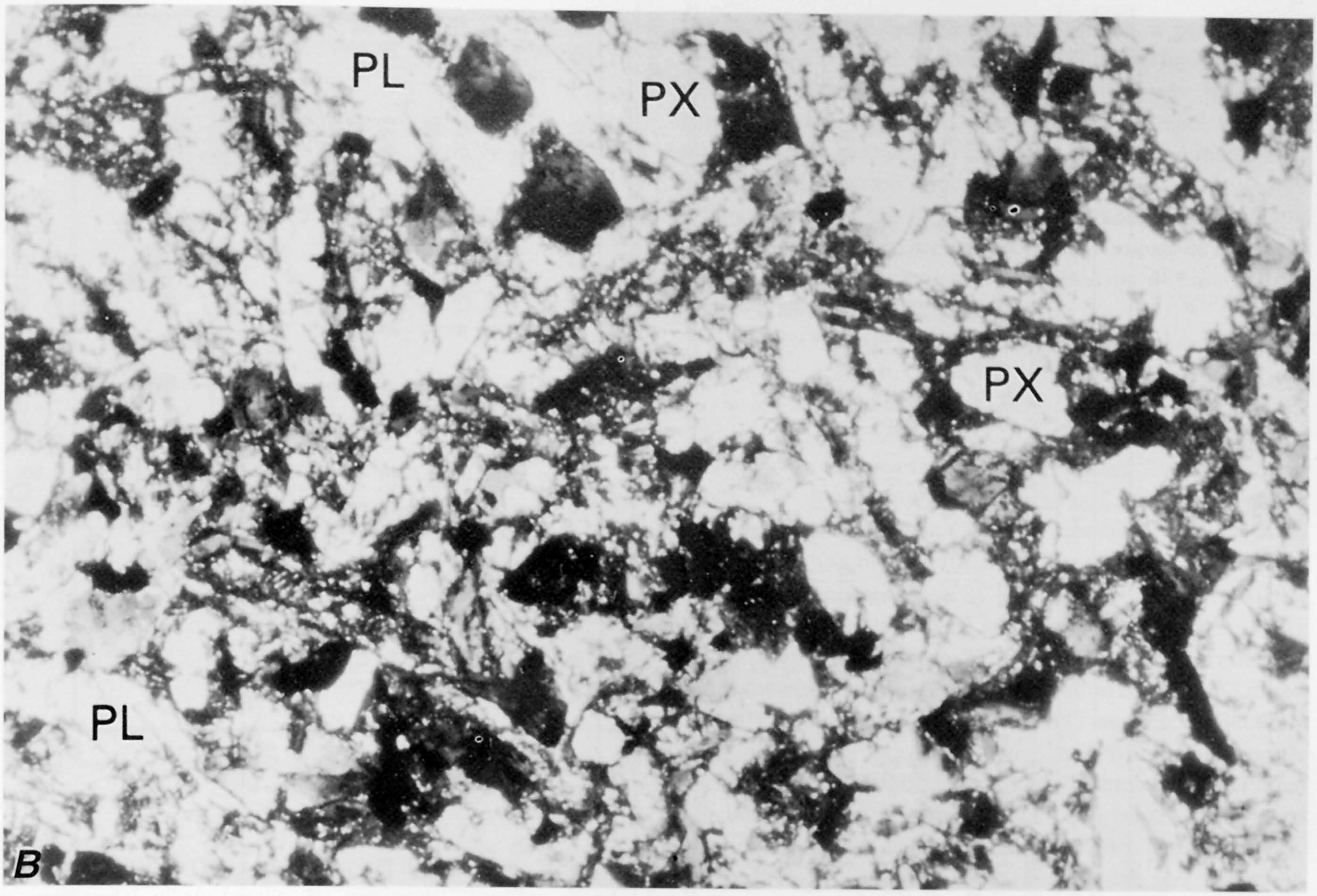

Figure 5. *B*, Fine-grained, subophitic diabase from margin of sample 81 showing plagioclase (PL) and anhedral clinopyroxene (PX). Crossed polars. Horizontal field of view in *A* is 1 mm and in *B* is 2 mm.

affinity relative to those dikes that are tholeiitic. Floyd and Winchester (1975) proposed using the Y/Nb ratio as a means of distinguishing between tholeiitic and alkalic basalts; the former have Y/Nb >1 and the latter <1. New Jersey Highlands dikes have Y/Nb ratios ranging from 0.29 to 3.0 and corresponding compositions that are tholeiitic, transitional, and mildly alkalic. On a plot of TiO_2 versus Y/Nb (fig. 6), the diabase dikes fall consistently within and overlap the fields of continental alkali basalt and continental tholeiitic basalt.

Dike rocks analyzed for this study typically contain 2.34–4.02 percent TiO_2, <14 percent Al_2O_3, 3.85–8.87 percent MgO, 4.24–10.1 percent CaO, 0.28–1.6 percent P_2O_5, <10–109 parts per million (ppm) Cr, and 112–450 ppm Zr. Despite the scatter seen in some elements on MgO variation diagrams (fig. 7), these rocks appear to plot as a continuous tholeiitic fractionation trend. In general, SiO_2, Na_2O, and Zr are inversely correlated with MgO, whereas Al_2O_3, CaO, and Cr are positively correlated. FeO_t, TiO_2, K_2O, Sr, and Ni show no discernible trend. Values for P_2O_5 define two distinct groups, one low in P_2O_5 (0.28–0.81 percent) (hereafter referred to as LPG) and one high in P_2O_5 (1.19–1.60 percent) (hereafter referred to as HPG) (figs. 7 and 8). Similar ranges in P_2O_5 contents are seen in the Bakersville Gabbro dikes from the southern Blue Ridge (Goldberg and others, 1986), in the basalts of the Catoctin Formation in Pennsylvania (Smith and others, 1991), and in New York Hudson Highlands diabase dikes (Ratcliffe, 1987). Values for the high P_2O_5 rocks from these occurrences range from 0.68 to 1.32 percent. These values are slightly lower than the upper range of the HPG reported here, but they bridge the gap between the LPG and HPG groups on figure 8 and help define a single trend.

Dikes from the LPG have Mg' values [100(Mg/$Mg+Fe^{2+}$) atomic] ranging from 42 to 66. The overall composition of this group is comparable to some of the more highly fractionated parts of continental tholeiitic series such as the dikes of the Keweenawan Supergroup (Green and others, 1987). The magma that generated LPG dikes, like many continental series, probably experienced olivine fractionation. This is supported here by the low MgO and Ni contents. However, the effects of clinopyroxene and

Table 2. Normalized major-oxide compositions of New Jersey Highlands diabase dikes (100 percent anhydrous).

	High P_2O_5										Low P_2O_5							
Sample no.	375	28	3	2	211	211b	211c	454	1250	15	542	503	437	554	202	172	174	210
SiO_2	51.63	50.77	48.92	49.11	49.97	52.90	51.97	48.01	52.02	51.03	49.69	49.55	49.26	50.34	49.99	52.53	50.95	50.81
TiO_2	2.96	3.01	3.42	4.03	3.61	3.98	3.64	4.00	2.73	4.12	2.69	2.72	3.82	3.58	2.67	2.52	2.69	2.63
Al_2O_3	13.42	13.56	13.98	14.05	13.62	13.35	12.51	14.26	14.15	14.01	15.18	16.33	13.33	12.22	11.27	12.98	13.12	16.09
Fe_2O_3	6.09	5.40	5.93	6.57	6.03	6.16	5.74	6.38	4.95	6.54	4.25	4.71	6.42	6.05	5.29	4.91	4.84	3.70
FeO	7.43	8.77	8.69	8.90	7.81	5.43	5.08	7.90	6.34	7.86	10.12	7.60	9.49	8.17	9.75	9.61	10.19	8.68
MgO	3.97	4.66	5.46	5.48	4.32	4.28	9.10	5.49	5.12	5.62	4.43	5.15	4.69	6.64	7.25	4.54	4.73	4.55
CaO	7.37	7.52	6.62	4.39	7.86	7.23	6.15	6.11	7.83	6.52	9.03	9.10	7.85	7.36	9.58	8.48	8.30	7.23
Na_2O	2.64	2.57	2.88	3.75	3.75	3.69	2.85	5.32	3.15	2.22	2.71	3.11	3.37	3.35	3.25	2.77	3.07	3.52
K_2O	2.97	2.24	2.30	2.07	1.44	1.50	1.35	1.13	2.13	0.13	1.42	1.36	1.03	1.23	.37	1.13	1.51	2.05
P_2O_5	1.27	1.21	1.52	1.53	1.36	1.29	1.35	1.27	1.63	1.61	.28	.38	.52	.82	.39	.31	.35	.54
MnO	.24	.29	.25	.12	.24	.22	.22	.14	.00	.32	.20	.00	.25	.23	.16	.22	.23	.19

	Low P_2O_5																	Jurassic
Sample no.	312	387	382	372	59	329	1	5	98	261	440	443	42	317	1252	83	81	364
SiO_2	511.39	52.19	51.74	52.21	50.75	50.70	49.91	50.86	49.10	50.24	49.49	49.59	50.62	50.09	48.81	47.49	46.97	49.15
TiO_2	2.83	2.73	2.65	2.70	2.79	3.25	3.67	3.43	3.42	3.18	2.55	2.39	3.30	3.55	3.07	2.69	2.85	0.87
Al_2O_3	13.38	12.08	13.63	12.18	12.94	13.26	13.36	13.08	13.10	13.43	13.86	14.85	13.20	12.83	13.33	14.22	14.22	16.38
Fe_2O_3	5.47	5.34	5.11	5.26	5.10	5.67	7.25	7.16	5.78	6.97	6.38	4.69	5.88	6.42	6.87	5.25	5.41	3.42
FeO	8.92	9.49	8.04	9.34	11.01	9.41	8.90	7.78	10.01	7.89	7.69	6.85	9.28	9.00	8.72	9.31	9.14	8.09
MgO	4.17	4.12	4.94	4.28	4.48	4.76	5.36	5.14	5.27	4.88	5.64	7.52	4.59	5.18	5.57	6.28	6.29	8.45
CaO	7.30	9.27	8.91	9.45	8.73	7.31	5.67	6.94	8.12	7.85	10.22	9.90	7.53	8.24	8.54	9.99	9.45	10.68
Na_2O	3.74	2.72	3.00	2.63	2.62	2.98	3.40	2.80	2.71	2.96	2.22	2.43	3.24	3.38	2.32	2.88	2.46	2.16
K_2O	1.94	1.44	1.27	1.33	1.09	2.00	1.72	1.97	1.76	1.73	1.32	1.21	1.65	.53	1.81	1.07	2.42	.52
P_2O_5	.63	.42	.50	.46	.30	.43	.58	.61	.50	.64	.48	.58	.53	.59	.76	.59	.58	.07
MnO	.24	.19	.21	.18	.23	.20	.19	.22	.23	.23	.16	.00	.22	.20	.22	.22	.20	.18

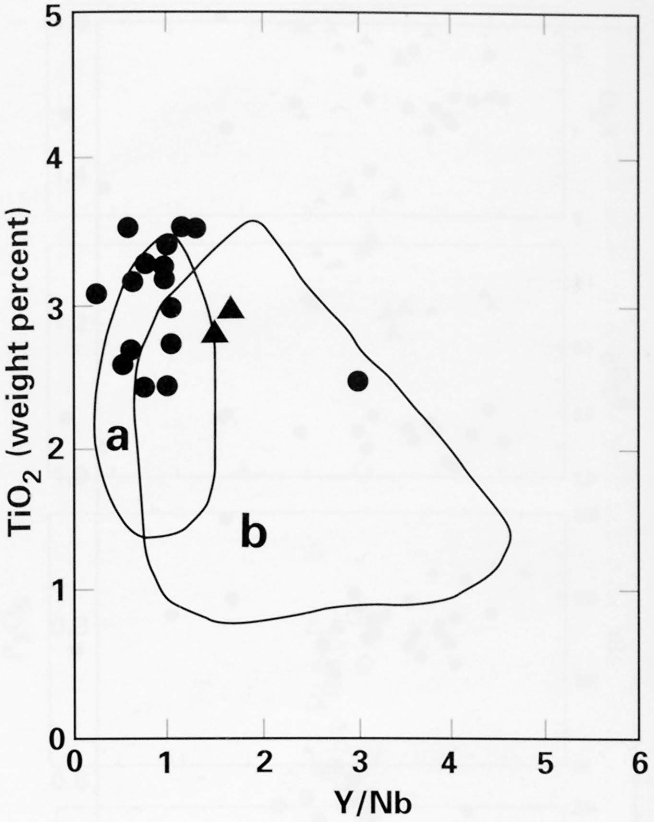

Figure 6. Plot of TiO_2 versus Y/Nb for diabase dikes. Fields are a, continental alkali basalts; b, continental tholeiitic basalts. Diagram modified from Floyd and Winchester (1975). Solid circles, low P_2O_5 dikes; solid triangles, high P_2O_5 dikes. Symbols in this and subsequent figures are the same except where stated.

plagioclase fractionation are evident on the MgO variation diagrams (fig. 7). The positive correlation of Al_2O_3 and CaO with MgO and the inverse correlation of the most incompatible elements with MgO, particularly SiO_2 and Zr, are consistent with the fractionation of clinopyroxene and calcic plagioclase.

The high levels of FeO_t (10.53–15.3 percent), TiO_2 (2.48–3.7 percent), and V (275–289 ppm) of LPG samples are probably the result of extreme tholeiitic trend iron enrichment. Magnetite and ilmenite may have been prevented from crystallizing during early stages of fractionation by low pO_2 conditions in a deep, dry magma chamber. The absence of magnetite or ilmenite phenocrysts and the abundance of late quench dendrites of magnetite suggest that pO_2 values were held low until after the dikes were emplaced.

Total concentrations of REE in LPG samples display a somewhat enriched pattern relative to chondrites with La/Yb_N ranging from 3.5 to 8.7. LREE are enriched from 43 to 112X chondrite, and overall the pattern mimics that of the HPG dikes (fig. 9). Two of the more MgO-rich dikes (>6 percent) have lower total REE concentrations than the other LPG dikes sampled and on figure 9 display a gentler negative sloping pattern. Ratcliffe (1987) identified a similar group of dikes from the Hudson Highlands that have slightly higher MgO and lower LREE contents than the other dikes he studied. On a MORB-normalized incompatible element diagram (fig. 10), LPG samples from widely separate areas of the New Jersey Highlands display nearly identical patterns that are enriched in incompatible elements and have a "humped" pattern characteristic of basalts from within-plate settings (Pearce, 1983).

The HPG dikes contain the same low concentrations of compatible elements (3.85–5.5 percent MgO and 5–30 ppm Ni) as the LPG but have higher concentrations of incompatible elements, particularly P_2O_5, TiO_2, and LREE. The Mg' of HPG dikes ranges from 48 to 76, values that are comparable to or slightly higher than those of LPG dikes. Despite the range in Mg' values, Cr and Ni remain low in all HPG dikes, including the less fractionated ones.

Total concentrations of REE are also slightly higher than in the LPG and have La/Yb_N ranging from 4.5 to 9.0. LREE are enriched from 77 to 140X chondrite, reflecting the somewhat more evolved composition of the HPG dikes. Overall, REE patterns for both LPG and HPG dikes are quite similar to those of other Late Proterozoic basaltic rocks such as the Tibbit Hill Volcanic Member of the Pinnacle Formation in Vermont (Coish and others, 1985) and Hudson Highlands diabase dikes (Ratcliffe, 1987).

Although complete trace-element data are not available for the HPG, sufficient data were obtained to permit a comparison with the LPG pattern in figure 10. There appears to be little observable difference in the patterns of the two groups with the exception of Nb to Zr. The HPG displays no trough here because of the high P content and instead has a more linear sloping pattern. Both groups exhibit a Ta-Nb peak that is characteristic of continental and oceanic alkali basalts and suggests a contribution from an enriched mantle source (Thompson and others, 1983; Wilson, 1989).

PETROGENESIS

Various discrimination diagrams using immobile elements were used to correlate the geochemical compositions of the New Jersey Highlands diabase dikes to a specific tectonic setting. All of the samples fall consistently in the field of within-plate basalts on diagrams of Zr-Zr/Y (fig. 11) and Nb-Zr-Y (fig. 12), as well as a number of other diagrams (not shown). Their continental affinity is constrained by their occurrence within Middle Proterozoic rocks and their absence in overlying continental margin shelf clastic and carbonate rocks.

The geographic overlap between the LPG and HPG dikes and the chemical similarities of the latter with the more highly fractionated part of the LPG, particularly the

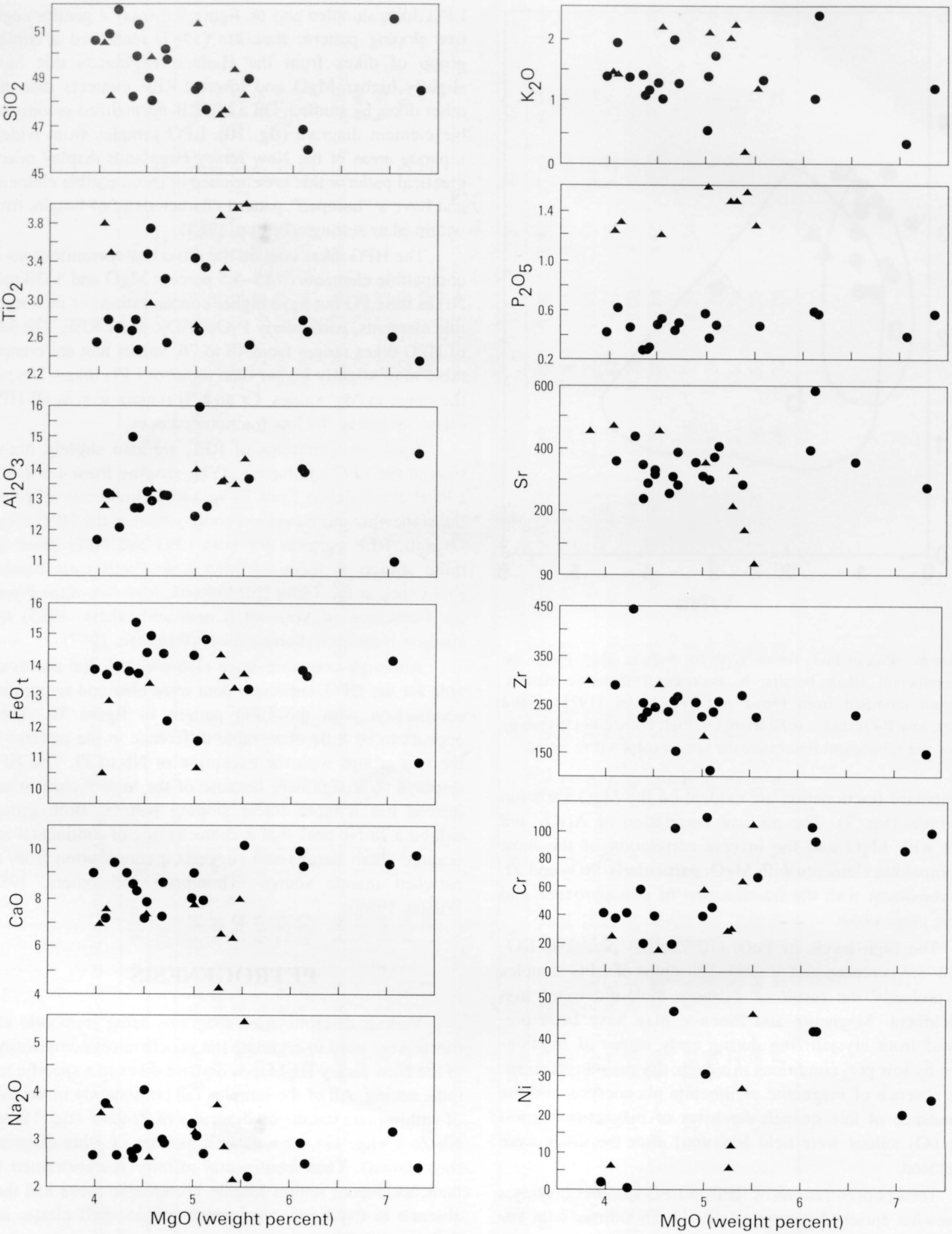

Figure 7. MgO variation diagrams of major oxides and selected trace elements for Highlands diabase dikes. Major oxides in weight percent; trace elements in parts per million.

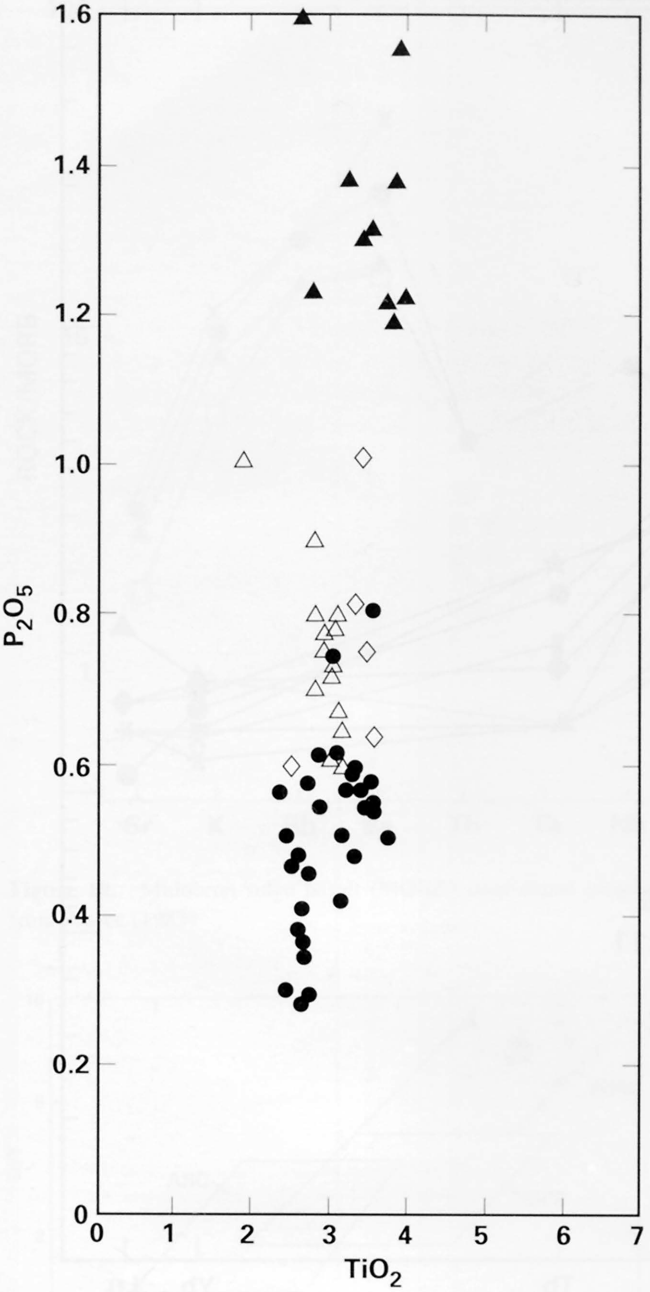

Figure 8. Plot of P_2O_5 versus TiO_2 for diabase dikes. Note the wide range in P_2O_5 content over the restricted range in TiO_2. Also shown for comparison are Late Proterozoic basaltic rocks containing >0.60 percent P_2O_5. Open triangles, Bakersville Gabbro dikes (Goldberg and others, 1986); open diamonds, Hudson Highlands dikes (Ratcliffe, 1987).

SiO_2, TiO_2, FeO_t, Al_2O_3, and CaO contents, as well as the overall similarity of the REE patterns, suggest a magmatic lineage. However, the contrasting P_2O_5 contents (fig. 8) imply that the HPG dikes may not have fractionated out of the same magma that produced the LPG dikes. Instead, we suggest that the HPG magma tapped a different mantle source.

The lack of consistent overlap and separate trends defined by LPG and HPG dikes on some major-oxide and trace-element diagrams precludes a model involving fractionation from a single melt to account for their genesis. However, the fact that these two dike groups do overlap and define trends on all other major-oxide and trace-element diagrams strongly suggests a petrogenetic relation. Therefore, any attempt to explain the origin of the New Jersey Highlands diabase dikes must take into account the disparate LPG and HPG groups. Differences between the two groups may reflect variation in the depth of the mantle sources and (or) the degree of partial melting of the magma sources. Gast (1968) has shown that differences in REE concentrations between tholeiitic and alkalic basalts are produced by smaller amounts of partial melting in the latter. Kay and Gast (1973) proposed that alkalic basalts may be produced by 1 to 2 percent partial melting of garnet peridotite at the top of the asthenosphere. This would occur beneath a more depleted mantle source. Green (1971) has suggested that an upwelling mantle plume, forming in response to crustal thinning, would produce increased melting at the top of the asthenosphere, generating basalts of transitional to tholeiitic composition.

Following the reasoning of Gast (1968) and Kay and Gast (1973), we propose that HPG dikes in New Jersey formed through early, small degrees of partial melting in response to decompression caused by rifting of eastern North America prior to the opening of the Iapetus Ocean. This is similar to the interpretation of Coish and others (1985) for the Tibbit Hill Volcanic Member of the Pinnacle Formation. Very small amounts of partial melting of an enriched mantle source could account for the more highly fractionated composition and REE enrichment in HPG dikes. Enrichment in P_2O_5 may be due to higher concentrations of a phosphate phase such as apatite present in the magma source. Beswick and Carmichael (1978) proposed that P_2O_5- and REE-enriched magmas may be derived from mantle sources containing LREE/HREE > chondrite that are residues from less depleted or undepleted mantle having undergone an earlier depletion. They suggested that this source probably had >chondritic P_2O_5 and may have contained >0.5 percent apatite. In terms of the Highlands dikes, increased amounts of partial melting of a slightly more depleted source, possibly in the lithospheric mantle, by the rising enriched mantle source may have produced the LPG dike magma. This is consistent with the model proposed by Green (1971). Increased partial melting likely was enhanced due to lithospheric decompression related to tectonic rifting of eastern North America. We favor an interpretation for dike genesis in which an initially small batch of mildly alkalic magma emplaced the HPG dikes, followed by the more voluminous, slightly depleted magma responsible for the LPG dikes.

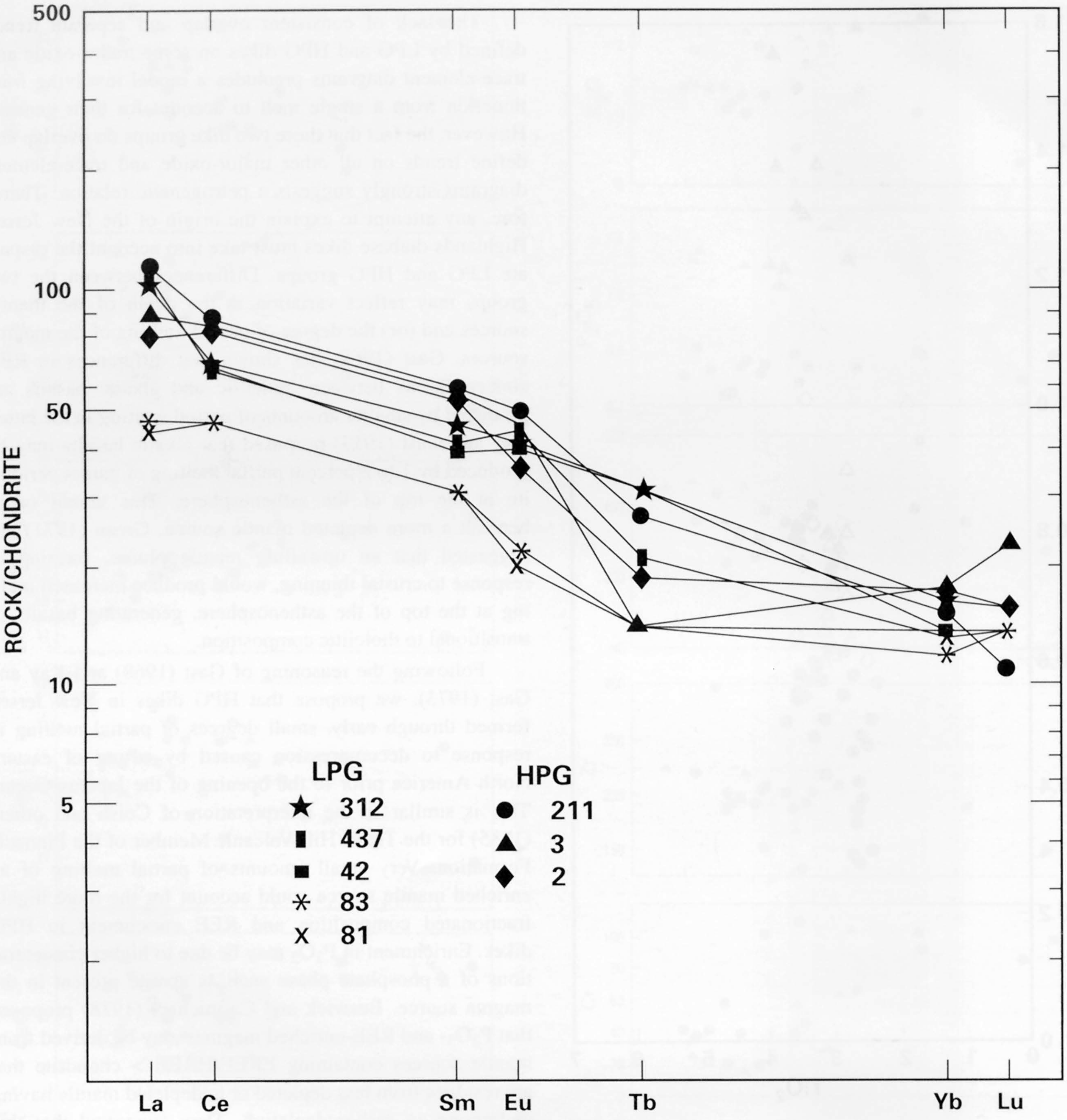

Figure 9. Chondrite-normalized rare earth element patterns for HPG and LPG dikes. Normalization values from Shimizu and Masuda (1986).

DISCUSSION

It is interesting to note that the dominant N.35°E. trend of the New Jersey Highlands diabase dikes is remarkably close to recorded dike trends of N.20°E. to N.30°E. for the Hudson Highlands (Ratcliffe, 1987) and N.25°E. for Catoctin Formation dikes in Virginia (Espenshade, 1986). Goldberg and others (1986) depicted N.40°E. as the dominant trend in their study area in North Carolina. As noted by Ratcliffe (1987), Late Proterozoic dike orientations from throughout the Appalachians are all very similar, suggesting emplacement during the same rifting event.

New Jersey Highlands diabase dikes have the same distinctive high TiO_2 and LREE-enriched composition as do other Late Proterozoic basaltic dikes occurring elsewhere in the Appalachians. All major-oxide and trace-element contents obtained during this study overlap the reported compositions of Bakersville Gabbro dikes from

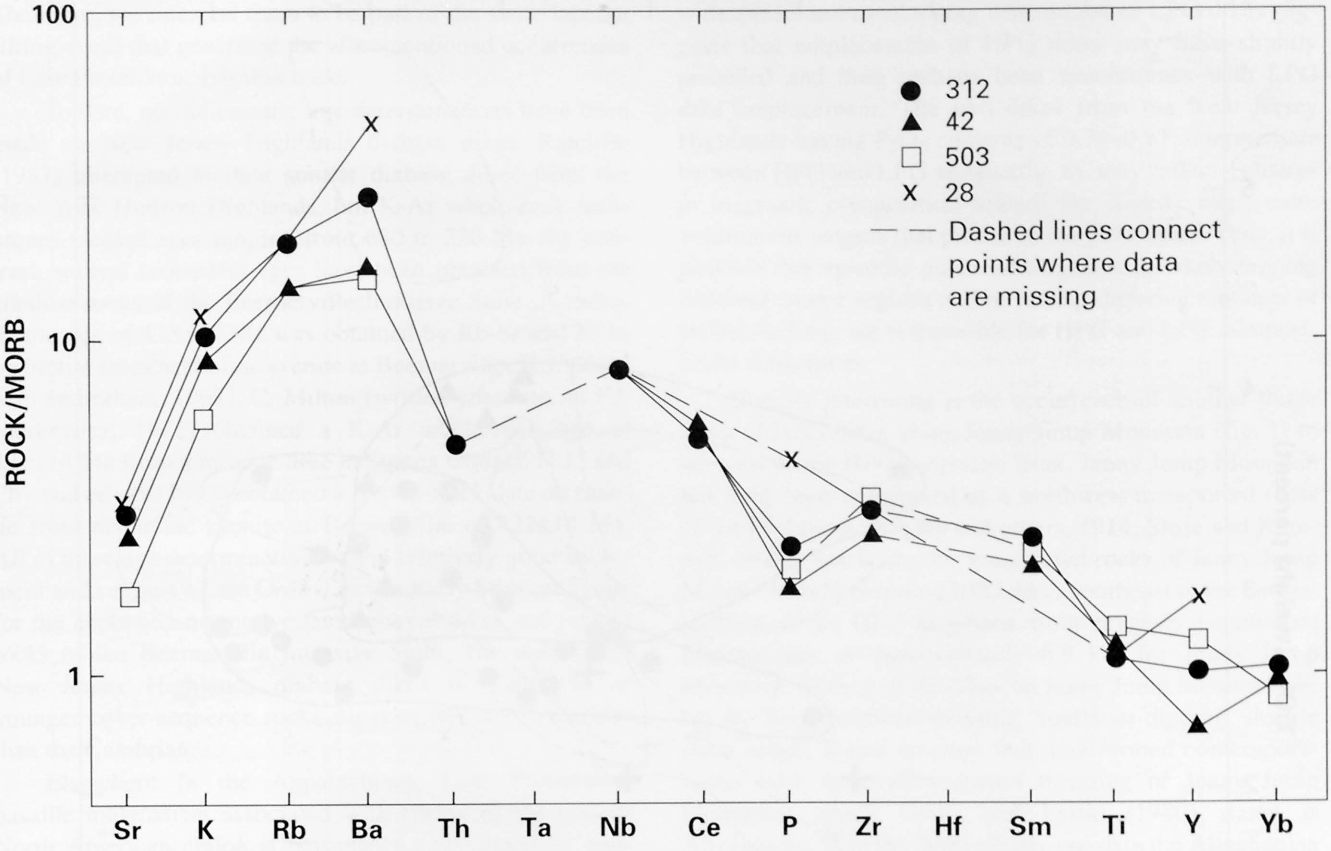

Figure 10. Midocean ridge basalt (MORB) normalized incompatible-element diagram for LPG diabase dikes. Normalization values from Pearce (1983).

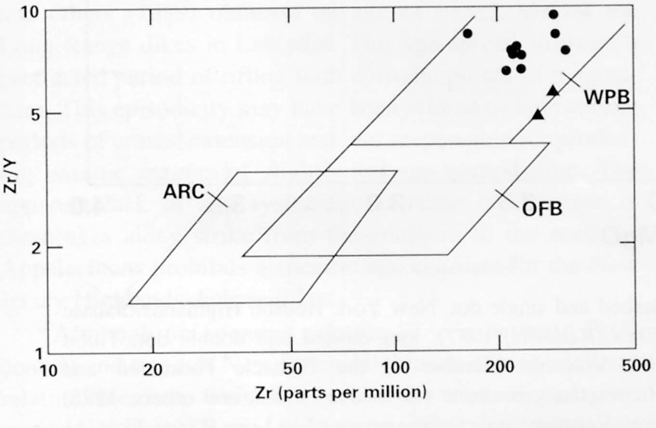

Figure 11. Plot of Zr/Y versus Zr for diabase dikes. Fields are WPB, within-plate basalt; OFB, ocean-floor basalt; and ARC, island-arc basalt. Diagram from Pearce and Norry (1979).

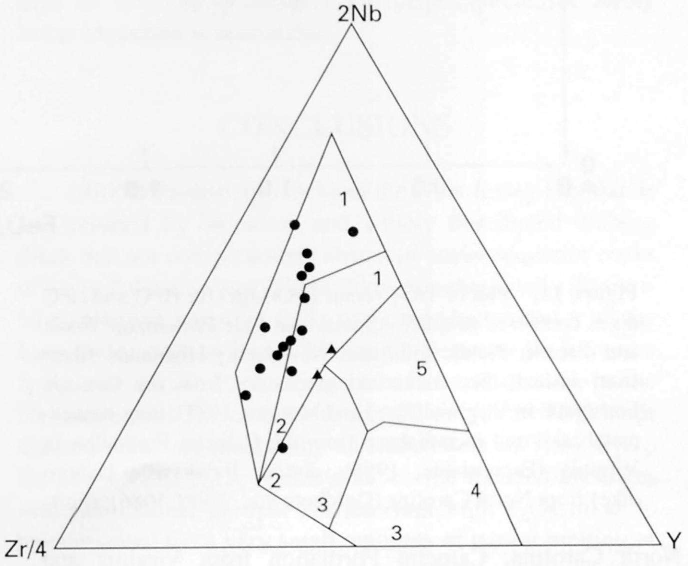

Figure 12. Plot of diabase dikes on Nb-Zr-Y ternary diagram from Meschede (1986). Fields: 1, within-plate alkalic; 2, within-plate tholeiitic; 3, volcanic-arc basalt; 4, N-type MORB; and 5, P-type MORB.

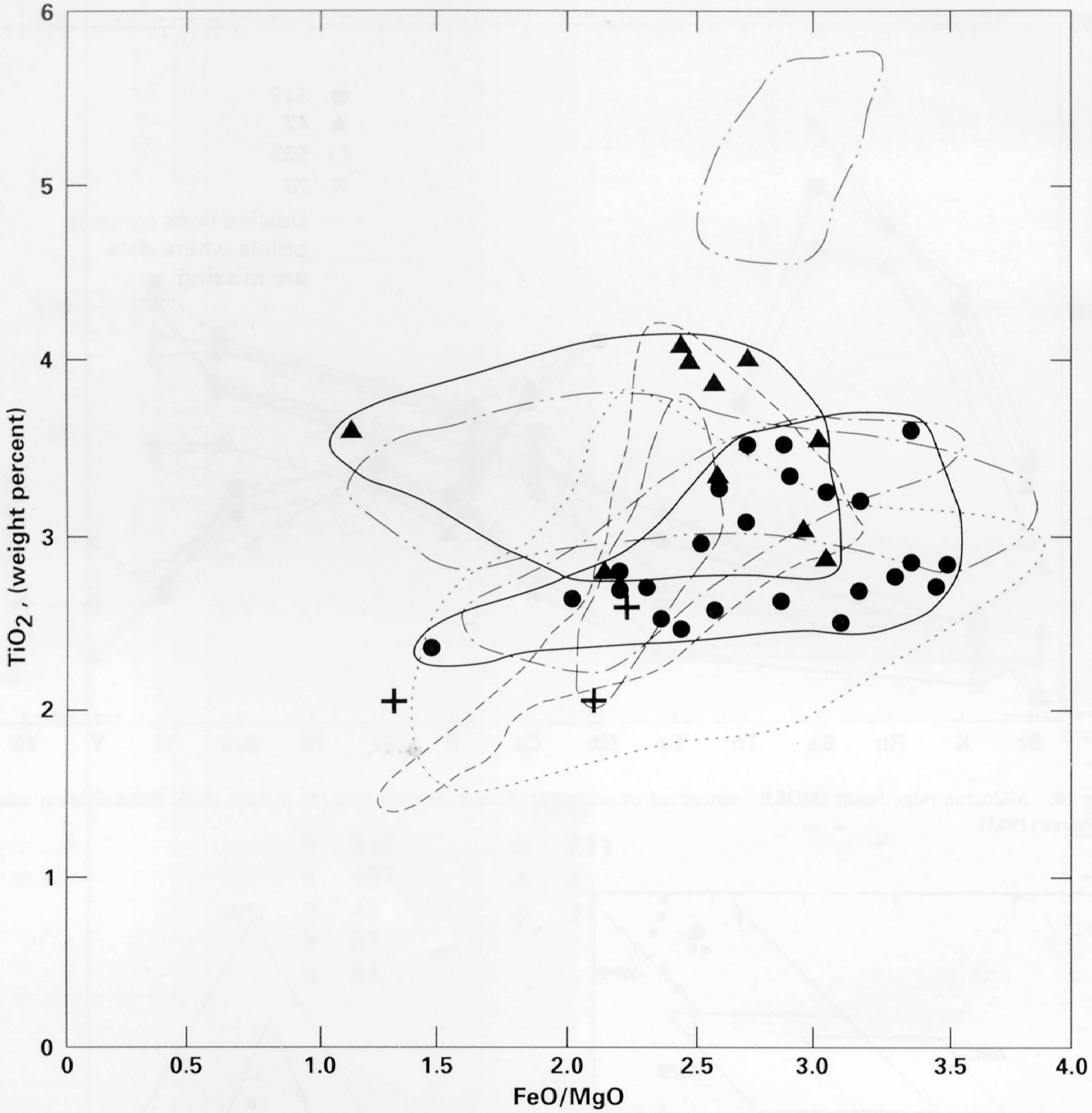

Figure 13. Plot of TiO_2 versus FeO/MgO for HPG and LPG dikes compared to other Appalachian Late Proterozoic basalt and diabase. Fields: solid line, New Jersey Highlands dikes; short-dashed, dike rocks and greenstone from the Catoctin Formation in Virginia (Reed and Morgan, 1971); long-dashed, metabasalt and metadiabase from the Catoctin Formation in Virginia (Espenshade, 1986); dotted, Bakersville Gabbro dikes from North Carolina (Goldberg and others, 1986); short-dashed and single dot, New York Hudson Highlands diabase dikes (Ratcliffe, 1987); long-dashed and double dot, Tibbit Hill Volcanic Member of the Pinnacle Formation and Huntington greenstone (as used by Coish and others, 1985) from Vermont; and crosses, means of 14 Long Range dikes, 11 Cloud Mountain flows, and 21 dikes and flows from Labrador (Strong, 1974).

North Carolina, Catoctin Formation from Virginia and Pennsylvania, Hudson Highlands dikes from New York, Tibbit Hill Volcanic Member of the Pinnacle Formation from Vermont, and dikes from Newfoundland and Labrador. This is easily seen on a plot of TiO_2 versus FeO/MgO (fig. 13). The similarity of the Highlands diabase compositions to compositions of each of these occurrences is striking and difficult to explain without evoking a similar Late Proterozoic age for their emplacement, as well as their generation through a similar petrogenetic process. For reasons stated earlier, New Jersey Highlands diabase dikes clearly are not Middle Proterozoic, early Paleozoic, or Jurassic in age.

Therefore, we interpret them to be part of the same Iapetan rifting event that generated the aforementioned occurrences of Late Proterozoic basaltic rocks.

To date, no radiometric age determinations have been made on New Jersey Highlands diabase dikes. Ratcliffe (1987) attempted to date similar diabase dikes from the New York Hudson Highlands, but K-Ar whole-rock techniques yielded ages ranging from 680 to 230 Ma. By contrast, several successful ages have been obtained from the alkaline rocks of the Beemerville Intrusive Suite. A radiometric age of 435±20 Ma was obtained by Rb-Sr and K-Ar on biotite from nepheline syenite at Beemerville, N.J. (Zartman and others, 1967). C. Milton (written commun. to F.J. Markewicz, 1972) obtained a K-Ar whole-rock age of 422±14 Ma from a minette dike in Sussex County, N.J., and Eby and others (1992) obtained a fission-track date on titanite from nepheline syenite at Beemerville of 422±14 Ma. All of these age determinations are in relatively good agreement and suggest a Late Ordovician to Early Silurian(?) age for the nepheline-normative lamprophyre dikes and related rocks of the Beemerville Intrusive Suite. The absence of New Jersey Highlands diabase dikes in Cambrian or younger cover-sequence rocks suggests that they are older than the Cambrian.

Elsewhere in the Appalachians, Late Proterozoic basaltic magmatism associated with rifting of the eastern North American craton is reasonably constrained by geochronological studies with bounding ages of 734±26 Ma for the Bakersville Gabbro dikes in the southern Blue Ridge (Goldberg and others, 1986) and 570±36 Ma (Badger and Sinha, 1988) for the Catoctin Formation in Virginia. Kamo and others (1989) obtained an age of 615±2 Ma for the Long Range dikes in Labrador. This age spread suggests a protracted period of rifting with episodic pulses of magmatism. This episodicity may have been related to intermittent periods of crustal extension and was responsible for producing basaltic magma of slightly varying composition. The apparent lack of any systematic increase or decrease in these ages along strike from the southern to the northern Appalachians prohibits a specific age estimate for the New Jersey Highlands diabase dikes.

Although no apparent relation is seen between P_2O_5 content and trend of New Jersey Highlands dikes, a definite relation seems to exist between P_2O_5 content and geographic location. Despite the fact that HPG and LPG populations overlap spatially, it is clearly seen on figure 1 that HPG dikes are restricted in their occurrence to the western Highlands, where they define an array trending approximately N.40°E. as determined by the strike of the dikes. No dikes having a HPG composition are seen east of this array, which is herein named the HPG magmatic front. Because these dikes are more evolved than LPG dikes, the HPG magmatic front quite possibly marks the limit of earlier, or perhaps earliest, magmatism associated with Late Proterozoic rifting in the New Jersey Highlands. The more widespread and overlapping distribution of LPG dikes suggests that emplacement of HPG dikes may have slightly preceded and then perhaps been synchronous with LPG dike emplacement. The two dikes from the New Jersey Highlands having P_2O_5 contents of 0.74–0.81, intermediate between HPG and LPG values (fig. 8), may reflect a change in magmatic composition toward the slightly later, more voluminous magma that produced the LPG dikes. Thus, it is possible that episodic pulses of magmatism, likely tapping different source regions and reflecting differing amounts of partial melting, are responsible for HPG and LPG compositional differences.

Equally interesting is the occurrence of another linear array of HPG dikes along Jenny Jump Mountain (fig. 1) to the west of the HPG magmatic front. Jenny Jump Mountain has long been recognized as a northwest-transported mass of the Highlands (Bayley and others, 1914; Stose and Kummel, 1929). Retracting the transported rocks of Jenny Jump Mountain and associated HPG dikes southeast to the current position of the HPG magmatic front suggests a minimum displacement of approximately 6.9 km for Jenny Jump Mountain. Several of the dikes on Jenny Jump Mountain are cut by thin, northeast-trending, southeast-dipping, ductile shear zones. If one assumes that they formed contemporaneous with the northwestward thrusting of Jenny Jump Mountain, which Drake and Lyttle (1980) stated is Alleghanian, then the dikes clearly pre-date the Alleghanian orogeny. It is noteworthy that none of the dikes east of Jenny Jump Mountain are cut by these ductile shear zones. Therefore, HPG dikes on Jenny Jump Mountain may have originally been part of the HPG magmatic front. If this is so, then an estimate of about 7 km displacement for Jenny Jump Mountain is reasonable.

CONCLUSIONS

Middle Proterozoic rocks in the New Jersey Highlands are intruded by abundant and widely distributed diabase dikes that are conspicuously absent in cover-sequence rocks of early Paleozoic age. These dikes are chemically dissimilar to alkaline intrusive rocks and dikes associated with the Late Ordovician to Early Silurian(?) Beemerville Intrusive Suite and also to Early Jurassic basalt and diabase in the Newark basin. The compositions of New Jersey Highlands diabase dikes are marked by an enrichment in TiO_2, P_2O_5, Zr, and LREE. P_2O_5 contents subdivide the diabase dikes into two distinct groups. We interpret high P_2O_5 dikes to have resulted from very small amounts of partial melting of an enriched mantle source that may have contained high concentrations of a phosphatic phase. Low P_2O_5 dikes were the product of increased amounts of partial melting of a slightly more depleted source. Increased partial melting was the result of the rising, more enriched HPG magma and (or) lithospheric decompression associated with tectonic rifting of eastern North America. Although HPG and LPG dikes appear to overlap spatially and temporally, the more limited geographic distribution of the HPG within the broader field of the LPG suggests that emplacement of HPG dikes may have slightly preceded that of LPG dikes. The former are restricted in occurrence to the western Highlands, whereas the latter overlap HPG dikes and are more widespread. The few New Jersey Highlands dikes of intermediate P_2O_5 content are transitional between HPG and LPG populations and may reflect a change in magmatic composition toward the slightly later, more voluminous magma that produced the LPG dikes.

We propose that diabase dikes in the New Jersey Highlands are geochemically correlative with the Catoctin Formation and other occurrences of Late Proterozoic basaltic magmatism and that they document another important remnant of Iapetan rift-related magmatism in the Appalachians.

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