Geochemical Features and ^{40}Ar/^{39}Ar Age of Tholeiitic and Mafic-Alkalic Dikes in Aroostook County, Northeastern Maine

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By DAVID GOTTFRIED, RAYMOND MACDONALD, JOHN F. SUTTER, and LOUIS PAVLIDES

Major, minor, and trace element contents of two tholeiitic suites in the Mars Hill and Bridgewater quadrangles and a teschenitic suite in the Presque Isle quadrangle

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Geochemical Features and $^{40}Ar/^{39}Ar$ Age of Tholeiitic And Mafic-Alkalic Dikes in Aroostook County, Northeastern Maine

By David Gottfried, Raymond Macdonald, John F. Sutter, *and* Louis Pavlides

Abstract

Major, minor, and trace element contents were determined in 16 samples of metabasaltic dike rocks from northeastern Maine. Chemical and petrographic studies of the rocks indicate widespread mobility of various major and minor elements and extensive development of secondary mineral assemblages. The contents demonstrate that these rocks represent at least three magma suites of diverse compositions, as follows. Stable minor and trace elements (such as Ti, P, Nb, Ta, Zr, Hf, Th, and Y and rare earth element abundances), together with variation trends, indicate that metabasaltic dikes in the Mars Hill and Bridgewater quadrangles are products of two similar, but not identical, continental-type tholeiitic magmas. The metabasaltic dikes in the Presque Isle quadrangle are primarily teschenitic mafic-alkalic rocks.

Two samples appear to be geochemically unique. One sample, from the Mars Hill dikes, is a depleted-type tholeiite. Another sample, from the Presque Isle quadrangle, is a biotite albite basalt with alkalic affinities.

On the basis of the trace element associations of the Mars Hill, Bridgewater, and Presque Isle dikes, we conclude that the parental magmas were generated within heterogeneous mantle magma sources. Variations in the melting process, within a tensional tectonic setting, during a relatively limited timespan produced these rock types.

We performed $^{40}Ar/^{39}Ar$ age spectrum analyses on six whole rock samples from each of the three geochemically identified magma suites. All age spectra are variably discordant, and only three of the six samples record plateau spectra. However, the age data are compatible with intrusion of all three magma types in Late Silurian to Middle Devonian times, with a subsequent low-grade metamorphic disturbance of the chemical and isotopic systems in the Pennsylvanian.

GEOLOGIC SETTING

Weakly altered tholeiitic basaltic and alkalic mafic dikes and plugs and greenstone dikes intrude folded calcareous sedimentary rocks of Ordovician (Caradocian) to Silurian (Wenlockian) age in northeastern Maine (Pavlides, 1965 and 1978). Basaltic and greenstone dikes occur in a more or less north-trending belt along the east side of the Bridgewater and Mars Hill quadrangles. Altered alkalic mafic dikes occur to the west of the tholeiitic dikes and are concentrated in one small area within the Presque Isle quadrangle (fig. 1; also see Pavlides, 1978).

Dikes in the region generally are not more than several meters wide and a few tens of meters to a hundred or so meters long. In many places, a thin contact metamorphosed zone has been formed in the impure limestones enclosing the dike. The dikes of northern Maine intrude a sequence of folded marine metasedimentary rocks such as the Perham and Spragueville Formations (Pavlides, 1978) that contain shelly faunas (Boucot and others, 1964) of relatively shallow water habitat. Therefore, the dikes were intruded into a continental rather than oceanic plate. All of the country rocks, up through Oriskany age of the Lower Devonian (Boucot and others, 1964, and Boucot, 1968, table 6-2), in the immediate area of the tholeiitic and teschenitic rocks were folded and cleaved, presumably during a phase of the Acadian orogeny (Pavlides, 1974, p. 70, and 1978). The upper age limit for the Acadian orogeny in northeastern Maine is fixed by the age of the youngest folded rocks below the unconformity that separates them from the overlying Mapleton Sandstone of Eifelian or Middle Devonian age. The folded Dockendorf Group of rocks of Lower Gedinnian or Early Devonian age constitute such pre-Mapleton rocks. Because cleavage is absent in the broadly synformal Mapleton Sandstone, we consider the cleavage in the subjacent folded rocks to have developed in post-Dockendorf and pre-Mapleton or Lower Gedinnian to Eifelian (Middle Devonian) times. The massive dikes and plugs cut rocks containing Acadian cleavage and are not themselves transected by this cleavage. We, therefore, consider them to be of postkinematic age.

All dikes are weakly metamorphosed. Until this report, this metamorphism was assumed to have taken place during the waning or cooling stages of the Acadian event (Pavlides, 1978). Geochronologic data presented in this report, however, indicate a Pennsylvanian age for this weak metamorphism. We did not observe the dikes and plugs to intrude the Mapleton Sandstone of Middle Devonian age, although they do cut Acadian structures. The Mapleton Sandstone, which rests with angular unconformity on the pre-Acadian folded rocks that are host to the plugs and dikes (Pavlides, 1978), is not obviously metamorphosed. However, the sandstone, which occurs in a broad dish-shaped syncline, was deformed in post-Acadian time by the Maritime disturbance of Pennsylvanian age

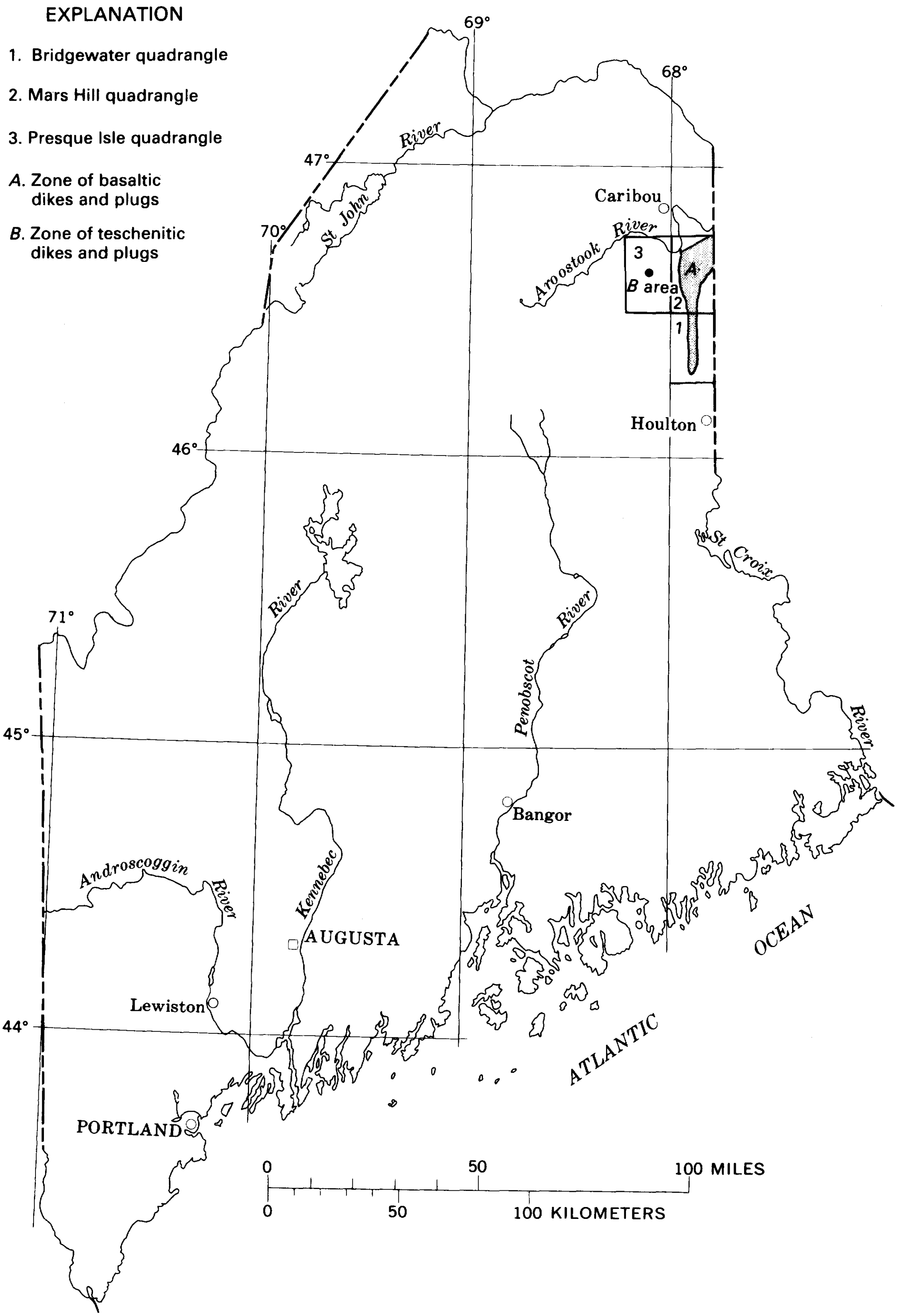

Figure 1. General location of zones of metabasaltic dikes of the Mars Hill and Bridgewater quadrangles (A, continental tholeiitic magmas) and of the Presque Isle quadrangle (B, teschenitic suite) in northeastern Maine.

(Pavlides, 1974, p. 71), which may be related to the time of metamorphism of these dikes.

The northeastern Maine dikes obviously represent a tensional phase of deformation following the compressional regime of the Acadian event. The chemical features of the basaltic magmatism that characterize this episode of tensional tectonics may be of interest for comparisons of similar events elsewhere in the Appalachian-Caledonide orogen.

PETROGRAPHIC FEATURES

Mars Hill quadrangle.—The weakly metamorphosed basaltic rocks of the small dikes and plugs of the Mars Hill quadrangle are generally massive, fine-grained to aphanitic, green to dark-green rocks and may contain a gray-white weathered rind up to 0.6 cm thick. In thin section, textures range from hypidiomorphic-granular to ophitic. Original plagioclase ranges in composition from andesine to labradorite; later saussuritization probably produced the less calcic varieties. The less calcic plagioclase commonly has fine-grained scapolite(?) alteration. Augitic pyroxene in some places is altered to chlorite or actinolite. Ilmenite, an abundant accessory, commonly occurs as skeletal crystals; epidote normally occurs in veinlets. Fine-grained granules of sphene are mostly enclosed in chlorite and may be abundant locally. Quartz is a sparse constituent in some rocks. Carbonate and rare flakes of brown biotite(?) or stilpnomelane(?) are present in a few rocks.

Bridgewater quadrangle.—The dikes of the Bridgewater quadrangle are more altered than those of the Mars Hill area and have been referred to as greenstone (Pavlides, 1965, p. 37-38). They are fine-grained rocks with allotriomorphic-granular texture in thin section. Chlorite is an abundant alteration product and replaces pyroxene and some plagioclase. Large crystals of ilmenite and magnetite are common, and locally some ilmenite is partly to completely altered to sphene or leucoxene. Quartz is a minor constituent, and carbonate occurs in thin veinlets. Well-formed elongate crystals of apatite also are present.

Presque Isle quadrangle.—The metabasaltic dikes in the Presque Isle quadrangle consist of analcime-bearing basalts and a biotite albite basalt with alkalic affinities (sample 16). The analcime-bearing basaltic rocks were originally described as teschenites by Gregory (Williams and Gregory, 1900, p. 179-185). They are aphanitic to medium-grained mesocratic massive rocks. According to Gregory, the principal minerals in these teschenites are augite (titanaugite?), andesine, apatite, biotite, analcime, and magnetite and lesser amounts of alteration products such as chlorite and calcite. We also noted thompsonite and nepheline(?) during this study. Gregory stated that the analcime in the teschenites formed through replacement of nepheline, but he gave no petrographic evidence for this reaction. He also described andesine as having been altered to analcime and chlorite and described analcime as an intergranular constituent. Alternatively, the analcime may be a prograde metamorphic product because prehnite-pumpellyite-grade metamorphism is known from rocks to the south (Pavlides, 1962, fig. 9, 1965, p. 35, and 1973) and to the west and northwest (Richter and Roy, 1976). Anita G. Harris (written commun., 1976) reports that color alteration index (Epstein, Epstein, and Harris, 1977) of two widely separated (30 km) conodont collections in the Mars Hill area (Pavlides, 1978) indicates temperatures of +300 °C and 150 °-200 °C, respectively. Such temperatures are compatible with zeolite and low greenschist facies metamorphism that may have affected the teschenites of the Presque Isle quadrangle and the tholeiitic basalts in the Mars Hill area and may have formed the greenstone in the dikes of the Bridgewater region.

A petrographic variant within the Presque Isle teschenitic dike area is a biotite albite porphyritic basalt represented by sample 16 (table 1). Phenocrysts are sodic plagioclase that has been heavily altered to white mica and pseudomorphs of chlorite after clinopyroxene. The groundmass consists of albite laths, fresh augitic(?) pyroxene, chlorite, abundant Fe-Ti oxides, and reddish brown biotite that occasionally encloses oxides and apatite. Whether the alteration is late deuteric or retrograde metamorphic is unclear. No analcime has been noted in this rock.

GEOCHRONOLOGIC DATA

The isotopic composition of Ar was measured with a VG Isotopes, Inc., Model MM-1200B,[1] mass spectrometer in the Branch of Isotope Geology, K-Ar Laboratory, at the U.S. Geological Survey in Reston, Va. Whole rock splits from the basaltic dikes were irradiated in the USGS Central Thimble facility TRIGA reactor (GSTR) at the Federal Center in Denver, Colo. (Dalrymple and others, 1981). The neutron flux monitor used in this study was MMhb-1 hornblende, 519.4 Ma (Mega-annum) in age (Alexander and others, 1978), and an estimated 1-percent error in the calculated J values has been assigned. Corrections for irradiation-produced, interfering isotopes of Ar were made by using the values suggested for the Central Thimble facility of the GSTR (Dalrymple and others, 1981). Values corrected for ^{37}Ar were determined by using a decay con-

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[1] Any use of trade names and trademarks in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Table 1. Major element chemistry and normative composition of dikes in northeastern Maine

Suites	Bridgewater			Mars Hill									Presque Isle			
Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Field no.	PA-74-8	PA-74-7	PA-74-9	P-64-8	P-64-27	P-64-6	P-64-5	P-64-77	P-63-3	P-64-9	P-64-26	P-64-7	PA-74-1	PA-74-2	PA-74-3	PA-74-4
Major oxide composition[1] (weight percent)																
SiO_2	49.7	50.9	53.2	47.1	47.7	47.9	48.9	48.9	49.9	50.6	50.6	51.6	48.6	48.6	48.7	49.5
Al_2O_3	14.8	13.6	14.4	16.6	17.4	15.8	18.0	19.0	16.7	14.9	16.7	15.0	15.4	15.6	15.7	16.1
Fe_2O_3	3.2	1.5	2.8	1.6	1.7	3.1	2.0	1.4	1.8	2.9	2.3	1.6	4.9	5.0	4.1	3.1
FeO	8.9	10.4	10.3	9.5	8.3	8.3	8.8	5.3	8.8	10.2	8.8	10.2	7.1	8.3	8.0	6.6
MgO	5.4	4.2	4.9	7.8	6.4	7.6	5.3	8.7	6.8	4.4	6.0	5.0	4.1	3.3	3.1	7.1
CaO	7.0	4.5	2.4	7.5	9.5	6.0	7.8	6.9	5.5	4.8	3.0	5.9	7.0	6.2	6.8	5.2
Na_2O	3.4	4.1	4.6	2.5	2.8	2.7	3.3	3.1	2.8	3.5	4.3	4.2	3.3	5.6	5.0	4.0
K_2O	1.9	.75	.57	1.7	.58	1.1	.95	1.5	.97	.86	.98	.75	1.4	2.0	2.4	1.9
H_2O-	.51	.31	.60	.21	.25	.70	.29	3.6	.52	.49	.51	.17	.93	.62	.81	1.2
H_2O+	2.7	2.8	.16	3.2	2.4	4.1	2.3	.44	3.5	3.4	4.0	1.8	2.8	2.9	3.5	2.2
TiO_2	2.7	3.0	3.3	1.9	1.8	2.1	1.9	.81	2.1	2.6	2.2	2.2	2.2	2.1	2.0	2.1
P_2O_5	.39	.48	.59	.24	.24	.27	.24	.09	.30	.49	.32	.39	.74	.60	.58	.53
MnO	.19	.19	.19	.19	.22	.23	.20	.13	.19	.23	.20	.25	.23	.52	.32	.18
CO_2	.53	3.9	.48	.05	.55	—	—	.06	.11	.49	.12	.52	.01	.01	.44	.01
Total	101.32	100.63	98.49	100.09	99.84	99.95	100.03	99.93	99.99	99.86	100.03	99.58	98.71	101.35	101.45	99.72
Adjusted oxides (H_2O and CO_2 free and Fe adjusted[2])																
SiO_2	51.41	54.38	55.46	48.7	49.4	50.4	50.2	51.0	52.1	53.0	53.0	53.2	50.87	49.34	50.43	51.94
Al_2O_3	15.30	14.53	15.00	17.2	18.0	16.6	18.5	19.8	17.4	15.6	17.5	15.5	16.11	15.83	16.25	16.89
Fe_2O_3	1.24	1.60	.83	1.7	1.8	3.3	2.1	1.5	1.9	3.0	2.4	1.7	3.03	3.04	2.17	1.15
FeO	10.35	11.10	11.47	9.8	8.6	8.7	9.0	5.5	9.2	10.7	9.2	10.5	10.15	11.16	10.25	7.97
MgO	5.58	4.49	5.10	8.1	6.6	8.0	5.4	9.1	7.1	4.6	6.3	5.2	4.29	3.35	3.20	7.45
CaO	7.24	4.80	2.50	7.8	9.8	6.3	8.0	7.2	5.7	5.0	3.1	6.1	7.32	6.29	7.04	5.46
Na_2O	3.52	4.38	4.79	2.6	2.9	2.8	3.4	3.2	2.9	3.7	4.5	4.3	3.45	5.68	5.17	4.20
K_2O	1.96	.80	.59	1.8	.60	1.2	.98	1.6	1.0	.90	1.0	.77	1.46	2.03	2.48	1.99
TiO_2	2.80	3.21	3.44	2.0	1.9	2.2	2.0	.85	2.2	2.7	2.3	2.3	2.30	2.13	2.07	2.20
P_2O_5	.40	.51	.61	.25	.25	.28	.25	.09	.31	.51	.34	.40	.77	.61	.60	.56
MnO	.20	.20	.20	.20	.23	.24	.21	.14	.20	.24	.21	.26	.24	.53	.33	.19
Total	100.00	100.00	99.99	100.15	100.08	100.02	100.04	99.98	100.01	99.95	99.85	100.23	99.99	99.99	99.99	100.00
Normative mineral composition[3] (weight percent)																
Q	—	4.5	7.2	—	—	0.4	—	—	4.0	5.9	2.7	0.4	1.0	—	—	—
C	—	—	3.4	—	—	—	—	—	1.9	.7	4.2	—	—	—	—	—
Or	11.6	4.7	3.5	10.6	3.5	7.1	5.8	9.4	5.9	5.3	5.9	4.5	8.6	12.0	14.6	11.8
Ab	29.8	37.1	40.5	22.0	24.5	23.7	28.8	27.1	24.5	31.3	38.1	36.3	29.2	31.6	30.0	35.5
An	20.2	17.6	8.4	29.9	34.3	29.2	32.3	34.9	26.2	21.5	13.2	20.7	24.2	11.7	13.8	21.4
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	8.9	7.4	—
Wo	5.5	1.2	—	3.0	5.3	.1	2.4	.1	—	—	—	2.9	3.0	6.5	7.2	.9
En	8.8	11.2	12.7	6.8	11.1	19.9	9.5	6.9	17.7	11.5	15.7	12.9	10.7	2.3	2.6	5.4
Fs	8.7	14.1	15.1	4.6	7.8	10.1	8.4	2.3	12.1	13.2	11.5	14.5	12.8	4.3	4.7	3.0
Fo	3.6	—	—	9.4	3.7	—	2.8	11.1	—	—	—	—	—	4.2	3.7	9.2
Fa	3.9	—	—	7.0	2.9	—	2.7	4.2	—	—	—	—	—	8.6	7.4	5.7
Mt	1.8	2.3	1.2	2.5	2.6	4.8	3.0	2.2	2.8	4.4	3.5	2.4	4.4	4.4	3.1	1.7
Il	5.3	6.1	6.5	3.8	3.6	4.2	3.8	1.6	4.2	5.1	4.4	4.4	4.4	4.0	3.9	4.2
Ap	.9	1.2	1.4	.6	.6	.7	.6	.2	.7	1.2	.8	.9	1.8	1.4	1.4	1.3
Total	100.1	100.0	99.9	100.2	99.9	100.2	100.1	100.0	100.0	100.1	100.0	99.9	100.1	99.9	99.8	100.1

[1] Major elements determined by rapid rock analysis. PA-74-7, PA-74-8, PA-74-9, PA-74-1, PA-74-2, PA-74-3, PA-74-4, K. Coates and H. Smith, analysts. P-64-8, P-64-27, P-64-6, P-64-5, P-64-77, P-64-3, P-64-9, P-64-26, P-64-7, P. Elmore, G. Chloe, J. Kelsey, S. Botts, H. Smith, L. Artis, and J. Glenn, analysts.

[2] Fe adjusted as follows: If $(Na_2O+K_2O) < 4$ percent set $Fe_2O_3 = 1.5$ percent. If $(Na_2O+K_2O) > 4$ percent set $Fe_2O_3 = 2.0$ percent.

$$\frac{Fe_2O_3 - 1.5\text{ percent}}{1.11134} = X \quad \text{or} \quad \frac{Fe_2O_3 - 2.0\text{ percent}}{1.11134} = X.$$

$FeO + X =$ adjusted oxide value.

[3] Based on adjusted oxides.

stant of 8.25 × 10^{-4} disintegrations per hour for ^{37}Ar. Apparent K:Ca ratios were calculated by using the equation given by Fleck and others (1977). Constants used in the age calculations were those recommended by Steiger and Jager (1977). Concentrations of ^{39}Ar were calculated by using the measured sensitivity of the mass spectrometer and thus have an estimated precision of only about 10 percent. Age plateaus have been assigned by using the criteria of Fleck and others (1977). The error estimates on the weight-averaged plateau ages are simply two times (2σ) the average error assigned to the individual ages at the different temperature intervals on the plateau, rounded to the next highest million years. Error estimates for the apparent ages of individual temperature steps are 1σ (67-percent confidence level) and have been assigned by using the equations suggested by Dalrymple and others (1981).

Previous geochronologic studies in this area are limited to two conventional K-Ar ages on biotite from a small pluton and a dike near Bridgewater and Monticello, Maine (Faul and others, 1963). Their samples Me26, from a rhyodacite dike, and Me27, from a small garnet porphyry pluton (Pavlides, 1965), yield dates of 392 ± 8 Ma and 401 ± 8 Ma, respectively, when the decay constants currently in use (Steiger and Jager, 1977) are applied to their data. Faul and others interpreted these dates as times of intrusion and included these in the earlier of two Devonian intrusive cycles they identified in Maine.

In the present study, six whole rock samples were analyzed by the ^{40}Ar/^{39}Ar age spectrum method of K-Ar dating. The goals of the dating were twofold: (1) to estimate the age of original emplacement and crystallization of the dikes and plugs belonging to the three general magma types and (2) to estimate the time at which the low-grade metamorphic overprint was superimposed on these intrusions. The geochronologic data will be discussed according to the three areas of occurrence, which also correspond to the three main magma types. These rocks are not especially good candidates for absolute age dating because of their altered nature, but dating was attempted to see whether the ^{40}Ar/^{39}Ar age spectrum technique could simultaneously address the questions of original crystallization and subsequent low-grade metamorphic overprinting.

Mars Hill quadrangle.—Two basaltic dike samples (samples 5 and 6, table 1) were chosen for dating. The analytical data are listed in table 2, and the age spectra are displayed in figure 2. The age spectrum from sample 6 forms an age plateau at 375 ± 8 Ma, and this age is interpreted as the time of intrusion. The age spectrum of sample 5 does not form an age plateau and contains no useful geochronologic information as to age of intrusion of this rock. As shown in subsequent age spectra of other samples, however, the total-gas age (roughly equivalent to a K-Ar age) of about 305 Ma suggests a significant disturbance to the K-Ar isotopic system in sample 5.

Bridgewater quadrangle.—Samples 2 and 3 (table 1) were chosen for analysis. These analytical data are given in table 2 and displayed graphically in figure 2. The data from sample 2 define an age plateau of 414 ± 8 Ma and are interpreted as a close approximation to the time of intrusion. An age of 414 ± 8 Ma must be construed with present absolute time scale information to represent upper Silurian to lowermost Devonian time. On the basis of the Lower Gedinnian to Eifelian age of cleavage development outlined on page 1, the plateau age of this dike is more likely to be Early Devonian than Silurian. However, we believe that this single ^{40}Ar/^{39}Ar plateau age should not be used to construe anything about the absolute time scale because this type of rock is not the best material for geochronologic studies employing the ^{40}Ar/^{39}Ar method. The data for sample 3 do not define an age plateau, again indicating a rather severe disturbance of the K-Ar isotopic system. The total-gas age of this sample (about 299 Ma) is similar to that of sample 5 in the Mars Hill area and perhaps reflects the same low-grade metamorphic event.

Presque Isle quadrangle.—Two samples from the teschenitic to alkalic basalt suite (samples 15 and 16, tables 1 and 2) have been analyzed by the ^{40}Ar/^{39}Ar technique. These samples are among the most highly altered (low-grade metamorphism) of the rocks in the area and, on the basis of conodont alteration indexes of nearby country rock samples, have been exposed to postintrusion metamorphic temperatures in the range of about 150–300°C (Pavlides, 1978). The data from sample 16 (table 2 and fig. 2) do not define an age plateau, but the total-gas age of about 298 Ma is very similar to that of other disturbed samples from the area. The data from sample 15 (table 2 and fig. 2) define an age plateau of 293 ± 6 Ma even though the spectrum is quite discordant. This age plateau is not interpreted to represent the time of initial intrusion but rather a close approximation to the time of low-grade metamorphism because of the high degree of alteration of the sample (sodic plagioclase heavily altered to white mica) and because of the temperature to which these rocks could have been exposed. In addition, the total-gas ^{40}Ar/^{39}Ar ages of the four highly disturbed samples (3, 5, 15, and 16) range from 298 Ma to 305 Ma, close to the plateau-age of sample 15.

All the ^{40}Ar/^{39}Ar age spectrum data are compatible with the interpretation that all dike rock types in the area originally intruded mid-Ordovician to mid-Silurian rocks during late Silurian to mid-Devonian times. The superimposed low-grade metamorphic event variably disturbed the K-Ar isotopic system in these rocks; this disturbance was most likely of Pennsylvanian age. This

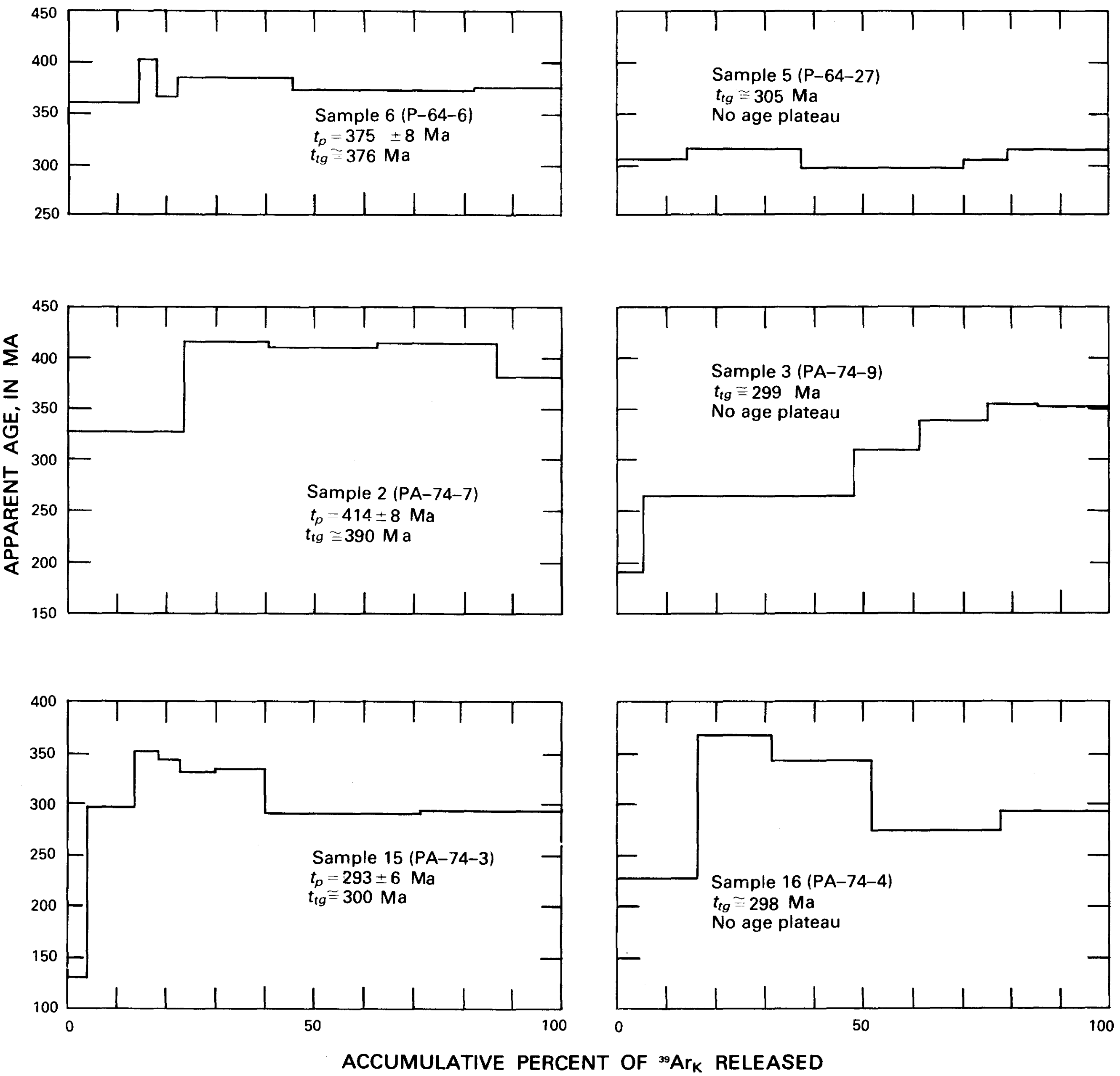


Figure 2. Spectrum diagrams for $^{40}Ar/^{39}Ar$ age of dikes in northeastern Maine (t_p, weight-average plateau age; t_{tg}, total-gas age).

may have been the time of folding of the Mapleton Sandstone, a unit of post-Acadian age (Pavlides, 1974, p. 71). Other areas of Pennsylvanian disturbance in Maine recently have been investigated by the $^{40}Ar/^{39}Ar$ age spectrum method (Dallmeyer, 1982, and Lux, 1982); an area of productive future research will be to delineate the region affected by this late Paleozoic metamorphic event.

ANALYTICAL METHODS

Sixteen dikes (samples 1-16) were selected for chemical analysis of major (table 1) and trace elements (table 3) to cover the petrographic range in our collections. Major elements were determined by using rapid-rock methods as outlined in Shapiro (1975). Abundances of Ba, Co, Cr, Hf, Rb, REE (rare earth elements), Sc, Ta, Th, U, and Zn were determined by instrumental neutron activation analysis (L. J. Schwarz, analyst), supplemented by epithermal activation analysis for Hf, Rb, Ta, and Th in certain samples (P. A. Baedecker, analyst). Occurrence of Nb was determined spectrophotometrically (Greenland and Campbell, 1974) (J. Kane, analyst). C. S. Annell analyzed for Ni and Y by using d-c arc emission spectroscopy, and R. G. Johnson determined Sr and Zr abundances by XRF spectrometry.

The estimated precisions (in percent) of trace element determinations (1σ) are as follows: Ba, 5; Co, 2; Cr, 5; Hf, 4; Nb, 10; Ni, 15; Rb, 5; Sc, 2; Sr, 5; Ta, 10; Th, 10; U, 11; Y, 5; Zn, 5; Zr, 5; La, 7; Ce, 4; Nd, 8; Sm, 8; Eu, 4; Gd, 17; Tb, 8; Tm, 18; Yb, 6; and Lu, 6.

ANALYTICAL RESULTS

Major Elements and Identification of Magmatic Lineages

The Maine dikes have been metamorphosed up to the greenschist facies. Furthermore, the dikes may have undergone varying degrees of postcrystallization hydrothermal alteration. Under such circumstances, mobility of critical major elements makes identification of original magmatic compositions uncertain. Mobility of Ca, Mg, Na, K, CO_2, and H_2O, as well as changes in the original Fe oxidation ratios, is very possible.

Mobility of the alkali and alkali earth elements is demonstrated by plotting these elements against an element stable during low-grade metamorphism. Previous investigators (Pearce and Cann, 1973; Floyd and Winchester, 1975; Winchester and Floyd, 1976; Gottfried and others, 1977) have shown that P_2O_5 and TiO_2 usually remain stable during low-grade metamorphism. P_2O_5 is also a particularly useful index of fractionation throughout the early and middle stages of fractionation of mafic magmas (Anderson and Greenland, 1969). However, alkalic suites normally have higher P_2O_5 contents than do tholeiitic suites at equivalent stages of differentiation. When rocks of both suites are plotted on one P_2O_5 variation diagram, P_2O_5 contents cannot be used to interrelate the differentiation stages of the suites.

Data presented in table 1 confirm petrographic evidence of secondary alteration and introduction of carbonate into several dikes. On figure 3, the major oxides have been plotted against P_2O_5. The scatter shown by K_2O, Na_2O, and CaO clearly reflects variable addition to and removal of these components from the dikes. This variation complicates recognition of the magmatic affinities of the dikes, but affinity assessment can be made by using stable minor and trace element data.

MgO is commonly used in differentiated mafic suites as a measure of fractionation (Wright, 1974). Although the scatter for MgO for these dikes is much less than the scatter for the alkalis, this oxide, or any parameter involving it (for example, the Mafic Index), still would not make a reliable measure of fractionation for the dikes.

The total Fe content ($Fe_2O_3 + FeO$) is represented on figure 3 as FeO. FeO is known to be relatively stable during weathering and low-grade metamorphism (Gottfried and others, 1977).

SiO_2 shows no scatter and falls within the basalt range (<53 percent). Therefore, SiO_2 appears to have been rather stable during metamorphism, and the variations in both FeO and SiO_2 may be taken to closely approximate magmatic variations. The SiO_2 contents, in particular, indicate that neither the tholeiitic nor the teschenitic dikes represent single magmatic lineages. Rather, three comagmatic lineages (corresponding to the three areas of occurrence) are readily discernible; two specimens (samples 8 and 16) represent separate geochemical entities and may be inferred to have been parts of different magmatic stems. The postulated lineages are shown on figure 3.

The TiO_2 data confirm these lineages. Specimen 8 is assumed to be part of a low Ti suite. The necessary increase in Ti relative to P required to associate specimen 8 with the remaining Mars Hill and Bridgewater basaltic rocks would imply that P was behaving more compatibly than Ti. Such a behavior is contrary to previous results of studies of basaltic sequences (Anderson and Greenland, 1969).

The TiO_2-P_2O_5 graph (fig. 3) also reveals that the Bridgewater and Mars Hill metabasaltic rocks probably represent separate, but subparallel, lineages, the Bridgewater dikes being slightly more Ti rich. Presque Isle sample 16 (table 1) is also slightly more Ti rich than the associated teschenites but is notably Fe depleted compared to them. The Fe and Ti data agree with the SiO_2 contents and suggest that sample 16 represents a rather different chemical type from the teschenites.

The major element data, therefore, indicate that the basaltic dikes in the eastern part of the area (fig. 1) can be divided into three types: (1) the Bridgewater group, (2) the Mars Hill group (excepting specimen 8, table 1), and (3) sample 8, which is geochemically unique. The dikes in the Presque Isle quadrangle are apparently represented by two chemically and petrographically distinct types: (1) the teschenites consisting of samples 13, 14, and 15 (table 1) and (2) another rock type of which sample 16 (table 1) is the only analyzed member.

Trace Elements

The trace element analyses for northeast Maine dike rocks are listed in table 3. Plots of these elements, either singly or in ratios, against P_2O_5 are given in figures 4–7.

Large Cations

Ba, Rb, and Sr.—These elements are particularly prone to remobilization during low-temperature

Table 2. Geochronologic $^{40}Ar/^{39}Ar$ data for dikes in northeastern Maine

Temp. (°C)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$ ($\times 10^{-2}$)	$^{39}Ar_K$ (percent of total)	^{40}Ar (percent of total)	$^{39}Ar_K$ (moles $\times 10^{-12}$)	Apparent K/Ca (mole/mole)	Apparent age (Ma)
				Sample 6[1]				
450	29.73	1.123	1.758	13.9	82.8	4.23	0.44	361 ± 4
550	34.38	.494	2.211	3.6	81.1	1.08	.99	404 ± 4
750	31.03	1.421	2.045	4.1	80.9	1.23	.34	367 ± 4
850	29.34	1.563	.998	23.4	90.3	7.11	.31	386 ± 4
1000	27.68	2.219	.764	36.9	92.4	11.2	.22	374 ± 4
FUSE	30.31	6.948	1.807	18.1	84.3	5.48	.07	377 ± 4
							Total gas age =	376
							Weight-average plateau age =	375 ± 8
				Sample 5[2]				
450	30.82	2.241	3.526	15.2	66.7	2.21	0.22	307 ± 4
750	27.26	6.019	2.194	12.6	77.9	1.82	.08	316 ± 4
850	23.07	3.970	1.184	43.5	86.2	6.31	.12	297 ± 3
1000	29.47	8.624	3.258	8.3	69.6	1.20	.06	306 ± 4
FUSE	27.00	19.24	2.449	20.4	78.7	2.92	.03	316 ± 4
							Total gas age =	305
							No plateau age defined	
				Sample 2[3]				
450	25.63	0.167	1.188	23.5	86.3	6.19	2.94	328 ± 4
600	30.45	.343	.521	16.9	95.0	4.45	1.43	418 ± 4
850	31.28	.112	.970	22.9	90.8	6.02	4.33	411 ± 4
1000	31.33	.180	.922	24.0	91.3	6.31	2.72	414 ± 4
FUSE	35.70	.494	3.256	12.6	73.1	3.32	.99	381 ± 4
							Total gas age =	390
							Weight-average plateau age =	414 ± 8
				Sample 3[4]				
350	31.71	0.361	6.601	5.9	38.6	0.64	1.36	188 ± 4
500	20.84	.289	1.144	43.2	83.9	4.75	1.69	264 ± 4
650	31.05	.332	3.458	12.7	67.2	1.39	1.47	310 ± 4
750	27.60	.464	1.572	14.2	83.3	1.56	1.05	339 ± 4
950	31.18	1.476	2.354	9.4	78.0	1.04	.33	357 ± 4
FUSE	43.89	5.400	6.843	14.5	54.9	1.59	.09	354 ± 4
							Total gas age =	299
							No plateau age defined	

geological processes and are unlikely to be present in the dikes in their magmatic concentrations. Plots of Ba, Rb, and Sr contents against P_2O_5 (fig. 4) show considerable scatter and, in the case of Rb and Sr, no systematic increase or decrease with changing P_2O_5 values. Ba shows a gross trend of increasing concentrations in more differentiated compositions.

Ascertaining the processes that modified the concentrations of Ba, Rb, and Sr is not possible. Thus, Rb may have been leached from, or added to, the dikes during postemplacement hydration and subsequently during metamorphism. In specimen 8, for example, the high Rb (and relatively high K) content is not in accord with the low contents of Nb, Ti, total REE, and Zr and the high content of MgO in this rock. Both Rb and K clearly have been added to the dike by postemplacement processes.

K:Rb ratio.—Despite the mobile nature of K and Rb, the K:Rb ratio in the Mars Hill samples (table 3) shows a relatively limited variation of 302 ± 84, a range encompassing that of fresh continental tholeiites (Wedepohl, 1975). This range implies grossly similar geochemical behavior of K and Rb during magmatic and postmagmatic processes in the Mars Hill dikes.

The K:Rb ratio is lower in two Bridgewater samples. The lower ratio can be ascribed to the preferential addition of Rb during alteration. In contrast, the range of K:Rb ratios (226–667) in the Presque Isle dikes indicates some separation of K and Rb during postmagmatic processes, possibly related to differing groundmass mineralogies and (or) textures of these rocks compared to the basaltic dikes in the Bridgewater and Mars Hill quadrangles.

Table 2. Geochronologic ^{40}Ar/^{39}Ar data for dikes in northeastern Maine—Continued

Temp. (°C)	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar ($\times 10^{-2}$)	^{39}Ar$_K$ (percent of total)	^{40}Ar (percent of total)	^{39}Ar$_K$ (moles $\times 10^{-12}$)	Apparent K/Ca (mole/mole)	Apparent age (Ma)
				Sample 15[5]				
300	66.20	1.379	21.76	0.5	3.0	0.29	0.35	32 ± 12
400	18.39	1.243	3.454	3.1	45.0	1.93	.39	130 ± 2
550	20.57	.346	.221	8.9	96.9	5.50	1.42	293 ± 3
650	25.86	.469	.685	4.9	92.3	3.02	1.04	351 ± 4
750	25.18	.301	.630	4.3	92.7	2.65	1.63	344 ± 4
850	25.45	.222	1.014	7.9	88.3	4.88	2.21	332 ± 4
1000	23.73	.264	.455	9.7	94.4	6.04	1.86	331 ± 4
1100	20.34	.901	.310	32.7	95.8	20.3	.54	292 ± 3
FUSE	21.27	2.157	.567	28.0	92.9	17.4	.23	295 ± 3
							Total gas age =	300
							Weight-average plateau age =	293 ± 6
				Sample 16[6]				
400	20.04	0.826	1.819	16.5	73.5	7.94	0.59	225 ± 2
700	26.96	1.348	.661	15.3	93.1	7.36	.36	368 ± 3
850	24.87	.347	.568	20.4	93.3	9.80	1.41	342 ± 3
1100	19.99	.868	.668	25.8	90.4	12.4	.56	272 ± 2
FUSE	23.20	4.001	1.347	21.9	84.2	10.5	.12	292 ± 2
							Total gas age =	298
							No plateau age defined	

[1] Sample 6: P-64-6; whole rock diabase dike; Mars Hill quadrangle; J = 0.009004; sample weight = 0.7717 g.

[2] Sample 5: P-64-27; whole rock diabase dike; Mars Hill quadrangle; J = 0.009004; sample weight = 0.7109 g.

[3] Sample 2: PA-74-7; whole rock basaltic dike; Bridgewater quadrangle; J = 0.009004; sample weight = 0.6900 g.

[4] Sample 3: PA-74-9; whole rock basaltic dike; Bridgewater quadrangle; J = 0.009004; sample weight = 0.7437 g.

[5] Sample 15: PA-74-3; whole rock basaltic dike; Presque Isle quadrangle; J = 0.009004; sample weight = 0.6778 g.

[6] Sample 16: PA-74-4; whole rock basaltic dike; Presque Isle quadrangle; J = 0.009004; sample weight = 0.7496 g.

High Valence Cations

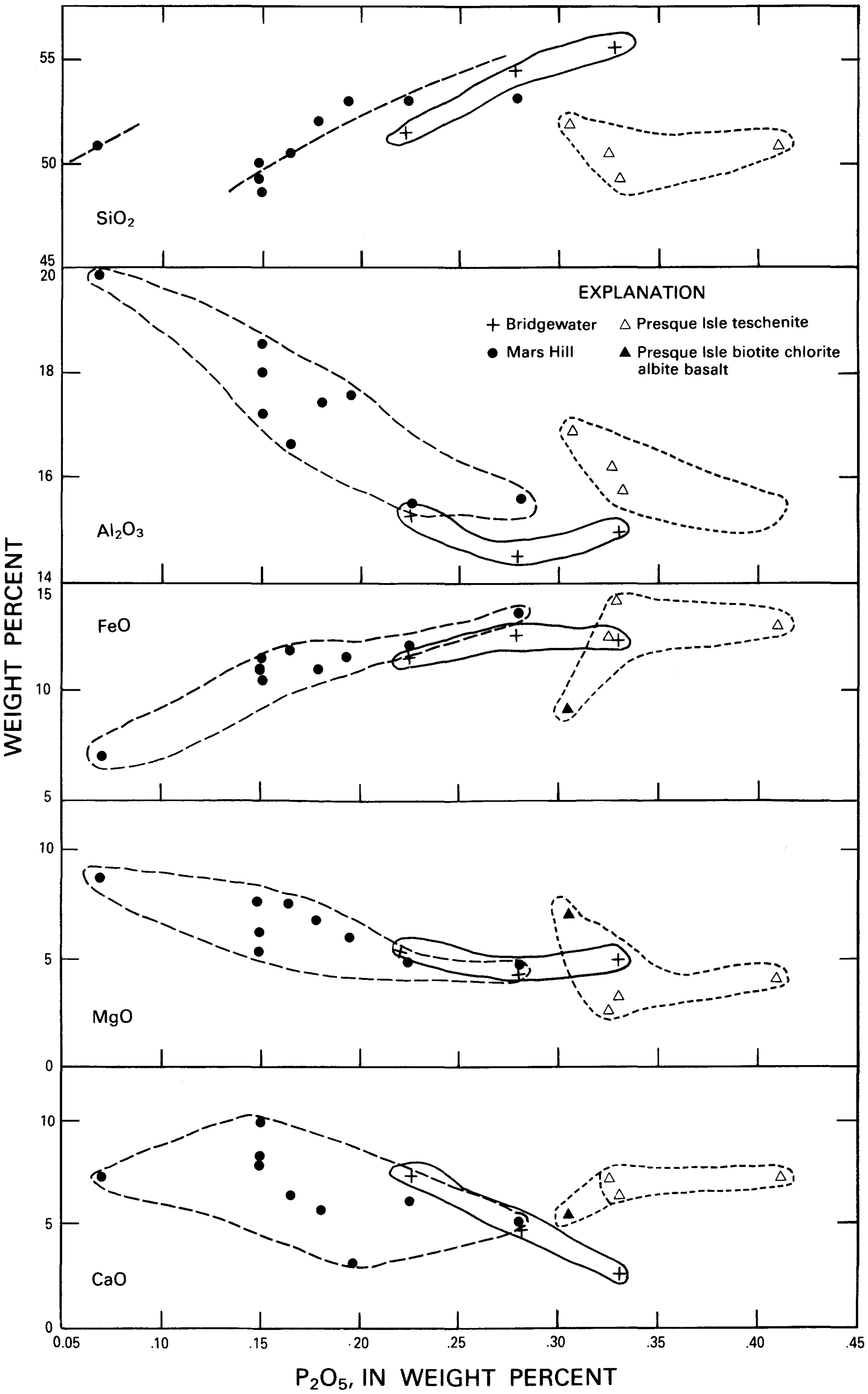
Nb and Ta.—On a Nb-P_2O_5 plot (fig. 5), at similar P_2O_5 levels, the Mars Hill dikes are slightly but systematically higher in Nb than those from the Bridgewater area, a reversal of the relative quantities of TiO_2 (fig. 3). The lower Nb content results in a lower 100 × Nb:Ti ratio for the Bridgewater dikes at similar P_2O_5 contents (fig. 5). The gentle increase in 100 × Nb:Ti ratio in the Mars Hill specimens contrasts with the more common situation in basaltic sequences where the ratio remains approximately constant in the early and middle stages of differentiation and increases significantly only when Fe and Ti oxides become important fractionating phases (Gottfried and others, 1968). However, a possible case of gently increasing 100 × Nb:Ti ratio with increasing differentiation has been recorded by Macdonald and others (1981) in a sequence of late Paleozoic Scottish tholeiitic dikes. In both the Scottish and Mars Hill suites, Ti may have been partitioned into the solid phases more rapidly than Nb.

The teschenitic rocks (samples 13–15), despite a higher alkalinity, do not contain more Nb than the tholeiitic diabases. However, the Nb content of 44 ppm for sample 16 is more than twice that of the teschenites at equivalent P_2O_5 contents. The high Nb content supports the suggestion, based on major element data, that sample 16 represents a different magmatic stem.

The behavior of Ta closely resembles that of Nb, and the Nb:Ta ratio varies (except for sample 8) between 11 and 21, largely within estimated analytical error. The high ratio of 27 in specimen 8 may not be significantly different from the ratios in the other diabase samples since Ta determinations in the very low ppm range are analytically uncertain.

Zr and Hf.—In the Mars Hill (excluding specimen 8) and Bridgewater dikes, Zr content increases slightly less than threefold, reaching a maximum of 321 ppm (fig. 6). Concentrations of Hf show a generally similar increase. Though scattered, the Zr:Hf ratio shows no indication of decreasing with increasing P_2O_5 content. This behavior differs from the behavior of the Great Lakes diabase-granophyre suite where the Zr:Hf ratio decreased by a factor of two during differentiation from the early mafic diabase to granophyric residua (Gottfried and others, 1968). The Zr:Hf ratio of sample 8 (fig. 6) seems to further distinguish that sample from the other Mars Hill dikes.

The Zr and Hf concentrations in the Presque Isle teschenites are uniform at about 255 ppm and 5 ppm


SiO$_2$
Al$_2$O$_3$
FeO
MgO
CaO
55
50
45
20
18
16
14
15
10
5
10
5
0
10
5
0
WEIGHT PERCENT
0.05
.10
.15
.20
.25
.30
.35
.40
.45
P$_2$O$_5$, IN WEIGHT PERCENT
EXPLANATION
+ Bridgewater
● Mars Hill
△ Presque Isle teschenite
▲ Presque Isle biotite chlorite albite basalt

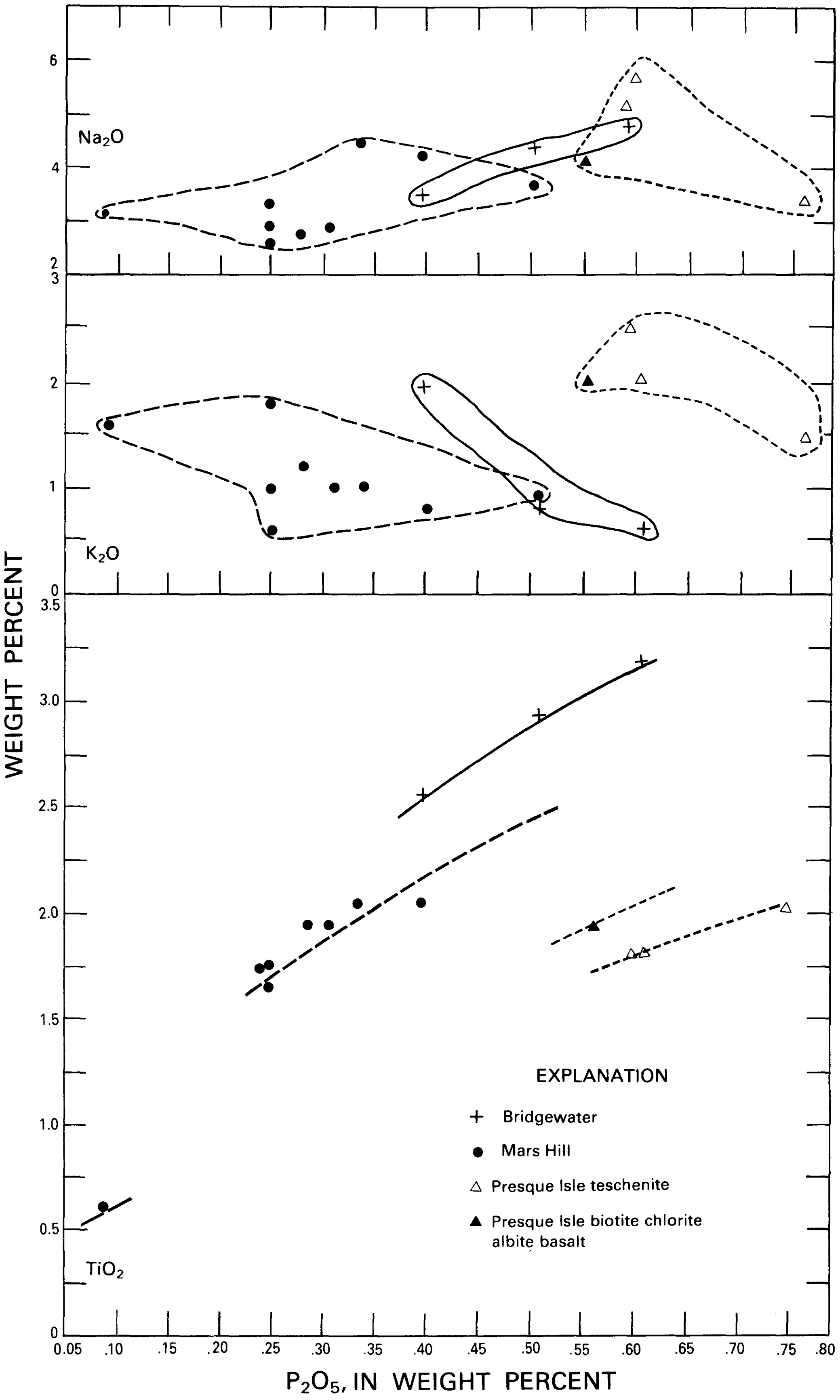


Figure 3. Major element variation diagram of dikes in northeastern Maine.

Table 3. Trace element abundances in parts per million in dikes in northern Maine

Suite	Bridgewater			Mars Hill									Presque Isle			
Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Field no.	PA-74-8	PA-74-7	PA-74-9	P-64-8	P-64-27	P-64-6	P-64-5	P-64-77	P-64-3	P-64-9	P-63-26	P-64-7	PA-74-1	PA-74-2	PA-74-3	PA-74-4
Large cations																
Rb	107	42	13	63	22	36	32	54	28	22	21	22	53	31	58	24
Ba	643	360	770	305	230	292	166	261	496	346	342	250	675	536	452	504
Sr	584	379	298	1070	346	561	701	516	764	410	288	401	594	515	573	1159
K:Rb	150	148	364	222	218	253	247	222	286	323	386	282	226	348	345	667
High-valence cations																
Th	2.3	3.2	3.0	0.6	1.0	0.9	1.8	0.3	1.4	2.3	2.2	3.4	8.6	6.8	8.2	3.5
U	—	1.1	—	.1	.3	.2	.5	.1	.2	.5	.5	1.0	2.6	1.8	2.8	1.4
Zr	217	256	321	124	112	117	141	69	139	208	188	231	266	251	257	248
Hf	4.9	5.8	6.9	2.8	2.7	3.2	3.7	1.3	3.2	5.0	4.5	6.1	5.8	4.4	5.4	4.6
Nb	14	14	17	8	8	10	9	3	10	17	13	15	15	18	17	44
Ta	.79	.96	1.07	.50	.47	.50	.51	0.11	.48	.89	.79	.80	1.35	1.05	1.28	3.29
Th:U	—	2.9	—	6.0	3.3	4.5	3.6	3.0	7.0	4.6	4.4	3.4	3.3	3.8	2.9	2.5
Zr:Hf	44	44	47	44	41	37	38	53	43	42	42	38	46	57	48	54
Nb:Ta	18	15	16	16	17	20	18	27	21	19	16	19	11	17	13	13
100 × Nb:Ti	.09	.08	.09	.07	.07	.08	.08	.06	.08	.11	.10	.11	.11	.14	.14	.35
Ferromagnesian elements																
Co	37	29	35	46	40	45	42	38	37	38	40	38	34	29	30	34
Ni	44	18	23	90	54	74	44	115	50	14	66	38	13	11	14	100
Zn	151	144	172	142	120	146	136	92	122	168	134	122	143	148	148	84
Cr	71	30	29	262	228	236	227	493	212	36	171	96	4	—	5	220
Sc	37	34	38	41	34	41	40	28	39	34	37	31	8	8	9	19
Ni:Co	1.2	.6	.7	2.0	1.4	1.6	1.1	3.0	1.4	.4	1.7	1.2	.4	.4	.5	2.9
Rare earth elements																
La	18	23	23	6	8	9	9	2	9	18	15	15	49	45	47	29
Ce	39	48	50	20	21	22	26	8	22	44	39	44	99	92	96	55
Nd	29	33	39	13	14	17	16	4	17	30	27	28	45	43	43	27
Sm	7.1	8.3	10.1	3.8	3.6	5.1	4.5	1.6	5.0	8.2	5.8	7.2	8.9	9.1	8.6	5.3
Eu	2.23	2.50	2.99	1.40	1.62	1.84	1.82	.68	1.64	2.50	2.04	2.48	2.23	2.23	2.20	1.55
Gd	5.8	6.7	8.8	3.8	3.5	5.0	5.4	—	4.2	7.4	5.6	8.9	7.6	7.2	7.1	4.2
Tb	1.2	1.6	1.6	1.0	.82	1.2	1.1	.48	1.1	1.6	1.3	1.7	1.3	1.3	1.5	.77
Tm	.61	.56	.70	.46	.37	.42	.55	.22	.42	.73	.56	.89	.70	.63	.60	.67
Yb	4.3	5.1	6.7	2.8	2.5	3.4	3.6	1.2	3.4	5.2	3.7	5.4	4.8	4.3	4.6	.31
Lu	.63	.72	.89	.48	.40	.53	.54	.22	.49	.78	.60	.78	.70	.59	.64	.31
La_n -Sm_n	1.39	1.52	1.25	.87	1.22	.97	1.10	.69	.99	1.20	1.42	1.14	3.02	2.71	3.00	3.00
Y	53	62	86	44	33	43	44	16	42	72	50	74	51	45	55	28

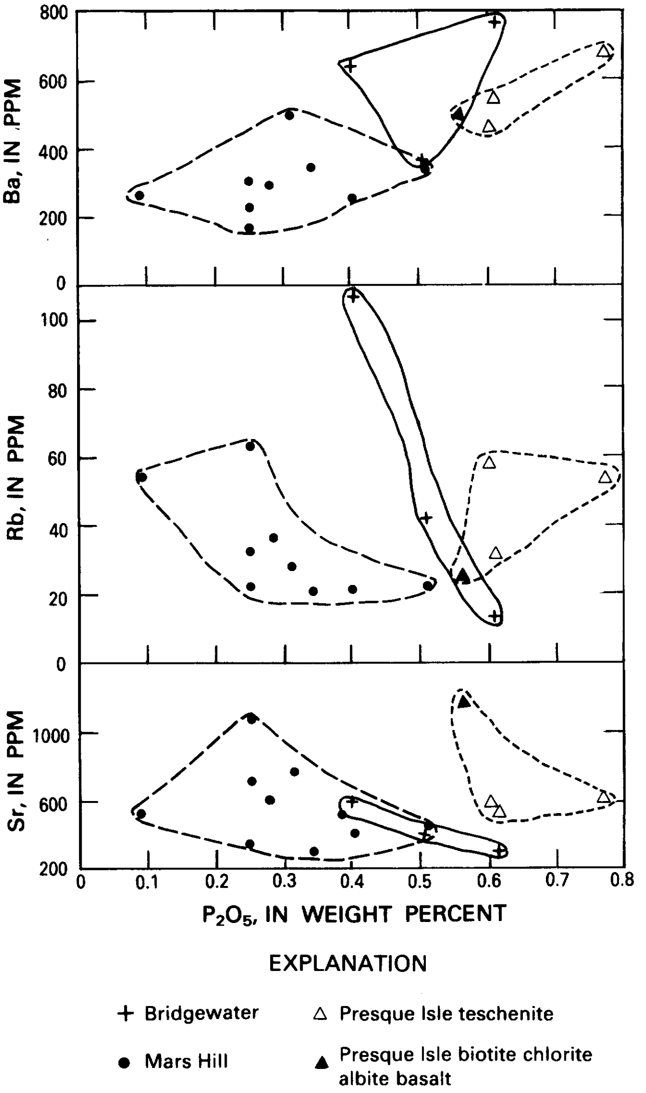


Figure 4. Plots of Ba, Rb, and Sr contents against P_2O_5 in dikes in northeastern Maine.

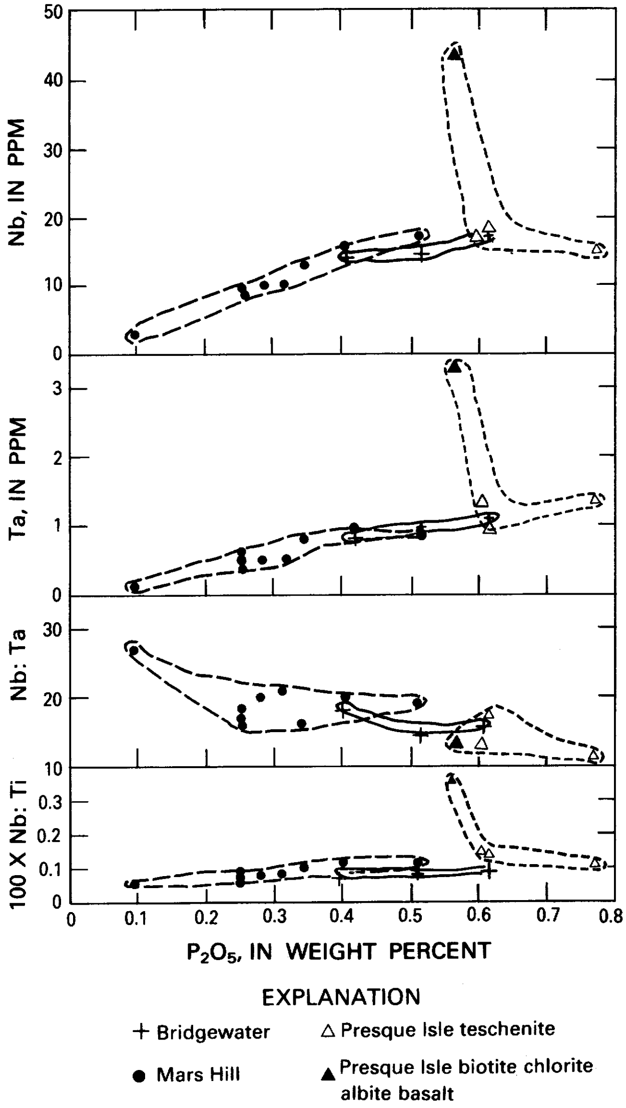


Figure 5. Nb and Ta contents and Nb:Ta and 100×Nb:Ti ratios in dikes in northeastern Maine.

(table 3), respectively, and fall within the range shown by the Mars Hill and Bridgewater dikes. These concentrations are unexpected because the Presque Isle dikes are more alkalic, but the concentrations are consistent with the Nb and Ta data.

Th and U.—In the Mars Hill dikes, Th and U increase five- or sixfold to a maximum in specimen 12 but apparently decrease in sample 10 (table 3). The trend is crossed by that of the Bridgewater dikes (fig. 7), which also demonstrates a maximum. The variation of Th and U thus mimics that of Nb and Ta and of Zr and Hf. Whether any phase likely to fractionate from such mafic compositions would remove all three elemental pairs from the liquids is not clear. If the Mars Hill dikes represent a cogenetic sequence, then sample 10 probably has lost the LIL (large ion lithophile) elements, perhaps as a volatile phase. More likely, sample 10 represents yet another geochemical type within the Mars Hill suite, closely comparable to the other members but with slight differences in trace element abundances.

The Th:U ratios of the Mars Hill and Bridgewater diabases show rather large variations, ranging from 2.9 to 7. The variations are consistent with the possibility that U has been variably mobilized during low-temperature alteration processes. Previous studies (Gottfried and others, 1968) have shown that the Th:U ratio demonstrates little change during fractional crystallization of diabasic magmas.

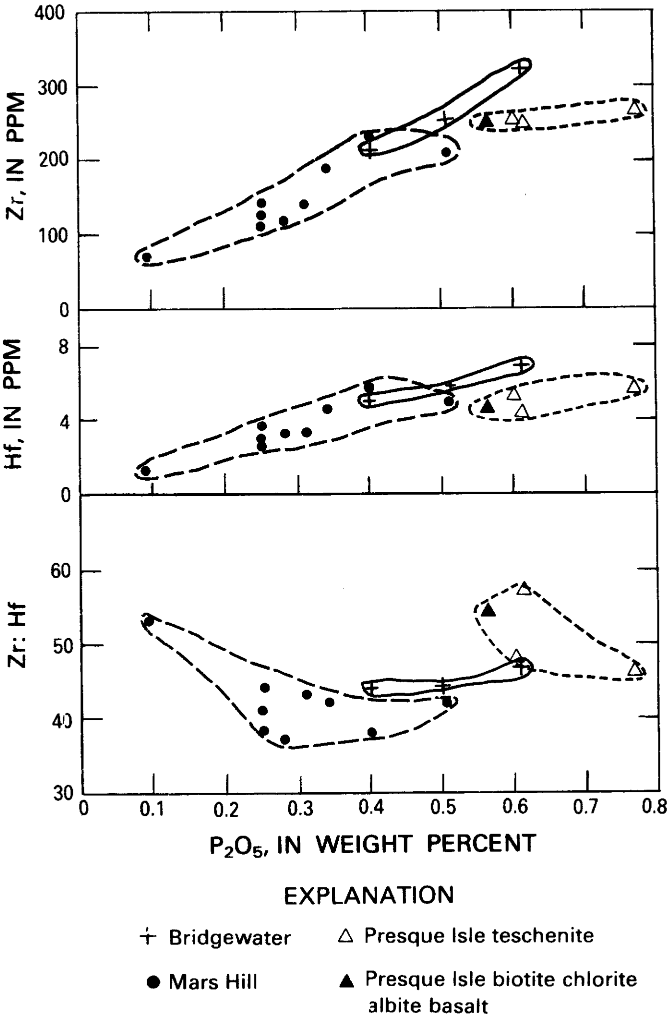


Figure 6. Zr and Hf contents and Zr:Hf ratios in dikes in northeastern Maine.

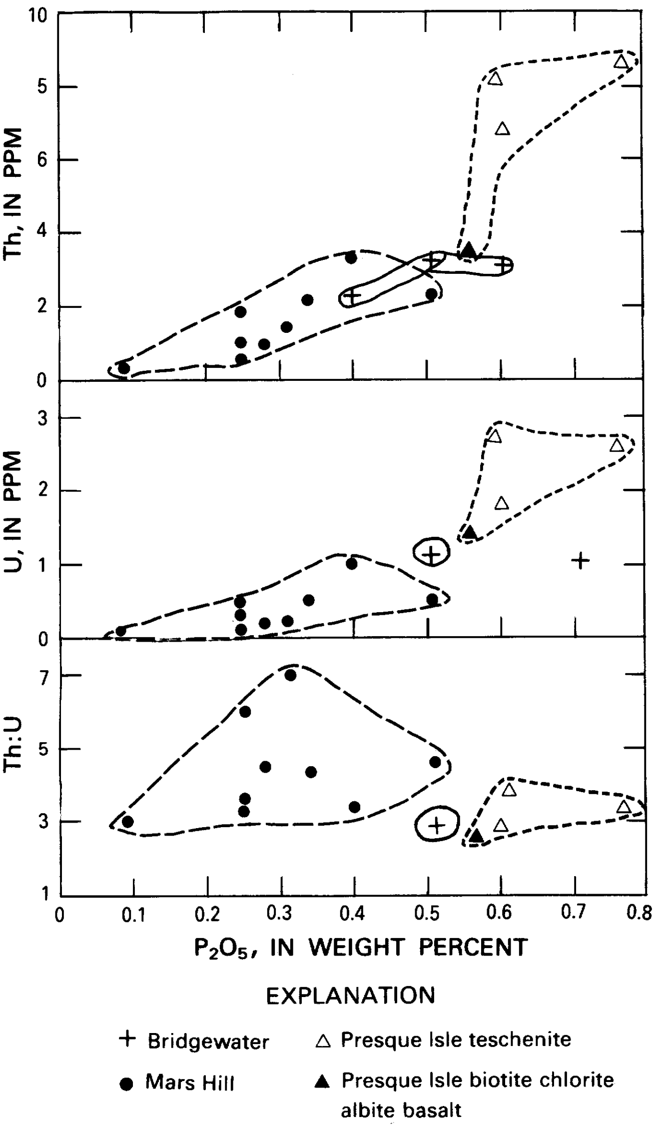


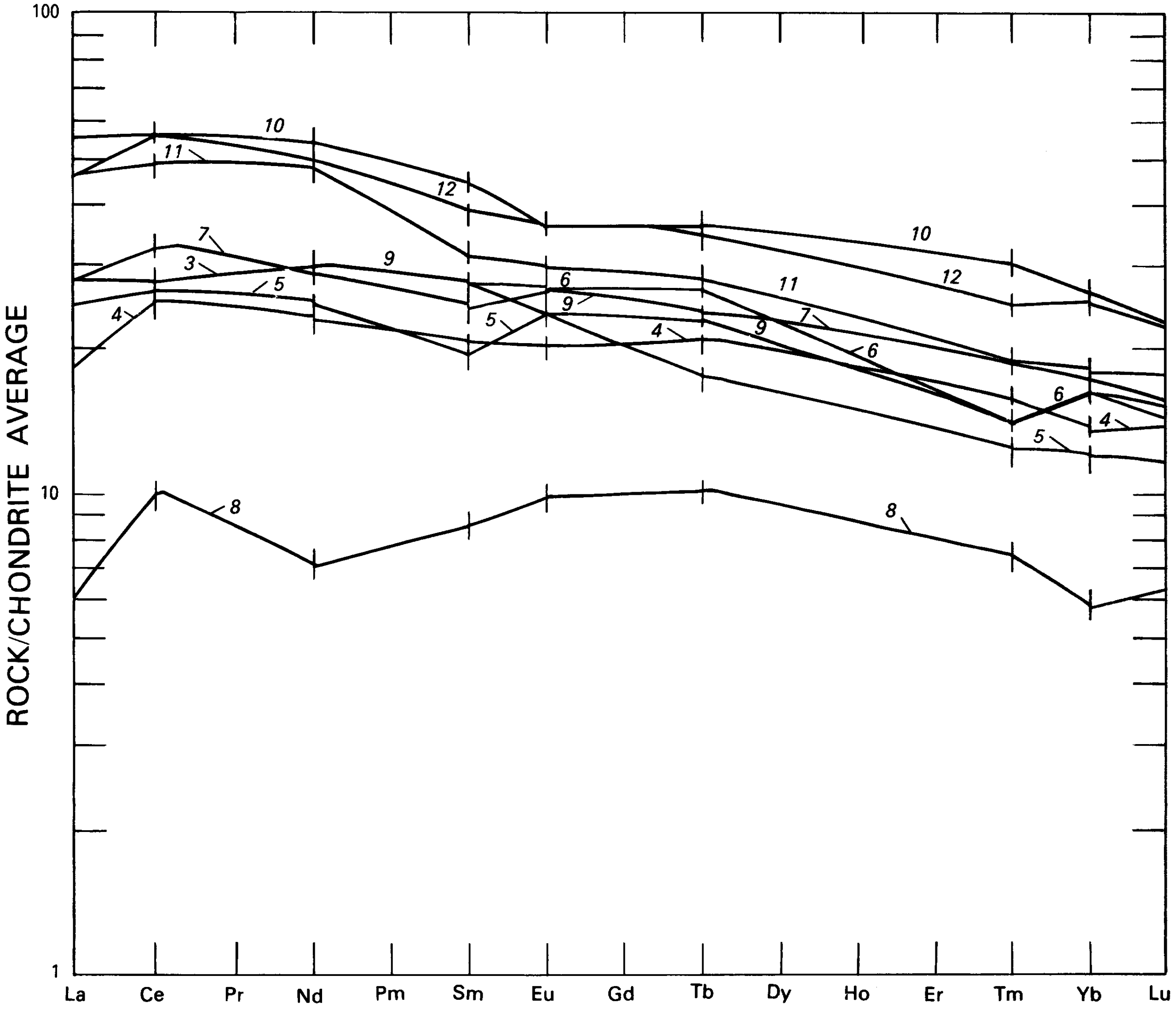
Figure 7. Th and U contents and Th:U ratios in dikes in northeastern Maine.

In contrast to the similarities found in Zr, Hf, Nb, and Ta between the teschenites and diabases, Th and U show significantly higher abundances in the teschenites (table 3). The higher abundances agree with the higher alkalinity of the teschenites. The abundances of Th and U in the teschenites are an example of the decoupling of LIL elements from each other; that is, relative enrichment of a suite of rocks in one or more LIL elements carries no implication that the suite will be enriched in all the remaining LIL elements.

Rare Earth Elements

The chondrite-normalized REE patterns of the Mars Hill diabase dikes (except sample 8) are rather flat, with only a modest enrichment of light rare earth elements (LREE) over heavy rare earth elements (HREE) and no systematic Eu anomaly (fig. 8*A*). The Bridgewater dikes are more LREE enriched (fig. 8*B*). The patterns are similar to those of continental tholeiites, though lower in LREE. Leeman (1977) lists La:Sm ratios of 1.4 to 3 for several continental tholeiite suites, higher than the 0.7 to 1.5 in the Mars Hill diabases. Although the flatter pattern of these rocks may be a real magmatic feature, the Mars Hill rocks may have lost some LREE during low-grade metamorphism (Hellman and others, 1979). The similarity of the REE patterns in all the Mars Hill diabase samples seems to contraindicate LREE loss during metamorphism, and we regard the REE values as magmatic.

Sample 8 has distinctly lower absolute abundances of the REE and a chondrite-normalized pattern that shows slightly more LREE depletion relative to HREE. These features are consistent with the lower Nb, Ta, Ti, Zr, and Hf contents (table 3) of this dike. The variation



A. MARS HILL DIKES

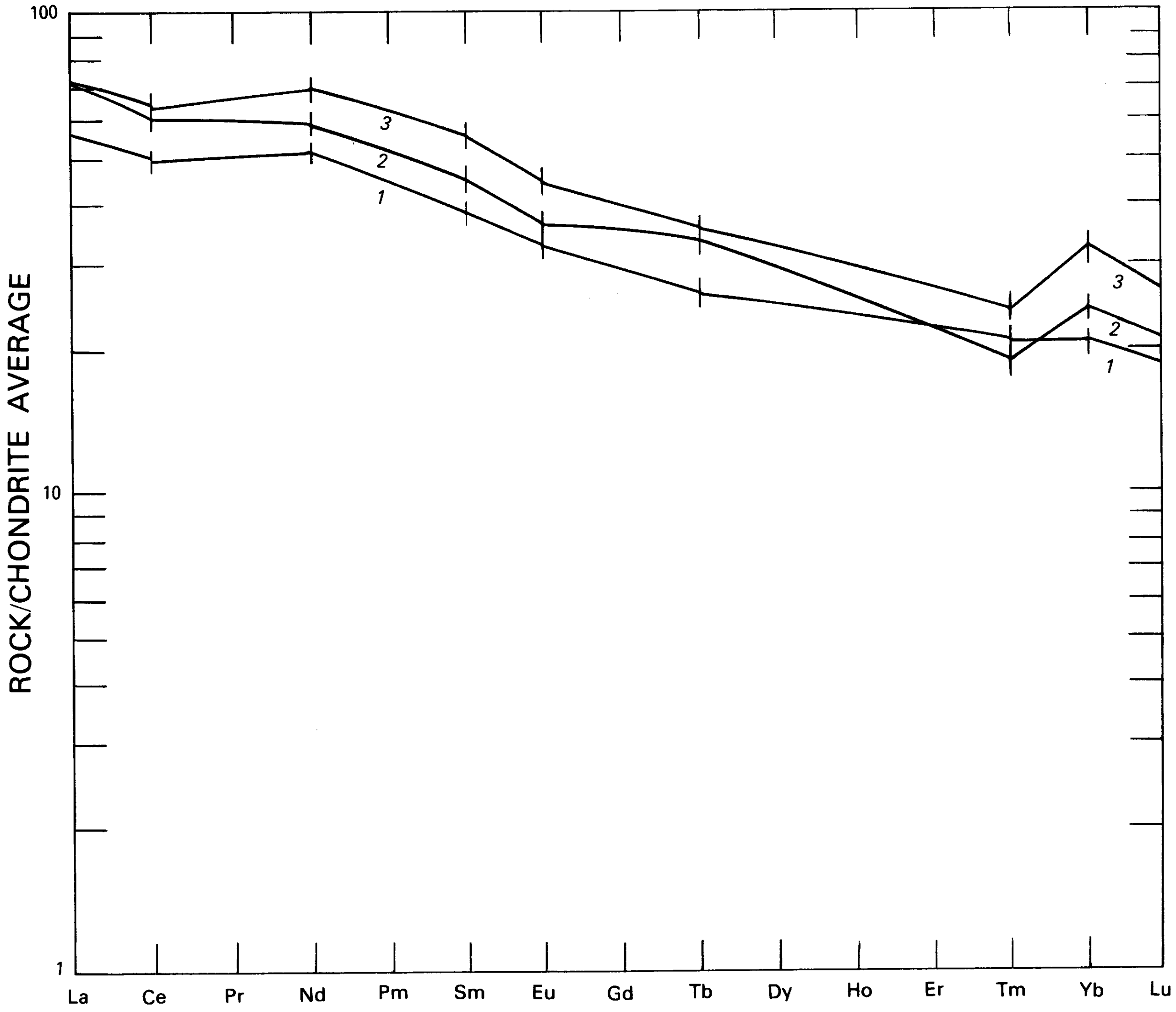
Figure 8. Chondrite-normalized REE abundance patterns in dikes in northeastern Maine. Numbers are sample numbers.

patterns of La, Yb, and Y (fig. 9) show small but consistent differences in the abundances of these elements between Mars Hill and Bridgewater dikes having the same P_2O_5 content. The La, Yb, and Y differences are consistent with the differences noted earlier for TiO_2 and for Nb and provide further support for the existence of two similar but distinct suites. The Presque Isle dikes (fig. 8*C*) are characterized by greater differences in the REE- and LREE-enriched patterns compared to those of the Mars Hill and Bridgewater dikes.

Ferromagnesian Elements

The variation patterns for Co, Cr, Ni, Sc, and Zn are shown in figure 10. Ni and Cr show strong depletion with higher P_2O_5 contents in the Mars Hill diabase dikes. These variations are similar to those noted in the Great Lakes diabase-granophyre suite (Greenland and Lovering, 1966). In the rocks from Mars Hill, the Ni:Co ratio decreases from 3 to 0.4 (table 3) with increasing fractionation. The teschenite dikes (samples 13–15) of the Presque Isle region have low Ni:Co ratios of approximately 0.5. The high ratio (2.9) in the biotite albite basalt (sample 16, table 3) confirms its distinction from the other Presque Isle dikes.

The variation in Co is rather limited, ranging from 29 to 46 ppm for all three suites of rocks (table 3). The abundance of Sc in the Mars Hill basaltic dikes is similar to that of Co, but the abundances in the teschenite samples are distinctly lower (<10 ppm) than those in the tholeiitic basalts (fig. 10).



B. BRIDGEWATER DIKES

Figure 8 (Continued). Chondrite-normalized REE abundance patterns in dikes in northeastern Maine. Numbers are sample numbers.

MAGMATIC AFFINITY OF THE DIKES

Results of modal and normative mineralogy of the altered Maine dikes do not reflect original magmatic compositions. A more effective approach to characterize the magmatic affinity is to use stable minor and trace element abundances and ratios. As discussed in the preceding section, several features of the trace element geochemistry suggest that the Bridgewater and Mars Hill dikes are of the tholeiitic magma type, whereas the Presque Isle rocks have more alkalic affinities. Chondrite-normalized patterns accentuate these differences. Specifically, the flat patterns and low REE abundances of the diabase dikes of Mars Hill and Bridgewater are consistent with tholeiitic affinity, whereas the LREE-enriched pattern abundances of the Presque Isle teschenitic rocks are more like those of alkalic basalt. This magma characterization has been further explored by using trace and minor element discriminators of magma types proposed by Pearce and Cann (1973), Floyd and Winchester (1975), and Winchester and Floyd (1976). Results obtained in this way for the Maine dikes, however, are contradictory. On the (Nb:Y)-(Zr:P_2O_5) diagram (fig. 11*A*) of Winchester and Floyd (1976), all the dikes, with the exception of sample 16, plot in the field of tholeiitic basalts. On the TiO_2-Zr:P_2O_5 diagram (fig. 11*B*) of the same authors, all rocks plot in or very close to the alkalic field, except specimen 8, which is in the tholeiitic field. This type of nonexclusive characterization also is obtained by using the TiO_2-Zr, TiO_2-(Nb:Y), and P_2O_5-Zr diagrams of Floyd and Winchester (1975).

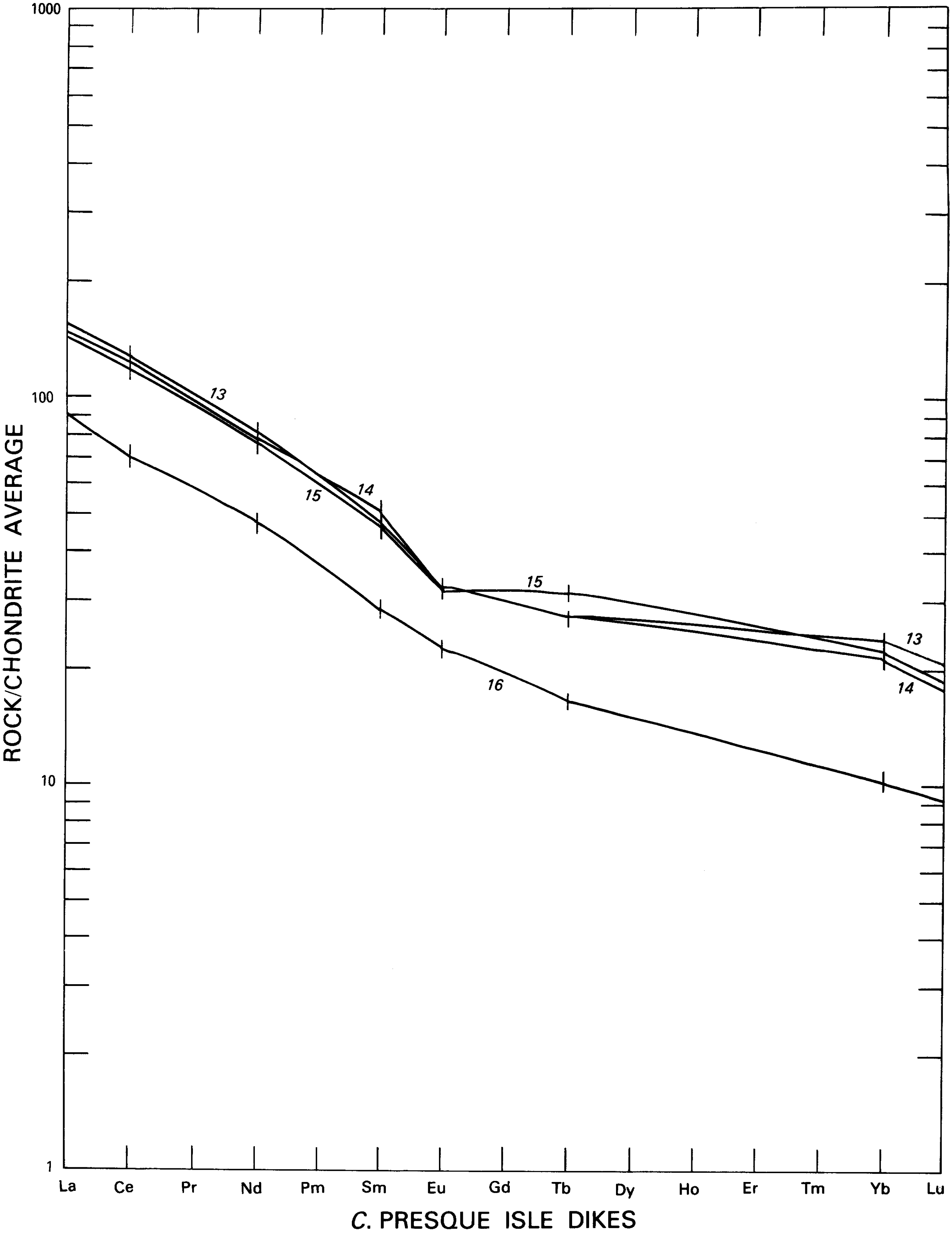


Figure 8 (Continued).

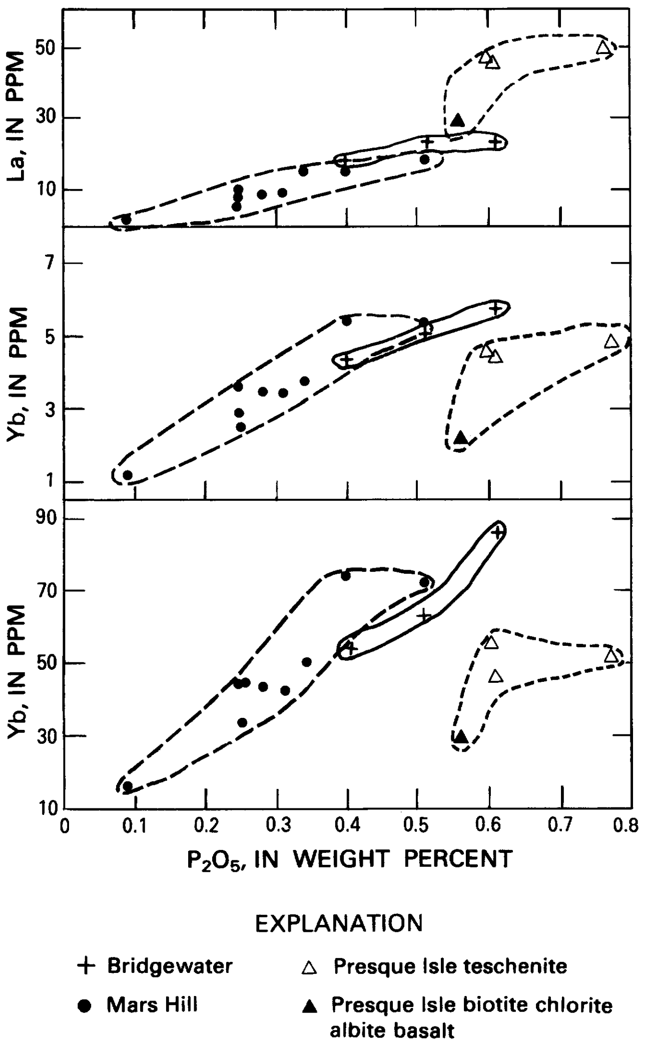


Figure 9. La, Yb, and Y contents in dikes in northeastern Maine.

The 100 × Nb:Ti ratio of <0.1 (fig. 5) for the more mafic diabases of Mars Hill is a feature only of tholeiitic basalts. Continental tholeiites from diverse geographical localities have shown values of this ratio within the range 0.05–0.15 (Gottfried and others, 1968; Gottfried and others, 1977; Macdonald and others, 1981). Similar ratios also have been found in the Kilauea and Mauna Loa tholeiitic suites from Hawaii and in island arc tholeiitic suites (Gottfried and others, 1977, and unpublished data). The slightly higher values in the Presque Isle rocks, especially in sample 16, also would be consistent with more alkalic chemistry.

We recognize, therefore, the following magma types among the dikes: (1) two rather similar tholeiitic suites contained in the Mars Hill and Bridgewater dikes (excluding specimen 8) with only minor differences between the suites; (2) the primarily teschenitic mafic-alkalic suite of the Presque Isle quadrangle; and (3) two isolated samples that appear to be geochemically unique (sample 8 from the Mars Hill dikes, a depleted-type tholeiite, and sample 16 from the Presque Isle quadrangle, a biotite albite basalt with alkalic affinities).

TECTONOMAGMATIC CLASSIFICATION

The possible tectonic setting at the time of emplacement of the Maine dikes can be assessed by using minor and trace element diagrams as tectonomagmatic discriminators.

On the (Ti:100)-Zr-(Y × 3) diagram (fig. 12) of Pearce and Cann (1973), the Mars Hill and Bridgewater dikes plot within the fields occupied by ocean-floor basalts and calc-alkali basalts of island arc series. The Presque Isle teschenites fall in the calc-alkalic basalt field, and the biotite albite basalt falls in the intraplate basalt field.

Wood (1980) has used a (Hf/3)-Th-Ta diagram to classify the tectonic setting of mafic rocks and their differentiates. On this plot (fig. 13), the Bridgewater dikes and the Mars Hill depleted tholeiite (sample 8) indicate a destructive plate margin environment. The other Mars Hill samples fall in the destructive plate margin field and the E-type MORB and tholeiitic within-plate basalt field. The three Presque Isle teschenitic dike samples suggest a destructive plate margin setting, whereas the Presque Isle biotite albite basalt suggests an alkaline within-plate association. Again, this discriminator fails to delineate unequivocally the dike environment.

The reasons for the inapplicability of these diagrams lie in the characteristics of the dike chemistries. The Maine rocks have high Y (and HREE) abundances relative to the data base used by Pearce and Cann (1973) in constructing the (Ti:100)-Zr-(Y × 3) diagram. As a result, the dikes are displaced towards the Y apex and plot in an "inapplicable" field. The analyzed Maine samples appear to have relatively low Nb contents, as indicated previously by their low 100 × Nb:Ti ratios, and by inference of geochemical affinity have low Ta contents. Thus, on the (Hf/3)-Th-Ta diagram, the dikes apparently have the characteristics of volcanic rocks from destructive plate margins.

Comparable reasoning may be applied to the results obtained in the assessment of magma types. Low Nb contents cause the teschenites to be classed as tholeiitic on the (Nb:Y)-(Zr:P_2O_5) plot (fig. 11*A*).

Among the factors that could result in the nonapplicability of tectonomagmatic discrimination diagrams to a particular suite of rocks, four may be particularly important:

(1) Gottfried and others (1977) pointed out that the data base of continental tholeiites used by Pearce and Cann (1973) in the construction of their

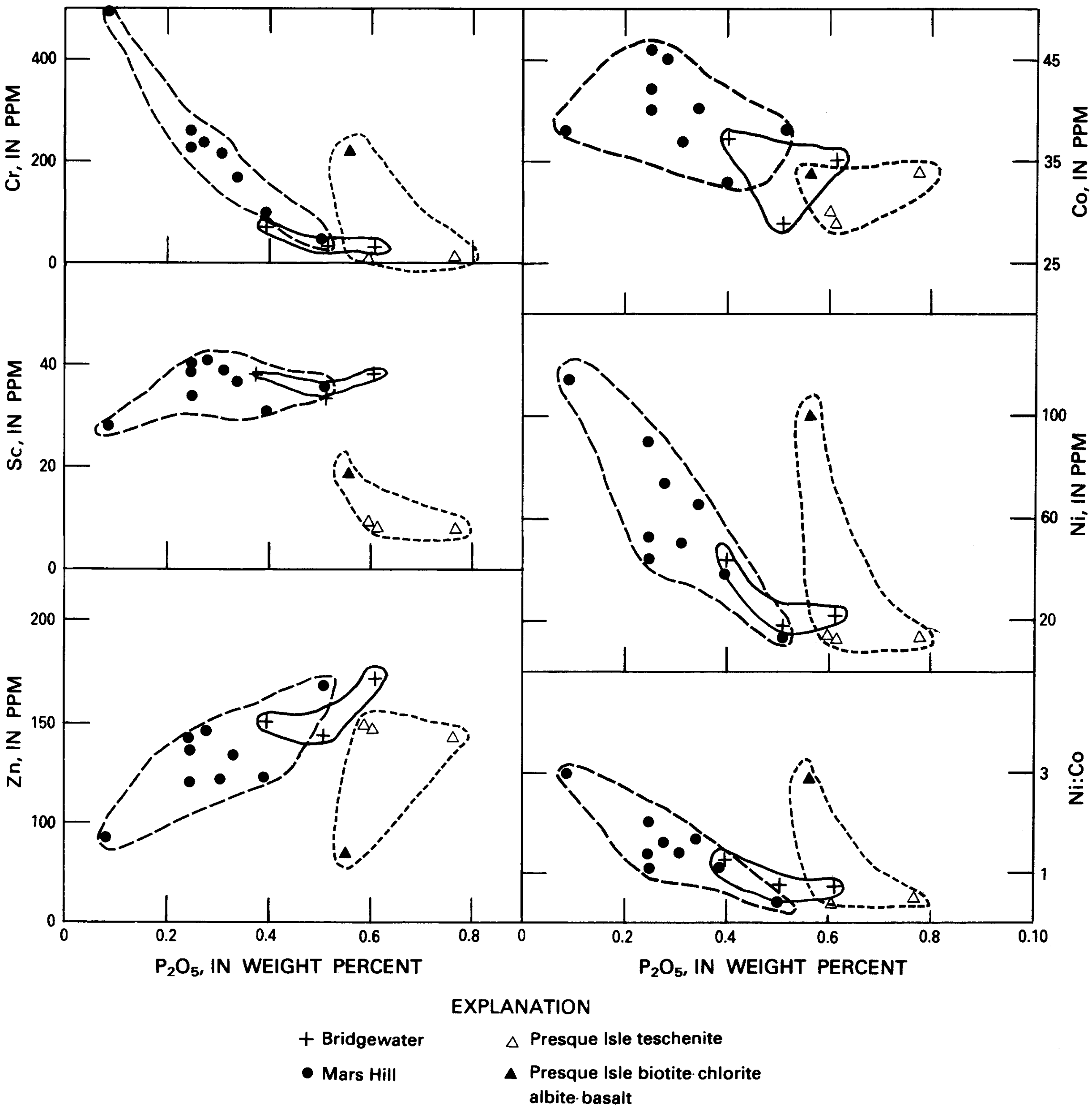


Figure 10. Co, Cr, Ni, Sc, and Zn contents and Ni:Co ratios in dikes in northeastern Maine.

(Ti:100)-Zr-(Y × 3) diagram was not representative of tholeiites from passive continental margins.

(2) Such tectonomagmatic discrimination diagrams may fail to consider the effects of fractionation of the relevant elements relative to each other, especially in the middle to later stages of differentiation (Graham, 1976).

(3) Selective contamination of mafic magmas by wall rock reactions during ascent through sialic crust may result in enrichment of the diagnostic elements.

(4) The likelihood that the mantle sources of within-plate basaltic magmas are markedly heterogeneous as regards the lithophilic elements is being increasingly recognized. Any relation between magma chemistry and tectonic setting is therefore complicated.

Of these petrogenetic factors, the preferred explanation of the nature of the trace element associations in the Maine dikes is that the parental magmas were generated within heterogeneous mantle sources, both

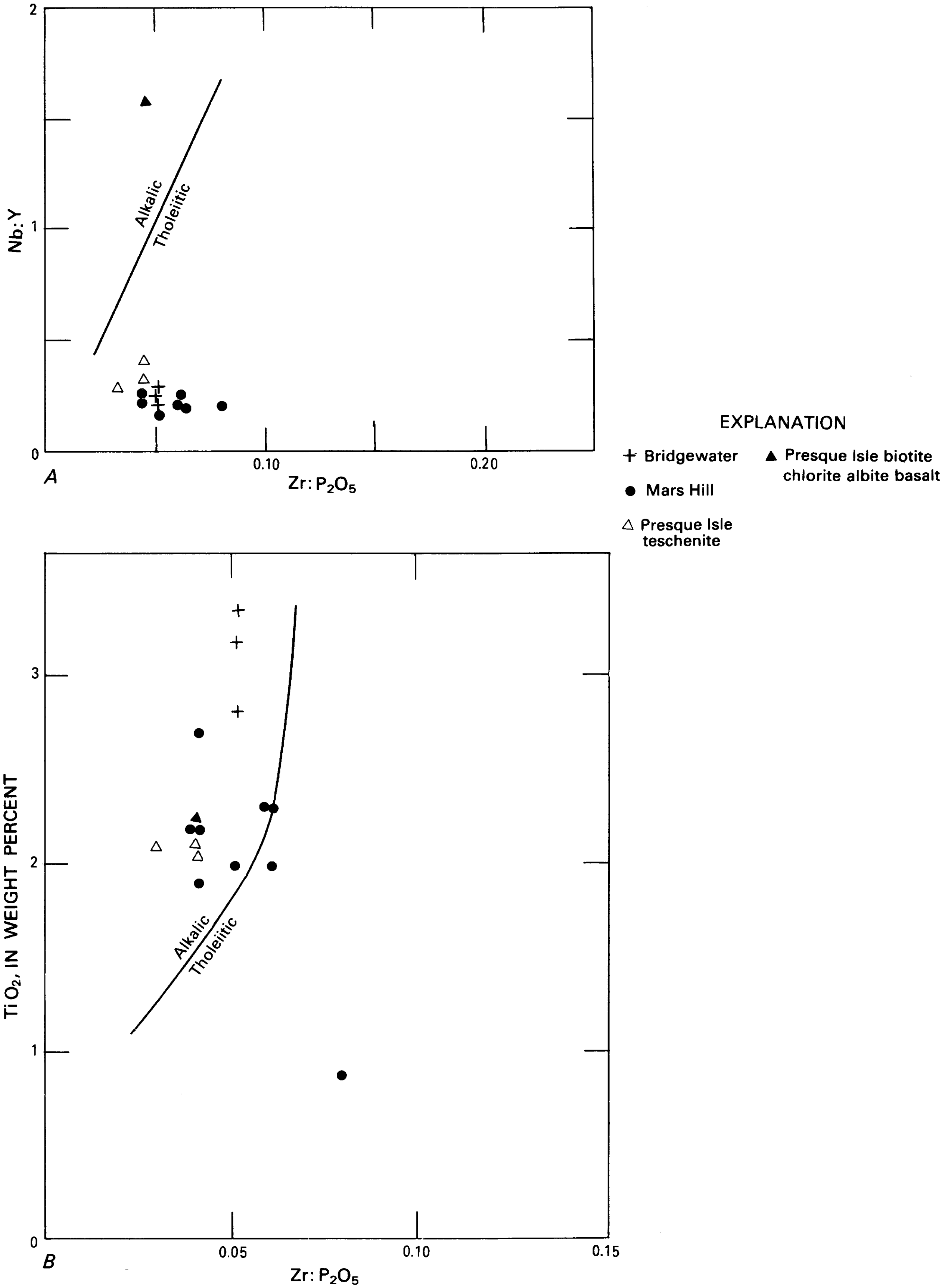


Figure 11. Samples of dike rocks from northeastern Maine plotted on variation diagrams for characterization of magma type (Winchester and Floyd, 1976). *A*, Plot of Nb:Y against Zr:P_2O_5. *B*, Plot of TiO_2 against Zr:P_2O_5.

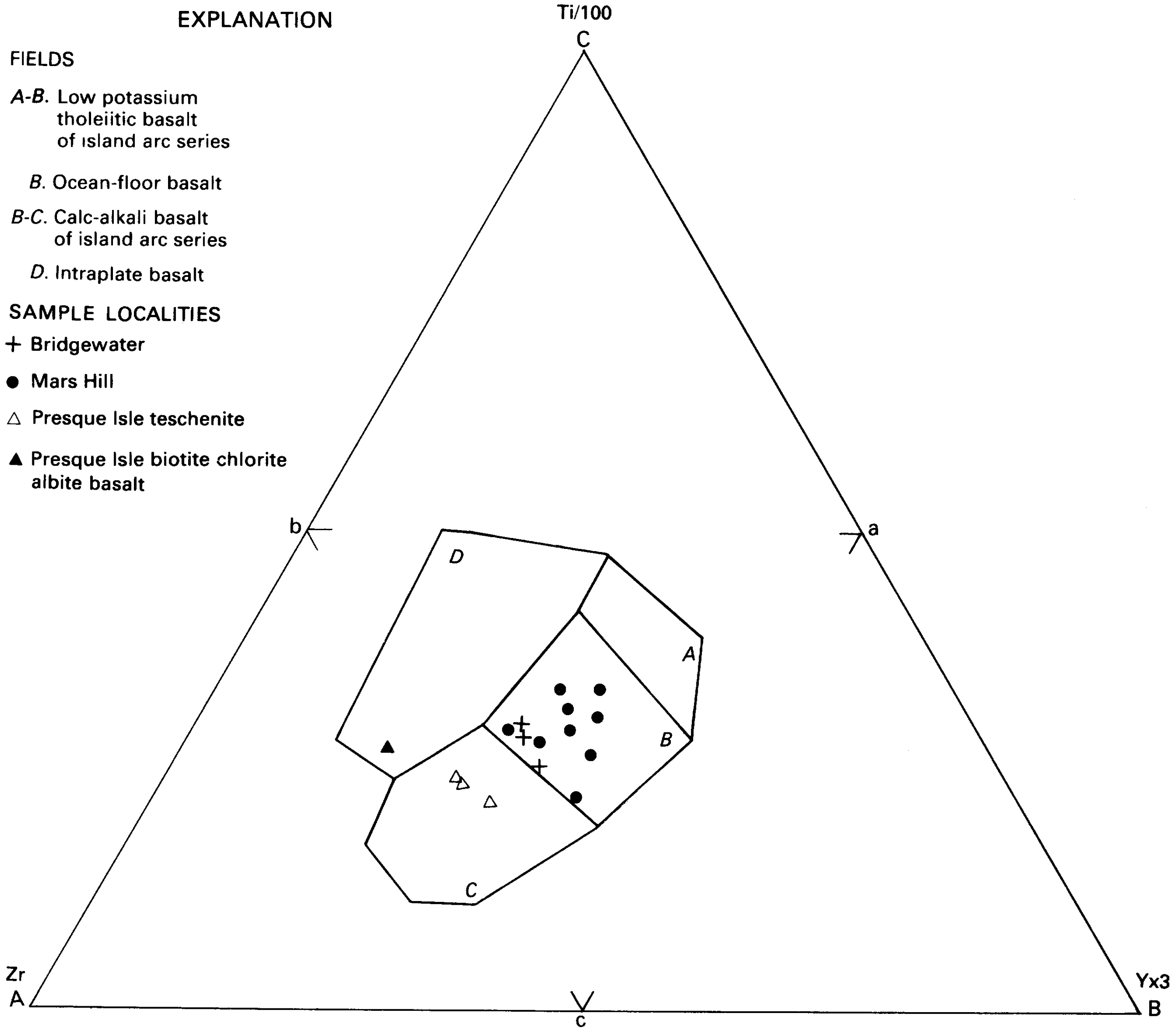


Figure 12. Samples of dike rocks from northeastern Maine plotted on the (Ti:100)-Zr-(Y ×3) discrimination diagram of Pearce and Cann (1973).

within the prescribed geographical area and when compared to the source areas of other within-plate suites. Variations in the melting process operating within such heterogeneous sources may have produced, in one tectonic setting and in a relatively limited time span, a range of mafic magmas representing a considerable proportion of the total spectrum of basaltic magmatism.

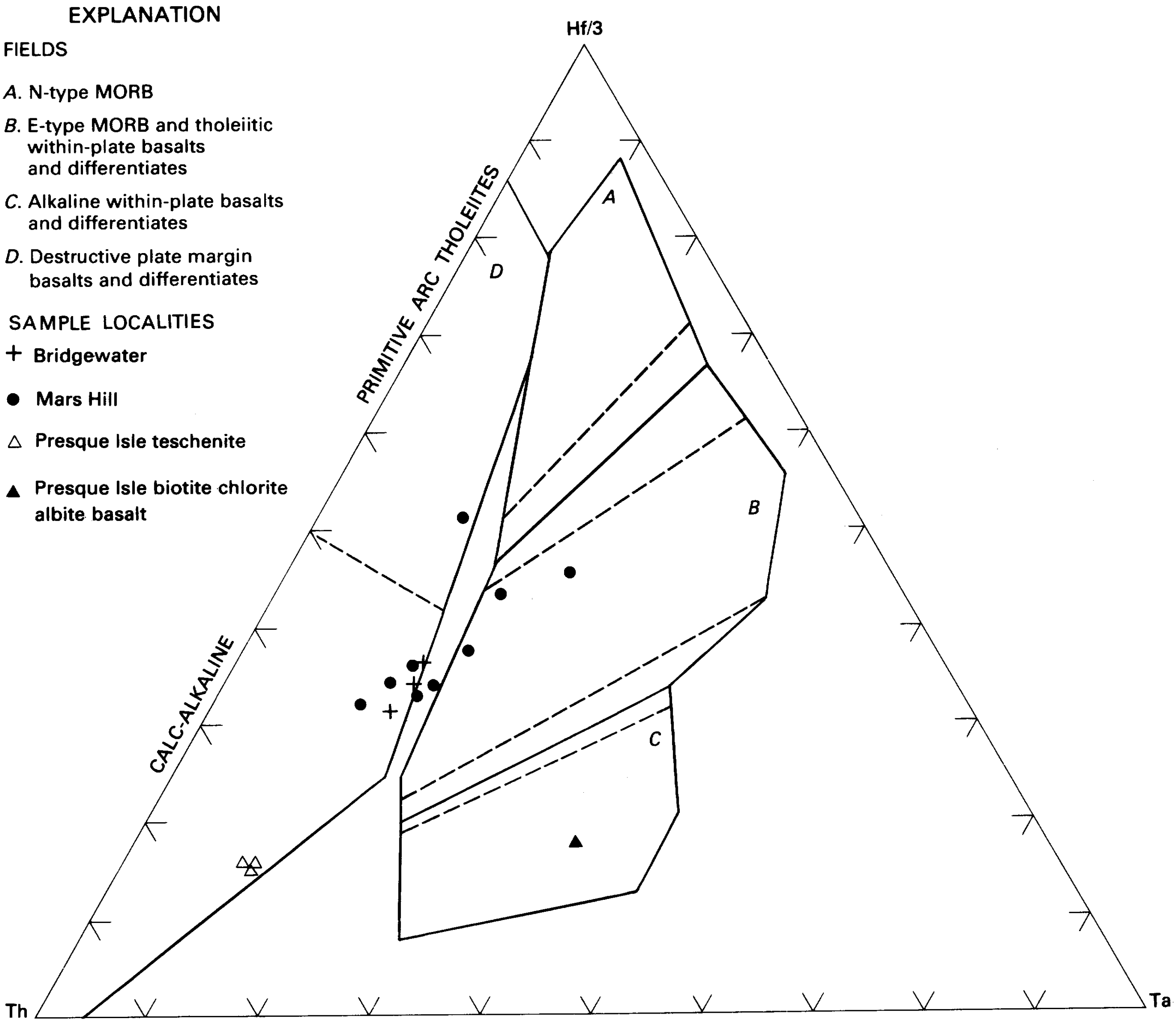


Figure 13. Samples of dike rocks from northeastern Maine plotted on the (Hf/3)-Th-Ta tectonomagnmatic discrimination diagram of Wood (1980). Dashed lines indicate areas of overlap.

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