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PALEOMAGNETIC EVIDENCE FOR A LATE TRIASSIC AGE FOR TRANSITIONAL THOLEIITIC TO ALKALIC DIABASE DIKES FROM CENTRAL RHODE ISLAND

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ABSTRACT. Post-metamorphic diabase dikes intrude Devonian granitoid rocks and metamorphosed Pennsylvanian strata of the Esmond-Dedham terrane in central Rhode Island. The dikes have a mineralogy and major- and trace-element chemistry typical of a transitional tholeiitic to alkalic suite compared to the tholeiitic diabases of the Early Jurassic Eastern North American suite. Based on trace-element discriminant diagrams, the dikes are considered to be within-plate diabases, an attribute they have in common with the Early Jurassic Holden tholeiite dikes in Massachusetts, which predate the breakup of Pangaea, as well as the Late Jurassic-Early Cretaceous Bliss Hill-Quabbin diabases that are much later. The Rhode Island, Holden, and Bliss Hill-Quabbin dikes have a distinctly different trace-element chemistry from the Pelham-Loudville and Ware diabases in central Massachusetts that were intruded just after breakup of Pangaea.

Detailed alternating-field and thermal demagnetization studies on eleven Rhode Island dikes (111 samples) show both normal and reversed stable paleomagnetic directions, D = 7.0°, I = 9.2°, a_{95} = 2.7°, N = 7, and D = 203.7°, I = −15.0°, a_{95} = 3.5°, N = 4, respectively. Peak unblocking temperatures and alternating field demagnetization studies indicate the predominant stable component is carried by titanomagnetite. The resultant paleopole, based on the primary magnetizations is 52.6°N, 88.4°E, a_{95} = 5.4°, N = 11, which plots east of the J1 cusp related to the breakup of Pangaea and slightly southward of the late Triassic-early Jurassic segment of the Apparent Polar Wander Path for North America. These results indicate that the Rhode Island dikes are Late Triassic.

INTRODUCTION

Although the age of the diabase intrusions in central Rhode Island has been assumed to be Mesozoic (Hermes and others, 1984), their age was not known prior to this study. In addition to obtaining information on the time of their intrusion, this study provides improved understanding of their tectonic setting and geochemistry, and comparison of this information with the more widespread Eastern North America (ENA) suite of Jurassic diabase intrusions, and the Cretaceous diabase intrusions in central Massachusetts.

The Rhode Island region has experienced little tectonic deformation since major orogenic events terminated in the late Paleozoic (O. Don Hermes, personal communication, 1991). All the diabases studied cut the Devonian-Carboniferous Scituate Igneous Suite which intrudes the Esmond-Dedham terrane of western Rhode Island, the related Spencer Hill Volcanic Suite, or metamorphosed Pennsylvanian strata at the west margin of the Narragansett basin (fig. 1). The country rocks yield

Permian post-metamorphic cooling ages in the range of 258 to 239 Ma (Dallmeyer, 1982) based on $^{39}Ar/^{40}Ar$ release spectra on a variety of minerals. In the Triassic-Jurassic, tensionally controlled basins with graben or half-graben structure developed along the east coast of North America. The Rhode Island dike suite lies between the Connecticut Valley graben to the west and offshore grabens to the east (Hermes and others, 1984).

The post-metamorphic diabase dikes of central Rhode Island have mineralogy and chemistry more typical of a transitional tholeiitic to alkalic suite unlike the tholeiitic diabases of the Jurassic Eastern North America (ENA) suite (Hermes and others, 1984; McEnroe and Hermes, 1991). Except for one sample with trivial normative quartz all are olivine-normative, and two are nepheline normative. In their study of the diabases throughout the ENA province, Weigand and Ragland (1970) reported olivine-normative tholeiitic diabases predominating south of Maryland and quartz-normative types predominating farther north. They did not characterize any of the diabases in or northeast of Rhode Island, thus omitting the olivine-normative dikes of Rhode Island, New Hampshire, and Maine studied by Pierce (ms), Hermes and others (1984), and McHone and Trygstad (1982) from their compilation. Olivine-normative diabases are far more common in the mid-Atlantic states than in any other part of the circum-Atlantic margin (Whittington, ms). Hermes and others (1984) reported a range of compositions in southeastern New England, including nepheline-normative, olivine/hypersthene-normative, and quartz-normative varieties. Though the Rhode Island dikes are a subset of the broader group of southeastern New England dikes and are located in a small geographic area, the complete range of compositions is present. Ragland and Whittington (1983) retain the nepheline-normative diabases of southeastern New England as a distinct type of olivine diabase. These nepheline-normative diabases are not observed in North Carolina, where most of the olivine-normative diabases of the ENA province occur. McHone (1992) characterized the Rhode Island dikes reported by Hermes and others (1984) as a southern extension of his Coastal New England (CNE) province.

Both the tholeiitic and the transitional tholeiitic to alkalic suites are compatible with a rift-tectonic setting, but, as Hermes and others (1984) noted, the more alkalic diabases may represent a deeper source for small volumes of melt compared to the ENA tholeiitic suite. This is also shown by McHone (1992), who plotted analyses of the two suites on a diopside-forsterite-silica projection (Elthon, 1983). Compared to the ENA suites, the Rhode Island diabases represent more alkaline compositions that may be more typical of off-flank melts as opposed to the less alkalic varieties which would occur in a central rift axis (Hermes and others, 1984). Alternatively the dikes could be related to early attenuation of the continental crust prior to or at the onset of rifting as McHone (1992) has suggested for the CNE igneous province.

Originally, the author sampled the Rhode Island diabases for a paleomagnetic study because of their possible geochemical similarity to the late Jurassic-Cretaceous diabases in Massachusetts (McEnroe, 1989) which differ in chemical signature from the earlier Jurassic diabases. Cretaceous magmatic activity in New England was associated with a hot spot (Foland and Allen, 1991), whereas the early Mesozoic rifting and subsequent generation of tholeiitic flows and dikes were related to the breakup of Pangea. It was hoped that the resulting paleomagnetic data would provide information on the age of emplacement of the Rhode Island dikes and their plate-tectonic setting in relation to the various igneous melts generated during the breakup of Pangaea and add to our understanding of plate motions in the Mesozoic.

SAMPLE COLLECTION

Samples were collected for paleomagnetic, geochemical, and petrographic work. Most were collected in the field with a portable gasoline-powered rock drill that produced 2.4 cm diameter cores. Six to twenty samples were drilled per site. Cores were oriented in situ using a magnetic Brunton compass and, whenever possible, a solar compass. Oriented blocks were collected from sites where it was difficult to drill. Cores were drilled from the blocks at the University of Massachusetts Paleomagnetic Laboratory and oriented using a non-magnetic orienting device and clinometer. Sample site localities are shown on figure 1. All the Rhode Island dikes and sills were collected in road cuts along major highways in central Rhode Island. The diabase locations, attitudes and thicknesses where measured, and their host rocks are listed in the app. 1.

PETROGRAPHY

Thin sections and polished cores from each dike were examined to characterize the phases present, textural relationships, and the nature and amount of alteration, particularly of the opaque minerals. Major-element chemistry shows these dikes range from barely quartz-normative tholeiites (5-3) through olivine tholeiites (1, 5-1, 5-2, 6-5, 6-7, 8) to alkali olivine basalts (3, 7-2), a compositional range reflected in their petrography. The one quartz tholeiite is olivine-bearing. All contain primary mineral assemblages and primary igneous textures ranging from ophitic and subophitic to intergranular.

The olivine tholeiite dikes commonly contain phenocrysts of plagioclase $An_{70\text{-}62}$ (normative), augite zoned from tan to pink, and altered olivine $Fo_{85\text{-}76}$. The matrix consists of plagioclase, pyroxene, magnetite, ilmenite, and common accessory minerals, including red-brown biotite, hornblende, pyrite, chalcopyrite, chrome spinel, apatite and secondary Fe-chlorite, and calcite. Amygdules filled with secondary sheet silicates and/or calcite are ubiquitous and may indicate a shallow level of intrusion. Locally the plagioclase phenocrysts are sericitized, though the matrix plagioclase is unaltered. The pyroxenes generally are unaltered, but the olivine is partially altered to a sheet silicate.

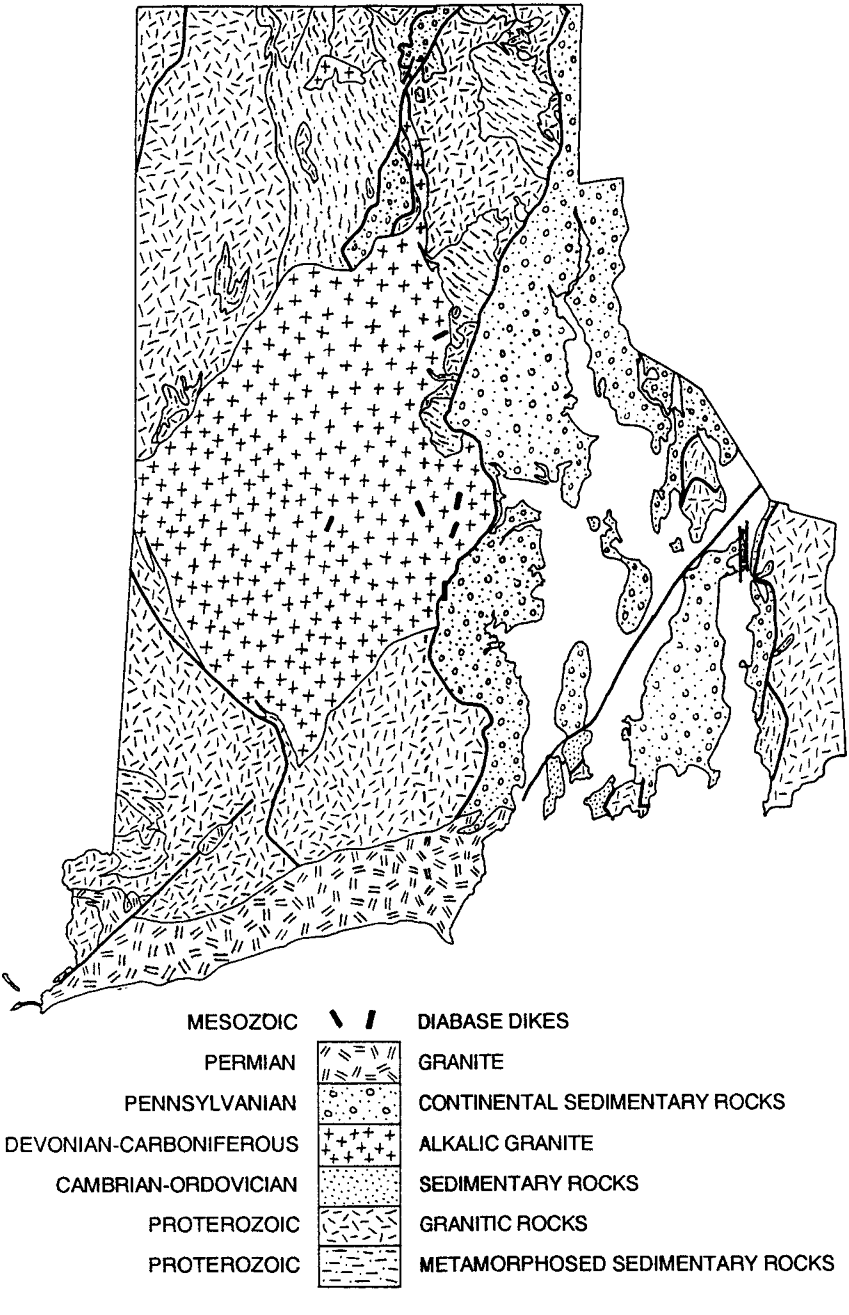


Fig. 1. Bedrock geologic map of Rhode Island showing Mesozoic dike localities in central Rhode Island. From Hermes and others, in press.

The alkalic dikes contain only phenocrysts of olivine and Ti-rich augite. The matrix is composed of olivine, Ti-rich augite, plagioclase, kaersutite, magnetite, ilmenite, pyrite, and chrome spinel. At locality 2 olivine is the only phenocryst mineral, and the matrix consists of olivine, Ti-rich augite, plagioclase, and abundant fine-grained magnetite and ilmenite.

Quartz-orthoclase micropegmatite is absent in all these diabases, contrasting with the common association of orthopyroxene, augite, plagioclase, and micropegmatite found in the Earliest Jurassic ENA diabases in New England (Philpotts and Martello, 1986; McEnroe, 1989).

MAGNETIC MINERALOGY

Polished cores of at least one sample per site were examined for opaque minerals using reflected-light oil-immersion microscopy. The classification system of Haggerty (1976) was used to describe the oxidation state of magnetite (C1-C7) and of ilmenite (R1-R7). Titanomagnetite is the primary remanence carrier and occurs in various degrees of oxidation (C1-C3), morphology, grain size, and alteration.

Numerous skeletal-growth morphologies of magnetite with a progressive trend toward cruciform type euhedral grains are present (fig. 2). These are all homogeneous, lacking ilmenite lamellae (C1), and range in size from ~0.01 mm to 0.05 mm. The lack of ilmenite oxidation-exsolution lamellae may be due to a kinetic factor, because these C1 grains are only present in chilled samples. Alternatively, high contents of MgO or Al_2O_3 may stabilize the titanomagnetite solid-solution under conditions where a normal solid-solution would undergo oxidation-exsolution of ilmenite in titanomagnetite (Haggerty, 1976). Scanning electron microscopy with energy-dispersive analyses from sample 8-2 (McEnroe, 1993) indicates that the magnetites have a small component of Al spinel, from 3 to 5.5 percent, and a large range in ulvöspinel component, from 17 to 68 percent. The Al_2O_3 content may have retarded the oxidation-exsolution in this sample.

Euhedral to subhedral titanomagnetite grains are generally in the range of C1 to C2. In C2 grains ilmenite lamellae are present in trellis and sandwich type. In samples from some of the reversely magnetized dikes, the titanomagnetites exhibit primary parquet-texture intergrowths. These are the result of exsolution of ulvöspinel at high temperatures, producing a fine intergrowth of ulvöspinel and titanomagnetite. Subsequently the ulvöspinel was oxidized to ilmenite, which produced a patchy anisotropic texture. At a later time, the titanomagnetite component was altered to titanomaghemite. This series of reactions has produced a highly stable magnetic component due to fine intergrowths formed by the exsolution and the subsequent alteration to titanomaghemite.

Homogeneous unoxidized ilmenite grains (R1) are present as skeletal crystals in chilled samples and as discrete grains. In samples from the interiors of several of the magnetically reversed dikes, discrete ilmenite

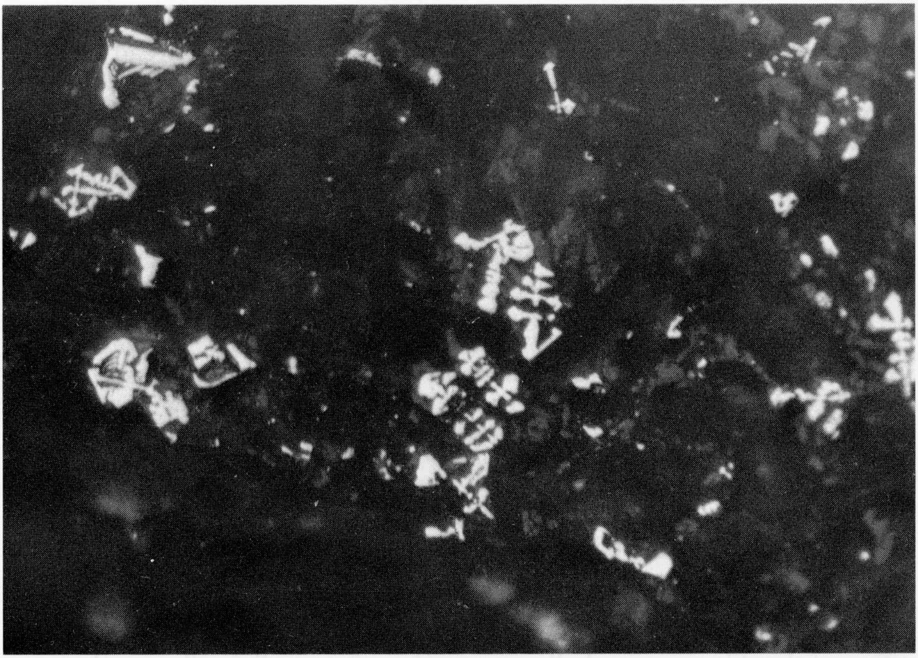


Fig. 2. Reflected-light photomicrograph from site 1. Shown are C1-C2 titanomagnetites in herring bone and cruciform morphologies. Photographed in oil immersion and using a blue filter. Width of field of view is 0.34 mm.

with exsolution lamellae of hematite is present. The intergrowths along the (0001) plane between hematite and ilmenite would have formed below 650°C, the critical temperature of the solid solution series according to Burton (1991). The ilmenites observed here contain minor amounts of Al^{3+} and Mn^{2+}, up to 0.061 and 0.094 per formula unit respectively (McEnroe, 1993).

In some olivine-phenocrysts, minor amounts of fine-grained magnetite were produced from olivine either by oxidation or during the later alteration of olivine to sheet silicates. The magnetite produced as a product of such reaction is very fine grained and may approach pseudo-single-domain size, which would result in an exceedingly stable remanence. At the level of detection of the microscope, no exsolution lamellae of ilmenite were observed in these magnetites. The assumption is that Ti was not available as a component for the olivine reactions that produced this magnetite.

Minor amounts of pyrite are present in all samples and vary in texture from droplets and filigree to euhedral crystals. Chalcopyrite is present in trace amounts. Chrome spinel is present and usually rimmed by titanomagnetite.

GEOCHEMISTRY

Two of the diabase dikes sampled in this study had already been characterized geochemically (Hermes and others, 1984). An additional seven samples were analyzed by XRF for major and trace elements at the Department of Geology, University of Rhode Island, or at the University of Massachusetts, Amherst, thus permitting detailed comparisons of the Rhode Island dikes with the Eastern North American (ENA) diabase suite. Approx 20 to 50 g of material were coarse-crushed in a steel percussion mortar. This was followed by grinding in a tungsten carbide shatterbox. Aliquants of powder sampled for X-ray fluorescence analysis (XRF) were prepared following a modification of the methods of Norrish and Chappell (1967) and Norrish and Hutton (1969). Samples were prepared in duplicate. Major elements were analyzed using fused glass disks. At Rhode Island, trace elements were analyzed using unpressed powders, a Compton scattering method, and a primary rhodium tube with secondary targets for three separate groups of trace elements. At Massachusetts trace elements were analyzed using pressed powder pellets and gold and molybdenum tubes.

The results show that the post-metamorphic dikes in central Rhode Island range in composition from tholeiitic to alkalic (table 1). The dike rocks straddle the boundary separating alkali basalts from tholeiitic basalts on the alkali versus silica plot of MacDonald and Katsura (1964). Two of the dikes are nepheline-normative, six are olivine/hypersthene-normative, and one is barely quartz-normative. These samples are more enriched in alkalis than the ENA suite. One nepheline-normative dike (loc. 3) contains Ti-rich augites with greater than 3 wt percent TiO_2 (Hermes and others, 1984). High TiO_2 contents ranging from 1.8 to 2.2 wt percent are characteristic of these rocks, placing them higher than any member of the ENA suite, even the high Fe-TiO_2 group. In a plot of $\Sigma Fe/(\Sigma Fe + MgO)$ versus TiO_2 (fig. 3) these diabases plot clearly away from the three groups of ENA diabases. Compared to the ENA diabases in New England, these are lower in SiO_2, CaO, and higher in Al_2O_3, Na_2O, K_2O, TiO_2, P_2O_5, Nb, Ni, Sr, Ba, and Zr. The magnesium value, from 49 to 62, is, on average, higher than the ENA suite in New England.

The separation of the Rhode Island diabases from the ENA diabases is also noted on plots of Y versus Sr (fig. 4A) with strong enrichment of Sr shown by the Rhode Island diabases. On a Zr versus Nb plot (fig. 4B) the Rhode Island diabases plot distinctly away from the Massachusetts ENA diabases with significantly higher Nb contents and enriched to overlapping Zr concentrations. In addition, amongst the Rhode Island samples there appears to be a difference in geochemistry between the normal and reversed polarity diabases. The normal polarity dikes have lower Nb, Zr, Y, Rb, and Ce than the reversed dikes. Hermes and others (1984) found that the distinctions in both major and trace elements imply that there is no simple petrogenetic relationship between the Rhode Island diabases and the ENA diabases. The additional analyses reported here support this interpretation.

TABLE 1

Major- and trace-element analyses and CIPW norms of the Rhode Island diabases. O. D. Hermes, analyst at University of Rhode Island, except sample 8, S. A. McEnroe, analyst at University of Massachusetts

Polarity Sample	N 1*	N 3*	R 5-1	N 5-2	N 5-3	R 6-5	R 6-7	R 7-2	R 8
SiO_2	48.69	45.90	50.34	48.16	51.69	48.55	49.77	49.21	49.41
TiO_2	2.03	1.97	2.20	1.81	2.00	1.98	2.20	1.99	2.24
Al_2O_3	14.91	14.6	16.32	14.53	14.55	14.65	15.94	16.29	15.83
Fe_2O_3#	9.59	12.11	11.59	13.17	11.52	13.63	12.38	12.15	12.30
MnO	0.18	0.23	0.18	0.17	0.16	0.18	0.17	0.17	0.21
MgO	7.41	10.02	6.19	10.03	8.39	8.85	6.36	5.88	6.58
CaO	7.82	8.67	9.14	8.60	8.06	8.60	9.11	9.12	9.3
Na_2O	2.94	2.36	2.60	2.26	2.63	2.34	3.37	3.36	2.66
K_2O	0.71	1.98	1.49	1.04	0.82	1.20	1.19	1.68	1.39
P_2O_5	0.29	-	0.41	0.31	0.24	0.28	0.39	0.34	0.42
Total	94.57	97.84	100.46	100.08	100.06	100.26	100.88	100.19	100.34
Trace elements (ppm)									
Rb	-	-	33.2	30.8	28.4	49.9	52.2	72.1	32.4
Sr	-	-	454.7	349.1	387.6	319.9	459.3	454.7	454.1
Y	-	-	24.7	22.6	21.1	35.3	25.2	23.7	25.8
Zr	-	-	180.3	122.8	114.3	145.5	172.2	145.5	177.0
Nb	-	-	28.1	17.5	14.5	21.6	24.3	21.3	26.0
Ba	-	-	306.4	184.4	165.7	178.6	245.9	262.0	295.5
La	-	-	28.5	19.0	26.9	33.1	28.9	24.0	24.4
Ce	-	-	47.0	35.1	40.9	51.7	48.1	41.6	50.6
Cu	-	-	40.5	50.8	32.3	50.4	46.7	34.8	42.2
Zn	-	-	76.9	57.3	71.4	103.5	82.6	88.9	70.6
Ni	-	-	72.9	259.7	211.4	227.7	95.4	91.8	88.6
CIPW norms (10% of ΣFe as Fe_2O_3)									
Q					0.08				
or	4.20	11.70	8.81	6.15	4.85	7.09	7.03	9.93	8.21
ab	24.88	13.38	22.00	19.12	22.25	19.80	28.52	25.41	22.51
an	25.39	23.40	28.46	26.43	25.47	25.93	24.85	24.41	27.15
ne		3.57						1.64	
di	9.39	16.00	11.74	11.63	10.60	12.26	14.73	15.45	13.43
hy	21.82		17.47	12.78	30.79	13.18	2.67		11.67
ol	2.98	24.29	5.18	17.90		15.62	16.20	17.02	10.36
mt	1.39	1.75	1.68	1.91	1.67	1.97	1.80	1.77	1.78
il	3.86	3.74	4.18	3.44	3.80	3.76	4.18	3.78	4.25
ap	0.69		0.95	0.72	0.57	0.65	0.90	0.79	0.97
plag an	51	64	56	58	53	57	47	49	55

*analyses reported by Hermes and others (1984), not plotted on figures 3 to 6.
#ΣFe analyses as Fe_2O_3.
-not analyzed.

DISCRIMINANT DIAGRAMS

Discriminant diagrams for the assignment of tectonic settings of basaltic rocks were developed by Pearce and Cann (1971, 1973) based on Sr, Ti, Zr, Y, and Nb. Ti, Zr, and Y were used as discriminators for

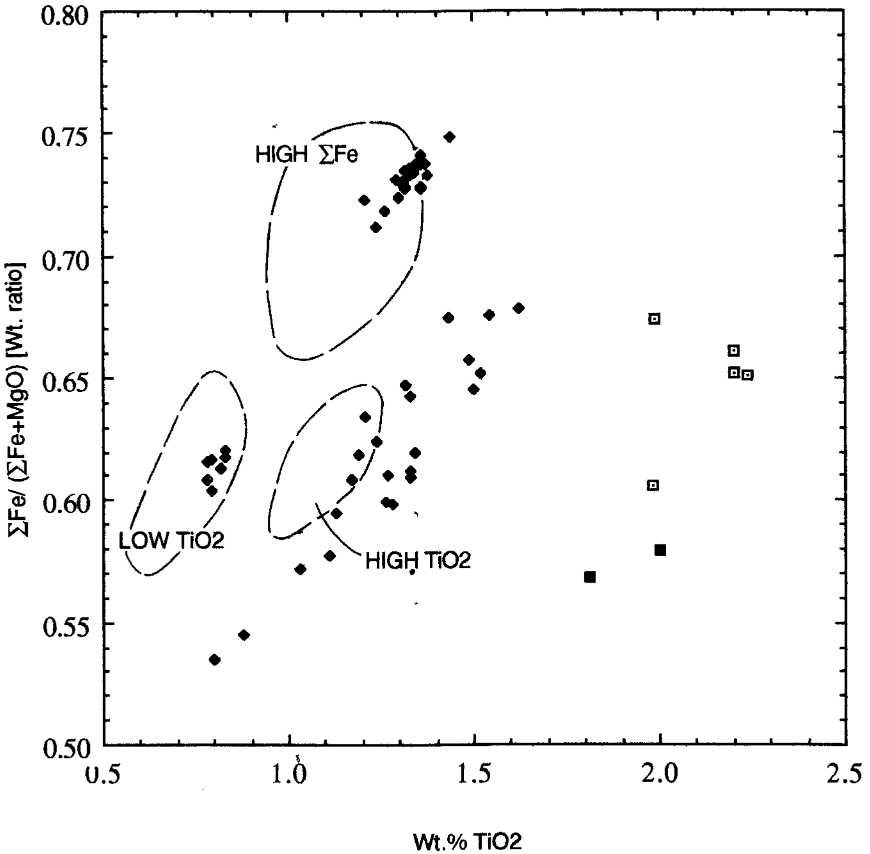


Fig. 3. Diagram of wt ratio $\Sigma Fe/(\Sigma Fe + MgO)$ versus wt percent TiO_2 for diabase analyses where $\Sigma Fe = Fe_2O_3$. Dashed lines indicate fields of low TiO_2, high TiO_2, and high ΣFe quartz-normative diabases as defined by Weigand and Ragland (1970). Rhode Island-reversed polarity samples are plotted as open squares, and normal-polarity samples as closed squares. Also shown are the Massachusetts diabase analyses (McEnroe, 1989) as closed diamonds.

tectonic fields of ocean floor basalts and low-K tholeiites, calc-alkaline basalts, and within-plate basalts. Pearce and Norry (1979) used Zr and Y as discriminants for tectonic settings for basaltic rocks shown in figure 5, with fields of mid-ocean ridge basalts (MORB), island arc basalts, and within-plate basalts. Superimposed on this is the boundary between continental arc basalts and oceanic arcs after Pearce (1983). Only the Holden, the oldest of the New England ENA diabases, plots in the within-plate field (McEnroe, 1989), in good agreement with paleomagnetic data (McEnroe, 1989) indicating they were intruded prior to the Early Jurassic J1-cusp and hence before plate-reorientation and break-up of the supercontinent Pangaea at around 200 Ma. The Rhode Island samples also plot as within-plate basalts in figure 5, as do the late Jurassic-early Cretaceous Bliss Hill and Quabbin dikes that post-date breakup.

Meschede (1986) used the immobile trace elements Nb, Zr, and Y to discriminate between N-type MORB's, P-type MORB's, within-plate tholeiites, and within-plate alkali basalts (fig. 6). Using these parameters only the oldest of the New England ENA diabases plot in the within-plate tholeiite field (McEnroe, 1989). This is in good agreement with their pre-cusp paleomagnetic pole position. The Rhode Island diabases as well as the Bliss Hill and Quabbin diabases plot in the fields of within-plate alkali basalts and tholeiites and within-plate alkali basalts, whereas none of the ENA diabases plots in these regions. Thus, on a geochemical basis the Rhode Island samples can be designated as within-plate basalts, but there is no geochemical basis to tell whether they were intruded in a within-plate location before the breakup of Pangaea, or a within-plate location long after breakup, for example in the Cretaceous.

PALEOMAGNETISM

Natural remanent magnetization.—The natural remanent magnetization (NRM) was measured on each sample using a Molspin Minispin spinner magnetometer at the University of Massachusetts Paleomagnetics Laboratory or at the Paleomagnetic Laboratory at the Norwegian Geological Survey (NGU) in a shielded area with an ambient magnetic field of less than 10 nT. The natural remanent directions show considerable scatter and are of normal and reversed polarity. The NRM intensities ranged from 0.3 to 4.0 A/m.

Alternating field (AF) demagnetization.—Two samples per site were progressively stepwise demagnetized in an alternating field (AF) in nine steps up to a peak field of 90 mT on a Schoenstedt GSD-1 AF Geophysical Specimen demagnetizer at the University of Massachusetts Paleomagnetism Laboratory or the tumbling AF demagnetizer at the NGU. Remaining samples were step demagnetized at fewer intervals with the peak field depending on the coercivity of the specimens. Under AF demagnetizations different dikes showed different coercivities. Demagnetization results were plotted in orthogonal vector-end-point diagrams (Zijderveld, 1967) for visual inspection of the primary direction and of any secondary overprints, and directions for the components of magnetization were calculated using standard paleomagnetic techniques. Stability spectra were analyzed using the Spectrum program of Smethurst (ms).

The mean destructive field ranged from 10 to 50 mT. Variability in coercivity among samples was usually a function of the grain size of the magnetic minerals, with finer-grained material having a higher coercivity.

In the normal polarity samples, progressive alternating field demagnetization usually showed the presence of two components of magnetization (fig. 7A). A soft component was easily removed at low fields up to 10

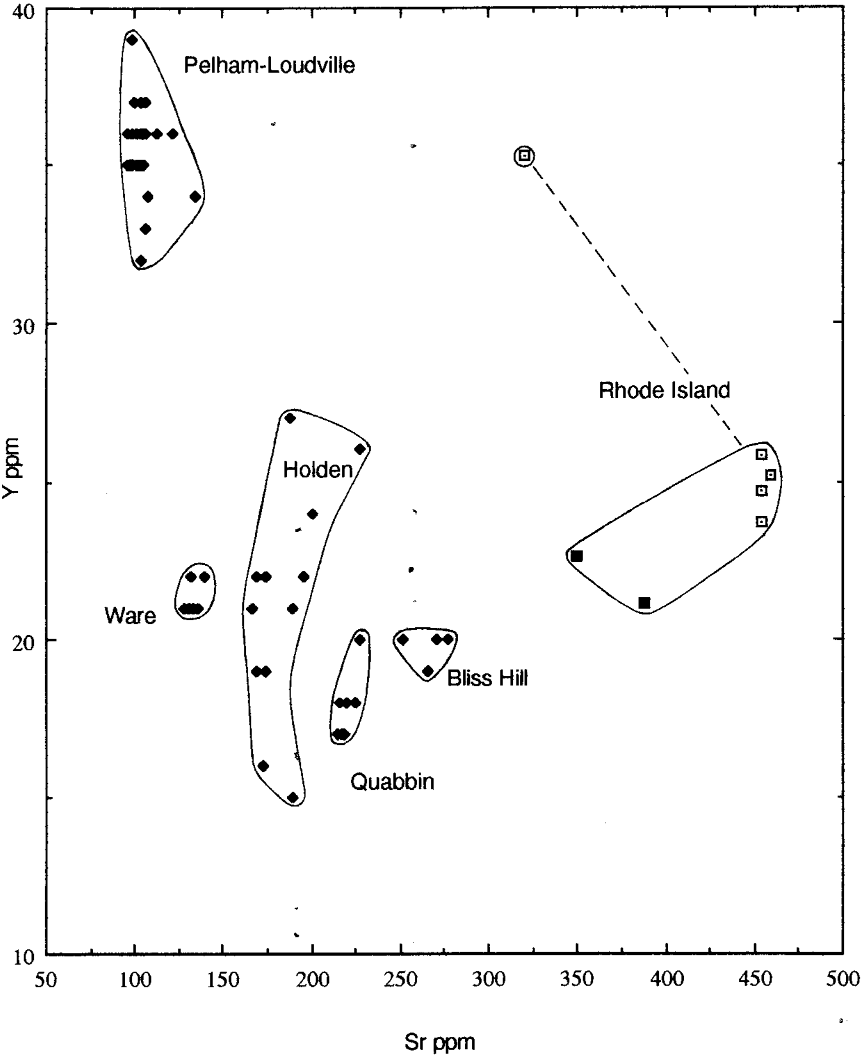
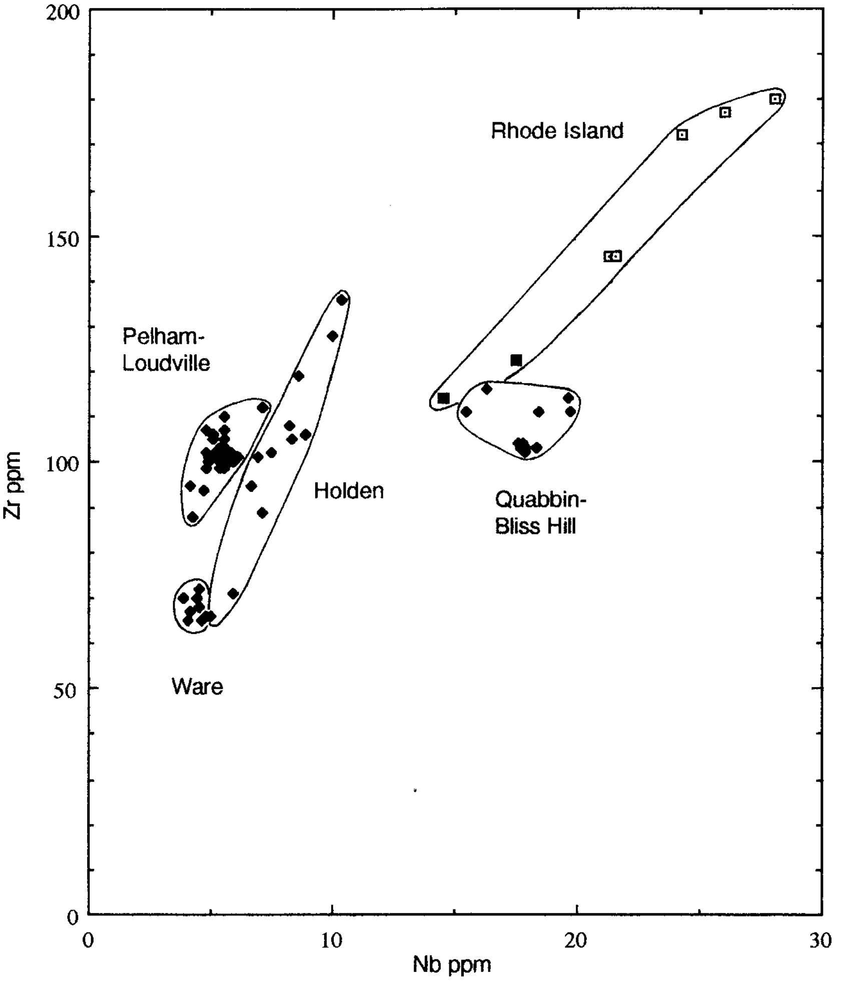


Fig. 4(A) Plot of Y ppm versus Sr ppm. Rhode Island reversed-polarity samples are plotted as open squares and normal-polarity samples as closed squares. Also shown are the central Massachusetts diabase analyses (McEnroe, 1989) as closed diamonds. Fields for the Holden, Pelham-Loudville, Ware, Quabbin, Bliss Hill, and Rhode Island diabases are indicated.

mT. In some samples a secondary higher coercivity component up to 50 mT was present. This component may be due to post-solidification alteration. In all cases above 50 mT a stable higher coercivity component was well isolated. The majority of these samples revealed a characteristic



(B) Plot of Zr ppm versus Nb ppm. Rhode Island reversed-polarity samples are plotted as open squares and normal-polarity samples as closed squares. Also shown are the Massachusetts diabase analyses (McEnroe, 1989) as closed diamonds. Fields for the Holden, Pelham-Loudville, Ware, Quabbin-Bliss Hill, and Rhode Island diabases are indicated.

remanent magnetization dominantly of a north to northeast and shallow to intermediate down direction. The variations in coercivities as shown on the stability diagrams (fig. 8, 5-3-2 and 5-4-1) indicate variations in grain size and textures of the predominant magnetic carrier, titanomagnetite, verifying petrographic observations.

In the reversed polarity samples (fig. 7B) progressive alternating field demagnetization also indicated the presence of two or three components of magnetization. A variety of low coercivity normal components

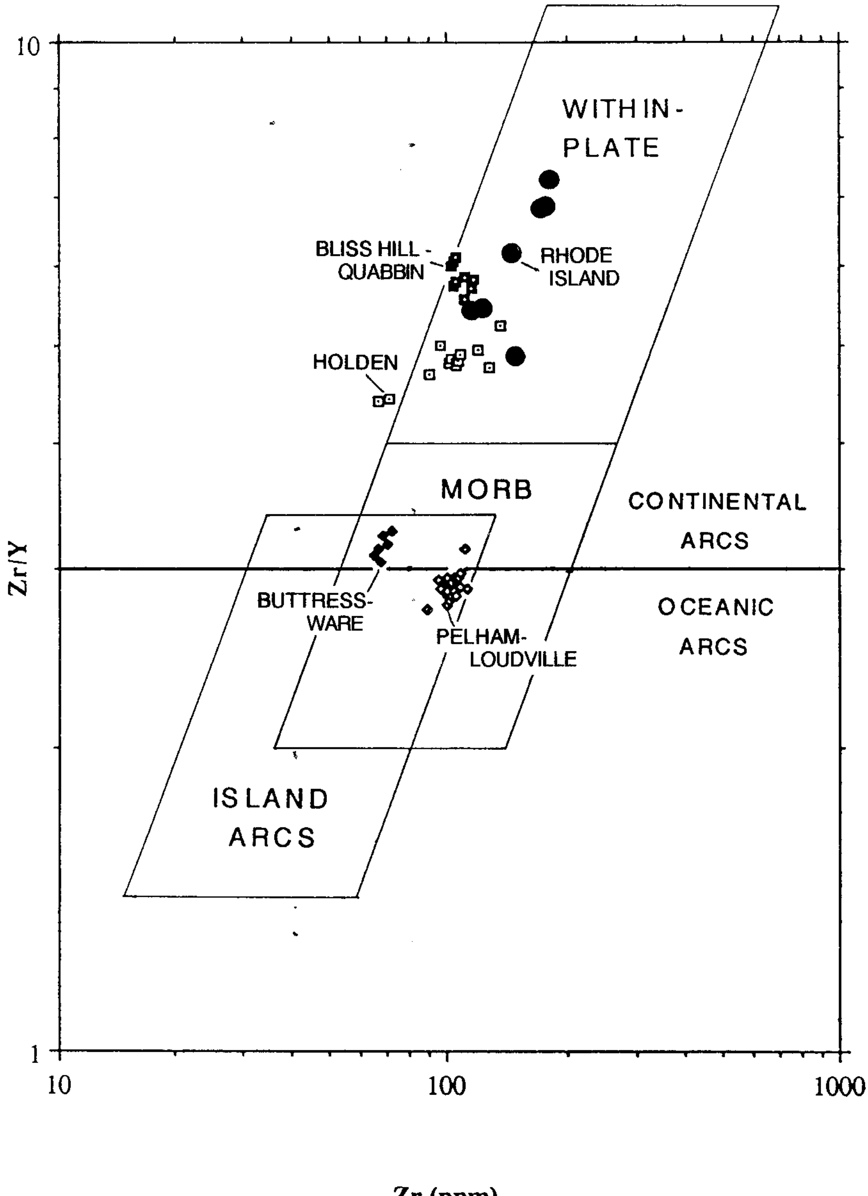


Fig. 5. Discriminant diagram of Zr/Y versus Zr ppm after Pearce and Norry (1979) modified by Pearce (1983). Heavy horizontal line is the separation of continental arc basalts from oceanic arc basalts. Rhode Island diabases are compared to Massachusetts diabases from McEnroe (1989). Symbols: Rhode Island—closed circles; Massachusetts Holden diabases—open squares; Pelham-Loudville—open diamonds; Ware—closed diamonds; Bliss Hill and Quabbin diabases—darker squares.

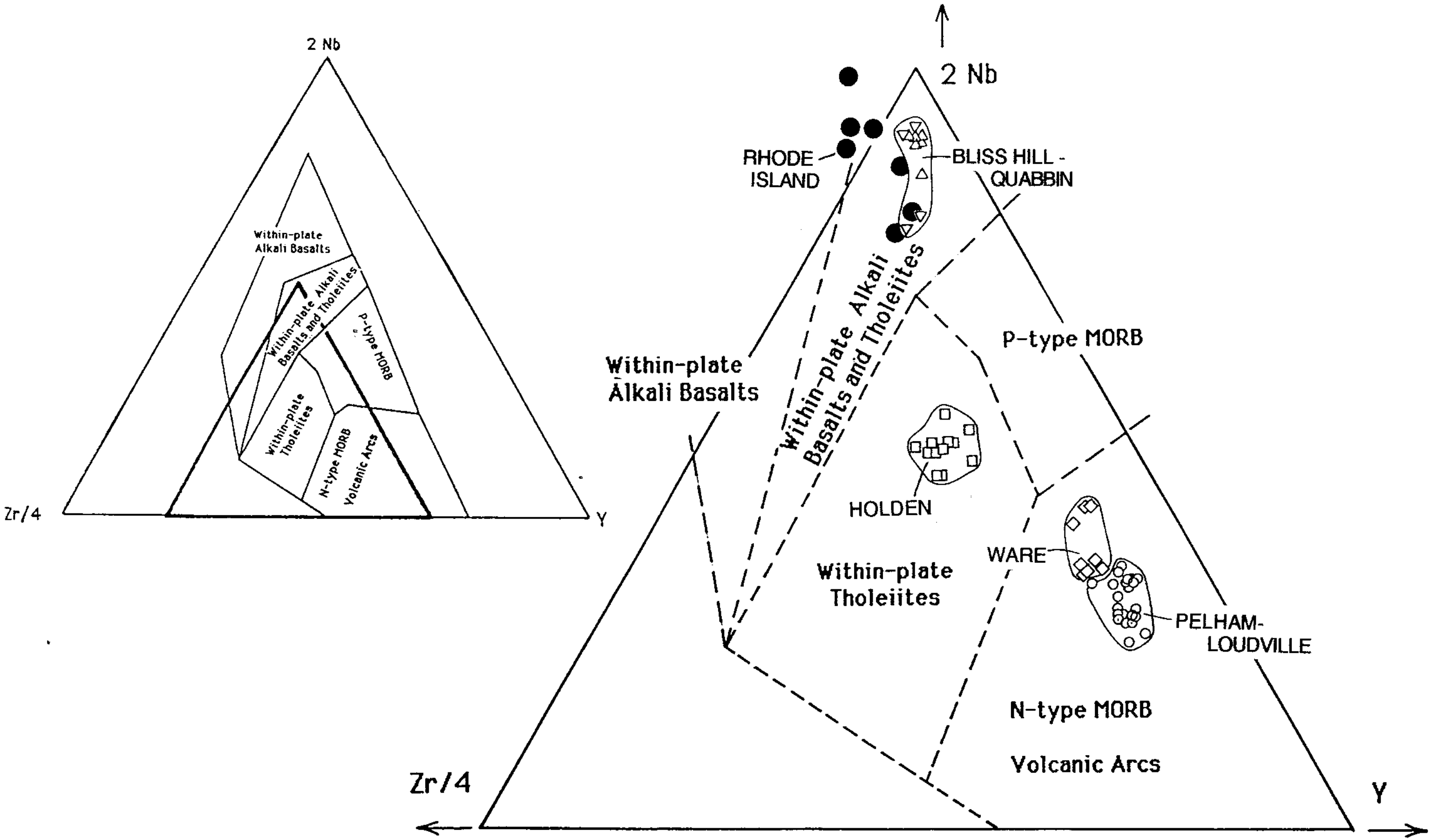


Fig. 6. Discriminant diagram for the trace elements Nb, Zr, and Y (after Meschede, 1986) indicating tectonic settings for tholeiites and all types of within-plate basalts. All diabases are plotted in the area of the enlarged inset. Symbols: Rhode Island—closed circles; Massachusetts Holden diabases—open squares; Pelham-Loudville—open diamonds; Ware—open diamonds; Bliss Hill and Quabbin diabases—open triangles.

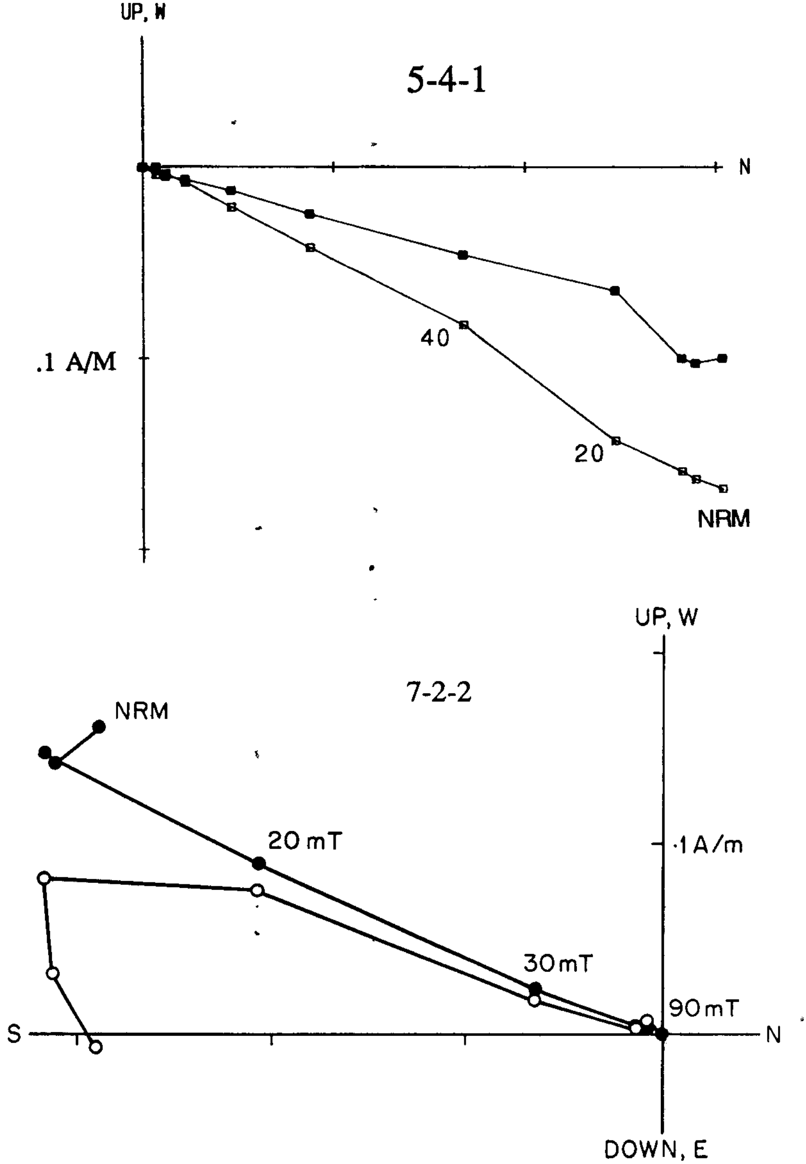


Fig. 7. Vector-end-point diagrams for selected samples of Rhode Island diabase of reversed and normal polarity under alternating field demagnetization. W = west, E = east, S = south, and N = north. Closed circles = horizontal component. Open circles = vertical component. Numbers adjacent to circles = alternating field level in milli-Teslas.

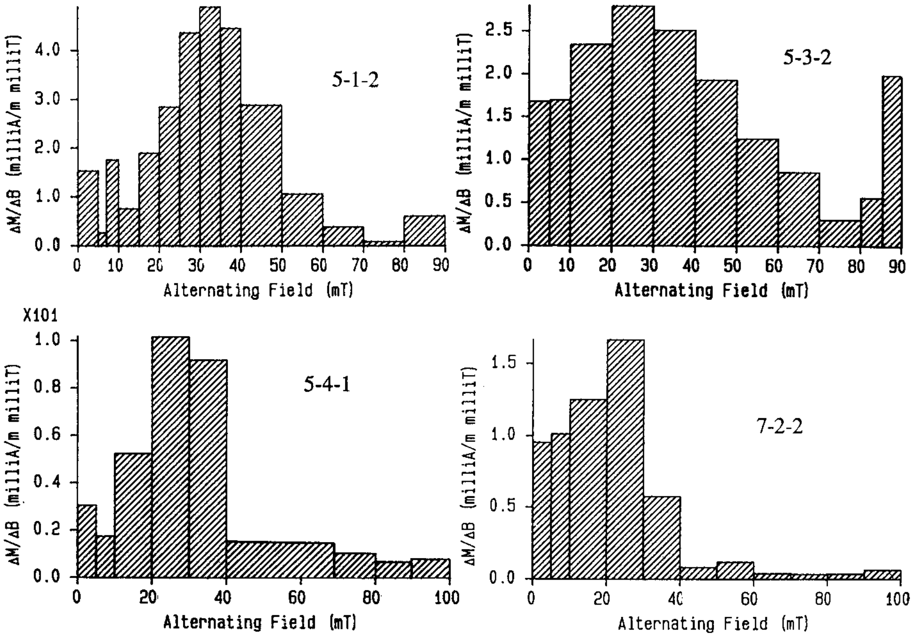


Fig. 8. Magnetic stability diagrams for representative samples from Rhode Island diabases of reversed polarity under alternating field demagnetization. $\Delta M/\Delta B$ is the change in magnetic moment/change in applied field in milli-amps per milli-Tesla.

with a west or northeast and down direction were easily removed at low fields up to 20 mT. The stable higher coercivity component was usually well isolated above 20 mT. The majority of these samples revealed a characteristic remanent magnetization of dominantly south to southwest and shallow up directions, though with slightly steeper inclinations than the normal polarity samples. The variations in coercivities as shown by the stability diagrams (fig. 8, 5-1-2 and 7-2-2) indicate variations in grain size and textures of the magnetic carriers, titanomagnetite, titanomaghemite, and fine-grained skeletal magnetites. The titanomaghemite and the fine-grained skeletal magnetites produced by the olivine probably contribute to the high-coercivity component.

Thermal step demagnetization.—For stepwise thermal demagnetization, specimens were heated in a noninductively wound shielded furnace with an accuracy of ±5°C and then cooled in a field-free chamber, at the Paleomagnetism Laboratory at Norwegian Geological Survey. Samples were thermally demagnetized up to 585°C, with remanent magnetizations measured after each step. Alternating field and thermal demagnetization data were compared for any variation in the resultant data as a function of the different demagnetization processes, mineralogy, or later chemical remanent magnetization.

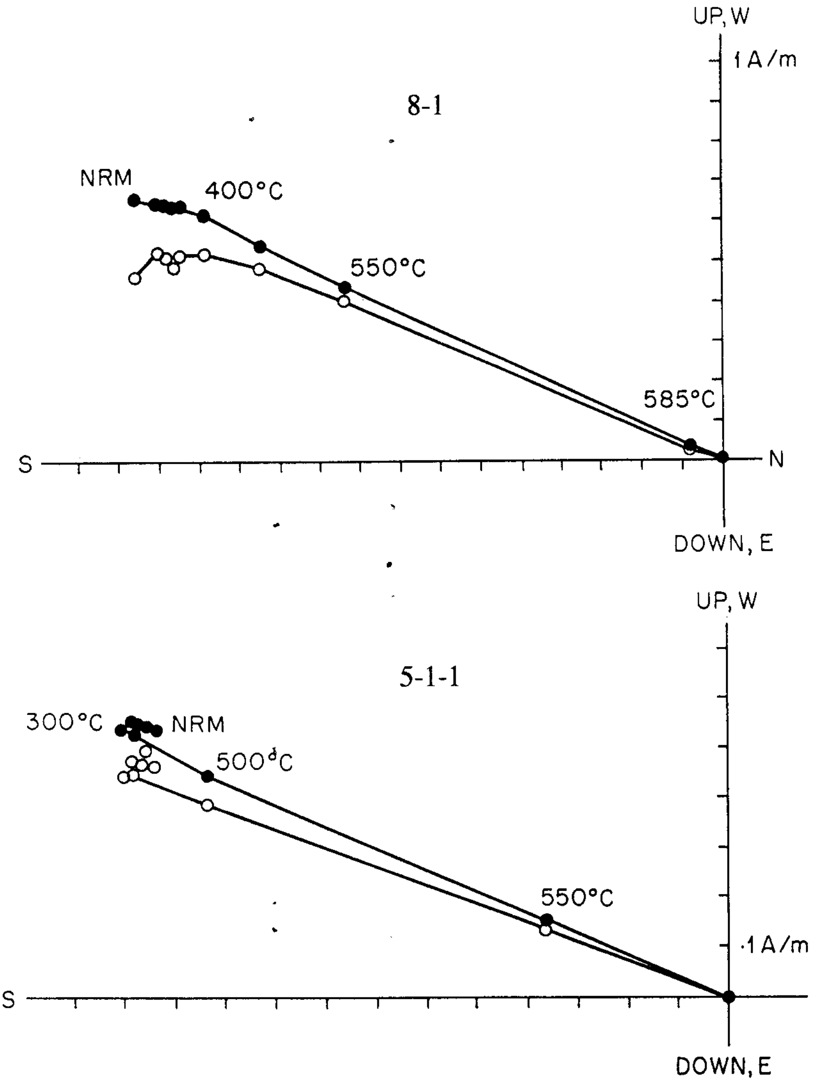


Fig. 9. Vector-end-point diagrams for selected samples from Rhode Island diabases of reversed polarity under thermal demagnetization. W = west, E = east, S = south, and N = north. Closed circles = horizontal component. Open circles = vertical component. Numbers adjacent to circles = temperature in °C.

Figure 9 shows two representative thermal demagnetization diagrams both from reversed polarity sites. The majority of samples revealed minor overprints that were removed at low temperature. Above 500°C a dominantly south to southwest and shallow up remanent direction was well isolated. Characteristic magnetizations displayed discrete unblocking temperature intervals generally between 500° and 585°C.

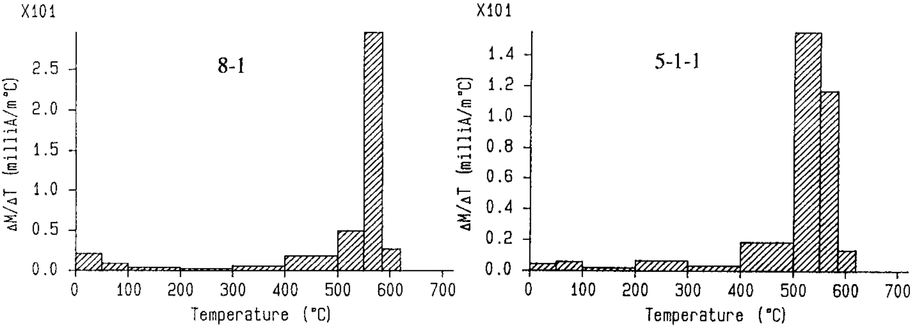


Fig. 10. Magnetic stability diagrams for representative samples from Rhode Island under thermal demagnetization. $\Delta M/\Delta T$ is the change in magnetic moment/change in temperature in milli-amps per °C.

These unblocking temperatures are consistent with a magnetite component of $Usp_{20\text{-}0}$. As shown on the stability diagrams (fig. 10) a small remanence persisted above 585°C, the unblocking temperature of pure magnetite. This component is less than 4 percent of the original magnetization and may be due to titanomaghemite and hematite lamellae in the ilmenites present in some samples. The remanent magnetization directions obtained from thermal demagnetization studies are consistent with those from the alternating field decay procedures.

Magnetic site directions.—Table 2 contains a summary of the mean magnetic directions and statistical parameters determined for the eleven sites. Fisher statistics (Fisher, 1953) were applied to the data to obtain site mean directions at the 95 percent confidence level. The normal and reversed directions are not exactly antipodal (see below) and are distinguishable at the 95 percent confidence level. The mean directions of the normal and reversed polarity sites are D = 7.0°, I = 9.2°, a_{95} = 2.7°, and D = 203.7°, I = −15.0°, a_{95} = 3.5°, respectively. The overall mean directions for the normal and reversed dikes would not change appreciably even if the excluded samples were used in the mean calculation. After inverting the reversed data a combined direction was calculated of D = 13.4°, I = 11.5°, a_{95} = 5.4°. The mean study paleoinclination yielded a paleolatitude of 5.8°. It should be noted that the normal and reversed data form two well clustered groups having small a_{95}'s for both within and between sites calculations. The smaller a_{95}'s for the separate normal and reversed data sets as compared to the overall mean may indicate that paleosecular variation was not completely averaged out.

The in-situ remanent magnetic directions determined for the samples from the eleven sites are plotted on an equal-area diagram in figure 11. The within-site dispersion is minor, and the between-site scatter is low in each polarity group. The reversed and normal directions are not antipodal at the 95 percent confidence level (McFadden and Lowes, 1981) as graphically shown in figure 12. The lack of complete antipodality might be explained in three ways:

TABLE 2

Summary of paleomagnetic site mean directions and virtual geomagnetic poles with statistical parameters of the Rhode Island diabases.

Site	N/No	D	I	a95	k	S
1	7/9	1.9	7.9	7.2	87	8.7
2	12/12	10.3	10.8	5.5	64	10.1
3	7/7	1.9	10.2	1.5	23	16.9
4	6/6	4.7	7.7	10.3	44	12.3
5-1	11/13	189.5	-9.4	8.8	28	15.3
5-2	8/8	1.0	7.8	5.8	93	8.4
5-3	11/11	9.0	11.8	5.2	26	15.9
5-4	8/8	15.8	11.2	6.6	71	9.6
6	11/12	221.0	-17.0	4.2	153	6.6
7	20/20	205.8	-19.0	3.0	124	7.3
8	10/14	198.0	-10.0	6.3	60	10.5
Mean	111/119	13.4	11.5	5.4	723	9.9

Study mean directions for the normal, reversed and combined sites and calculated virtual geomagnetic poles with confidence limits.

Group	N/No	D	I	a95	Plat°N	Plong°E	dp	dm
Normal-Mean	7/7	7.0	9.2	2.7	52.7	97.1	1.4	2.7
Reversed-Mean	4/4	203.7	-15.0	3.5	50.2	70.2	1.8	3.6
Combined-Mean	11/11	13.4	11.5	5.4	52.6	88.4	3.7	7.3

N/N_0—number of sites (samples) used in determining mean directions to the number of sites (samples) collected; **D, I**—mean declination and mean inclination; **a95**—radius of 95 percent confidence circle; **k**—statistical parameter of Fisher (1953); **Plat, Plong**—latitude (°N) and longitude (°E) of magnetic pole; **dp** and **dm**—semi-minor and semi-major axis, respectively, of ellipse around the paleopole; **S**—estimate of paleosecular variation.

1. The most plausible explanation is that dikes were intruded at two significantly different times. Each group could have intruded and cooled quickly representing a short sampling of the geomagnetic field with paleosecular variation not completely averaged out, as indicated by the low between-site scatter. The time between the intrusions of the normal and reversed dikes could have been short, on the scale of 10^4 or 10^5 yrs. The slightly different geochemistry and petrography of the normal and reversed dikes also support different intrusive events.

2. The lack of antipodality might be due to an unremoved contaminating component, either of viscous or chemical origin. Such a component should lie somewhere along the great circle joining the two directions. The trend and plunge of this great circle is N6°W, 30°NE, so that the contaminating component would have had a maximum plunge of 30°. Such a shallow plunge could not have been produced by a viscous remanence from a present-field overprint. Alternatively, the dikes could have originally been antipodal and suffered a post-intrusion remagnetization of chemical nature (CRM). Because there is slightly more dispersion in the data from the reversed dikes than the normal dikes, it appears that they might have been more affected by a CRM. In some of the polished cores from the reversed dikes a small percent of titanomaghemite was

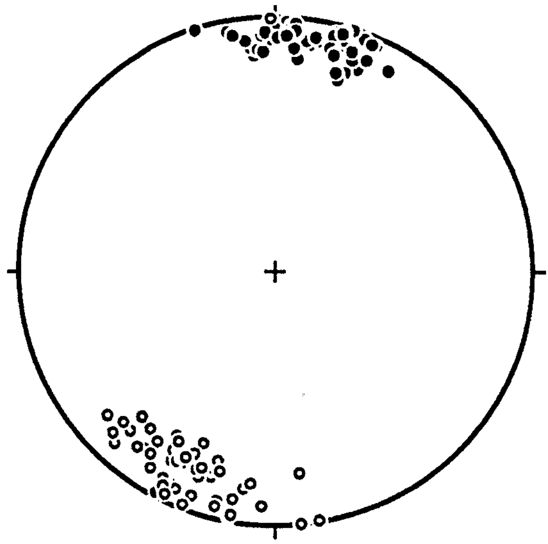


Fig. 11. Equal area diagram of summary data, n = 111 samples. Open circles indicate upper hemisphere projections; closed circles are lower hemisphere projections.

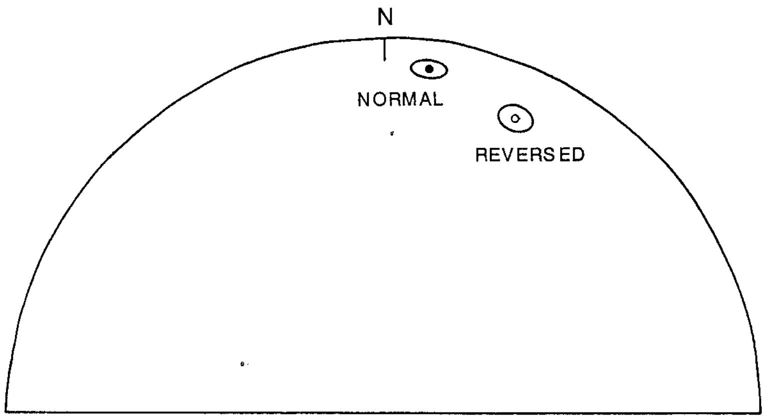


Fig. 12. Equal area diagram of mean site paleomagnetic directions from the Rhode Island diabases. The reversed mean site direction has been inverted and plotted in the lower hemisphere to inspect for the reversal test. The two mean directions do not overlap and are distinguishable at the 95 percent confidence level.

observed. If, at a later time, some titanomagnetite in the reversed dikes was altered to titanomaghemite, producing a new chemical remanent magnetization, then a highly coercive component would be produced, which would not be removed either by a strong alternating field or by thermal demagnetization prior to the removal of the original thermal remanent magnetization carried by titanomagnetite. Because approx 96 percent of the magnetization is carried by titanomagnetite or magnetite, such a proposed alteration component could not be solely responsible for the lack of antipodality of the paleomagnetic directions, though the final direction would still be a mixture of the two components. In this case the normal and reversed dikes could be temporally associated but fail the reversal test due to a later CRM alteration in the reversed dikes. The alteration to titanomaghemite in the reversed dikes does appear to be deuteric in nature. If this had occurred at a time when the geomagnetic field contained a standing nonaxial component, then other late Triassic coeval paleomagnetic studies should show a similar lack of antipodality. There is evidence for lack of antipodality in the Newark red beds in New Jersey (Witte and Kent, 1990).

3. The possibility of a stable remanent magnetic direction obtained through self-reversal of an ilmenite has been discussed by Nord and Lawson (1992). It is highly unlikely in this case due to the composition of these ilmenites (McEnroe, ms) and the fact that the mechanism of self-reversal requires a very rapid chill from high temperature.

Pole position.—The virtual geomagnetic poles (VGP) obtained from this study are given in table 2. The mean pole position for the dikes of normal polarity is 52.7°N, 97.1°E (dp = 1.4, dm = 2.7), similar to the Carnian-Norian paleopole for the Newark sediments, 53.6°N, 101.6°E, a_{95} = 4.8° (Witte and Kent, 1990). The Rhode Island normal paleopole with its 95 percent confidence circle overlaps the May and Butler (1986) Apparent Polar Wander Path for North America (fig. 13) and is similar to the Carnian synthetic reference pole (54.6°N, 102.3°E) calculated by Gordon, Cox, and O'Hare (1984). The reversed dikes produce a paleopole at 50.2°N, 70.2°E (dp = 1.8, dm = 3.6). This is displaced in a southwesterly direction from the Late Triassic-Early Jurassic segment of the Apparent Polar Wander Path. This westward displacement of the reversed paleopole could be a result of secular variation of a long-standing nonaxial dipole component in the late Triassic field. If this displacement is a result of secular variation then it should be seen in other coeval studies. Other similar paleopoles are the Late Triassic (?)-Early Jurassic diabases from North Carolina with a paleopole 52.6°N, 60.2°E, a_{95} = 7.8° (Smith, 1987) which is statistically indistinguishable from the middle Norian Owl Rock Member of the Chinle Formation, 56.9°N, 73.6°E, a_{95} = 2.6° (Bazard and Butler, 1991). However, there does not seem to be enough evidence to attribute this displacement conclusively to secular variation.

The Rhode Island pole calculated using both the normal and reversed dikes is 52.6°N, 88.4°E (dp = 3.7°, dm = 7.3°) and is plotted on figure 13. This pole falls slightly southward of expected Late Triassic directions. However, at the 95 percent confidence level, it is statistically

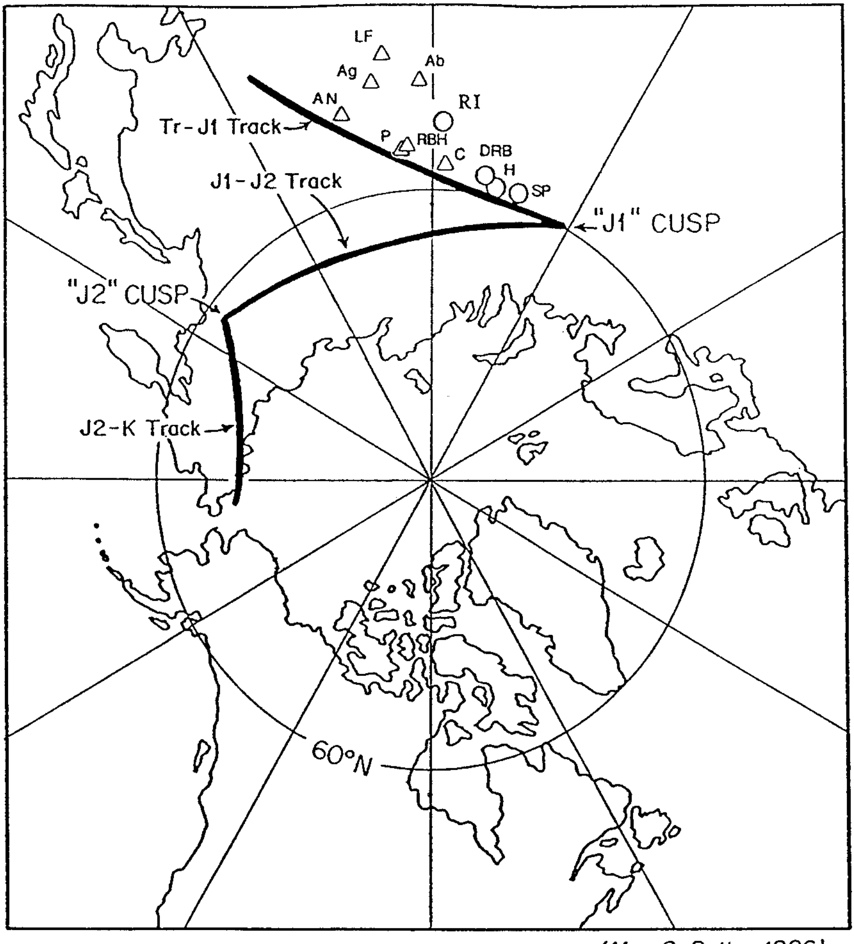


Fig. 13. Mean paleomagnetic pole for the Rhode Island diabases of normal and reversed polarity plotted in reference to the May and Butler (1986) Mesozoic APW path for North America. Also plotted are other North American Late Triassic to Early Jurassic paleopoles, as cited in text. Ab = Abbott pluton; Ag = Agamenticus pluton; AN = Ankareh Formation; C = Chinle Formation; DRB = Deerfield red beds; H = Holden Diabases; LF = Lower Fundy Group red beds; P = Popo Agie Formation; RBH = Red Beds Hettangian, Newark basin; RI = Rhode Island diabases; SP = Seaward Point, Maine.

indistinguishable from other Late Triassic paleopoles, including Newark basin Hettangian red beds (RBH) at 55.5°N, 94.6°E (Witte and Kent, 1990), the Lower Fundy Group (LF) at 45.3°N, 97.1°E (Symons, Bormann, and Jans, 1989), the Abbott pluton (Ab) at 48.3°N, 92.3°E (Wu and Van der Voo, 1988) which is dated at 221 ± 2 (Foland and Faul, 1977), the Pogo Agie Formation (P) at 56°N, 96°E (Van der Voo and Grubbs, 1977), and the Upper Shale Member of the Chinle Formation (C) at 57.4°N, 87.8°E (Bazard and Butler, 1991). It also plots distinctly earlier than the pole obtained from detrital remanence in the earliest Jurassic red beds of the Deerfield Mesozoic basin (DRB, McEnroe and Brown, 1992), the Early Jurassic Holden diabases in Massachusetts (H) (McEnroe, 1989), and the Seaward Point dike in Maine (SP) (S. A. McEnroe, unpublished data).

CONCLUSIONS

The Rhode Island dikes were intruded after the Permian Alleghanian orogeny but prior to the breakup of Pangaea. The Rhode Island dikes exhibit a primary magnetization acquired in the Late Triassic. The majority of the magnetization in the Rhode Island diabases was acquired as a thermal remanent magnetization during the cooling of the dikes. Alternating field demagnetization was successful in removing secondary overprints in most samples and isolating the primary directions. Thermal demagnetization and reflected light-microscopy were used to interpret thermal unblocking temperature and stability. The majority of the magnetization is unblocked below the Curie temperature for magnetite. A very small component of the remanent magnetization obtained from the reversed polarity dikes may have been acquired as a later CRM by the formation of titanomaghemite, though this could as likely have occurred during deuteric alteration of the dikes. The combined normal and reversed pole calculated from the high unblocking temperature magnetization yields a paleopole of 52.6°N, 88.4°E and paleolatitude of 5.8°N, consistent, at the 95 percent confidence level, with other recently determined late Triassic poles.

The Rhode Island dikes differ in their geochemical signatures and petrology from the Jurassic Eastern North America diabases. The Late Triassic paleomagnetic age is in good agreement with the more alkalic within-plate chemical signatures obtained from these dikes. These even differ from the oldest members of the early Jurassic ENA diabases which are also characterized as within-plate tholeiites, and the paleomagnetic poles show that both groups were intruded prior to the breakup of Pangaea. A progression toward more MORB-like tholeitiic signatures of the ENA diabases as shown on discriminant diagrams is observed for the two geochemically distinct Pelham-Loudville and Ware and correlative groups. These have paleopoles that plot at higher latitudes and after the J1 cusp, which may well represent the onset of spreading in the modern Atlantic.

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Professor Don Hermes at the University of Rhode Island took the author to the sample localities and provided six new XRF analyses. Laurie Brown, Cathy Ervin, and Peter Robinson helped with field collecting. Early drafts of this manuscript were reviewed by Professors Laurie Brown, Tony Morse, Don Wise, and Peter Robinson. Their comments were very helpful. Doctors Trond Torsvik and Mark Smethurst at the Norwegian Geological Survey guided me in the use of their equipment and kindly shared software they had written, enabling me to evaluate and model the data. The Survey under Knut Heier, Director, provided me with office space and full access to the Paleomagnetic Laboratory for visits in 1990 and 1991. Dr. Peter Panish helped with the drilling and orienting of paleomagnetic block samples. Reviews by Don Hermes and an anonymous reviewer helped in improving the manuscript. Each of the above persons and institutions is gratefully acknowledged.

Appendix I

Sample locations

1: On Route Interstate 95, 45 m south of Exit 6, which is the intersection with Route 35. Dike 0.5 m wide, N62E 59NW, intruding porphyritic member of Devonian Scituate pluton.

2: On Route Interstate 95, 3.2 km west of Route 2 on the crest of Andrews Hill. Dike 1 m wide, N21W 87W, intruding one-feldspar granite of Devonian Scituate pluton.

3: On Route Interstate 295, 0.8 km south of Route 14 overpass near south end of outcrop. Dike 1 m thick intruding Scituate pluton.

4: On Route Interstate 95 South across from the point where Route 4 exits to the south Partly amydaloidal dike 2 m thick, N11E, 88W, intruding Spencer Hill Rhyolite.

5: Large outcrops to right on Route 4 South, 2.4 km south of intersection with Route 401. Northern outcrop (5-1) contains a very irregular dike 0.7 m thick, N25E 63E. Southern outcrop is 78 m to south and has three collecting locations all along a zone of dikes parallel to the highway: 5-2 at north end; 5-3 18 m south where dike is 1.5 m wide, N7E 65W; and 5-4 25 m south where zone of dikes is 1.5 m thick, N1E 85W. The host rock is a mafic monzodiorite of the Scituate pluton.

6: Outcrop adjacent to warehouse east of northbound lane of Route 4, about 180 m south of intersection with Route 2. Three sills, two of coarse porphyry each 1 m thick, and one aphanitic, 0.6 m thick, N 2W 65E and N3E 55E, parallel to foliation of Pennsylvanian schists and volcanics of Narragansett basin.

7: South end of large cut on west side of southbound lane of Route 4, about 90 m south of intersection with Route 2. Large spheroidally weathered dike collected 23 m and 35 m north of south end. Intrudes Pennsylvanian schists and volcanics of Narragansett basin.

8: Same roadcut as 7, 41 m north of south end of outcrop. Sill, N16W 70E intruding same host.

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