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DIABASE FEEDER DIKES FOR THE MESOZOIC BASALTS IN SOUTHERN NEW ENGLAND

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ABSTRACT. The three regional, northeasterly-trending diabase dikes that traverse southern New England correlate, on the basis of petrography and chemistry, with the three basaltic flows in the Mesozoic Hartford Basin. Although previously thought to be younger than the flows, in our opinion the dikes fed the flows. The successively younger basalts, Talcott, Holyoke, and Hampden, were fed by the Higganum (eastern dike), Buttress-Ware (central dike), and Bridgeport-Pelham (western dike) dikes, respectively. The magmatic activity, thus, progressed westward with time. A fourth, shorter dike, the Fairhaven, occurs only in the southern part of the Hartford Basin and is interpreted as the upper part of the Higganum dike downfaulted, possibly as much as 10 km, into the Basin. At one exposure, the Fairhaven dike connects with and feeds the Talcott basalt.

The chilled margin of each dike is petrographically distinct. All contain phenocrysts of plagioclase and, except for the Buttress-Ware dike, rounded glomeroporphyritic aggregates of augite. The Higganum dike has euhedral orthopyroxene phenocrysts, whereas the Fairhaven contains rounded, resorbed orthopyroxene and euhedral olivine phenocrysts. These differences result from the different depths at which the dikes crystallized. The Buttress-Ware dike has microphenocrysts of olivine and widely scattered centimeter-sized plagioclase phenocrysts. The Bridgeport-Pelham dike also contains olivine phenocrysts. These same phenocryst assemblages occur in the corresponding basalts.

The four petrographically distinct dikes form three chemically separate groups, with the Fairhaven and Higganum chemically identical. The compositions of the Higganum dike and Talcott basalt and the Bridgeport-Pelham dike and Hampden basalt correspond, respectively. The Buttress-Ware dike, however, is compositionally more primitive than the Holyoke basalt but can be related to it by fractionation. The Holyoke basalt shows a wide range of composition and may have come from a large, zoned magma chamber, whereas the Buttress-Ware dike may represent the lower part of this chamber. The chemistry of the dikes and flows indicates that no simple differentiation scheme relates the three episodes of Mesozoic magmatic activity.

INTRODUCTION

Mesozoic tholeiitic dikes and lavas, which have been correlated with the early opening of the Atlantic ocean, occur throughout the eastern coastal region of North America. The dikes are widespread and cut rocks of the older Appalachian fold belt. The lavas, on the other hand, are now restricted to a few down-faulted Mesozoic basins but may originally have been more extensive. The dike rocks fall into a number of well-defined chemical categories (Weigand and Ragland, 1970; Smith, Rose, and Lanning, 1975). The lavas can be similarly classified, but alteration can make this difficult (Puffer and Lechler, 1980; Puffer and others, 1981; Gottfried, Annell, and Byerly, 1983). The relative ages of the different dikes and their relation to the lavas are, in most cases, unknown or uncertain. Variable amounts of excess radiogenic argon in the rocks have caused serious problems with absolute dating (Sutter and Smith, 1979; Dooley and Wampler, 1983; Seidemann and others, 1984), and paleomagnetic studies have produced conflicting results (de Boer, 1968; Smith and Noltimier, 1979). These uncertainties have made it difficult to develop petrogenetic models to explain the diversity of these rocks. In Connecticut, however, field and chemical relations provide clear evidence of the temporal and spatial relations between a number of these tholeiitic dikes, offering the possibility for unravelling their genesis.

The Hartford Basin of Connecticut, like many other Mesozoic basins of eastern North America had its sedimentary fill interrupted early in the Jurassic period by three distinct eruptions of flood basalt. Unlike the other exposed basins, it has a considerable thickness of Jurassic sediments overlying these lavas. Diabase dikes cut the sediments beneath the lavas, but none has yet been found to cut the sediments above the lavas. This feature suggests that the dikes are of the same general age as the flows. Correlation of the three regional dikes with the three flows provides an important means of establishing the relative ages of the dikes. This paper details the evidence for this correlation.

DISTRIBUTION AND PETROGRAPHY OF THE DIABASE DIKES

Most of the Mesozoic rocks of Connecticut are preserved as a series of red beds and basaltic flows and sills within the Hartford Basin and as a series of diabase dikes which occur both within the Basin and in the older surrounding rocks. Three of these dikes are of regional extent, trending in a north-northeasterly direction through Connecticut and Massachusetts. A fourth shorter one occurs only in the southern part of the Hartford Basin (fig. 1). Each of the dikes is tens of meters wide, with 70 m being the typical maximum width. In southern Connecticut, the dikes are spaced approx 10 km apart, but they diverge slightly northward. They trend obliquely to the Basin, with the two western dikes cutting the older Paleozoic rocks on both sides of the Basin. Three of the dikes cut the Mesozoic red beds beneath the lavas (New Haven arkose), but nowhere have they been found to cut the red beds above the flows (Portland arkose). Numerous north-northeasterly trending faults, which parallel and in places coincide with the dikes, cut the lava flows and younger sedimentary rocks. These faults would have provided ready zones of access for magma had intrusion occurred at a later date. Moreover, it cannot be argued that the dikes did not extend far enough north to intersect the younger sediments, for all but one of the dikes cut the older Paleozoic rocks to the northeast of the Basin (fig. 1).

The dikes to the west and east of the Basin can be correlated on the basis of simple geometric extrapolation or petrography. The dikes are named, from west to east, Bridgeport-Pelham, Buttress-Ware, Fairhaven, and Higganum (fig. 1). In the following descriptions emphasis is given to chilled margins, because these are distinctive, whereas the coarser interiors of the dikes, which consist largely of plagioclase, augite, and pigeonite, appear quite similar.

The *Bridgeport-Pelham* dike extends northeasterly from Westport, Conn., through the Paleozoic highlands into the Mesozoic basin at Wolcott, Conn. and then reappears in the eastern Paleozoic highlands at Pelham, Mass. An outcrop in the Farmington River is the most northerly exposure of the dike in the Basin; however, a number of small plug-like

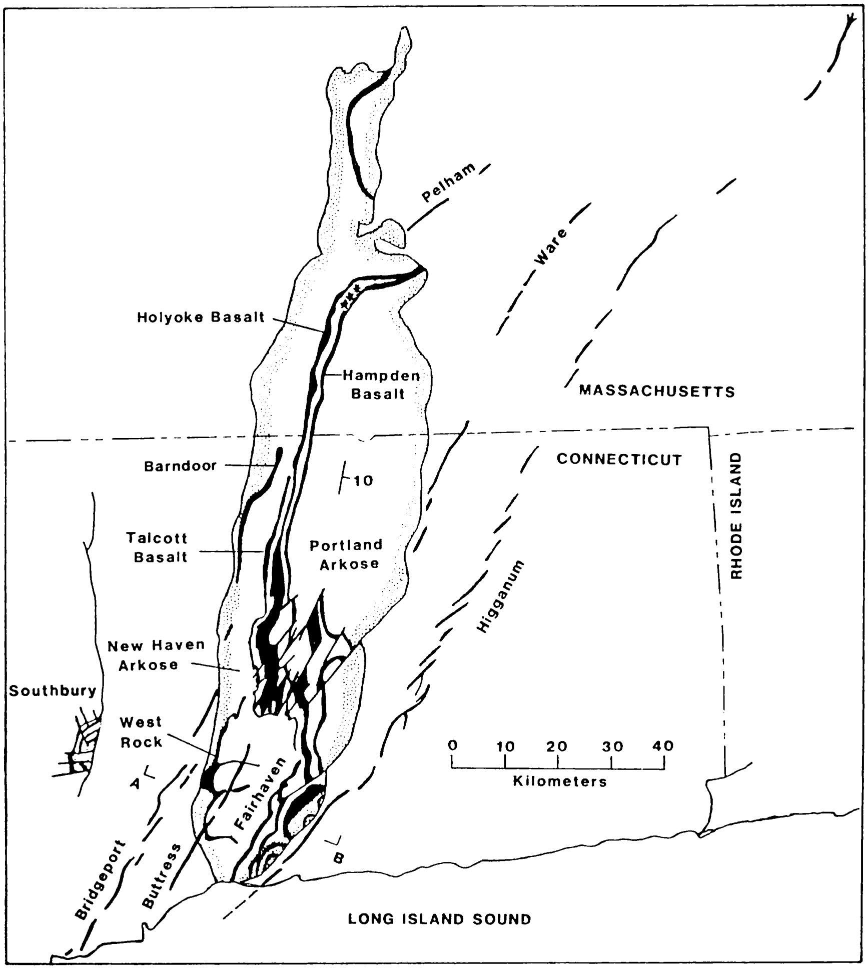


Fig. 1. Geologic map of southern New England showing location of Mesozoic basalt flows and diabase intrusions.

bodies, located on a line extending from the exposure of this dike in the Farmington River to the Pelham dike in Massachusetts, cut the Holyoke basalt. These plugs have been interpreted as feeders to the nearby Granby tuff, which is stratigraphically equivalent to the Hampden basalt to the south (Balk, 1957; Foose, Rytuba, and Sheridan, 1968). Although severely altered, these plugs appear petrographically identical to the Bridgeport-Pelham dike.

The chilled magins of this dike contain abundant subhedral to euhedral microphenocrysts (~0.6 mm) of plagioclase (An_{63-70}), glomeroporphyritic aggregates (~0.5 mm) of augite ($\sim Wo_{37}En_{45}Fs_{18}$), and euhedral microphenocrysts (~0.3 mm) of olivine (Fo_{65-67}) in a brown-black glassy matrix (pl. 1-A). Away from the chilled margins olivine is absent, and its place is taken by pigeonite. In the coarser central parts of the dike, however, olivine reappears as a late crystallizing phase with a composition of Fo_{20}.

The *Buttress-Ware dike* extends from Orange, Conn., to Ware, Mass. At the southwestern end of the Hartford Basin, it cuts the West Rock sill in the cliffs (The Buttress) immediately north of the Wilbur Cross Parkway and again at Cross Rocks in Cheshire, Conn., firmly establishing the relative ages of these two bodies. The chilled margins of the Buttress-Ware dike contain subhedral to euhedral microphenocrysts (~0.2 mm) of plagioclase (An_{71-73}) and olivine (Fo_{75-78}) in a dark brown devitrified glassy matrix (pl. 1-B). Widely scattered centimeter-sized phenocrysts of altered plagioclase are also present. Immiscible sulfide globules, consisting largely of pyrrhotite, are common in this dike.

In Cheshire, the dike is autobrecciated. This breccia, which is indicative of near-surface intrusion, consists of particles 1 to 3 cm in diameter of devitrified glass and fine-grained hypohyaline basalt and medium-grained holocrystalline diabase. Many of the glassy bodies form micropillows. Cavities between the particles are filled with carbonate and some detrital grains derived from the surrounding arkose. Some blebs of glassy diabase are completely surrounded by sediment, indicating, perhaps, that the sediments were wet and unconsolidated at the time of intrusion.

The arkose in contact with the Buttress dike has been reduced from red to dark green-gray, and in some localities the arkose was extensively melted. On Tallman Hill, north of the Sleeping Giant intrusion (part of the West Rock sill), melted arkose forms lobate intrusions into the chilled margin of the diabase.

The *Fairhaven dike* extends from New Haven Harbor to Wallingford, Conn. as a series of dikes and sills. Unlike the other dikes, no extension to the east of the Hartford Basin exists. The chilled margins contain a complex variety of phenocrysts, including ~0.9 mm anhedral to subhedral phenocrysts of orthopyroxene ($\sim Wo_5En_{77}Fs_{18}$), glomeroporphyritic aggregates (~2.4 mm) of augite ($\sim Wo_{34}En_{55}Fs_{11}$), individual subhedral to euhedral phenocrysts (~1.1 mm) of augite ($\sim Wo_{32}En_{55}Fs_{13}$), subhedral to euhedral phenocrysts (~1.0 mm) of plagioclase (An_{73-77}), and euhedral phenocrysts (~0.4 mm) of olivine (Fo_{80}) (pl. 1-C). Some augite phenocrysts have cores of orthopyroxene ($Wo_5En_{80}Fs_{15}$), which are not only considerably more magnesian than the separate phenocrysts of orthopyroxene, but contain 0.5 percent Cr_2O_3 in contrast to 0.1 percent in the separate phenocrysts.

The New Haven arkose in contact with the Fairhaven dike was extensively melted. The contact of the diabase with the sediments is convoluted, with bulbous masses of fine-grained diabase protruding into the partially melted arkose. The diabase is also back-veined by rheomorphic granophyre derived from the melted sediments.

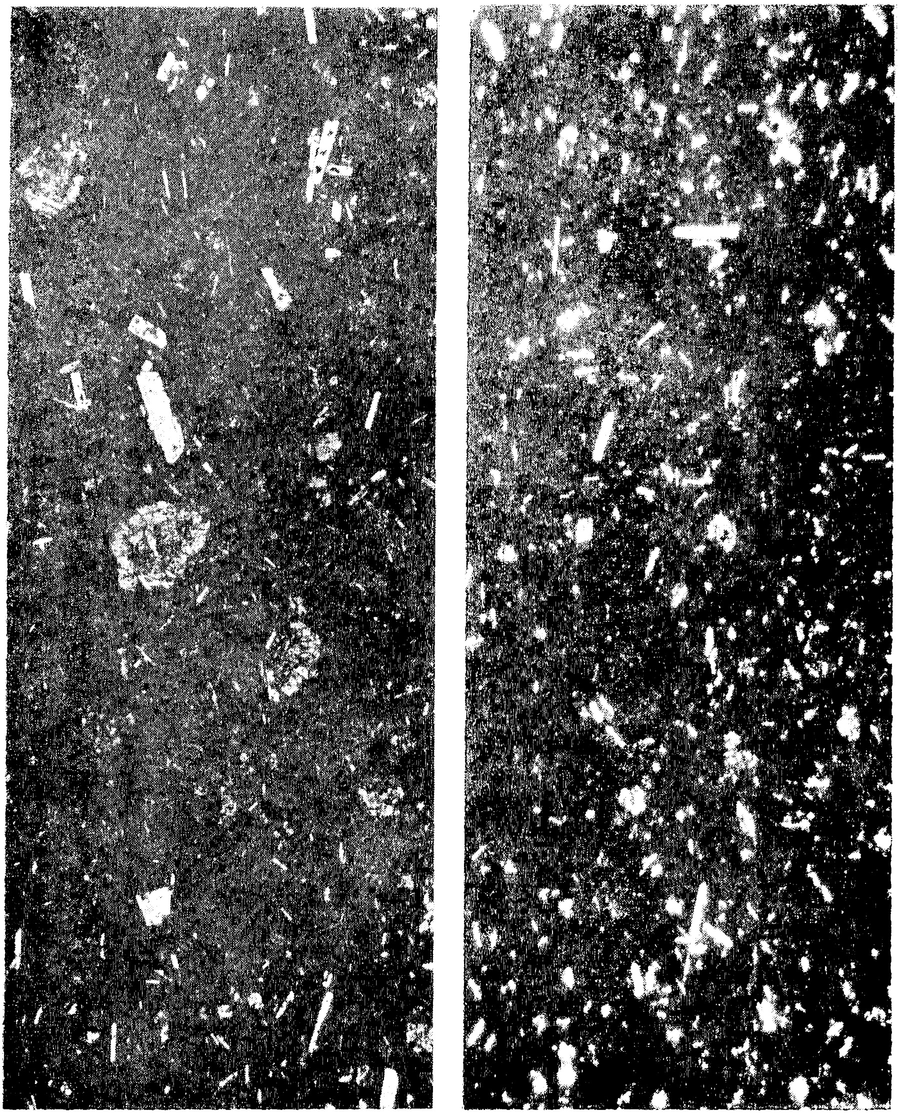
On Warner Road in East Haven, Conn., the vertically-dipping Fairhaven dike passes upward into a breccia which forms an agglomeratic flow with interlayered arkosic sediments. This agglomerate, in turn, is interlayered with pillowed Talcott basalt. The gradation from vertical dike to extrusive agglomerate is completely exposed. The dike, at this point, clearly fed the Talcott flow. Within the vertical, massive part of the dike, numerous internal contacts are evident, with some of the later injections having brecciated the earlier diabase. The youngest injection is of particular interest because it forms centimeter-wide dikelets emplaced along the columnar joints formed from the earlier intrusions. Although this phase of injection carries phenocrysts identical to the earlier ones, the magma was quenched to a glass that, remarkably, escaped devitrification. It contains pristine phenocrysts of olivine and delicately preserved whisker-barbed microlites of pyroxene and plagioclase (pl. 1-C).

The *Higganum dike* lies entirely within the eastern highlands, so its age, relative to the Mesozoic rocks, cannot be determined from field relations. Nonetheless, it parallels the other dikes and thus appears to belong to this family of dikes. It is the most continuous of the four, extending from beneath Long Island Sound, where it has been detected by shipboard magnetometer survey (Martello and others, 1984), through eastern Connecticut and Massachusetts almost to the New Hampshire border, a distance of 200 km. Nowhere is it more than 70 m wide, and along much of its length it forms a series of en echelon sinistrally-offset segments.

The Higganum dike is the most porphyritic of the dikes, with the chilled margin containing euhedral phenocrysts of plagioclase (~0.8 mm) and orthopyroxene (~1.0 mm) and rounded glomeroporphyritic aggregates (~1.1 mm) of augite and augite plus plagioclase (pl. 1-D). The orthopyroxene phenocrysts exhibit monoclinic morphology (Philpotts and Gray, 1974). Koza (ms) found that the relative proportions of plagioclase and orthopyroxene phenocrysts to fine-grained groundmass in the chilled margin remain remarkably constant along the entire 200-km-length of this dike. The abundance of augite aggregates, in contrast, varies considerably, from 0.5 to 22 percent (fig. 2). Koza (ms) concluded that the glomeroporphyritic aggregates may be xenocrystic rather than phenocrystic in origin. Several internal chilled contacts reveal that the dike served as a conduit for repeated surges of magma. Unlike the Fairhaven dike, the Higganum contains no olivine.

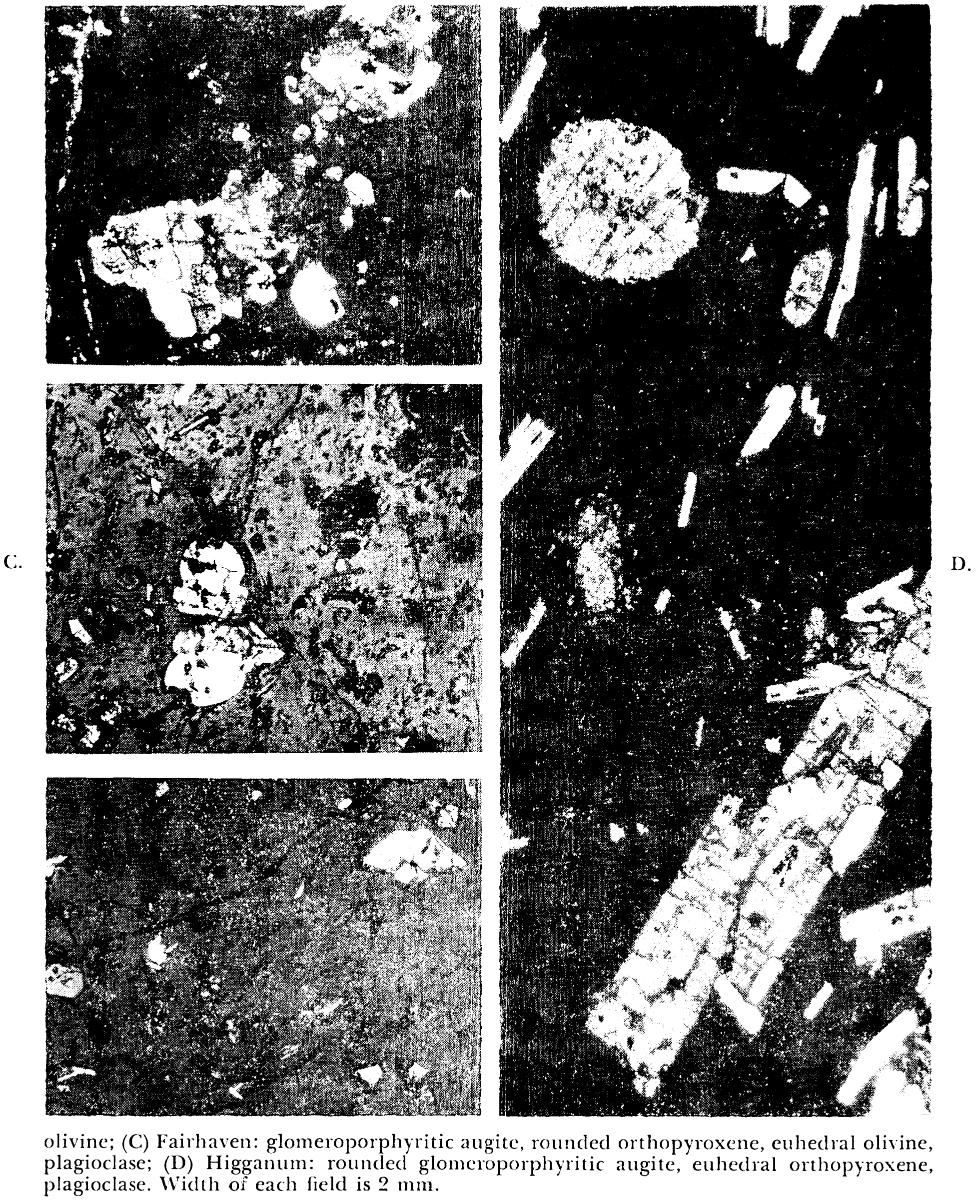
PLATE 1

A.



B.

Phenocryst assemblages in chilled margins of Mesozoic diabase dikes. (A) Bridgeport-Pelham: glomeroporphyritic augite, plagioclase, olivine; (B) Buttress-Ware: plagioclase,



olivine; (C) Fairhaven: glomeroporphyritic augite, rounded orthopyroxene, euhedral olivine, plagioclase; (D) Higganum: rounded glomeroporphyritic augite, euhedral orthopyroxene, plagioclase. Width of each field is 2 mm.

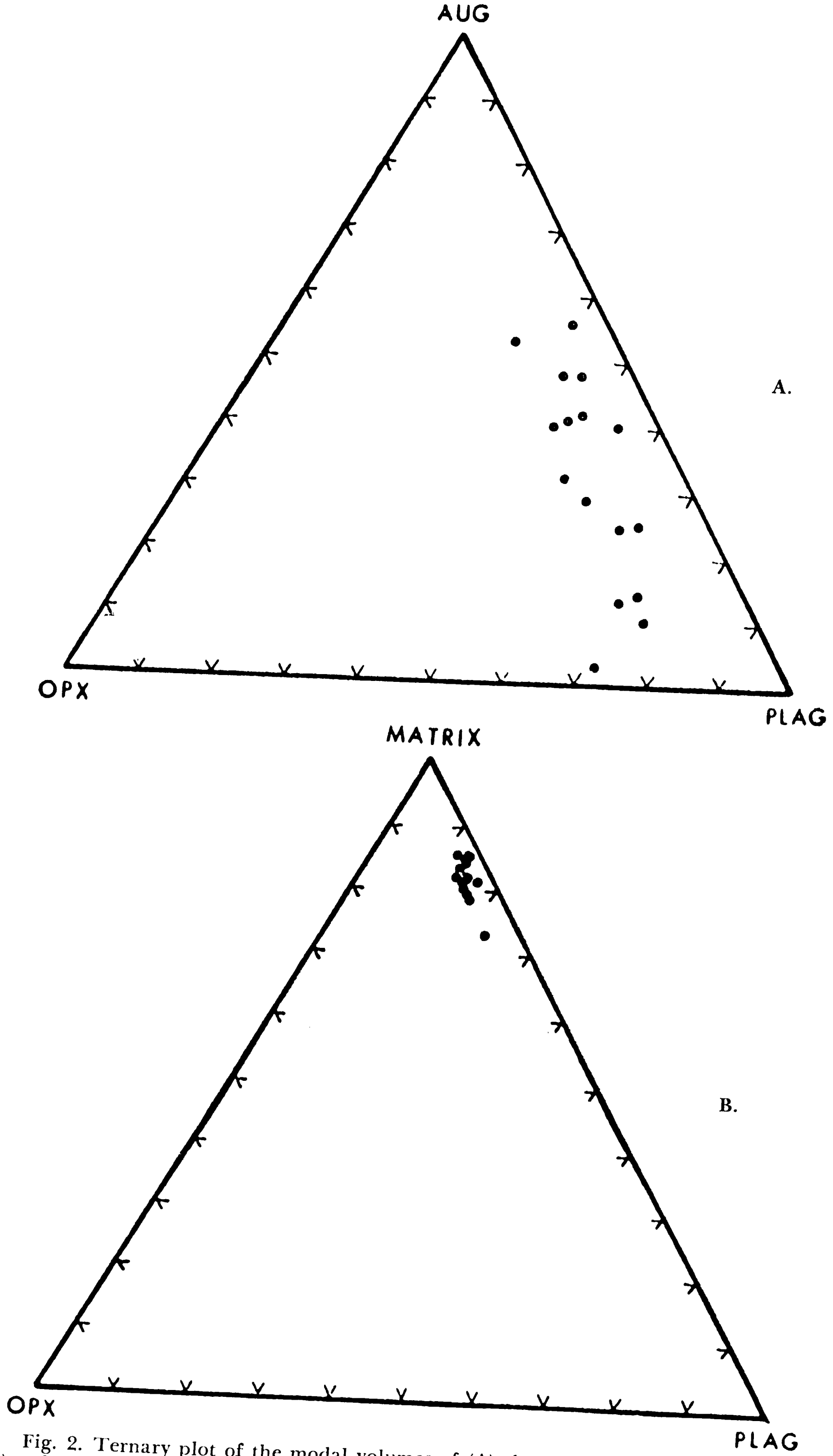


Fig. 2. Ternary plot of the modal volumes of (A) the three phenocryst phases and (B) orthopyroxene and plagioclase phenocrysts and matrix in the chilled margins of the Higganum dike (from Koza, 1976).

In summary, the chilled margins of the dikes are petrographically distinguishable. All are porphyritic and contain phenocrysts of plagioclase, but only the Buttress-Ware dike contains the large centimeter-sized plagioclase phenocrysts. Except for the Buttress-Ware dike, all contain rounded glomeroporphyritic aggregates of augite. The Bridgeport-Pelham, Buttress-Ware, and Fairhaven dikes contain olivine phenocrysts. The Higganum dike does not contain olivine but, instead, contains euhedral orthopyroxene phenocrysts. The Fairhaven is the only other dike that contains orthopyroxene, but in this dike the orthopyroxene crystals are either rounded or resorbed and rimmed by augite. Clearly, these dikes constitute four petrographically distinct types.

CHEMISTRY OF DIKES

Whole-rock XRF analyses were done for major elements using glass discs formed by fusion of two parts lithium tetraborate to one part rock (Gunn, 1967); trace elements were done on pressed pellets of powdered rock. Table 1 presents the averages and standard deviations of analyses of each of the dikes. For purposes of comparison, the average compositions of the Talcott, Holyoke, and Hampden basalts obtained by Puffer and others (1981) are included.

Although the four dikes all belong to Weigand and Ragland's (1970) high-TiO_2 quartz-normative division of eastern North American diabases, they fall into three distinct compositional groups. Within each dike there is considerable compositional variation which might be due, in part, to different phenocryst concentrations, as in the Higganum samples (fig. 2) but might also reflect compositional differences in the melts. Because variations across a dike can be greater than those along its length, no geographical variation in composition along the dikes has yet been firmly established.

Among the major elements, the dikes are most clearly distinguished by their magnesium and titanium contents (fig. 3). The Fairhaven and Higganum dikes both contain high amounts of MgO and similar TiO_2 contents; the other two dikes both contain low MgO contents, but the Bridgeport-Pelham dike is TiO_2-rich. Within each dike, the titanium contents form tightly clustered linear trends with TiO_2 decreasing with increasing MgO content. Linear regression lines fitted to each of the data sets provide a means of characterizing each dike. These lines, which express the TiO_2 percentages as functions of the MgO contents, are as follows:

Bridgeport-Pelham	3.17 - 0.305*MgO	($R^2 = 0.62$)	(MgO < 6.5)
Buttress-Ware	1.61 - 0.112*MgO	($R^2 = 0.82$)	(all data)
	1.83 - 0.142*MgO	($R^2 = 0.78$)	(excluding one Mg-rich point)
Fairhaven	2.51 - 0.190*MgO	($R^2 = 0.50$)	(MgO > 6.7)
Higganum	2.34 - 0.168*MgO	($R^2 = 0.63$)	

The second regression line for the Buttress-Ware data is obtained by omitting one highly magnesian sample. Both lines are included in figure 3, the longer one being for the data excluding the magnesium-rich rock.

TABLE 1

Average compositions of southern New England diabase dikes and lavas*

	Bridgeport - Pelham		Average Hampden	Buttress - Ware		Average Holyoke	Fairhaven		Average Talcott	Higganum	
No. of Anal.	10		6	10		10	6		7	12	
	wt%	σ	wt%	wt%	σ	wt%	wt%	σ	wt%	wt%	σ
SiO_2	49.99	0.66	50.73	51.74	0.36	52.73	52.03	0.58	51.86	52.92	0.67
TiO_2	1.33	0.07	1.45	0.79	0.03	1.08	1.15	0.05	1.07	1.18	0.14
Al_2O_3	13.85	0.32	13.92	15.12	0.23	14.42	14.79	0.29	14.27	15.04	0.97
FeO^t	14.82	0.69	14.19	10.63	0.40	11.74	10.43	0.50	10.86	10.09	0.91
MnO	0.22	0.01	0.24	0.19	0.01	0.19	0.16	0.01	0.16	0.18	0.05
MgO	6.03	0.25	5.78	7.40	0.30	6.09	7.17	0.28	7.98	6.88	0.94
CaO	9.98	0.35	10.97	11.11	0.37	10.63	11.11	0.39	11.24	10.85	0.35
Na_2O	3.01	0.65	2.28	2.43	0.50	2.54	2.38	0.37	2.06	2.31	0.23
K_2O	0.60	0.14	0.44	0.44	0.11	0.58	0.58	0.19	0.50	0.55	0.14
P_2O_5	0.17	0.04	----	0.15	0.05	----	0.20	0.07	----	----	----
Trace Elements in ppm.											
V	438	45	355	291	49	317	263	51	270	259	60
Cr	88	16	---	202	21	---	260	31	---	233	165
Mn	1796	69	---	1507	104	---	1292	72	---	1305	26
Ni	40	3	50	51	4	19	80	5	72	73	28
Cu	155	12	187	104	29	84	125	10	123	125	7
Rb	20	5	---	12	4	---	15	6	---	21	2
Sr	78	5	163	111	4	159	163	18	186	150	20
Y	48	11	49	29	10	34	29	7	30	27	6
Zr	85	6	94	66	10	94	123	4	116	114	14

* Average compositions of lavas from Puffer and others (1981). All compositions recalculated to 100%.

On the basis of titanium and magnesium concentrations, the Fairhaven and Higganum dikes are indistinguishable. Indeed, comparison of the average compositions of these dikes (table 1) reveals no significant difference between any of the major oxides nor any of the trace elements. This is surprising in view of their striking petrographic differences.

The Bridgeport-Pelham samples all contain less than 6.5 percent MgO, whereas those from the Fairhaven and Higganum dikes contain more than 6.7 percent. The similar trends of these two groups in figure 3 suggest that they might be related, but the trace element data show this is not possible (see below). The Bridgeport-Pelham dike is clearly distinguished from the others by its exceptionally high Fe content, which ranges from 13.8 to 15.7 percent expressed as FeO; the Higganum, Fairhaven, and Buttress-Ware dikes only contain between 10 and 11 percent FeO.

Trace element data for the four dikes are presented in figure 4 as plots of each trace element versus the Zr content of the sample. In each plot, the four dikes form three distinct chemical groupings, with the Fairhaven and Higganum samples forming a single group. The Fairhaven-Higganum group is the most Zr-rich, as it is in most incompatible elements. The Buttress-Ware samples are generally the poorest in incompatible elements.

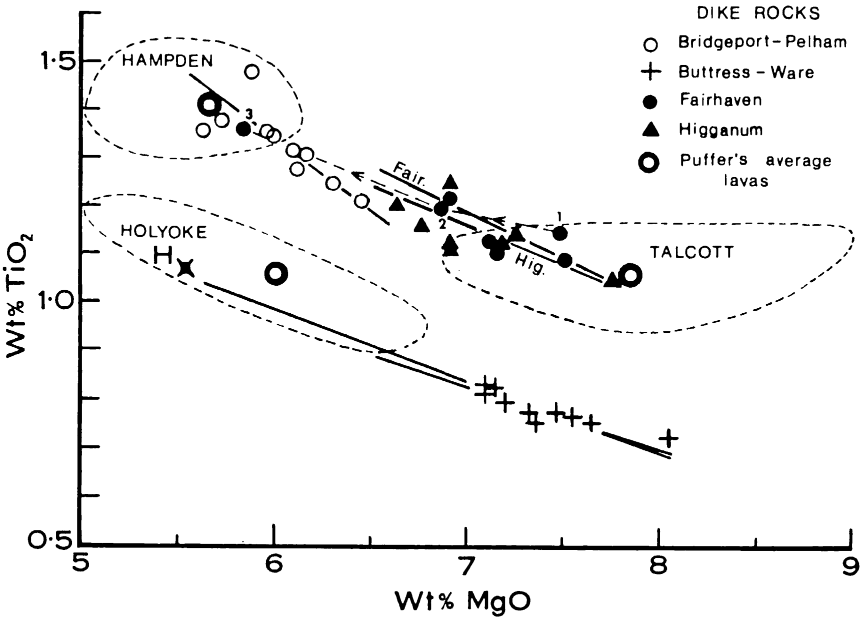


Fig. 3. TiO_2 versus MgO plot for Mesozoic diabase dikes and flows (Puffer, 1981) in southern New England. See text for explanation.

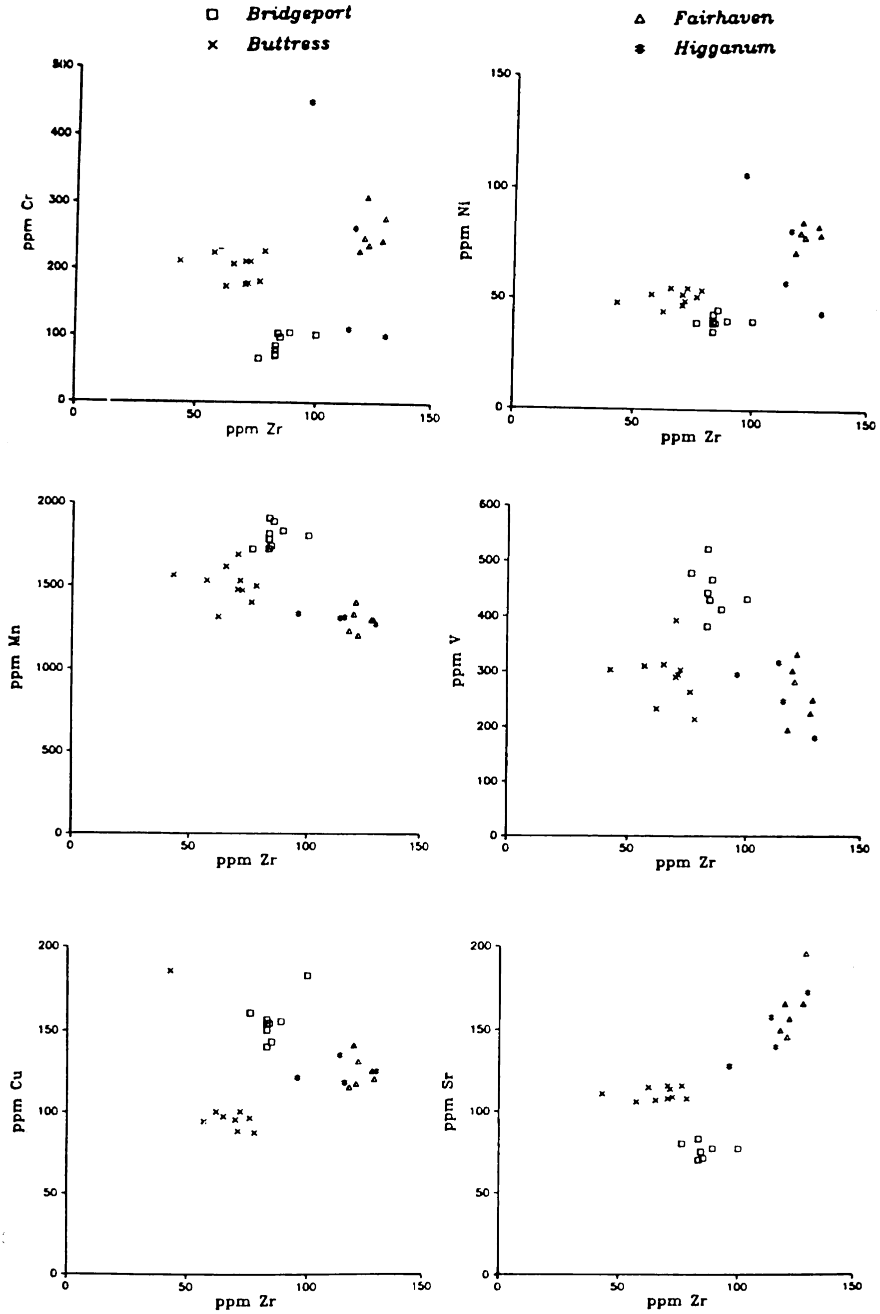


Fig. 4. Trace element variations in southern New England Mesozoic diabase dikes.

The plots of Cr and Ni versus Zr produce almost identical patterns, which in large part reflect the content of phenocrysts of pyroxene and olivine in the various samples. This is particularly noticable in the case of the Higganum samples, where the one containing the highest Cr and lowest Zr contents contains 12 percent glomeroporphyritic aggregates of augite, whereas the one with the lowest Cr and highest Zr contains only 3 percent of these aggregates. The much smaller variation in these elements in the other dikes indicates that their phenocryst contents are less variable than that of the Higganum dike.

The plots of Mn, V, and Y versus Zr are also similar to each other and seem to parallel the iron distributions in the dikes. The Cu distribution is also similar, except that the Cu contents of the Buttress samples (with one exception) are slightly lower by comparison with the other dike samples. Because all Buttress samples contain sulfide droplets, which indicate saturation with an immiscible sulfide liquid at the time of intrusion, the low copper content might be attributed to an earlier separation of Cu in a sulfide liquid.

The Rb contents of all the dikes are low, and the plot versus Zr shows considerable scatter. The Sr plot, on the other hand, shows the three tightly clustered groupings of dike samples. The slight linear variation in the Fairhaven and Higganum samples is consistent with both Zr and Sr behaving incompatibly in these rocks. The horizontal trend in the Buttress samples, however, suggests that Sr was not an incompatible element in this dike, and perhaps the large, widely scattered phenocrysts of plagioclase, which are invariably present, may have played some role in the differentiation of this magma. The low Sr content of the Bridgeport dike is of interest in view of the abundance of plagioclase phenocrysts in this rock. Clearly this dike must have formed from a Sr-poor magma.

In summary, the major and trace element data indicate that the four petrographically and geographically distinctive dikes form only three chemically distinguishable groups. The Fairhaven and Higganum dikes appear to be chemically identical, despite their striking petrographic differences.

COMPARISON OF DIKES WITH LAVAS

Puffer and others (1981) have analyzed the lavas of the Hartford Basin and have shown that the three volcanic units have distinct compositional ranges. Their averages for each of the volcanic units are included in table 1 for comparison with the average compositions of each of the dikes. Unfortunately, their analyses include only some of the trace elements determined for the dike rocks. Nonetheless, a meaningful comparison between the dikes and lava flows can be made.

The major elements that most clearly distinguish between the three volcanic units are magnesium and titanium, as in the dikes (fig. 3). The oldest lava, the Talcott basalt, is characterized by the highest magnesium content. The next unit, the Holyoke basalt, has lower magnesium but has approximately the same titanium content as the Talcott basalt. The youngest volcanic unit, the Hampden basalt, is markedly richer in iron and titanium than either of the other units. The compositional range of each of the volcanic units, as determined by Puffer and others (1981), has been included in figure 3 for comparison with the dike rocks. The Bridgeport-Pelham samples plot in or near the field of the Hampden basalt, both having the same remarkably high iron and titanium contents. The Fairhaven and Higganum samples correspond well with part of the Talcott field, but some Talcott samples have more magnesium compositions. The Buttress-Ware samples, however, plot well outside the field of the Holyoke samples.

Before trying to explain the chemical discrepancies between the volcanic and dike rocks, it is instructive to consider the possible causes for the compositional variation within each dike. For this purpose, figure 3 is particularly useful, because it plots titanium, which in these rocks behaves essentially as an incompatible element, against magnesium, which provides a simple measure of ferromagnesian fractionation. Fractional crystallization or different degrees of partial melting would produce the negative slopes obtained in this plot. Also, these slopes should be less negative for magmas with higher Mg′ values (MgO/(MgO + FeO)) because of the higher magnesium contents of the fractionating ferromagnesian minerals. For example, the Fairhaven dike contains olivine phenocrysts of Fo_{80} composition, and the slope of the linear regression line in figure 3 for the rocks from this dike is −0.19. In contrast, the Bridgeport-Pelham dike, with lower Mg′, contains phenocrysts of Fo_{67}, and the linear regression line has a slope of −0.31. Indeed, if a group of rocks covered a wide enough range of magnesium contents, the points in figure 3 would be expected to follow smooth curves with steepening slopes at lower magnesium values (see, for example, Irvine, 1979).

Clear evidence of fractional crystallization is provided by the glassy veins that intrude the columnar joints in the Fairhaven dike. This glass, which carries phenocrysts of olivine, pyroxene, and plagioclase, has a whole-rock MgO content of 6.86 percent (no. 2 in fig. 3). It occurs as dikelets up to a centimeter in width emplaced along columnar joint fractures in an earlier crystalline diabase which has an MgO content of 7.49 percent (no. 1 in fig. 3). As the melt intruded along the narrow fractures, phenocrysts were likely filtered out, causing enrichment of the distal ends of the dikelets in the liquid fraction. Had this process continued, a composition similar to that of the residual liquid in this rock would have resulted. Electron microprobe analyses indicate this residual melt contains only 5.8 percent MgO (no. 3 in fig. 3). The fractional crystallization trend followed by these samples (1, 2, and 3 in fig. 3) is very close to the linear regression line for all Fairhaven samples. The slopes of the regression lines can therefore be taken as typical of those resulting from fractional crystallization in this particular composition range.

The elongate trend formed by the Holyoke samples (Puffer and others, 1981) in figure 3 is similar to that expected for fractional crystallization. The Talcott samples, on the other hand, produce a trend that is not consistent with fractional crystallization or melting. It is important to emphasize that the Talcott does not contain any phenocrysts of Ti-magnetite or ilmenite. With increasing magnesium content, the Talcott samples maintain a relatively constant titanium content. This most likely results from alteration of the basalt which, throughout most of the Hartford Basin, is a pillowed unit. Titanium is a relatively immobile element during alteration, but magnesium tends to concentrate in altered basalt. For example, glassy selvages on pillows of Talcott basalt contain up to 20 percent MgO. It is likely, therefore, that only the samples at the magnesium-poor end of Puffer's field of Talcott samples are representative of magmatic compositions. The lack of horizontal trends in the Holyoke and Hampden samples is most likely attributable to the less altered nature of these basalts which form massive flows.

Because of the unusual iron-rich composition of both the Hampden basalt and the Bridgeport-Pelham dike, there is little doubt these two are related. They are petrographically similar, both containing higher concentrations of plagioclase phenocrysts than any of the other dikes or lavas. They also both contain glomeroporphyritic aggregates of augite and phenocrysts of olivine. Moreover, northeasterly flow directions in the Hampden basalt in the Hartford Basin (Elefson and Rydel, 1985) and southwesterly flow directions (Manspeizer, 1969) in the Hook Mountain basalt of the Newark Basin, which has been correlated with the Hampden basalt (Puffer and others, 1981), are consistent with this dike being the source for this unusual lava in both basins.

Despite the correspondence in composition between the Hampden and Bridgeport-Pelham samples, approximately half of the dike analyses lie just outside the Hampden field. They deviate, however, in a direction that is consistent with fractionation; that is, the dike samples outside the Hampden field have more primitive or less evolved compositions than the Hampden itself. It is significant that the regression line for the dike samples passes through Puffer's average Hampden composition. The lavas and dike rocks can, therefore, be interpreted as a comagmatic group, with the lavas formed from the first erupting magma and the dikes from the last. The first magma was slightly more evolved than the final one and thus likely came from the top of a zoned magma chamber.

The lack of correspondence between the Holyoke and Buttress-Ware samples might be accounted for in a similar way. The wide compositional range of the Holyoke samples indicates that they exhibit varied degrees of fractionation. Because there is no evidence of this fractionation having taken place within the flow, it must have occurred prior to eruption, most likely in a large magma reservoir. If the lava and dike rocks are comagmatic, the range of fractionation is indeed large (5-8 percent MgO). Such a range, however, would not be unusual in a body with the volume necessary to form the Holyoke basalt, which is the most extensive and thickest of the three volcanic units in the Hartford Basin.

The fact that the linear regression lines for the Buttress-Ware data pass through the Holyoke field in figure 3 and have approximately the same slopes as the Holyoke trend could indicate that these two groups are related through differentiation. The lavas might have come from the top of a zoned magma chamber depleted in early crystallizing, dense minerals, whereas the dike would consist of material from lower in the chamber where early crystallizing minerals accumulated. This could account for the almost aphyric nature of the Holyoke basalt and its complete lack of glomeroporphyritic aggregates of augite which do occur in the other flows. Inverted compositional zoning might even be expected within the flow itself. Unfortunately, no extensive study of the compositional variation through the Holyoke has been made. However, one sample from the base of the unit at Tariffville, Conn. (Philpotts and Reichenbach, 1983), has a highly evolved composition (H in fig. 3).

If the Holyoke and Buttress-Ware rocks constitute a series formed from the emptying of a large, zoned magma reservoir, a continuous series of compositions would be expected. Instead, there is a distinct gap of almost 0.5 percent MgO between the lavas and dike rocks. Assuming that originally there was continuity, several factors could account for the gap. First, the sampling may not be sufficiently extensive to encounter the full range of compositions. Second, the top of the lava consisting of the final erupted material may not be exposed or may have been eroded away. Third, and perhaps most important, is that the dike may be vertically zoned and the present exposures of the dike are of material that, in many cases, would originally have been at some considerable depth beneath the surface. The recent state geological map of Massachusetts (Zen, 1983) indicates a displacement on the eastern border fault of the Hartford Basin of 8.5 km. Consequently, where the dike is exposed to the east of the Basin, at least 8.5 km of overlying rocks must have been removed by erosion. Within the Basin, however, depths of exposure of the dike would be shallower. It is significant that the most magnesian sample is from Soapstone Mountain, which is located just to the east of the Hartford Basin, and one of the least magnesian samples comes from within the Basin at the Buttress itself. A vertical compositional zoning in the dike may therefore exist, and the eroded upper part of the dike may have contained the rocks that form the compositional gap between the intrusive and extrusive rocks.

In addition to the compositional gap, there is the problem of why no material of Holyoke composition has been found preserved anywhere within the dike. For example, chilled margins might be expected to retain some of the initial magma. This would be so if there had been a single injection. But everywhere the contact has been studied, the country rocks show signs of extensive melting, which indicates that the dike must have continued to flow for some time. Any early magma would, therefore, probably have been flushed out by later injections.

Petrographically the Holyoke and Buttress-Ware rocks are similar. Both are almost aphyric, containing only small phenocrysts of olivine and plagioclase in rapidly chilled samples. Both contain widely scattered, large phenocrysts of plagioclase. Finally, both contain abundant immiscible sulfide globules.

The Fairhaven dike and Talcott basalt are clearly related, as shown by the dike connecting with the volcanics. Petrographically they are identical, both containing euhedral phenocrysts of plagioclase and olivine, rounded glomeroporphyritic aggregates of augite, and large, partially resorbed phenocrysts of high-Cr orthopyroxene (Philpotts and Reichenbach, 1983).

The chemical relation of the Fairhaven samples to the Talcott basalt is quite different from that of the other dikes to their corresponding flows. In figure 3 the Fairhaven samples are seen to occupy the Mg-poor end of the Talcott field. No dike samples trail off from this field to more primitive compositions. If there is any significant deviation between the intrusive and extrusive rocks, it is that slightly more evolved compositions are found in the dike. This can be explained by local differentiation, as for example in the case of the glassy rock (no. 2 in fig. 3). Such differentiation was not possible in the pillowed basalt.

The correspondence of the Talcott and Fairhaven samples and the lack of more primitive rocks in the dike suggest that this magma may indeed be primitive, despite its low Mg′ value, and may have risen directly from a source region without undergoing significant compositional modifications. Philpotts and Reichenbach (1983) have argued this for the Talcott basalt on the basis of its content of Cr-rich orthopyroxene phenocrysts which are rimmed by olivine and augite. In experiments at 1 atm, these pyroxene crystals incongruently melt within hours to olivine plus liquid. Thus, their preservation in the lava requires that the magma rose rapidly from a depth where orthopyroxene was stable as a primary liquidus phase. Iron-rich ocean-floor basalt having a composition almost identical to that of the Talcott basalt has orthopyroxene as a primary liquidus phase at pressures in excess of 8 kb (Fujii and Kushiro, 1977). The Talcott and Fairhaven rocks, therefore, most probably represent magma that rose rapidly from depths corresponding to the base of the crust.

Whether a magma with as low an Mg′ value (0.59) as that of the Talcott could be primitive is open to considerable question. Magmas derived directly from the mantle would be expected to have higher Mg′ values based on what is known of the composition of olivines in samples from the mantle. The question of whether magmas of basaltic composition, such as the Talcott, or more magnesian ones, such as picrites, are the true primary magmas of flood basalts has been discussed by Cox (1980). The question is still open and cannot be resolved with data presented here. But the lack of magmas with higher Mg′ values than that of the Talcott and the remarkably constant composition of this magma throughout eastern North America argue in favor of it being primitive. If it is primitive, however, it could not have come from a source containing olivine with compositions as magnesian as $\sim Fo_{90}$, the typical value found in mantle-derived nodules.

The compositional relations between the dikes and lavas are, therefore, interpreted to indicate that the earliest magma, the Talcott, is a primitive one, whereas the later ones, the Holyoke and Hampden, are derived from magmas undergoing differentiation at the time of eruption. Magma of Talcott composition is ubiquitous throughout the northern part of the eastern North American Mesozoic province, and where stratigraphic control permits relative dating, it is the oldest (although farther south, olivine normative types may have this distinction). In the Newark Basin it forms the Orange Mountain basalt and the Palisades sill (Puffer and others, 1981); in Pennsylvania, the York Haven (Smith, Rose, and Lanning, 1975); in the Fundy Basin, the North Mountain basalt (Colwell and Papezik, 1984); in eastern Nova Scotia, the Shelburne dike (Papezik and Barr, 1981); and in Newfoundland it forms the Avalon dike (Papezik and Hodych, 1980). Such widespread occurrence supports the contention that the Talcott is a primitive magma.

Field relations show that the Fairhaven and Talcott rocks are clearly related. Compositionally, however, the Higganum dike could just as well have been the source for the Talcott. It is the most extensive of all the dikes, and numerous internal contacts and melted country rock along its contacts indicate extended periods of flow (feeder flow?). The important difference between the two dikes is that the primary calcium-poor ferromagnesian phase is orthopyroxene in the Higganum and olivine in the Fairhaven, as it is in the Talcott. But the presence of partially resorbed orthopyroxene phenocrysts in the Fairhaven dike and the Talcott basalt indicate that this mineral was a primary phase in this magma at depth. Furthermore, preliminary melting experiments, conducted in this laboratory, on the Higganum dike from Branford, Conn., indicate that at 1 atm pressure, olivine is the primary liquidus phase, and that orthopyroxene does not crystallize from this composition at any temperature at this pressure. Apparently, high pressures are required for orthopyroxene to grow in this magma. It is possible, therefore, that the Fairhaven is the near-surface expression of the deeper Higganum dike.

Along the southeast side of the Hartford Basin, the Higganum dike comes within 1 to 2 km of the eastern border fault (fig. 1). The dike, which is approximately vertical, would have been intersected at some distance above the present erosion surface by the westward-dipping border fault. The normal movement on this fault would then have downdropped and shifted the upper part of the dike westward, possibly to form the Fairhaven dike.

Whether the normal faulting could offset the Higganum dike far enough west to correspond with the Fairhaven dike depends to a large extent on the dip of the border fault and the amount of displacement on it. Wheeler (1939), who studied the folds in the Mesozoic rocks developed as a result of differential amounts of subsidence along this fault, reviewed all the evidence then available for the dip angle on the fault. His values at different localities include 48°, 45° to 70°, 64° to 79°, 30° to 60°, and 55°. Only the last value was a direct measurement on the fault surface, but the other estimates are in general agreement with it. At an exposure of the eastern border fault produced by highway construction at a site between the Fairhaven and Higganum dikes, Digman (1950) also measured the dip on the fault to be 55°. The recent state geologic map of Massachusetts (Zen, 1983) indicates a dip of 52° on the fault near the Connecticut border. In figure 5 a dip of 55° is used to construct a simplified cross section through the southern part of the Hartford Basin along the line AB in figure 1. Other smaller faults within the basin have been omitted for simplicity, and the dips on the dikes have been idealized because their precise dip is unknown; in general, however, they are all nearly vertical.

With a dip of 55° on the border fault, the Mesozoic basin must be lifted approx 10 km to bring the Fairhaven and Higganum dikes into line. Similar displacements are shown on this fault in Massachusetts (Zen, 1983). If this reconstruction is correct, 10 km must have been eroded from the eastern highlands of Connecticut subsequent to the faulting. Coarse fanglomerates throughout the Portland formation, which lies stratigraphically above the lava flows, as well as in the sedimentary units between the flows, attests to considerable relief along this fault for an extended period of time. Of particular importance in this fanglomerate at Durham, Conn., are large boulders of basalt which, although severely weathered, contain abundant relict olivine and plagioclase phenocrysts and high Cr-contents, making them similar in appearance to the Talcott basalt. This lava must therefore have extended over at least part of the eastern highlands and was not restricted to the Mesozoic basin alone. LeTourneau (personal commun.) has described boulders of Hampden basalt in a more northerly fanglomerate. The Hampden, then, also must have extended east of the border fault.

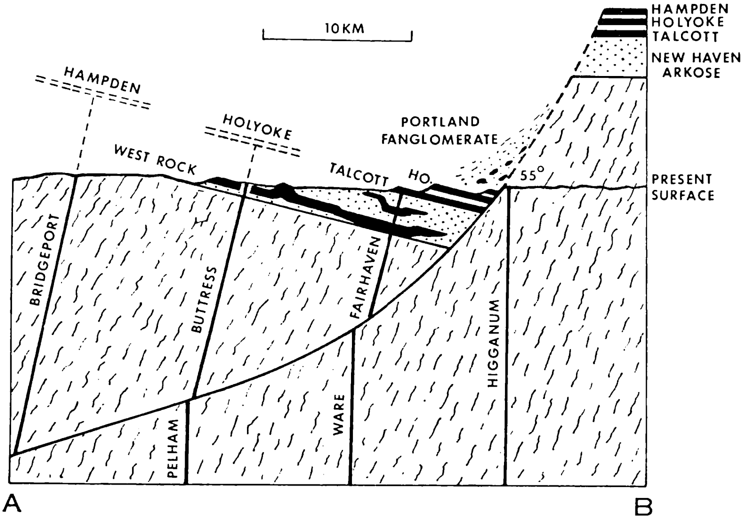


Fig. 5. Proposed cross section along line AB in figure 1 through southern part of the Hartford Basin.

Several problems are resolved by interpreting the Fairhaven dike as the downfaulted upper part of the Higganum dike. First, it accounts for the lack of any trace of the Fairhaven dike to the east of the Basin, despite the short distance between its most northern exposure and where it would intersect the eastern highlands. Its northeasterly extension would, in fact, be the Higganum dike. Second, if the Fairhaven has been offset westward by the border fault, the Buttress dike must also have been displaced by approximately the same amount. Reference to figure 1 reveals that the Buttress dike does not line up with its northeasterly extension at Ware. If, however, the southern part of the Basin is moved eastward so that the Fairhaven lies directly on the Higganum dike, the Buttress lines up with the dike at Ware. The amount of displacement between the Bridgeport and Pelham dikes is, on the other hand, very small. This, however, is to be expected, because the eastern border fault, on extending northward into Massachusetts, splays into a number of faults extending into the eastern highlands. As a result, the Bridgeport and Pelham dikes are in almost the same fault block and consequently there is little displacement between them. Furthermore, if 478,000 yrs separate the intrusions of the Higganum and Bridgeport dikes (as the cyclical lacustrine sediments suggest) and the motion on the eastern border fault was continuous through that period (as the fanglomerates between the basalt units attest), then the Bridgeport-Pelham dike would have been offset less than the Higganum-Fairhaven dike. The fact that the Buttress-Ware dike is apparently offset by the same amount as the Higganum-Fairhaven dike may indicate that significant movement on the eastern border fault did not occur until after the intrusion of the Buttress dike. More precise control on the attitudes of the dikes and faults, however, would be needed for this conclusion to be drawn with any certainty.

Finally, if the Higganum dike is the feeder to the Talcott basalt, its northeasterly trend takes it away from the Hartford Basin in the north, and, as a result, the Talcott basalt may not have been able to flow far enough westward to be exposed in the northern part of the Hartford Basin. The other two dikes, however, occur farther to the west and would have been ideally situated to have their lavas preserved in the Basin.

CONCLUSIONS

The three major regional diabase dikes in southern New England were feeders to the three Mesozoic lavas which are now preserved only in downfaulted basins. The oldest and most easterly dike, the Higganum, fed the Talcott basalt. This dike occurs only in the eastern highlands of Connecticut and Massachusetts where the level of exposure of the dike is believed to correspond to a depth of approx 10 km at the time of intrusion. A short segment of the upper part of this dike has been downfaulted into the Hartford Basin where it forms the Fairhaven dike. Approx 10 km to the west of this is the Buttress-Ware dike which fed the younger Holyoke basalt, and still another 10 km farther west is the Bridgeport-Pelham dike which fed the youngest, Hampden, basalt.

Each of the dikes has a distinct chemical composition. The Fairhaven dike is chemically identical to the Higganum dike. Compositional variations within each dike and within the lavas can be attributed in most cases to fractional crystallization. The only exceptions are the Mg-rich samples of Talcott basalt which are thought to have been affected by alteration. In the younger two magmatic events, the dike rocks consist of less evolved material than the lava flows, suggesting that zoned magma chambers were tapped. This does not appear to have been the case in the first magmatic period, where the dikes and lavas have the same general composition. The presence of partially resorbed Cr-rich orthopyroxene, which was probably a primary liquidus phase at pressures in excess of 8 kb, is thought to indicate that this first magma rose rapidly from its source. It may be a primary magma.

Correlation of the dikes with the lavas indicates that the igneous activity progressed westward with time, and although new fractures were used during successive episodes, the dikes are all parallel. They cut the regional Appalachian trends and the Mesozoic basins at a small angle and thus probably reflect tensional stresses in the lower part of the lithosphere. The eastern border fault of the Hartford Basin is thought to have a displacement of approx 10 km on it, but none of the dikes has taken advantage of this fracture, which indicates that either faulting succeeded magmatism, or, if it did not, the faults did not provide ready zones of access for magma at the times of intrusion.

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