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LATE PROTEROZOIC STRATIGRAPHY AND STRUCTURE IN THE AVALONIAN MAGMATIC ARC, SOUTHWEST OF BOSTON, MASSACHUSETTS

MARGARET D. THOMPSON
Geology Department,
Wellesley College, Wellesley, Massachusetts 02181

ABSTRACT. The Avalon zone in southeastern New England contains calc-alkaline granitoids and volcanic rocks formed during Late Proterozoic arc magmatism. Southwest of Boston, Massachusetts, arc-related units include the Dedham Granite, rhyolitic ash-flow tuffs of the Mattapan Volcanic Complex, and the Westwood Granite. Roxbury Conglomerate and interbedded Brighton Volcanics overlying these "basement" units have previously been interpreted as distinct rift-related deposits formed during the tectonic transition from Avalonian magmatic arc to stable Cambrian platform. The present study shows that several east-northeast-trending faults control thickness changes and clast assemblage variations in the conglomerate, thus strengthening the case for Late Proterozoic rifting. The calc-alkaline Brighton Volcanics, however, are here expanded beyond traditionally accepted interbeds near the base of the Roxbury Conglomerate to include geochemically similar andesites and basaltic andesites on the west side of the map area formerly assigned to the Mattapan Volcanic Complex. The expanded Brighton Volcanics with minor sedimentary interbeds measure at least 2100 m on the west and interfinger eastward with the Roxbury Conglomerate to form a volcanic-sedimentary complex that is locally conformable on the Mattapan Volcanic Complex. These relationships indicate continuing arc magmatism throughout Roxbury deposition. In this context, the Roxbury/Brighton Complex (proposed name) is interpreted as graben fill in depressions reflecting intra-arc extension as found in modern and ancient arc systems. The Avalonian arc/platform transition should be sought stratigraphically above the Roxbury/Brighton Complex.

INTRODUCTION

The volcanic arc model first proposed for Late Proterozoic volcanic, plutonic, and associated volcaniclastic sedimentary rocks in the Avalon Peninsula of Newfoundland (Hughes, 1970; Hughes and Bruckner, 1971) was soon extended to correlative assemblages in the northern Appalachians and the British Isles (Rast and others, 1976). This relatively undeformed arc sequence, together with overlapping platformal Cambrian strata containing Atlantic realm trilobite faunas, comprises the Avalon tectonostratigraphic terrane. The area described here is located southwest of Boston, Massachusetts within the southeastern New England portion of this zone (inset in fig. 1, opp. p. 732). The arc interpretation for the Late Proterozoic rocks in this area derives primarily from the calc-alkaline character and trace element geochemistry of granitoids (Dedham, Esmond, and Westwood) and felsic volcanic rocks (Lynn Volcanic Complex and Mattapan Volcanic Complex) (Hermes and others, 1981; Smith and Hon, 1984; Hermes and Murray, 1990). Available U-Pb zircon ages from these rocks fix magmatic activity between 650 to 600 Ma (Kaye and Zartman, 1980; Zartman and Naylor, 1984; Hermes and Zartman, 1985; Markus and others, 1993).

Late Proterozoic Cambridge Argillite and Roxbury Conglomerate of the Boston Bay Group (Lenk and others, 1982) cap calc-alkaline "basement" units around Boston. Several recent interpretations construe Roxbury Conglomerate deposition in terms of rifting that dismembered the former magmatic arc (Hon and Smith, 1987; Nance, 1990; Rast and Skehan, 1990; Smith and Socci, 1990). The present study supports rift-related conglomerate sedimentation based on evidence that several faults (both long known and newly recognized) in the map area were active syndepositionally with the Roxbury Conglomerate and associated Brighton Volcanics (altered basalts and andesites also called the Brighton Melaphyre by LaForge, 1932; Billings, 1929 and 1976; Zen, 1983). The calc-alkaline Brighton Volcanics (Cardoza and others, 1990), however, are here shown to be thicker and more laterally extensive than previously thought, indicating that arc volcanism continued significantly throughout Roxbury deposition. The interfingering Roxbury/Brighton Complex (proposed name) is interpreted to have accumulated in a graben that was an integral part of the Avalonian magmatic arc and thus to record intra-arc extension as found in modern and ancient arc systems.

BRIGHTON VOLCANICS

The Brighton Volcanics appear in the accepted stratigraphy of Boston as approx 200 m of intermediate to mafic flows, pyroclastic rocks, and intrusive rocks near the base of the 1310 m thick Roxbury Conglomerate (fig. 1 *in* Billings, 1976). This representation is based on surface mapping in Brookline and Newton, Massachusetts, augmented by subsurface sections in water supply, drainage and sewerage tunnels (Billings and Tierney, 1964; Tierney and others, 1968) on the east side of figure 1. Intermediate to mafic volcanics are also found, however, west of the northwest-trending Mother Brook Fault (MBF in fig. 1; name based on LaForge, 1932) where conglomerates are rare. One basaltic series (Zmm, fig. 1) occurs near the top of the rhyolitic High Rock Tuff and thus clearly belongs to the Mattapan Volcanic Complex. A second, much thicker series of basaltic andesite and andesite extending from Eliot Hill on the west side of the map to the Mother Brook Fault has been interpreted previously both as Mattapan ("intermediate" and "laharic" members of Nelson, 1975) and as Brighton (Zen, 1983). This ambiguous series, temporarily called the western volcanic rocks below, has been re-mapped and compared geochemically with unequivocal Brighton and with mafic

Mattapan in order to establish a consistent volcanic stratigraphy in the map area.

The western volcanic rocks as exposed at Eliot Hill (S1, figs. 1 and 2) are approx 810 m thick and consist primarily of gray, green, and purple-mottled breccia, tuff-breccia, and tuff. Several flows and white to pale-green ash beds are also present. The flows are most easily recognized in thin section by sericitized plagioclase with sub-ophitic or intersertal textures (fig. 3A). Interstitial chlorite, epidote, and opaque material may be altered glass or mafic minerals. Vesicles, when present, are filled with quartz and epidote ± chlorite. The tuffs are also highly altered, but locally they retain pumice fragments (fig. 3B) and rounded ash concretions interpreted as accretionary lapilli (fig. 3C). The breccias are poorly sorted with mafic and felsic volcanic clasts ranging from less than 1 cm to tens of centimeters. Some of these breccias are matrix supported (lahars of Nelson, 1975), but others are clast supported and thus may represent lag deposits of pyroclastic flows ("co-ignimbrite lag-fall deposits" of Wright and Walker, 1977) or hyperconcentrated flood flow deposits (Smith, 1986).

Conglomerate and sandstone are also present at Eliot Hill (fig. 2). Some of these are epiclastic facies in the volcanic sequence. For example, conglomerate at Station 644 in figure 1 (projected into the covered interval in the middle of fig. 2) is green and contains abundant subangular intermediate-mafic volcanic clasts typically ranging from a few millimeters to 2 cm in size. Some of the clasts are jasper, which has not been reported in typical Roxbury Conglomerate east of the Mother Brook Fault (further discussion of clast assemblages in later section). Sandstone at Station 644 contains pale pink- to buff-colored ash laminations. More typical of the eastern Roxbury Conglomerate are gray to purple conglomerate and associated trough cross-bedded sandstone at the top of figure 2 and at Station 635 and vicinity in figure 1. These conglomerates contain subrounded clasts measuring 2 to 8 cm and have clast assemblages dominated by felsic volcanic lithotypes.

The western volcanic rocks with minor sedimentary interbeds continue northeastward from Eliot Hill to the Mother Brook Fault. The north-dipping sequence comprising stratigraphic column S2 in figure 1 measures approx 2100 m. Above this, outcrop is poor, and the only visible bedding is in penetratively deformed breccia and tuff (sample loc. 3 and 4 in fig. 1) which strike nearly parallel to the S2 section line. Because of these structural complications, the total thickness of the western volcanic sequence remains uncertain. Nevertheless, it appears to be considerably thicker than unequivocal Brighton Volcanics interbedded with the Roxbury Conglomerate on the east side of the map area.

Four new XRF analyses from the western volcanic rocks (analyses 1-4 in table 1) were compared for possible geochemical correlation with available analyses for unequivocal Brighton Volcanics (16 published analyses, table 2a *in* Cardoza and others, 1990; five additional unpublished analyses *in* Durfee-Cardoza, ms) and mafic Mattapan (analyses 5

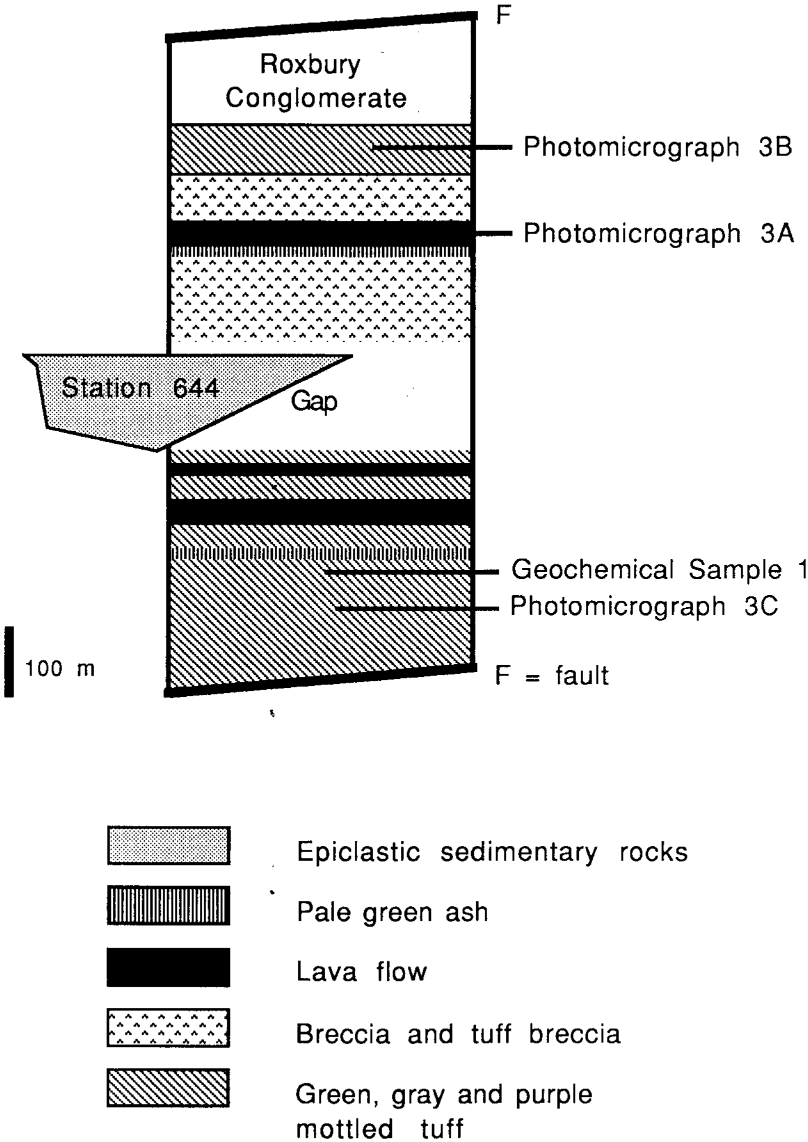

Fig. 2. Stratigraphic sequence at Eliot Hill (S1 on the west side of fig. 1) consists of andesitic and basaltic andesitic flows and pyroclastics with minor sedimentary interbeds. Sedimentary interbeds in the middle of the column (projected eastward from Station 644 in fig. 1) include green, jasper-bearing conglomerate that differs from typical gray-to-purple Roxbury Conglomerate at the top of the section. Thickness of section below Roxbury Conglomerate is approx 810 m.

and 6 in table 1). This approach has some inherent limitations. First of all, major elements in unequivocal Brighton analyses are referenced to unignited powders so that some samples have low totals compared to new analyses in table 1 which are referenced to ignited powders. Furthermore, both data sets show alkali mobility manifested by K_2O/Na_2O ratios, sometimes higher but usually lower than normal, probably reflecting the pervasively altered condition of analyzed samples.

Geochemical comparison reveals that all three groups of volcanic rocks overlap in terms of individual major element abundances. Both the western volcanic rocks and the mafic Mattapan fall virtually entirely within published major element ranges for unequivocal Brighton Volcanics (last column in table 1). More instructive for correlation is a variation diagram showing TiO_2 versus Al_2O_3, elements considered immobile in altered volcanic rocks (Winchester and Floyd, 1977). On this plot (fig. 4A), western volcanic samples cluster nicely with unequivocal Brighton samples, while the two mafic Mattapan samples fall well outside this cluster (sample 5 with much higher Al_2O_3, sample 6 with much higher TiO_2). These data support a correlation between the western volcanic rocks and the unequivocal Brighton Volcanics. Both are clearly distinct from rhyolitc ash-flow tuffs (plotted as felsic Mattapan in fig. 4A) that form the bulk of the Mattapan Volcanic Complex. Without wider sampling, however, it remains unclear whether or not the mafic Mattapan is truly separate from the Brighton Volcanics.

SiO_2 in the expanded Brighton (unequivocal Brighton and western volcanic rocks) varies from 49.12 to 61.56 wt percent (table 1). Ratios of immoble trace elements plotted according to Winchester and Floyd (1977) indicate compositions from basalt to andesitic basalt to andesite (fig. 4B). Rare earth signatures are calc-alkaline in character (Cardoza and others, 1990).

RELATIONSHIP BETWEEN BRIGHTON VOLCANICS AND ROXBURY CONGLOMERATE

Stratigraphic columns from several parts of the map area (S1, S2, and S3 in fig. 1; fig. 5) show dramatic changes in the thickness and position of the Brighton Volcanics with respect to the Roxbury Conglomerate. On the west side of the map area, approx 810 m of Brighton Volcanics underly 200 m of Roxbury Conglomerate in column S1, whereas in column S2 somewhat thicker conglomerate interbeds occur approx 380 m above the exposed base of a predominantly volcanic section measuring approx 2100 m. East of the Mother Brook Fault in column S3, there are approx 50 m of volcanic rocks near the base and approx 500 m of volcanic rocks near the top of a 2200 m section composed mainly of Roxbury Conglomerate.

All three stratigraphic columns are truncated at the bottom by the Eliot Fault (proposed name; EF in fig. 1) which passes eastward from Eliot Hill and south of the John Eliot School (geochemical sample loc. 3 in fig. 1) into Newton. In the absence of any regionally distinctive marker bed, the Eliot Fault has been taken as a reference level for tying these

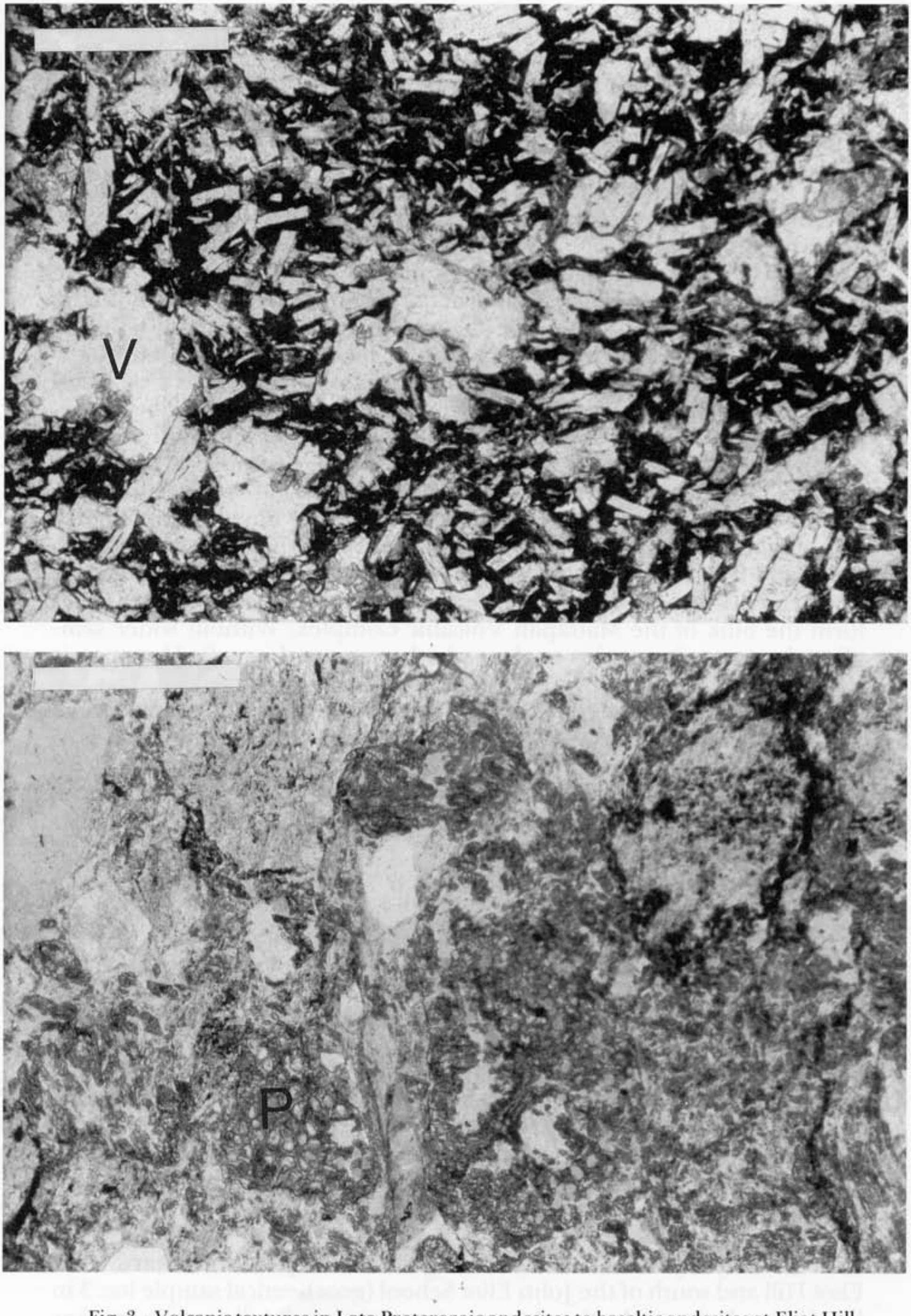

Fig. 3. Volcanic textures in Late Proterozoic andesites to basaltic andesites at Eliot Hill, Massachusetts. (A) Flow showing plagioclase laths (white) and interstitial epidote, chlorite and opaque minerals (dark). Vesicles (V) are filled with quartz and epidote. Scale bar 1 mm; plane light. (B) Relict pumice altered to sericite and epidote. Tubular texture is preserved in lapilli marked P. Scale bar 1 mm; plane light.

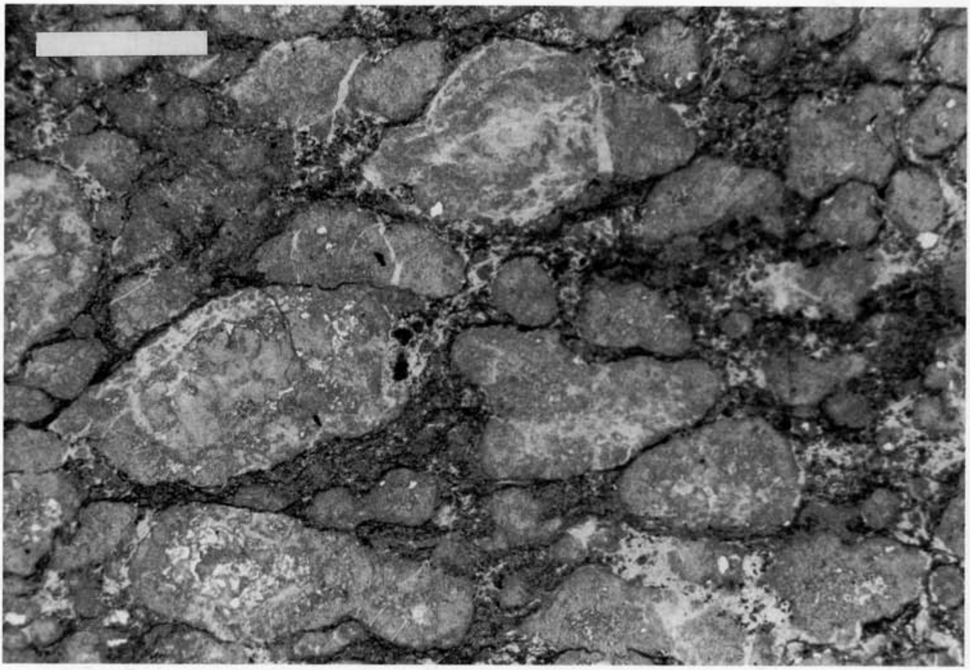

Fig. 3(C) Rounded ash concretions interpreted as accretionary lapilli are slightly flattened and altered to sericite, epidote, and quartz. Darker matrix contains more epidote and opaque minerals. Scale bar 1 mm; plane light.

stratigraphic columns together. The resulting cross section (fig. 5) is necessarily schematic but serves to illustrate an interfingering relationship between thick Brighton Volcanics on the west and thick Roxbury Conglomerate on the east.

Socci and Smith (1987, 1990) have questioned the usefulness of the historic subdivision (dating from Emerson, 1917) of Roxbury Conglomerate into Brookline, Dorchester, and Squantum Members. The interpretation shown in figure 5 further challenges accepted stratigraphy which portrays the Brighton Volcanics as a thin sequence near the base of the conglomerate. Roxbury/Brighton Complex is here proposed as a more accurate descriptor for this regionally interfingering volcanic/sedimentary assemblage.

EVIDENCE FOR LATE PROTEROZOIC NORMAL FAULTING

Late Proterozoic rifting has commonly been invoked in depositional interpretations of the Roxbury component of the Roxbury/Brighton Complex (for example, Galli and Bailey, 1986; Socci and Smith, 1987; Rast and Skehan, 1990). Several faults in figure 1 define a pattern of east-northeast-trending fault blocks in which the Roxbury Conglomerate

TABLE 1

Sample†	Western Volcanic Rocks* 1	2	3	4	Mafic Mattapan* 5	6	Unequivocal Brighton Volcanics Cardoza and others, 1990; Durfee Cardoza, 1987
X-ray fluorescence Analyses, %							
SiO_2	58.78	54.55	53.76	53.23	52.90	48.90	49.12-61.56
TiO_2	1.14	1.12	1.32	1.28	1.38	2.10	0.94-1.47
Al_2O_3	15.99	17.22	17.15	16.64	22.30	16.32	15.79-20.03
Fe_2O_3§	7.62	9.02	9.48	9.39	8.53	11.85	6.08-10.16
MgO	3.13	4.18	4.13	3.90	4.00	7.45	2.64-9.24
CaO	3.70	7.10	8.03	10.68	2.90	5.55	2.76-9.74
Na_2O	4.93	4.05	4.36	3.33	3.53	7.23	1.61-7.84
K_2O	3.84	1.93	0.87	0.42	4.16	0.33	0.19-4.45
MnO	0.12	0.15	0.15	0.16	0.18	0.11	0.09-0.27
P_2O_5	0.41	0.44	0.58	0.39	0.45	1.09	0.20-0.79
Total	99.65	99.64	99.33	99.82	100.33	100.93	
X-ray fluorescence Analyses, ppm							
Rb	96.6	57.8	19.2	11.8	99.9	9.8	1-93
Sr	254.1	1465.8	995.2	1232.8	268.0	1073.1	414-1652
Y	36.7	18.0	21.1	16.9	12.4	17.3	14-27
Zr	269.4	213.7	236.3	195.2	139.6	237.6	109-244
Nb	17.9	9.0	11.4	8.6	6.4	8.6	1-13
Ba	715.5	698.5	910.4	404.5	1666.8	176.9	254-1803
La	28.9	26.0	33.5	33.2	13.1	77.4	17.26-40.09
Ce	60.8	60.1	63.7	60.1	55.6	152.6	37.77-86.46
Zn	78.7	100.9	104.6	80.5	133.3	127.9	86-246
Ni	46.6	57.1	50.8	44.7	28.7	109.4	23-202

* Western volcanics (west side of fig. 1 between Eliot Fault and Mother Brook Fault) and mafic Mattapan analyzed by O. Don Hermes, University of Rhode Island.

† Numbered localities for samples 1 to 6 shown in figure 1 are described in app. 1; localities for unequivocal Brighton samples are un-numbered in figure 1.

§ Total iron.

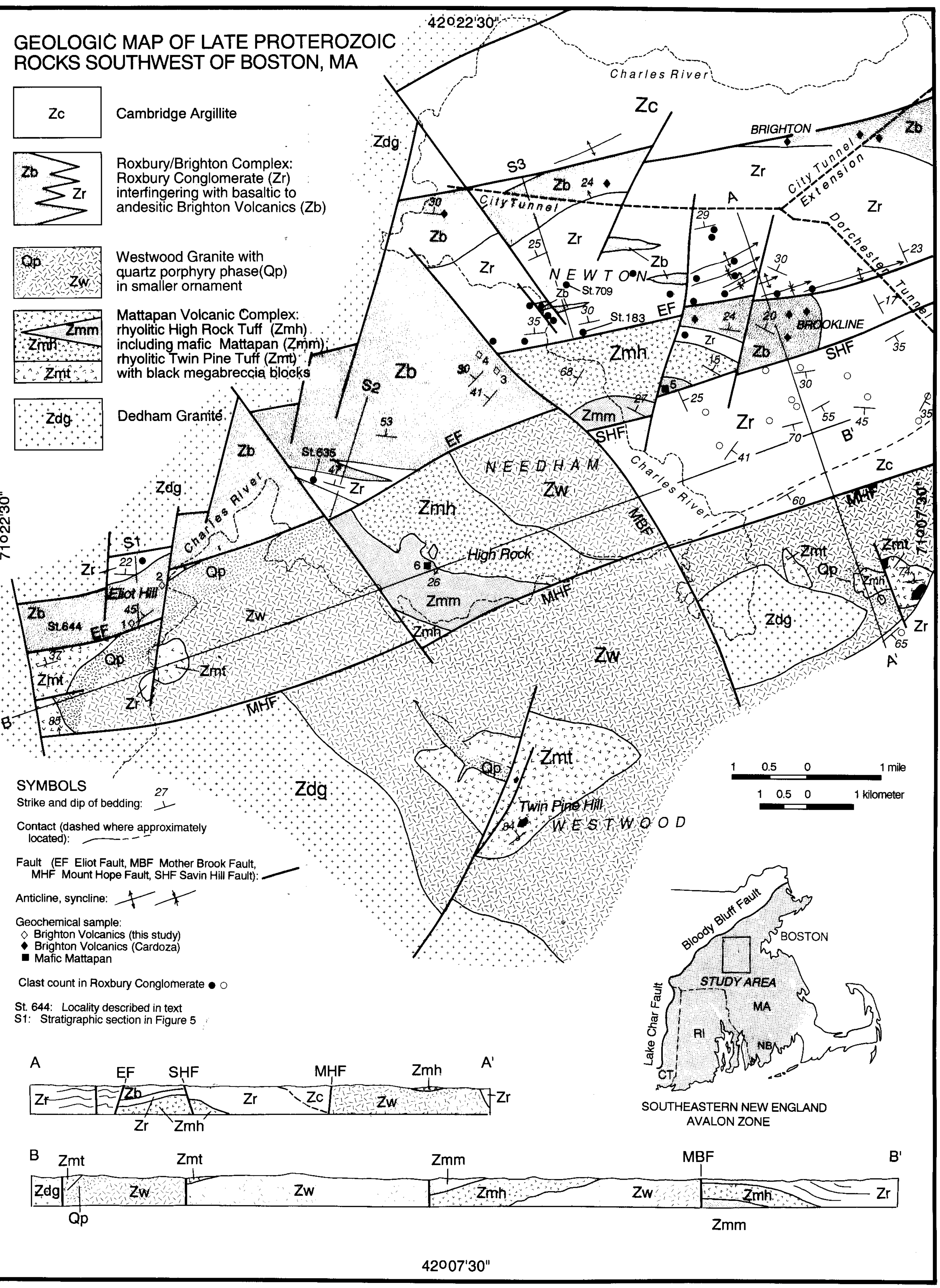

Fig. 1. Geologic map of Late Proterozoic rock formations, southwest of Boston, Massachusetts. Avalon zone of southeastern New England stippled in inset map.

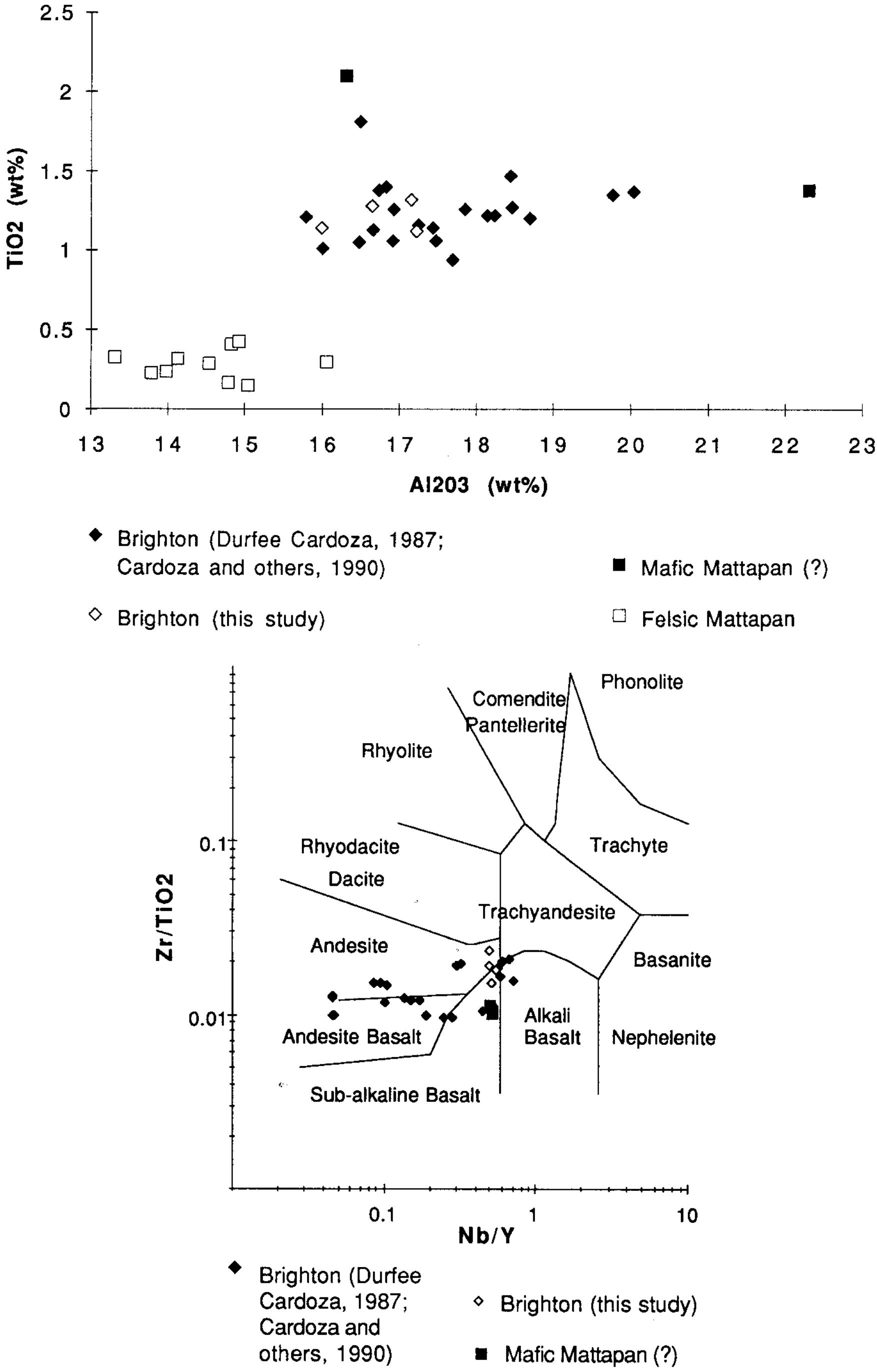

Fig. 4. Geochemical comparison between unquivocal Brighton Volcanics (interbedded with Roxbury Conglomerate) and other intermediate to mafic volcanic rocks southwest of Boston, Massachusetts. Sample localities shown in figure 1 and detailed in app. 1. (A) TiO_2 versus Al_2O_3; (B) Zr/TiO_2 versus Nb/Y classification diagram after Winchester and Floyd (1977).

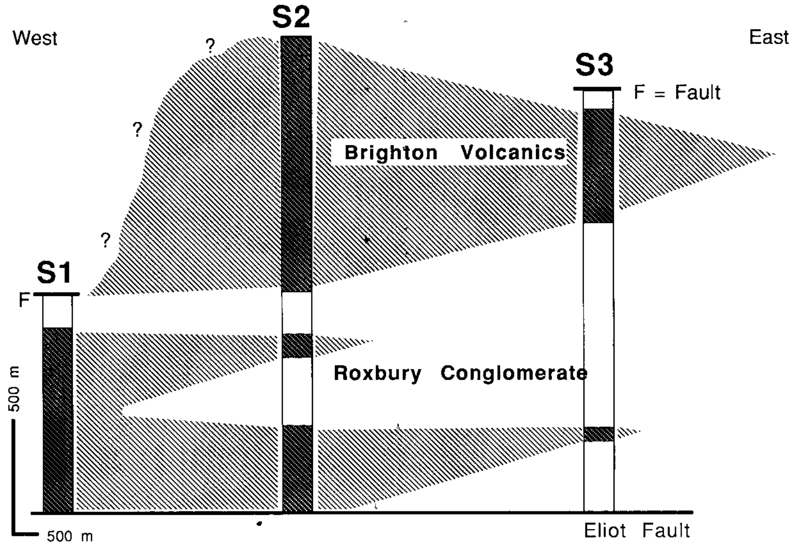

Fig. 5. Proposed east-west interfingering between Late Proterozoic Brighton Volcanics (shaded) and Roxbury Conglomerate (unornamented). Lighter shading where volcanics inferred between control columns S1, S2, and S3 (loc. in fig. 1).

differs in thickness, in clast assemblage, and in its basal relationship to older formations. The Brighton Volcanics are also variably developed in different fault blocks. These variations can be interpreted in terms of Late Proterozoic faulting contemporaneous with conglomerate deposition and volcanism. The faults include the Mount Hope Fault (Billings, 1929; MHF in fig. 1), the Savin Hill Fault (LaForge, 1932; SHF in fig. 1) known from previous mapping and the proposed Eliot Fault (EF in fig. 1).

The Mount Hope Fault which dips 85°N (west side of fig. 1 and Richardson, 1977) controls two primary variations in the Roxbury Conglomerate. The conglomerate changes thickness markedly across the fault from several hundred meters on the south to approx 1500 m on the north (sec. AA′). Basal relations of the Roxbury/Brighton Complex also change across the Mount Hope Fault. South of the fault, south-dipping conglomerate rests unconformably on unroofed Westwood Granite and included pendants of Mattapan Volcanic Complex. The basal contact is not exposed between the Mount Hope Fault and the Savin Hill Fault, but, between the Savin Hill Fault and the Eliot Fault, the section west of AA′ passes upward from Mattapan Volcanic Complex (High Rock Tuff) through 100 m of Roxbury Conglomerate into Brighton Volcanics. The uniform dips of all these units as well as a conglomerate interbed (too thin to show at the scale of fig. 1) near the top of the High Rock Tuff indicate a conformable, gradational contact.

Other primary features in the Roxbury/Brighton Complex vary across other faults. First, Brighton Volcanics are present north of the Eliot Fault and between the Eliot and Savin Hill faults but absent between the Savin Hill and Mount Hope faults. Second, clast assemblages in the Roxbury Conglomerate differ across the Savin Hill Fault as determined from stretched line counts of 100 clasts in localities indicated by circles in figure 1 (Summa, ms; fig. 6). Two apices in this diagram represent significant stratigraphic associations of rock types rather than individual lithologies. Pre-Mattapan units, including coarse-grained Dedham Granite and quartzite of presumed Westboro Formation (described by Bell and Alvord, 1976, and Bailey, 1984), are combined as one apex. Felsic volcanic rocks together with Westwood Granite and associated porphyries related to the Mattapan caldera cycle (Thompson and Hermes, 1990) are combined as the second apex. Intermediate to mafic volcanic rocks and breccias defining the third apex are not stratigraphically restricted, because these lithologies are found both in the mafic Mattapan and in the Brighton Volcanics. This group forms less than 20 percent of most clast assemblages.

Conglomerate from stations north of the Eliot Fault and Savin Hill Fault (solid circles in figs. 1 and 6) tends to contain more pre-Mattapan clasts than conglomerate between the Savin Hill Fault and the Mount Hope Fault, which generally contain more felsic volcanics rocks and Westwood Granite (open circles in figs. 1 and 6). Individual stratigraphic columns do not show upward enrichment in basement clasts as would be expected if the clast variation simply reflected progressive erosion through Mattapan/Westwood source rocks into older units. The lowest conglom-

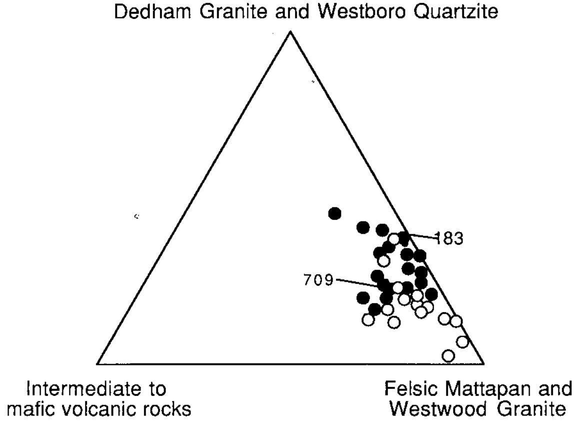

Fig. 6. Clast assemblages in Roxbury Conglomerate based on counts of 100 clasts at stations marked by circles in figure 1. Conglomerates north of the Savin Hill Fault (solid circles) tend to be richer in lithotypes resembling Dedham Granite and Westboro Quartzite than conglomerates south of the Savin Hill Fault (open circles) which contain more felsic Mattapan volcanic rocks and Westwood Granite. Detailed locations of clast count stations given in app 1.

erate at Station 183 in column S3, for example, contains a more basement-rich clast assemblage than higher conglomerate at Station 709 (figs. 1 and 6). An alternative interpretation, which accounts for thickness as well as clast assemblage variations, is that conglomerates were deposited in slightly separated depressions fed by distinct source areas.

The foregoing evidence suggests that the Mount Hope Fault, the Savin Hill Fault, and the Eliot Fault are Late Proterozoic normal faults defining an east-northeast-trending system of syndepositional horsts and graben. According to this interpretation, movement on the Mount Hope Fault controlled uplift and erosion to the south of the fault versus subsidence and thick conglomerate accumulation in a graben extending northward across the map area for a minimum width of 10 km. The east-northeast structural grain is complicated westward by the northwest-trending Mother Brook Fault (MBF in fig. 1) cutting a Westwood Granite-cored dome (cross section BB′ in fig. 1) which probably formed during magmatic resurgence following Mattapan caldera eruptions (Needham Dome of Thompson and Hermes, 1990). The major sediment transport directions in the Roxbury Conglomerate are northerly and east-northeasterly (Socci and Smith, 1987), so clast assemblages immediately north of the Mount Hope Fault are dominated by felsic Mattapan/Westwood lithotypes shed from the Mount Hope footwall block as well as the Needham Dome (fig. 7). The block between the Savin Hill Fault and the Eliot fault is interpreted as a small horst (1–2 km wide in cross section AA′) upthrown within the major graben early in the Brighton volcanism, so that most Brighton eruptions were confined to the north side of this barrier. Here northerly transport supplied Mattapan/Westwood lithotypes while east-northeast transport brought Dedham Granite and Westboro Quartzite lithotypes from source areas west of the map area (fig. 7 and Zen, 1983).

The Mount Hope Fault has been described previously as a north-directed thrust subsequently rotated to a north dip (Billings, 1929 and 1979). Microfabrics localized in the north walls of both the Mount Hope Fault and the Eliot Fault, however, indicate north-over-south transport (Thompson and Burks, 1992). The proposed late Proterozoic normal faults in the Boston area may thus have been reactivated during Late Paleozoic (Alleghanian) compression inferred from thrust faults in neighboring parts of the New England Avalon zone (Thompson and Skehan, 1992).

DISCUSSION

Significance of Rifting

Calc-alkaline granitoids and related volcanic rocks (Dedham Granite, Westwood Granite, Mattapan Volcanic Complex) are usually highlighted in discussions of arc magmatism in the Avalon zone around Boston, Massachusetts. Stratigraphic data presented above show that calc-alkaline basaltic to andesitic units in the overlying Roxbury/

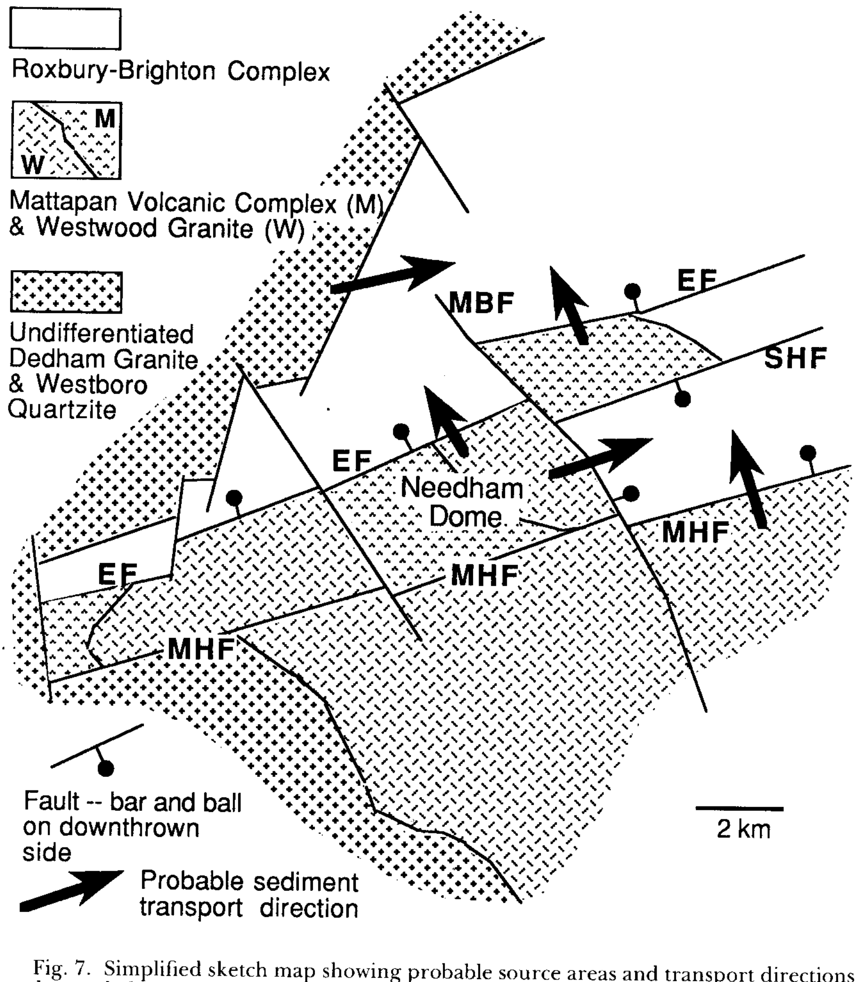

Fig. 7. Simplified sketch map showing probable source areas and transport directions for observed clast assemblages in Roxbury Conglomerate. EF, Eliot Fault; MBF, Mother Brook Fault; MHF, Mount Hope Fault; SHF, Savin Hill Fault.

Brighton Complex are more than 2000 m thick, thus recording significant ongoing magmatism in the Avalonian arc. Structural analysis in the previous section further indicates that the Roxbury/Brighton Complex is ponded in a graben floored by deeper units of the arc (Mattapan Volcanic Complex, Westwood Granite) and bounded by syn-volcanic/syn-depositional normal faults. The overall stratigraphic and structural picture suggests that the Avalonian arc around Boston resembles active systems in which intra-arc extension (or transtension) is the typical regime in the plate above a subducting slab (Hamilton, 1988 and authors cited by him). Several modern analogues are discussed below.

The Taupo Volcanic Zone, New Zealand which is located at the southern termination of the Tonga-Kermedec arc (Karig, 1970) coincides with a north-northeast-trending, 16 to 24 km wide structural basin filled with Quaternary pyroclastic deposits (volcano-tectonic depression of Van Bemmelen, 1949). Gravity data place basement at depths exceeding 2000 m below sealevel in most of the basin (Modriniak and Studt, 1959). Rhyolitic volcanism within this zone involves pyroclastic flows, caldera collapse, and dome formation at the Taupo, Maroa, Okataina, and Rotorua centers. Basaltic and andesitic to dacitic eruption centers also follow north-northeast alignments presumably controlled by the same regional faults that bound a series of tilted fault blocks across the volcanic zone (Cole, 1979).

Overlapping arc magmatism and rifting are also documented in Sumatra which sits above the Indian Plate as it descends obliquely northward into the Sunda Trench (Hamilton, 1979). Here the modern magmatic arc, which approximates rhyodacite (granodiorite) in bulk composition, culminates the "geanticlinal" Barisian Mountains where summit elevations reach 3000 m. Also present along the belt of active volcanism are rift valleys arising from right lateral strike slip faulting. A fault trough cuts conspicuously through the welded tuff sheet around Lake Toba, a 500 m deep moat associated with an immense (87 km long by 31 km wide) Late Pleistocene caldera. Volcanic centers associated with extension are found in the Andean arc as well (Zeil, 1979) where graben-like depressions in Chile ("valle longitudinal"), Bolivia (salar Uyuni and Altiplano), and Columbia (Cauca and Magdalena graben) are flanked by volcanoes towering thousands of meters above the valley floors. Thick Cenozoic sediments have accumulated during deep subsidence of the graben-like sections, so that 12,000 m of non-marine molasse are reported in the upper Magdalena valley (Van Houten and Travis, 1968), and profiles across the Bolivian Altiplano reveal 14,000 m of sedimentary deposits (Evernden, Kriz, and Cherroni, 1977).

The modern examples cited above show that intra-arc graben depressions are commonly associated with modern magmatic arcs. An example from the Mesozoic arc of western North America further indicates that such depressions can be filled with deposits closely resembling the Roxbury/Brighton Complex. Lithostratigraphic sections from Arizona, California, and western Nevada show sediments closely associated with siliceous to mafic calc-alkaline (and minor alkalic) volcanic rocks (Busby-Spera, 1988). For the present discussion, the 4.5 km thick, vertically, and laterally discontinuous pyroclastic/effusive/epiclastic sequence from the Lower Jurassic Mount Wrightson Formation in Arizona is especially instructive. Mount Wrightson lithofacies are grouped into four facies assemblages (Riggs and Busby-Spera, 1990) including (1) near-vent facies, hypabyssal intrusives, and dacite lava flows; (2) proximal intermediate lava flows, ignimbrites (that is, welded pyroclastic flows), and debris flows; (3) medial ignimbrites, debris flows, and reworked pyroclastic deposits; and (4) distal non-welded ignimbrites and fluvial deposits. The succession of lava flows, pyroclastic flows, and breccias with subordinate volcaniclastic sedimentary rocks on the west side of the Roxbury/Brighton Complex at Eliot Hill (fig. 2) resembles proximal facies in this scheme, whereas the dominantly sedimentary S3 section east of the Mother Brook Fault could represent distal parts of the facies succession. The paucity of debris flows and burial of near-vent facies in the Mount Wrightson Formation was interpreted by Riggs and Busby-Spera to suggest that these deposits were the product of a low-relief volcanic complex rather than a high-standing central volcano. Near-vent facies are not represented in the Roxbury/Brighton Complex, but the low proportion of coarse breccias in the Brighton Volcanics (fig. 3) suggests that the Roxbury/Brighton Complex may record a similar low-relief complex.

Avalonian Arc-platform Transition

The Avalonian magmatic arc around Boston, Massachusetts was succeeded by platformal shales, siltstones, and minor limestones of the Lower Cambrian Weymouth Formation and Middle Cambrian Braintree Slate (LaForge, 1932). The Roxbury/Brighton Complex with its calc-alkaline volcanic component and locally conformable basal contact with the underlying, arc-related Mattapan Volcanic Complex probably represents a waning arc assemblage rather than a distinct transitional package separating arc and platform assemblages as suggested by Nance (1990). If the mafic Mattapan proves to be geochemically similar to the Brighton Volcanics as is indicated by the limited data base of this paper, the continuity of the arc throughout the Late Proterozoic would be further reinforced. Recent U-Pb dating of the alkaline Dartmouth pluton near New Bedford, Massachusetts (NB in fig. 1 inset) as 595 ± 5 Ma indicates here at least that post-collisional granite immediately succeeded calc-alkaline igneous activity, thus suggesting that some portions of the Avalonian arc closed down abruptly (Hermes and Zartman, 1992). Given the 602 ± 3 Ma age of the Mattapan Volcanic Complex (U-Pb age from Kaye and Zartman, 1980), the proposed continuity of the magmatic arc into Roxbury/Brighton time is consistent with this view. The Avalonian arc-platform transition should thus be sought stratigraphically above the Roxbury/Brighton Complex, either in the Late Proterozoic/Cambrian unconformity (Rast and Skehan, 1983) or even perhaps within the Cambridge Argillite, part of which overlies the Roxbury/Brighton Complex. The subdivision of The Cambridge Argillite into argillaceous and tuffaceous units (Kaye, 1980) is potentially significant and should be further explored.

CONCLUSION

Observations presented above argue for several revisions in the stratigraphy and structure of the Late Proterozoic Brighton Volcanics and Roxbury Conglomerate which overly Avalonian arc-related granitoids (Dedham Granite, Westwood Granite) and volcanic rocks (Mattapan Volcanic Complex) southwest of Boston, Massachusetts: (1) The Brighton Volcanics correlate geochemically with calc-alkaline basaltic to andesitic volcanics measuring at least 2100 m thick on the western side of the map area which have formerly been assigned to the Mattapan Volcanic Complex. (2) The expanded Brighton Volcanics interfinger eastward with the Roxbury Conglomerate, and the resulting Roxbury/Brighton Complex is locally conformable on the Mattapan Volcanic Complex. (3) The distribution of the Brighton Volcanics and the thickness and clast assemblages of the Roxbury Conglomerate vary across the east-northeast-trending Mount Hope Fault, Savin Hill Fault, and Eliot Fault (proposed name) which are interpreted as syndepositional/synvolcanic normal faults. Although the Roxbury/Brighton Complex has previously been interpreted as distinct rift-related deposits formed during the tectonic transition from Avalonian magmatic arc to stable Cambrian platform, the preceding conclusions are more consistent with intra-arc extension as found in modern and ancient arc systems. The Avalonian arc/platform transition should be sought above the Roxbury/Brighton Complex.

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APPENDIX I

Sample localities for new XRF analyses reported in table 1 and for numbered stations in figure 1 and text. Coordinates are relative to Universal Transverse Mercator grid in indicated quadrangle.

Sample 1. $^{46}80^{625}$N, $^{3}07^{400}$E in Natick Quadrangle: Broadmoor Wildlife Sanctuary
Sample 2. $^{46}81^{175}$N, $^{3}07^{750}$E in Natick Quadrangle: west side of Deep Woods Drive
Sample 3. $^{46}86^{025}$N, $^{3}15^{213}$E in Newton Quadrangle: north side of Eliot School playground
Sample 4. $^{46}86^{275}$N, $^{3}14^{950}$E in Newton Quadrangle: west entrance into St. Mary Cemetery
Sample 5. $^{46}85^{200}$N, $^{3}18^{900}$E in Newton Quadrangle: north side of Nahanton Road
Sample 6. $^{46}81^{550}$N, $^{3}13^{800}$E in Natick Quadrangle: northwest corner of White Pine Road and Gatewood Drive
Station 183. $^{46}86^{525}$N, $^{3}17^{150}$E in Newton Quadrangle: north side of Cheney Street
Station 635. $^{46}83^{400}$N, $^{3}11^{275}$E in Natick Quadrangle: intersection of Grove Street and Dover Road
Station 644. $^{46}80^{500}$N, $^{3}05^{675}$E in Natick Quadrangle: bedrock exposures in abandoned gravel pit
Station 709. $^{46}88^{450}$N, $^{3}16^{800}$E in Newton Quadrangle: turn-around at end of Silver Birch Road

REFERENCES

Bailey, R. H., 1984, A Precambrian continent margin sequence (slope deposits and olistostromes), Boston North Quadrangle, Massachusetts, *in* Hanson, L. S., editor, Geology of the Coastal Lowlands, Boston, Massachusetts to Kennebunk, Maine: New England Intercollegiate Geological Conference, 76th Annual Meeting, Salem, Massachusetts, Guidebook, p. 145–164.

Bell, K. G., and Alvord, D. C., 1976, Pre-Silurian stratigraphy of northeastern Massachusetts, *in* Page, L. R., editor, Contributions to the stratigraphy of New England: Geological Society of America Memoir 148, p. 179–216.

Billings, M. P., 1929, Structural geology of the eastern part of the Boston Basin: American Journal of Science, 5th series, v. 18, p. 97–137.

——— 1976, Geology of the Boston Basin: Geological Society of America Memoir 146, p. 5–30.

——— 1979, Boston Basin, Massachusetts, *in* Skehan, J. W., and others, The Mississippian and Pennsylvanian (Carboniferous) systems in the United States—Massachusetts, Rhode Island and Maine: United States Geological Survey Professional Paper 1110-A, p. A15–A20.

Billings, M. P. and Tierney, F. L., 1964, Geology of the City Tunnel Extension, Greater Boston, Massachusetts: Journal of the Boston Society of Civil Engineers, v. 53, p. 116–141.

Busby-Spera, C. J., 1988, Speculative tectonic model for the early Mesozoic arc of the southwest Cordilleran United States: Geology, v. 16, p. 1121–1125.

Cardoza, K. D., Hepburn, J. C., and Hon, R., 1990, Geochemical constraints on the paleotectonic settings of two late Proterozoic mafic volcanic suites, Boston-Avalon Zone, Eastern Massachusetts, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 113–131.

Cole, J. W., 1979, Structure, petrology, and genesis of Cenozoic volcanism, Taupo Volcanic Zone, New Zealand—a review: New Zealand Journal of Geology and Geophysics, v. 22, p. 631–657.

Durfee Cardoza, K., ms, 1987, Geochemistry of the Middlesex Fells Volcanics (mafic member) and Brighton Volcanics, Boston-Avalon zone, eastern Massachusetts: M. S. thesis, Boston College, Chestnut Hill, Massachusetts, 130 p.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: United States Geological Survey Bulletin 597, 289 p.

Evernden, J. F., Kriz, S., and Cherroni, C. M., 1977, Potassium-argon ages of some Bolivian rocks: Economic Geology, v. 72, p. 1042–1061.

Galli, K. G., and Bailey, R. H., 1986, Secular variation in sandstone composition and sedimentary tectonics: Boston terrane, eastern Massachusetts: Geological Society of America Abstracts with Programs, v. 18, p. 17–18.

Hamilton, W. B., 1979, Tectonics of the Indonesian Region: United States Geological Survey Professional Paper 1078, 345 p.

——— 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100, p. 1503–1527.

Hermes, O. D., Gromet, L. P. and Zartman, R. E., 1981, Zircon geochronology and petrology of plutonic rocks in Rhode Island, *in* Boothroyd, J. C., and Hermes, O. D., editors, Guidebook to geologic field studies in Rhode Island and adjacent areas: New England Intercollegiate Geologic Conference, 73d Annual Meeting, Kingston, Rhode Island, Guidebook, p. 315–338.

Hermes, O. D., and Murray, D., 1990, Geochemical distinctions of Late Proterozoic and Paleozoic volcanism in the Avalon zone of New England, *in* Socci, A. D. Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 97–112.

Hermes, O. D., and Zartman, R. E., 1985, Late Proterozoic and Devonian plutonic terrane within the Avalon zone of Rhode Island: Geological Society of America Bulletin, v. 96, p. 272–282.

——— 1992, Late Proterozoic and Silurian alkaline plutons within the southeastern New England Avalon zone: Journal of Geology, v. 100, p. 477–486.

Hon, R., and Smith, C. J., 1987, Boston Basin: an aborted Late Proterozoic transcurrent rift: Geological Society of America Abstracts with Programs, v. 19, p. 19.

Hughes, C. J., 1970, The Late Precambrian Avalonian orogeny in Avalon, southeast Newfoundland: American Journal of Science, v. 269, p. 183–190.

Hughes, C. J., and Bruckner, W. D., 1971, Late Precambrian rocks of eastern Avalon Peninsula, Newfoundland—a volcanic island complex: Canadian Journal of Earth Science, v. 8, p. 899–915.

Karig, D. E., 1970, Ridges and basins of the Tonga-Kermedec Island arc system: Journal of Geophysical Research, v. 75, p. 239–254.

Kaye, C. A., 1980, Bedrock geologic map of the Boston North, Boston South and Newton Quadrangles: United States Geological Survey Map MF 1241, scale 1:24,000.

Kaye, C. A., and Zartman, R. E., 1980, A Late Proterozoic Z to Cambrian age for the stratified rocks of the Boston Basin, Massachusetts, U. S. A., *in* Wones, D. R., editor, The Caledonides in the USA: Blacksburg, Virginia, Virginia Polytechnic Institute and State University Memoir 2, p. 257–261.

LaForge, L., 1932, Geology of the Boston area, Massachusetts: United States Geological Survey Bulletin 839, 105 p.

Lenk, C., Strother, P. K., Kaye, C. A., and Barghoorn, E. S., 1982, Precambrian age of the Boston Basin: new evidence from fossils: Science, v. 216, p. 619–620.

Markus, R., Dunning, G., and Hon, R., 1993, Geochemistry and zircon geochronology of Late Proterozoic leucogranites north of Boston, Eastern Massachusetts: Geological Society of America Abstracts with Programs, v. 25, p. 61.

Modriniak, N., and Studt, F. E., 1959, Geological structure and volcanism of the Taupo-Tarawere district: New Zealand Journal of Geology and Geophysics, v. 2, p. 654–684.

Nance, R. D., 1990, Late Precambrian-early Paleozoic arc-platform transitions in the Avalon terrane of the Northern Appalachians; review and implications, *in* Socci, A. D. Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 1–11.

Nelson, A. E., 1975, Bedrock geologic map of the Natick Quadrangle, Middlesex and Norfolk Counties, Massachusetts: United States Geological Survey Map GQ 1208, scale 1:24,000.

Rast, N., O'Brien, B. H., and Wardle, R. J., 1976, Relationships between Precambrian and Lower Paleozoic rocks of the "Avalon Platform" in New Brunswick, the northeast Appalachians and the British Isles: Tectonophysics, v. 30, p. 315–388.

Rast, N., and Skehan, J. W., 1983, The evolution of the Avalonian plate: Tectonophysics, v. 100, p. 257–286.

Rast, N., and Skehan, J. W., 1990, The Late Proterozoic geologic setting of the Boston Basin, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 235–247.

Richardson, S. M., 1977, Geology of the Dorchester Tunnel, greater Boston, Massachusetts: Journal of the Boston Society of Civil Engineers, v. 63, p. 247–269.

Riggs, N. R., and Busby-Spera, C. J., 1990, Evolution of a multi-vent volcanic complex within a subsiding arc graben depression: Mount Wrightson Formation, Arizona: Geological Society of America Bulletin, v. 102, p. 1114–1135.

Smith, C., and Hon, R., 1984, Geology, petrology and origin of the Precambrian igneous rocks in the area north of Boston, *in* Hanson, L. S., editor, Geology of the Coastal Lowlands, Boston, Massachusetts to Kennebunk, Maine: New England Intercollegiate Geological Conference, 76th Annual Meeting, Salem, Massachusetts, Guidebook, p. 292–309.

Smith, G. A., 1986, Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process: Geological Society of America Bulletin, v. 97, p. 1–10.

Smith, G. W., and Socci, A. D., 1990, Late Precambrian sedimentary geology of the Boston Basin, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 75–84.

Socci, A. D. and Smith, G. W., 1987, Recent sedimentological interpretations in the Avalon terrane of the Boston Basin, Massachusetts: Maritime Sediments and Atlantic Geology, v. 23, p. 13–39.

——— 1990, Stratigraphic implications of facies within the Boston Basin, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 55–74.

Summa, C. L., ms, 1983, Clast assemblages in the Brookline Member of the Roxbury Conglomerate, Newton Quadrangle, Massachusetts: stratigraphic and depositional significance: Honors thesis, Wellesley College, Wellesley, Massachusetts, 77 p.

Thompson, M. D., and Burks, R. J., Shear band fabric in Late Proterozoic Roxbury Conglomerate, Boston, MA: Geological Society of America Abstracts with Programs, v. 24, p. 81.

Thompson, M. D., and Hermes, O. D., 1990, Ash-flow stratigraphy in the Mattapan Volcanic Complex, greater Boston, Massachusetts, *in* Socci, A. D. Skehan, J. W., and Smith, G. W., Geology of the composite Avalon terrane of southern New England: Geological Society of America Paper 245, p. 85–96.
Thompson, M. D., and Skehan, J. W., 1992, Re-evaluating the Boston "Basin": Northeastern Geology, v. 14, p. 102–107.
Tierney, F. L., Billings, M. P., and Cassidy, M. M., 1968, Geology of the City Tunnel, Greater Boston, Massachusetts: Journal of the Boston Society of Civil Engineers, v. 55, p. 60–96.
Van Bemmelen, R. W., 1949, The geology of Indonesia, v. IA: The Hague, Government Printing Office, 732 p.
Van Houten, F. B., and Travis, R. B., 1968, Cenozoic deposits, upper Magdalena Valley, Columbia: American Association of Petroleum Geologists Bulletin, v. 87, p. 481–495.
Winchester, J. A., and Floyd, P. A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–343.
Wright, J. V., and Walker, G. P. L., 1977, The ignimbrite source problem: significance of a coignimbrite lag-fall deposit: Geology, v. 5, p. 729–732.
Zartman, R. E., and Naylor, R. S., 1984, Structural implications of some radiometric ages of igneous rocks in southeastern New England: Geological Society of America Bulletin, v. 95, p. 522–539.
Zeil, W., 1979, The Andes, a geological review: Berlin, Gebruder Borntraeger, 260 p.
Zen, E-an, editor, 1983, Bedrock geologic map of Massachusetts: United States Geological Survey, scale 1:250,000.