AN INTEGRATED STUDY OF THE BLUE HILLS PORPHYRY
AND RELATED UNITS
QUINCY AND MILTON, MASSACHUSETTS

by

SUZANNE SAYER
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ABSTRACT

A field and petrologic study, including two new chemical analyses and trace element determinations on three samples, was undertaken to define possible subvarieties of the Blue Hills porphyry, a member of the Blue Hills Igneous Complex. It is concluded that, the Blue Hills porphyry is geologically and mineralogically a single unit, dominantly granite porphyry, which grades into a porphyritic granite on one side. The Blue Hills porphyry becomes more aphanitic with fewer phenocrysts near the contact with the country rocks. Textural variations correlate well with the topographic features: the higher the elevation the more aphanitic the Blue Hills porphyry becomes.

The outcrop at the Route 128-28 intersection has traditionally been interpreted as a "fossil soil zone", but on the basis of detailed field and petrographical studies, it is reinterpreted as an extrusive facies of the Blue Hills porphyry. The controversial "spheroidal" unit with eutaxitic features, the extremely variable textures of the Blue Hills porphyry, and high-temperature pseudomorphs of quartz, all indicate that the Blue Hills porphyry was emplaced at relatively shallow depths.

Results of trace element analyses of the Quincy granite and Blue Hills porphyry are nearly identical and confirm the long-held belief that the two units are comagmatic. Thus, the Blue Hills porphyry intrusion is nearly contemporaneous with the Quincy granite.

The Blue Hills porphyry and Quincy granite are both younger than the aporhyolite member of the Blue Hills Igneous Complex. The aporhyolite is tentatively correlated with the Mattapan, Lynn and Newbury volcanics, with its interbedded Siluro-Devonian fossils. The Quincy granite yields an Pb^{207}/Pb^{206} age of 437±32 MY. Hence, volcanic activity occurred in the Boston area starting with the aporhyolite, at least 437± 32MY ago and continued for at least 25 MY until the late Silurian Newbury volcanics.

Thesis Advisor: Richard S. Naylor

Title: Associate Professor of Geology

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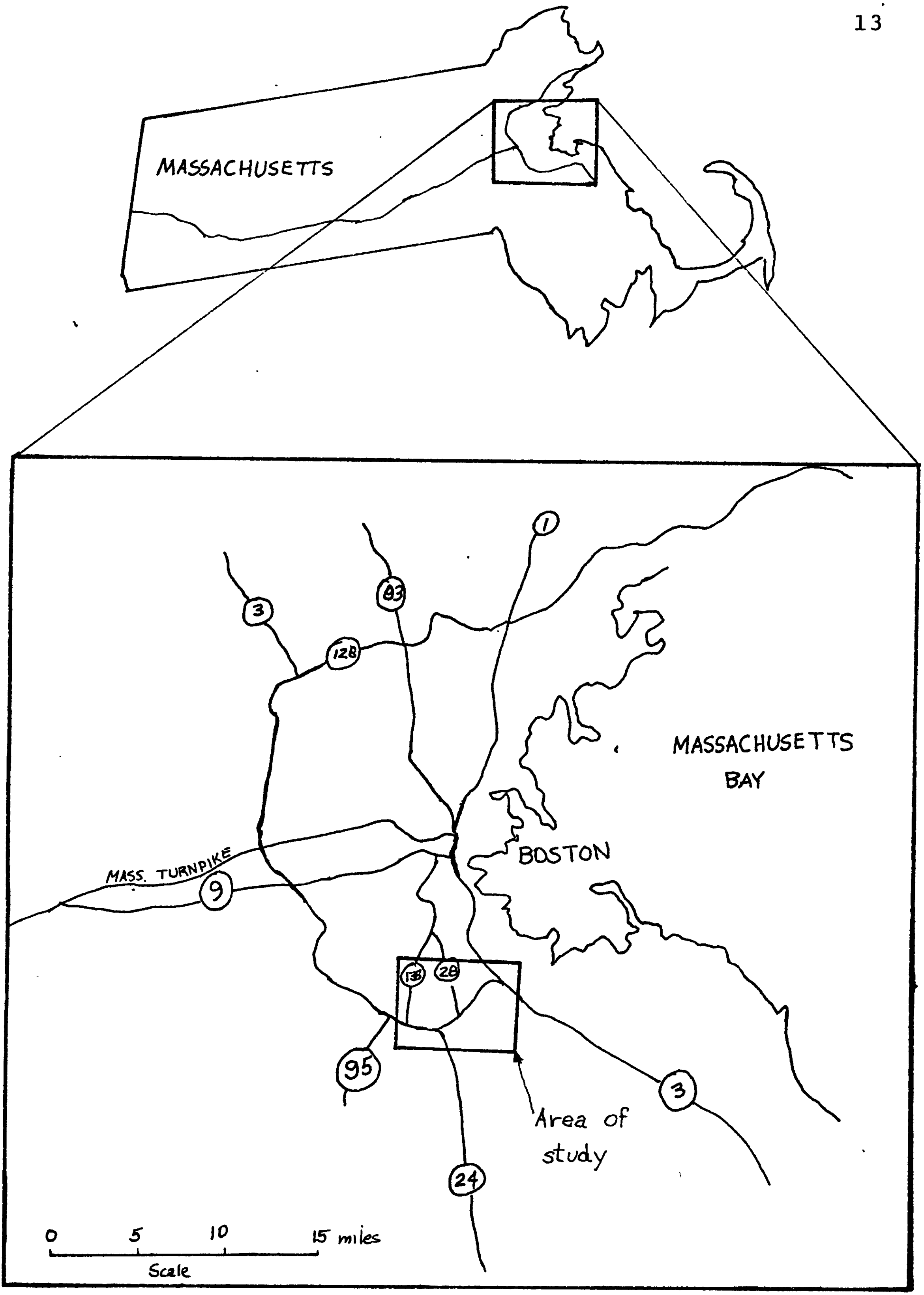
MASSACHUSETTS
MASSACHUSETTS BAY
BOSTON
MASS. TURNPIKE
1
93
3
128
9
138
28
95
24
3
Area of study
0
5
10
15 miles
Scale

INDEX MAP

I. INTRODUCTION

The purpose of this thesis is to restudy the Blue Hills porphyry member of the Blue Hills Igneous Complex. The previous isotopic age determinations, new trace element data, and major element chemical analyses are combined with new field studies of the Blue Hills porphyry, aporhyolite, and Quincy granite. The area of this study is limited to the Blue Hills, south of Boston, in Milton and Quincy, Massachusetts (see Index Map).

The whole Boston area, including the Blue Hills, has been affected by large scale tectonic disturbances (Quinn, 1971; Woodward, 1957; Rodgers, 1952, 1967; and Lyons and Faul, 1968), and by repeated glaciations which have obscured many important relationships. Thus, identification of units, and of their stratigraphic position, has proved controversial (Quinn and Moore, 1968).

The Blue Hills Igneous Complex is composed of the fine-grained riebeckite granite, the Blue Hills porphyry, the aporhyolite, and the Quincy granite.

Crosby (1880) noted that the Blue Hills Igneous Complex is younger than the middle-Cambrian Braintree argillite, and all subsequent geologists have agreed with this conclusion. Similarily, it is widely agreed that the Complex antedates the Pennsylvanian aged rocks of the Norfolk and Narragansett Basins (Knox, 1944; Woodworth, 1894; Shaler, Woodworth and Foerste, 1899). From fossil evidence alone, no more precise limits can be placed on the Blue Hills Igneous Complex.

The isotopic ages are contradictory to the classical interpretation of the temporal emplacement of the units within the Complex (Crosby, 1900, 1905; LaForge, 1909, 1932; Warren, 1913; Chute, 1940). Isotopic dating of these rocks has proved confusing (Bottino, 1963a, 1963b, 1966, 1968; Bottino, Fullager, Fairbairn, Pinson and Hurley, 1970; Bottino, Pinson, Fairbairn and Hurley, 1963; Zartman, Brock, Heyl and Thomas, 1966). The ages obtained by three methods differ widely although all the isotopic ages are within the limits imposed by fossil evidence (Zartman and Marvin, 1971). Despite disagreements about relative ages, most previous studies (Crosby, 1900; Warren, 1913; Chute, 1940, 1950, 1964, 1966, 1969) have agreed on a genetic relationship between the units of the Blue Hills Igneous Complex. The Quincy granite and Blue Hills porphyry are both slightly peralkaline, containing similar, distinctive accessory and trace minerals such as riebeckite, aegirine, astrophyllite and aenigmatite.

A novel departure from the conventional hypothesis regarding the origin of the Blue Hills Igneous Complex was suggested by D. R. Wones and D. K. Riley (1971, personal communication). Their hypothesis is based on the following observations:

1) Both,Warren (1913) and Crosby (1900) in their earlier writings about the Blue Hills porphyry, described different varieties, i. e., the quartz-porphyry, the granite porphyry, and the paisanite porphyry.

2) Bottino (1963a, 1963b) reported an Rb-Sr whole-rock age of 245± 10 MY for the Blue Hills porphyry and a 325± 15 MY age for the Quincy granite. The Blue Hills porphyry isochron is based on samples selected near the contact of the Blue Hills porphyry with the Pondville conglomerate. These ages, if taken literally, suggest at least part of the Blue Hills porphyry might be related to the Carboniferous Wamsutta volcanics (Lytton, 1941; Eaton, 1925; Coomerswamy and Ray, 1954) and not to the older Blue Hills Igneous Complex.

3) A roadcut, made in the early sixties at the intersection of Massachusetts Routes 128 and 28, exposes the contact of the Pondville Conglomerate with the Blue Hills porphyry. Certain gradational features, formerly attributed to a fossil soil zone, can be interpreted as being volcanic or pyroclastic

(G. Boone, personal communication).

4) According to Chute (1969) the Blue Hills porphyry is younger than the Quincy granite and older than the Pondville conglomerate, thus setting the upper and lower limits for the emplacement of the Blue Hills porphyry.

The above facts and speculations led Wones and Riley to suggest that the Blue Hills porphyry can be divided into two or more units. Hence, they hypothesized that at least part of the Blue Hills porphyry could be a Carboniferous aged agglomerate underlying the Pondville conglomerate. Therefore, the systematic, yet contradictory, results of the age dating could be attributed to sampling different units.

One objective of this study is to test the Wones and Riley hypothesis stated above. This warrants a thorough review of all the available data. In order to correlate field relationships with the latest evidence from isotopic data, the field relationships within the Blue Hills Igneous Complex and with the surrounding units have been reviewed and were examined in more detail than in previous geochronological studies.

In the period from 1971 to 1974 four months were spent studying the rock units of the Blue Hills Igneous Complex and their relationships with each other and with the surrounding rocks. The results of the general field work are in Chapter II. The more extensive work on the outcrops at Routes 128-28 is described in Appendix B. Appendix A reviews the evolution of the interpretation of the relationships of these units through a literature survey.

Trace element analyses on three samples of the Blue Hills are reported and discussed in Chapter III. The isotopic ages determined for various units in the Blue Hills Igneous Complex are reviewed in Chapter IV. By pooling the data from previous investigations, observations from the various age dating techniques are made in ChapterIV. The replotting of data with the removal of marginally suitable samples yields no new information. No new isotopic ages were measured for this study although an unsuccessful attempt was made to extract zircons from the Blue Hills porphyry.

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Laboratory assistance from R. Hon, W. J. Olszewski, H. J. Noyes and L. Lopez-Escobar is greatly appreciated. I am indebted to C. A.

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II. GEOLOGIC AND TECTONIC POSITION OF THE BLUE HILLS PORPHYRY

The nomenclature used follows Chute (1969) except for the utilization of the term "aporhyolite" when referring to what he called "Mattapan volcanics" and "Blue Hills porphyry" instead of "Blue Hills granite porphyry".

The boundaries of the rock units mapped follow those of Chute (1969) (see Figure 2). Discrepancies occurred with respect to Chute's (1969) interpretation of what he observed at some contacts. Chute's (1940) earlier interpretations are felt to be more accurate. The rock units and their contacts are described in the order of their inferred age. Figure 1 should be referred to for locality names.

A. BRAINTREE ARGILLITE

The Braintree argillite is a dark-grey slate with thin beds of light and medium-grey siltstone. It is fossilferous in some localities (A. W. Grabau, in Crosby's Appendix (1900). The Braintree argillite occurs in large, oriented blocks which are thought to be roof pendants of the country rock intruded by the Blue Hills Igneous Complex (BHIC). It is metamorphosed to greenish-grey hornfels near the contact (Chute, 1969).

The middle Cambrian Braintree argillite is older than both the Quincy granite (QG), and BHP, a relationship noted by all previous

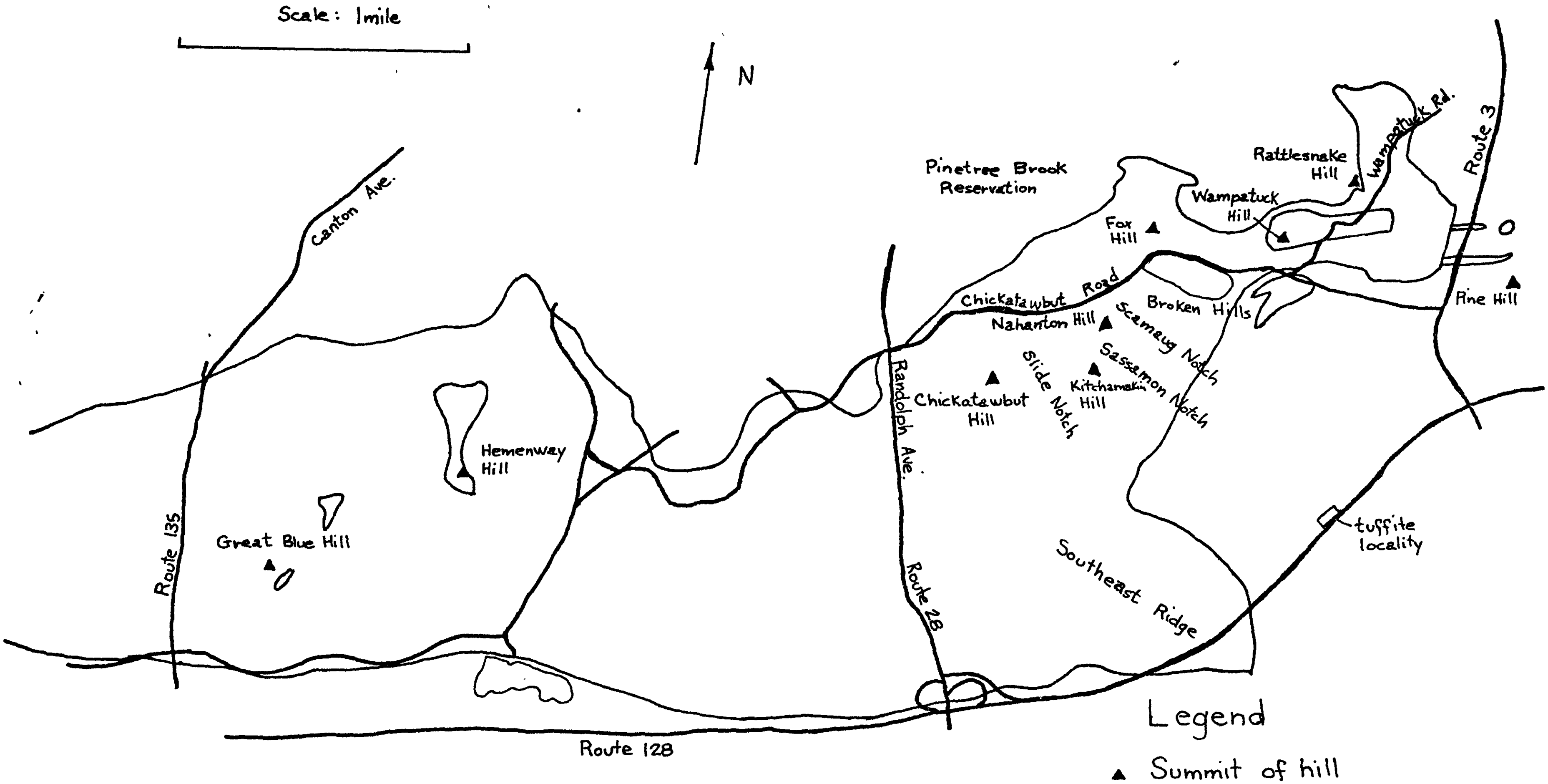


Figure 1 Geographical Names Referred to in Text

Legend

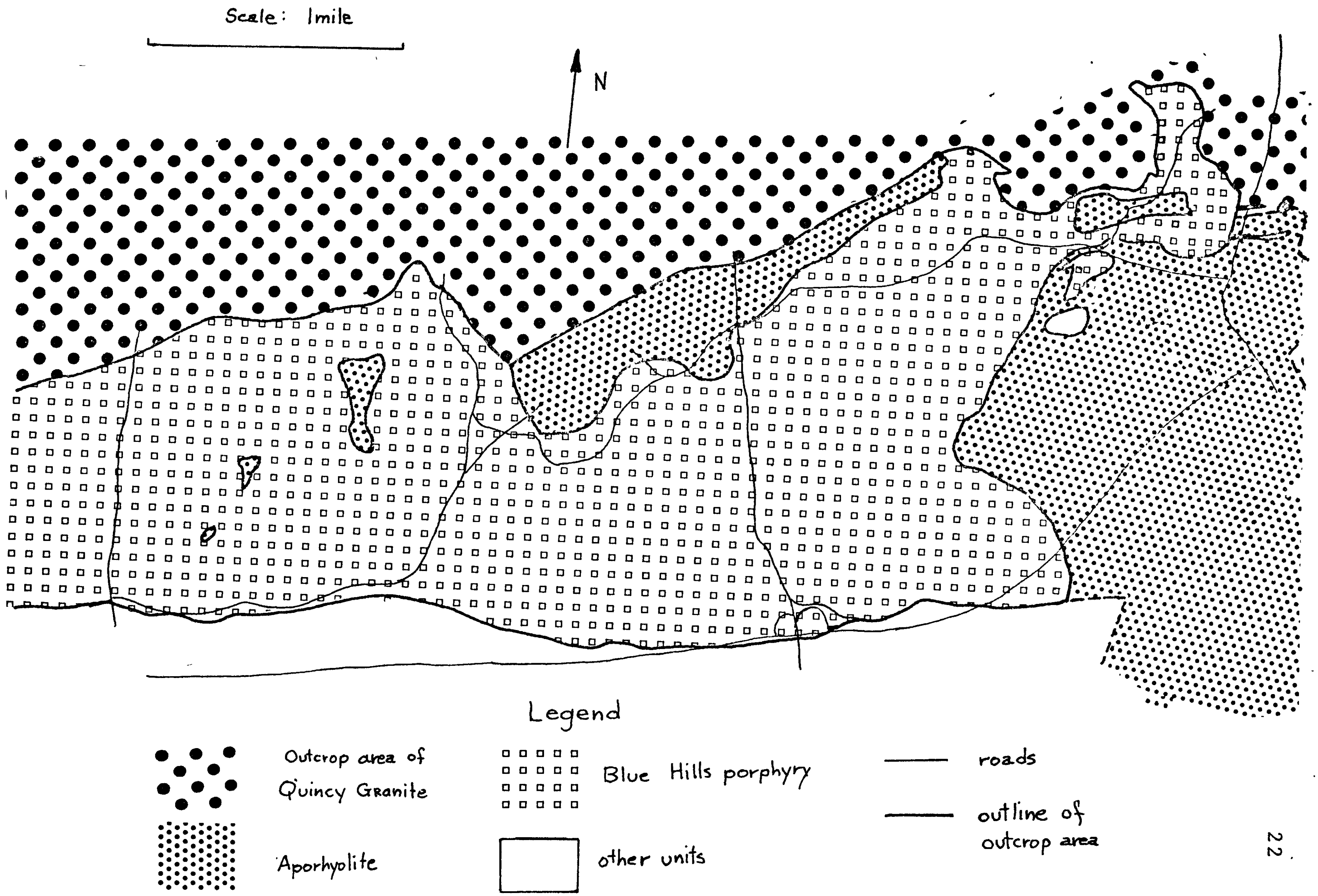
▲ Summit of hill

— outline of Blue Hills porphyry

— roads

— outline of ponds

Figure 2 Bedrock Map of Rock Units (after Chute, 1969)



workers. Minor dikes of QG cut the Braintree argillite in the locales of Canton Avenue and the Pine Tree Brook area. Slate inclusions, which are thought to be Braintree, are found in the QG on Rattlesnake Hill. Slate inclusions have also been found in the BHP in the Slide Notch area.

B. RHOMBPORPHYRY

The rhombporphyry (RP) crops out as a roof pendant in the QG near Pine Hill in Quincy. It also occurs southeast of the Broken Hills in an intrusion breccia with the QG. The Braintree argillite is often found in conjunction with the RP. This suggested to earlier workers (Crosby, 1900) that the RP was produced from a reaction of BHIC magma with the Braintree and produced this as a hybrid.

The RP has euhedral, acutely terminated, rhomb-shaped plagioclase (anorthoclase?) feldspar phenocrysts in a groundmass of fine-grained microperthite and pyroxene with some hornblende. Magnetite, pyrite, quartz, sphene, and apatite occur as accessory minerals (Chute, 1969). Augite is present as phenocrysts and as microlites in both the matrix and the feldspar phenocrysts. Epidote is found in the cores of some of the feldspar phenocrysts.

The RP is fairly abundant as xenoliths in the QG, especially near its contact with the BHP. It is also found as xenoliths in the BHP about the Slide Notch area, Chickatawbut Hill, and on the southeast side of Wampatuck Hill. Other than the three localities mentioned above, the

RP does not appear as xenoliths in the BHP.

C. APORHYOLITE

Aporhyolite was used by both Crosby (1900) and Warren (1913) to denote a devitrified and altered rock of rhyolitic composition. It will be used here to denote the same rock. Aporhyolite (AR) refers to the unit in the BHIC corresponding to the Mattapan volcanics, as named by Chute (1969). In the absence of proof that the AR correlates with the Mattapan volcanics, it seems preferable to use the older nomenclature and to retain the AR as a separate unit.

C. 1 General Description

The AR consists of interbedded pyroclastic materials and rhyolite flows (Katkins, 1969). Locally, it has obvious flow banding, and in other places it resembles a welded tuff, with elongated, flattened volcanic fragments. Some outcrops show the original volcanic textures of the unit clearly; other outcrops are completely recrystallized. Whether all occurrences of the AR belong to the same igneous episode is difficult to assess because of discontinuous field relationships and intense recrystallization features. Outcrops cannot be traced for any distance before they are lost in the woods.

The AR has an extremely fine-grained, almost aphanitic texture, and is composed mainly of anhedral quartz and feldspar. The AR generally has a few phenocrysts of microperthite and quartz. The feldspars are usually somewhat sericitized, even in the freshest looking rocks. Spherulites are common in some areas. Magnetite is always present in varying amounts, usually partially altered to hematite. Devitrified glass shards were noted as well, but they are not common. The AR is locallyporphyritic and is in some places easily confused with the chilled margins of the BHP.

The AR crops out near the summit of Great Blue Hill, on the summit of Hemenway Hill, west of Fox Hill (on Wampatuck Hill), and in a large area on the eastern side of the Blue Hills.

C.2 Outcrop Description

Great Blue Hill and Hemenway Hill - On the summit of Hemenway Hill, and near the summit of Great Blue Hill, the AR is a dirty pink rock. It is intensely recrystallized and bears little resemblance to the fresher volcanics in the area. Devitrified glass shards and spherulites were noted. Brecciated blocks of the AR are found within a rhyolitic matrix. The groundmass of both the blocks and matrix is coarsely recrystallized. Here the AR appears to have been deeply buried and may have undergone late stage hydrothermal activity. No pyroxene or amphibole was noted. Magnetite hematite and leucoxene are present in various proportions.

Wampatuck Hill - The AR on the north and western parts of Wampatuck Hill is distinctly flow-banded. The flow-banded AR occurs as alternating pink and white or yellowish-white and light green bands. Spherulites are fairly common. This area of the AR is massive, and aphanitic or only slightly porphyritic.

Fox Hill - The outcrop area to the west of Fox Hill is composed of a dense, dark reddish-purple, massive flow. Some broken pink or white feldspars occur in the AR. Hematite gives the rock a dark red color. The groundmass is an aphanitic quartz-feldspar mixture.

Eastern Part of the Blue Hills - By far the largest exposure of the AR occurs on the eastern portion of the Blue Hills Reservation. This area appears to be a big volcanic pile. It has massive outcrops of fluidal lava and units of ash flow or welded tuff. Ovoid, stretched, eutaxitic bombs occur in some areas. One locality is on the south side of Chickatawbut Road, just east of the intersection with Wampatuck Road. Also found in this area are thin units which appear to be fossil soil horizons between successive flows or falls.

A tuffite (see Figure 1) is intercalated with subaerial volcanic rocks along a roadcut on Route 128. Here, the AR is bleached to a light cream or greenish-cream color and contains pyrite or siderite. There is a large north-south fault in the vicinity that can be traced from just west of Pine Hill southward towards Great Pond. The AR in this area is remarkably fresh and only slightly recrystallized, indicating that it has never been deeply buried. This is in sharp contrast to the AR found near the summit of the Great Blue Hill which shows strong evidences of recrystallization.

D. BLUE HILLS PORPHYRY

The Blue Hills porphyry (BHP) occurs over the largest area of any rock type within the Blue Hills. The BHP varies in texture and appearance from place to place. In the past, it has been called quartz-porphyry, quartz-feldspar porphyry, and granite porphyry. No single type has ever been mapped separately. Chute (1969) "lumped" it into one single unit called "the Blue Hills granite porphyry". The name used herein is Blue Hills porphyry, dropping the descriptive term "granite" in Chute's (1969) name.

The main intent of this work was to distinguish some feature which would enable the subdivision of the BHP, in the hope of resolving the conflict produced by geochronology (see Chapter IV). This is found to be nearly impossible as the BHP is variable in its texture and color and grades from one textural facies to another and back to the original within a few paces (Crosby, 1900, p. 367, 474; Warren, 1913, p. 240).

These sharp variations in texture are characteristic of the BHP. These facies cannot be mapped as units in the BHP. Because of the rapid vertical variations in texture, the different facies occur as isolated patches within the Blue Hills. Locally, the more granitic facies occur at a lower elevation in the notches of the Blue Hills and closer to the QG. The aphanitic varieties occur closer to the aureole in the surrounding rock.

D. 1 Type Locality

The type locality of the BHP is the small quarry on the eastern flank of Rattlesnake Hill, and where Warren (1913) obtained his sample for major-element chemical analysis (see Table 2, column5). Warren (1913, p.243) gave the composition at the type locality as 40.5% feldspar, 12.4% quartz and 47.1% groundmass. The trace element abundances for this rock were determined by instrumental neutron activation analysis for this thesis (see Chapter III). The major element analysis determined by the electron microprobe may be found in Table 2, column 8 .

The BHP of the type locality is light greenish or bluish-grey to dark grey, with a medium-grained granophyric crystalline texture. It has subhedral, rounded quartz phenocrysts and euhedral, turbid feldspars.

The BHP of the type locality is light greenish or bluish-grey to dark grey, with a medium-grained granophyric crystalline texture. It has subhedral, rounded quartz phenocrysts and euhedral, turbid feldspars.

The feldspar is a mixture of albite and orthoclase, a crypto- or microperthite. It is commonly euhedral to subhedral and broken. Albitization (see Figure 3) is common along the edges and fractures in the perthite. Previous authors (such as Warren, 1913, p. 236) have determined that the albite ranges between Ab_{95}-An_5 and Ab_{97}-An_3. Antiperthite (anorthoclase) is also present.

The feldspar phenocrysts are larger and more abundant than the quartz phenocrysts. The amount and size of the phenocrysts vary greatly. The feldspars "may measure as much as 8 mm long" (Warren, 1913, p. 239). "Quartz phenocrysts maybe up to 3.5 mm long but more often are about 1 mm long" (Warren, 1913, p. 246).

Riebeckite, arfvedsonite, and aegirine occur in dense, tabular masses with poikiolitic rims. They also occur as needles in the feldspar and, more rarely, in quartz phenocrysts. Astrophyllite, aenigmatite and magnetite occur as accessories. Hematite occurs as an alteration product.

D.2 Textural Variations

The different facies of the BHP are composed of the same minerals.

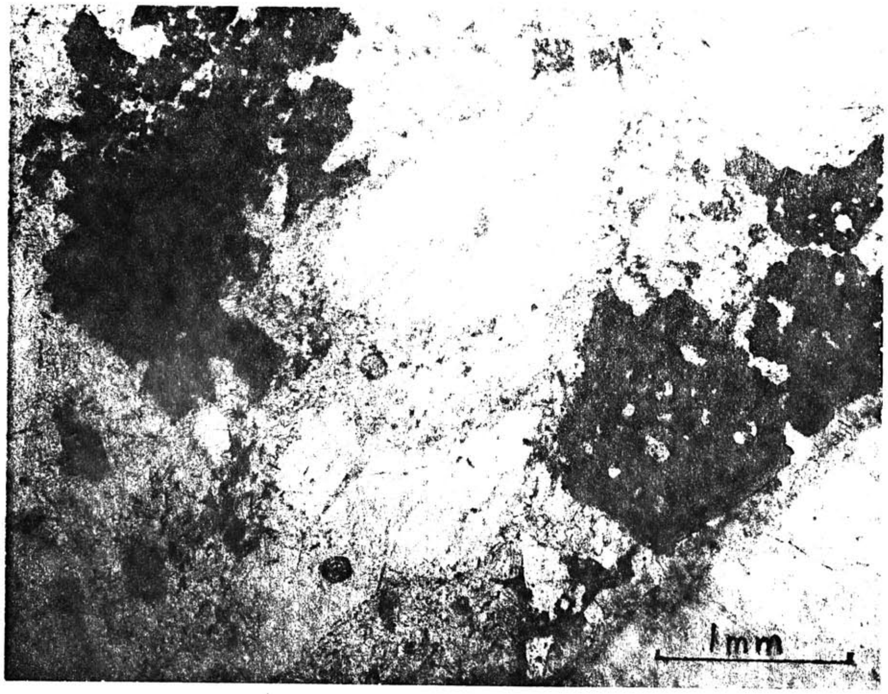


Figure 3. This is Blue Hills porphyry from the type locality on the eastern flank of Rattlesnake Hill. Poikiolitic riebeckite is prominent on either side of the center. The phenocryst in the center is a fractured, albitized feldspar with matrix intruded along the fracture. The matrix is a fine-grained quartz-feldspar mixture with needles of riebeckite altering to hematite. Riebeckite or aegirine needles are present in the quartz phenocryst in the upper right-hand corner. (Plane polarized light).

The facies differ because of different groundmass textures, different proportions of groundmass to phenocrysts, the different habits of riebeckite and aegirine, and the proportion of quartz to feldspar and alteration products.

31% to 66.5% of the rock is groundmass; 19 to 46% of the rock is microperthite phenocrysts. Quartz and a few percent riebeckite phenocrysts and accessories make up the remainder of the rock (see Table 1).

The BHP occurs in dark purple, brown, green and tan. The differences in color are due partly to superficial weathering of the rock and partly to late magmatic (deuteric?) alterations oxidizing the pyroxene, amphibole or fluid inclusions. Pink feldspars have hematite inclusions. The light-colored feldspars (possibly later feldspars) do not contain the same inclusions.

In many places the BHP shows evidence of late stage magmatic movements as the groundmass and phenocrysts are sheared. Albitization occurs along the fractures in the feldspar phenocrysts.

The textures of the BHP are probably controlled by the proximity to some contact surface and water vapor pressure. Besides the type locality described above, there is an aphanitic matrix type porphyry which generally occurs at the BHP-AR contacts, "the truely dense quartz-feldspar porphyry" (Warren, 1913, p. 240);

Sample Number Minerals Present	123	123B	15A	Ave.	28-1	GBH	Rosival Estimates**		
							I	II	III
Microperthite	27.0	39.7	46.1	26.6	32.01	30.06	40.5	32.2	19.0
Quartz	12.6	10.7	6.6	12.5	14.77	11.11	12.4	16.3	14.5
Riebeckite *	—	—	—	—	9.16	15.68			
Dark Minerals	0.8	4.6	0.2	0.8	1.68	2.48			
Ground Mass	59.6	45.0	47.1	60.1	42.85	40.52	47.1	51.5	66.5
Points Counted	500	500	1000	19,000					

Sample

123 - collected by P. Lyons - B.H.P, corner of Chickatawbut Road and Randolph Ave, Milton, Blue Hills Quadrangle, (Data from Lyons, 1969)

123B - collected by P. Lyons - B.H.P., across from Blue Hills Reservoir, Quincy (Lyons, 1969)

15A - collected by P. Lyons - B.H.P., roadcut on east side of Pine Hill, Quincy (Lyons, 1969)

Ave. — B.H.P. average of 19 analyses on stained rock slabs, from data of D. Kelly and L. Gray

range -		
feldspar phenocrysts	20.6	- 35.2 %
quartz phenocrysts	9.3	- 15.7 %
dark mineral phenocrysts	0	- 4.5 %
groundmass	31.5	- 51.0 %

28-1 - collected by L. Morgenstern, B.H.P. 1970, thin section analysis (Morgenstern, 1970)

GBH - collected by L. Morgenstern, Great Blue Hill, B.H.P. - thin section analysis (Morgenstern, 1970)

* Includes small amounts of magnetite

** Warren, 1913, p. 243

I. unaltered B.H.P., Rattlesnake Hill, average of two sections.

II. B.H.P. ledge south of Administration Road, south of Wampatuck Hill, 1.5 feet from A.R. contact,

III. B.H.P. same, three inches from contact.

TABLE 1 Modal Abundances of minerals present in the Blue Hills porphyry "the aporhyolite porphyry" (Crosby, 1900, p. 367), and even resembles the AR.

The aphanitic matrix porphyry differs from the type locality in that the riebeckite is more likely to occur as needles in the groundmass and not phenocrysts. Quartz phenocrysts are larger and outnumber the feldspar phenocrysts. This aphanitic type porphyry corresponds to Type Three porphyry of the "spheroidal" zone as described in Appendix B.

Several intermediate types between the aphanitic matrix facies and the granophyric facies occur. One of these intermediate facies has a fine-grained saccariodal matrix; a second type has prominent feldspar and quartz phenocrysts; and a third has feldspar phenocrysts more prominent than the quartz.

The fine-grained saccariodal groundmass texture facies has large blocky, euhedral feldspar and occurs as scattered patches throughout the upper portions of the Blue Hills.

In areas, such as along the roadcut on Southeast Bridge, the matrix of the saccariodal facies grades from a light green to a reddish-brown, and shows evidence of flow having occurred. Riebeckite and aegirine are not present as phenocrysts and occur only as microlites. Quartz is also of lesser importance in this variety.

Other localities of the BHP with the saccariodal to aphanitic matrix occur at Position D (see Figure 19) at the Route 128-28 outcrop. Here more abundance and larger quartz phenocrysts are present than at the Southeast Ridge exposure. Riebeckite, aegirine and feldspar are less important. The Route 128-28 outcrop is dealt with in detail in Appendix B. Where the matrix is fine-grained and much more prominent than the phenocrysts, Warren (1913, p. 242) terms the rock a "paisanite".

D.3 Contact Features of the Blue Hills Porphyry

The BHP appears to be chilled against its contact with the AR. It also forms an intrusion breccia with the AR on Hemenway Hill and Great Blue Hill. Its contact phenomena with the younger QG will be reserved for a later section.

At the contact of the BHP and AR on the corner of Randolf Avenue and Chickatawbut Road, the BHP shows characteristics that are parallel or sub-parallel to the contact. There are no abrupt or broken features within the BHP. Aegirine and riebeckite needles are prevalent in the matrix and flow around grains and earlier formed crystal clusters, or recrystallized microxenoliths. Quartz and perthite phenocrysts are present in approximately equal proportions. The quartz is strained and broken, or rounded. Aegirine is rimmed with riebeckite or arfvedsonite. The perthite lamellae are generally coarser than in any other localities of the BHP.

On the south side of Hemenway Hill, another contact of the BHP and AR occurs. Here the BHP has broken and included fragmental pieces of the AR within itself. The BHP becomes distinctly finer-grained as it approaches the contact both at Hemenway Hill and Great Blue Hill, as well as at the contact at the junction of Chickatawbut Road and Randolph Avenue. A contact between AR and BHP also occurs on the south side of a rock knob where Wampatuck Road branches from Chickatawbut Road. The contacts are very indurated and dense, probably a result of baking during contact metamorphism. There is no evidence of a weathered zone or fossil soil developed between the units. The AR does not appear to be flow-banded parallel to the contact; it is rather brecciated and "welded".

The evidence appears to favor the conclusion that the BHP intruded since at least some of the AR is older than the BHP. This was first concluded by Warren (1913, p. 256).

E. FINE-GRAINED RIEBECKITE GRANITE

The fine-grained riebeckite granite (FGRG) retains the name given to it by Chute (1969). It is a fine-grained, hypidiomorphic, pink to light grey rock, composed mainly of microperthite and quartz. In places the microperthite occurs in a micrographic intergrowth with quartz. The FGRG has riebeckite and aegirine as minor constituents which may attest to its affinity with the QG. It contains magnetite, hematite, and leucoxene as accessories.

The FGRG only occurs locally and is not an important unit in the BHIC. It crops out on the northeast side of Fox Hill between the BHP and QG. It is also found in small outcrops on the north and northwest side of Pine Hill near the contact with the BHP, QG and aporhyolite. Its exact age relationship to the RP-AR, and Braintree argillite is not known, but it is believed to be younger than all three. The FGRG is found as inclusions in the QG, and it is believed to be an earlier part of the QG intrusion (Chute, 1969).

F. QUINCY GRANITE

The Quincy granite (QG) bounds the BHP on the north in the towns of Quincy and Milton.

The QG is a coarse-grained hypidiomorphic, light-greenish or bluish-grey rock. The granite is generally massive and is slightly porphyritic near its boundaries. Light grey quartz and greyish-green to pinkish-white feldspars are present in hand specimen. Black or dark green hornblende is present in lesser amounts. In some places it is pinkish (pyrolitized?). Riebeckite-arfvedsonite and augite occur either as tabular masses with poikiolitic borders or as needles in feldspar.

The feldspars are subhedral and occur as fine perthite. Accessory minerals include fluorite, apatite, astrophyllite, aenigmatite, zircon, and monazite (see Washington, 1899, 1898, 1896; Dale, 1923; Hawes, 1908; Wadsworth, 1883, 1882, 1876; White, 1897; Warren and Palache, 1911; and Warren, 1909, p. 15, for description of the QG).

F. 1 Contacts with the Quincy granite

This section describes the contacts of the QG with the older rock units. It will try to point out that:

1) The QG is younger than the BHP as the QG develops a porphyritic border near its contacts;
2) The BHP is not chilled at the contact with the QG but the BHP is chilled at the contact with the AR;
3) There is no QG-AR contact of any note; and,
4) The QG occurs as dikes in the BHP.

Rattlesnake Hill Contact - The QG becomes slightly finer-grained and porphyritic near the contact with the BHP, as noticed by Crosby (1900) and Warren (1913). The BHP is uniform in appearance throughout the strike of the contact area.

At the "sharp" contact described by Warren (1913, p.225) and Chute (1969) on Rattlesnake Hill, the QG grades over an interval of several meters through a finer-grained granite to a slightly porphyritic granite.

At the immediate contact with the BHP the porphyritic QG changes into BHP in about 5 cm. The line of contact is marked by abundant RP xenoliths in the QG. The rock is not continuously exposed, but is covered by regolith, brush, and lichen, thus an exact contact between the QG and BHP has only been observed in one locality.

The only known exposure of the contact between the QG and BHP occurs on a slab that is rotated slightly from its original position on the edge of a small cliff on the southwest side of Rattlesnake Hill. The contact could not be followed in either direction due, in part, to the proximity of the cliff and partly to the discontinuous and covered nature of the rock adjacent to the cliff. The contact was not sampled for petrographic study due to the massiveness and smoothness of the rock slab. No other contacts between the QG and BHP were observed.

The texture of the BHP remains constant up to the contact with the younger QG and then the fine-grained matrix of the BHP is replaced by a granite matrix with larger subhedral crystals of feldspar, quartz, and poikiolitic amphiboles. There is no evidence of more abundant or larger quartz phenocrysts in the BHP, as there is at the contact with the older AR. The BHP is not finer-grained nor does it show any chilled characteristics. The groundmass is not aphanitic and the BHP resembles the BHP of the type locality.

The feldspars of the QG at the contact are whiter and have fewer riebeckite-arfvedsonite crystallites in them. The QG changes its aspect along the strike of the contact and in areas becomes very coarse, pegmatitic, aplitic or even slightly porphyritic.

Chickatawbut Hill - Numerous ledges of BHP with RP inclusions crop out. If the area is diligently searched, a granitic rock mass which is believed to be QG can be found. It is a large elongated body and resembles a dike with poorly defined contact relationships.

The contact of the coarse-grained granite with the BHP can be traced for several hundred feet, but due to the nature of the outcrops (i. e., not continuous, deeply weathered, stained, and covered with lichen and bushes), no sharp contact can be observed.

The granite from the Chickatawbut Hill locality has quartz and feldspar occurring in a granophyric intergrowth. The magnetite is poikiolitic, probably replacing riebeckite. Magnetite altering to hematite occurs with astrophyllite in the center of a perthite crystal. The granite is weathered and resembles the QG to a large degree, but it is redder than any of the QG exposures in the Blue Hills area. It is comprised basically of a pink microperthite with sparsely distributed quartz. Ferromagnesian silicates are absent; if they ever were present they have all been oxidized to magnetite or hematite, which is common in the rock. Others (M. P. Billings, personal communication; and Chute, 1969) have questioned that this is a dike of QG as asserted by Crosby (1900), Warren (1913), and Chute (1940). In hand-specimen, the rock has fewer quartz crystals than the QG and appears slightly porphyritic. The hornblende typical of the QG is absent and hematite is more abundant.

The rock was sampled and a major element chemical analysis made. The result is present in Table 2, column 7. It is similar in chemical composition to the QG. The contact of the granite and BHP is very weathered, but the texture of the rock can be seen to change in the space of a few centimeters.

Other Contacts with Blue Hills Porphyry - On Nahanton Hill another coarse-grained porphyritic rock crops out for several meters. It is coarser than the typical BHP but more porphyritic than typical QG. Xenoliths of RB and a dense aphanitic rock (either broken off chilled margin of the BHP or part of the AR) occur, reminding one of other QG-BHP contacts. The surface is jointed and covered with paint, so not identification of the dense xenoliths could be made. The coarse-grained rock is tentatively designated as the porphyritic border of the underlying QG, as it was originally described by Crosby, (1900, pp. 359, 365).

In Sassamon, Scamaug, and Slide Notches, there are other occurrences of a granite, which crops out in elongated shapes. The area was thoroughly searched by this author and no "sharp" contacts were located, although both Chute (1969) and Warren (1913, p. 210) observed sharp contacts.

Contact Features of the Quincy Granite and Aporhyolite - The contact of the QG and AR was observed along a small fault on Pine Hill. It was also noted on a roadcut where a trap dike cuts both units and the outcrop is very weathered and broken up. No clear exposure of the contact between the AR and QG was observed.

Intrusive Breccia - The QG and RP occur in a grained intrusion breccia in the area just south of the Broken Hills. The QG occurs as the matrix intruding the RP.

F.2 General Statement on Quincy Granite Contacts

The results of all the field work along the anomalous bodies of granite locally exposed between Chickatawbut and Kitchamakin Hills is, that such bodies do occur, their lithological affinities are uncertain although the chemistry points to the QG, and the petrographic examination does not rule out the QG. They appear to be dikes although their relationship to the BHP is uncertain. It is not surprising the contacts are not sharp, as both rocks are chemically and mineralogically similar, thus minimizing any contact feature such as baking or chilling.

The large, elongated, coarse-grained granite bodies occur over a considerable area and are probably related to the underlying QG. Crosby (1900) interpreted the exposure as a gradational one between the underlying QG and the chilled border of BHP (pp. 359, 364, 365-366).

Warren (1913, p. 210) and Chute (1940, p. 12) considered them to be dikes of QG cutting the BHP cover. Chute (1969) interpreted them as large xenoliths. They probably are dikes of QG or of some other granite.

G. PONDVILLE CONGLOMERATE

The Pondville conglomerate (PC) crops out on the south side of the BHIC. The clasts consist mostly of flow-banded rhyolite cobbles, rhyolite breccia cobbles, of minor amounts of quartzite pebbles, minor amounts of small dark aphanitic clasts of hornfels (probably metamorphosed Braintree argillite), and of large boulders of the FGRG. The matrix material is made up of lithic fragments derived from the rhyolite, quartz, and feldspar grains and fine-grained clay minerals. In a few localities some cross-bedding structures are evident and indicate that the PC is dipping steeply to the south. The PC passes into the tan and red sediments of the Wamsutta Formation to the south. The PC disappears under a cover of glacial drift to the east and west. Appendix B discusses the relationship of the PC and BHP.

III. MAJOR AND TRACE ELEMENT CHEMISTRY

The Blue Hills porphyry (BHP) has been associated with the Quincy granite (QG) because of features they have in common, two of these features being their chemical composition and mineralogy. The essential minerals in both rock types are quartz, microperthite, aegirine, and alkali-rich hornblende. Accessory minerals common to both units are zircon, sphene, magnetite, hematite, aenigmatite, fluorite, and occasional calcite, and astrophyllite (Warren, 1913, p. 243; Buma, Frey and Wones, 1971, p. 302).

MAJOR ELEMENT CHEMISTRY

Chemical analyses of both the BHP and QG are shown in Table 2. Because of the chemical similarities a common origin of the two rock units has been assumed (Warren, 1913, Crosby, 1900). The silica and alumina values differ only one to three percent and the variation within each intrusive is of the same magnitude. The total iron content is approximately the same despite the differences in the ferrous to ferric iron ratio in each body. The total soda and potash content remains nearly constant, and in only one case does potash occur in the lesser amount. The agpaitic ratio $\left(\frac{Na_2O + K_2O}{Al_2O_3} \right)$ clearly indicates that the QG is peralkaline.

TABLE 2 Analyses of QUINCY GRANITE, and Blue Hills Porphyry

	1	2	3	4	5	6	7	8	9
SiO_2	75.08	75.58	73.93	72.97	72.88	74.21	73.62	74.35	73.62
Al_2O_3	11.57	11.17	12.29	12.13	12.30	12.77	11.74	13.60	12.57
Fe_2O_3	2.25	1.71	2.91	2.77	1.67	2.51	~ 3.22	0.82	
FeO	0.93	1.26	1.55	1.09	2.10	2.04	~0.73	0.65	
MnO	Tr.	0.05	Tr.	Tr.	0.10	Tr.	0.03±	0.07	
MgO	0.03	0.04	0.04	0.20	0.09	1.04	0.11	0.43	0.05
CaO	0.44	0.49	0.31	0.74	0.87	0.98	0.06	1.11	0.25
Na_2O	4.21	4.03	4.66	4.61	4.43	2.17	4.11	3.71	4.68
K_2O	4.62	4.68	4.63	4.79	4.90	5.44	4.61	4.52	4.76
H_2O^+	0.19	0.34	0.41	0.35	0.31		n.d.	0.29	
H_2O^-	0.04	0.10		0.10	0.15		n.d.	0.03	
TiO_2	0.20	0.22	0.18	0.30	0.35		0.37±	0.26	0.31
P_2O_5	Tr.	Tr.	Tr.	0.20	Tr.		Tr.	0.07	0.03
ZrO_2	0.20	0.20	(.20)†	0.20	0.10		n.d.		
CO_2					0.36				
S								0.03	
Total	99.76	99.87	100.95	100.25	100.55	101.16	98.6	99.94	99.56
$\frac{Na_2O+K_2O}{Al_2O_3}$	1.03	1.05	1.05	1.05	1.02	0.74	1.002	0.81	

† assumed to be equal to previous analyses

1. Medium grey granite, Hitchcock Quarry, North Common Hill, Quincy, Mass. Analyst, C.H. Warren, 1913. p.227.
2. Very dark granite, Reinhalter Quarry, W. Quincy, from about 300 feet below surface. Analyst. C.H. Warren, 1913. p.227.
3. Medium dark granite, Hardwick Quarry, North Common Hill Analyst, H.S. Washington, 1898.
4. Slightly porphyritic phase from near contact with granite-porphyry. Quarry North side of Rattlesnake Hill, Blue Hills Reservation. Analyst, C.H. Warren, 1913. p.227.
5. Blue Hills Porphyry, east side of Rattlesnake Hill, analyst, C.H. Warren, 1913, p.260.
6. Blue Hills Porphyry, east part of Blue Hills, average of several analyses by M.I.T. students pre-1900, p.362. (Crosby, 1900)
7. Dike on Chickatawbut Hill, Electron microprobe, analyst, R. Hon, 1974, unpublished data.
8. Rhombporphyry, Pine Hill Area, analyst, C.H. Warren, 1913. p.271.
9. Blue Hills porphyry, quarry east side of Rattlesnake Hill, Electron microprobe, analyst, W.J. Olszewski, 1974 unpublished data.

The analysis of the BHP (Table 2, columns 4 and 5) by Warren (1913) indicates that the rock he sampled had a major element chemistry similar to the QG as well as a similar agpaitic ratio. The BHP analyzed by Crosby's students (Table 2, column 6) indicates that the rock is not peralkaline. The sodium content is markedly lower than in any of the other analyses, and the agpaitic ratio is definitely not peralkaline. A possible explanation for the radical difference in agpaitic ratio and chemistry is the fact that Crosby did not distinguish in the field between the RP and the BHP. Thus Crosby's (1900) data most probably included several analyses of the RP, as well as the BHP, and his results, therefore, should be considered as being somewhat suspect. The other obvious discrepancy is the M_gO content, which is much greater than in any other unit.

TRACE ELEMENT CHEMISTRY

Analytical Procedures

Instrumental neutron activation analysis (INAA) was used to determine trace element abundances in the BHP. A comparison of trace elements in the BHP and QG is useful in testing the hypothesis that these rocks are petrogenetically related (Taylor, 1965).

The INAA was carried out using procedures similar to those described by Gordon and others (1968). A standard (prepared by L. Lopez, 1972) was irradiated with three BHP samples collected from recent cuts. The localities are shown on the map (see Figure 4).

TABLE 3 TRACE ELEMENT ABUNDANCES (ppm)

Rock Element	G-2**	QG_1+	QG_2+	QG_3+	73-4-1	73-4-2	73-4-56	PG_3+	PG_4+	PG_6+	CA_1+	CA_2+	CA_3+
Sc	3.3±0.2	0.27	0.31	0 22	0.63±0.006	0 29±0.004	0 55	3.11	3 31	1 34	1 38	1 67	0.64
La	94±2	70.3	100.2	98.3	126 7±5.47	75 7±3 2	126 4	94.5	105 5	84	75 4	77 9	60 9
Ce	173±3	168	231	236	251±0.9	161±0.6	247.4	218	243	195	173	182	150
Nd	55±3	–	–	–	122 6±4.1	70 9±2 5	118.6	–	–	–	–	–	–
Sm	7.9±0.3	16.3	20 4	23 4	28 0±0.1	14.9±0 06	27.2	18 3	19 5	15 8	14 1	13 9	15.9
Eu	1.48±0.02	0.76	0 82	0 85	1 58±0 17	0 87±0 13	1 49	1 44	1 63	1 30	1 82	1 61	1.13
Gd	3.7±0.1	–	–	–	26 86±1.2	14 46±0 69	23 07	–	–	–	–	–	–
Tb	-	1 71	2 20	2.70	4 63±0.2	2 52±0.13	4.32	2 30	2 20	1 77	1 92	1.75	2.35
Dy	-	13.78	16 60	11.26	–	–	–	13 94	12 84	10 74	16 5	16.0	22.2
Yb	0.74±0.02	6.73	8.03	12.02	10 25±0 34	8 28±0 28	9.45	6.18	5 24	3 92	4.51	4.89	6.24
Lu	0.1±0.05	1.09	1 34	1.76	1.88±0.059	1.47±0.049	1 78	1.09	0 97	0 81	0 81	0 80	0 97
Zr	-	608	846	1354	426±60.7	334±48	4 19	850.8	780.1	686.2	484	505	352
Hf	-	14.6	20.1	33.6	27.03	20 32	25.98	20.38	19.40	14.74	14 85	15.09	11.11
Ta	0.97±0.06	4.69	4 74	6.58	6.55	5.07	6.19	4.08	3 28	2.84	3 15	2.93	4 19
Th	23.9±0.5	13 1	13.3	16 3	19 03	13.41	18.78	16.6	14 2	11 0	11.1	11.5	17.4
Zr/Hf		41.6	42 09	40.3	15.8	16.4	16.12	41.7	40 2	46.6	32.6	33 66	31.7
Eu*		66	85	94	134	71	127	79	82	66	62.5	60.5	73.5
Eu/Eu*		0.17	0 14	0.13	0 17	0.18	0.17	0.26	0.29	0 28	0.42	0 39	0 22
La/Sm		4.3	4.9	4.2	4.5	5.1	4.64	2 83	2 96	5.31	5 35	5.60	3.83
La/Yb		10.4	12 5	8.2	12.4	9.1	13.38	9 25	12.19	21.43	16.72	15.93	9 76
Sm/Yb		2.4	2.5	1.95	2.7	1.8	2.88	3.72	4.12	4.03	3.13	2.84	2.55

** Data from L. Lopez Escobar 1972

+ Data analyzed by G. Buma, F. A. Frey, personal communication

QG = Quincy Granite
PG = Peabody Granite
CA = Cape Ann Granite

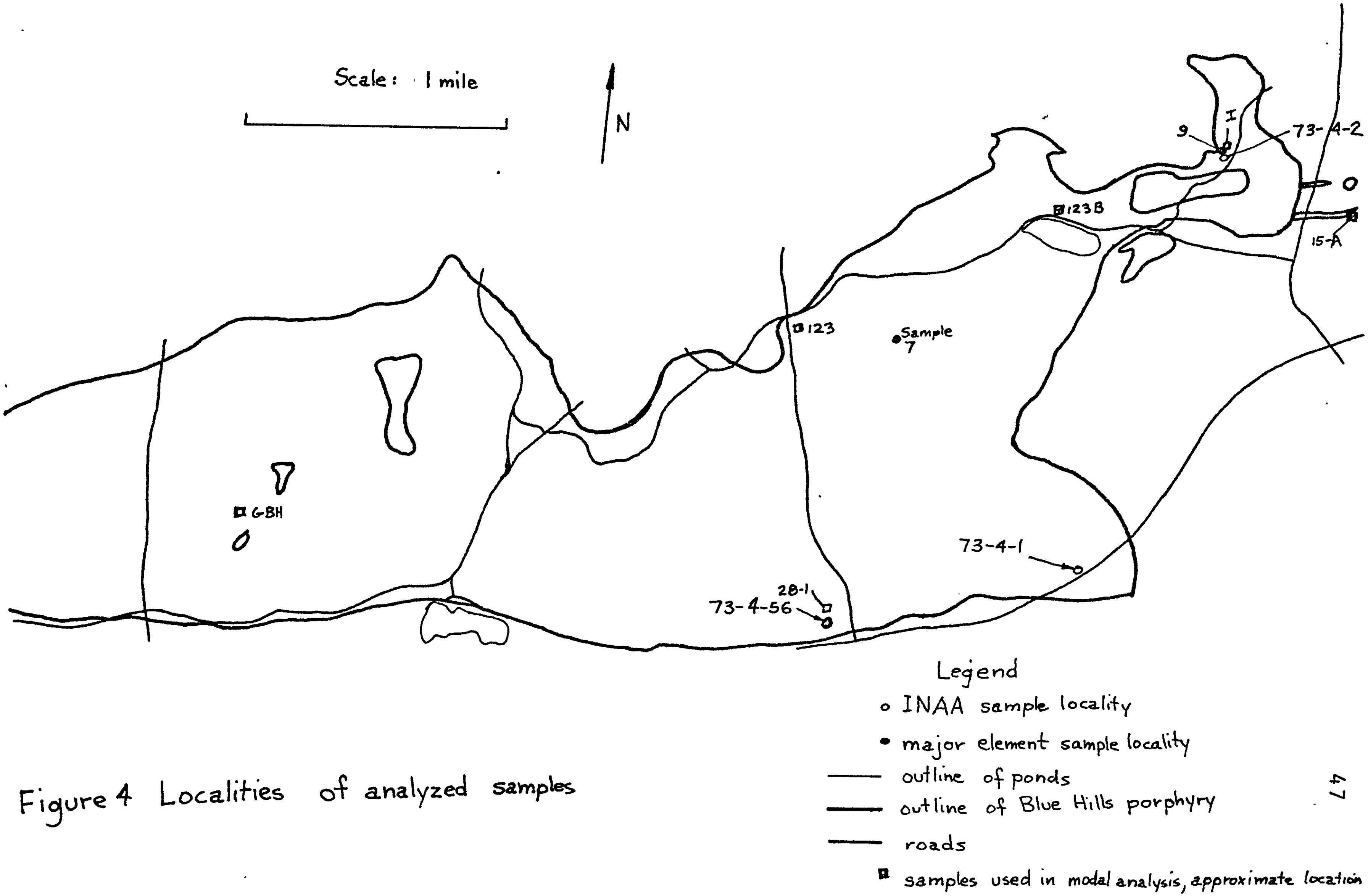


Figure 4 Localities of analyzed samples

The QG, Peabody (PG), Cape Ann (CA), Narragansett Pier (NP), and Westerly (W) granites were not analyzed in this study as sufficient data is available from the work of Buma and others (1971). Figures 5, 6 and 7 show the rare earth elements (REE) trends of the CA, PG, and QG for comparison to some other nearby intrusions, NP and W.

Sample Descriptions

Sample 73-4-1 was collected from the Route 128-Route 28 cloverleaf road cut in the BHP zone (see Figure 19). Samples 73-4-1 and 73-4-56 were collected about 1.2 kilometer apart, but both within fifty meters of the contact with the Pondville conglomerate (PC). Sample 73-4-56, a porphyry paisanite (paisanite refers to the fact that the matrix is much finer-grained and more prominent than the feldspar and quartz phenocrysts) was collected midway in the newly blasted road cut on the north side of Route 128 where Southeast Ridge is cut by Route 128. Sample 73-4-2 was collected from the south side of the quarry on the eastern flank of Rattlesnake Hill. This sample is very close to the contact with the QG and is more crystalline than 73-3-56. This is the type of locality of the BHP chosen for Warren's (1913) chemical analysis.

Petrographic Descriptions

73-4-1: The matrix is a fine-grained mixture of quartz and feldspar, and appears to have been partially recrystallized. Rounded

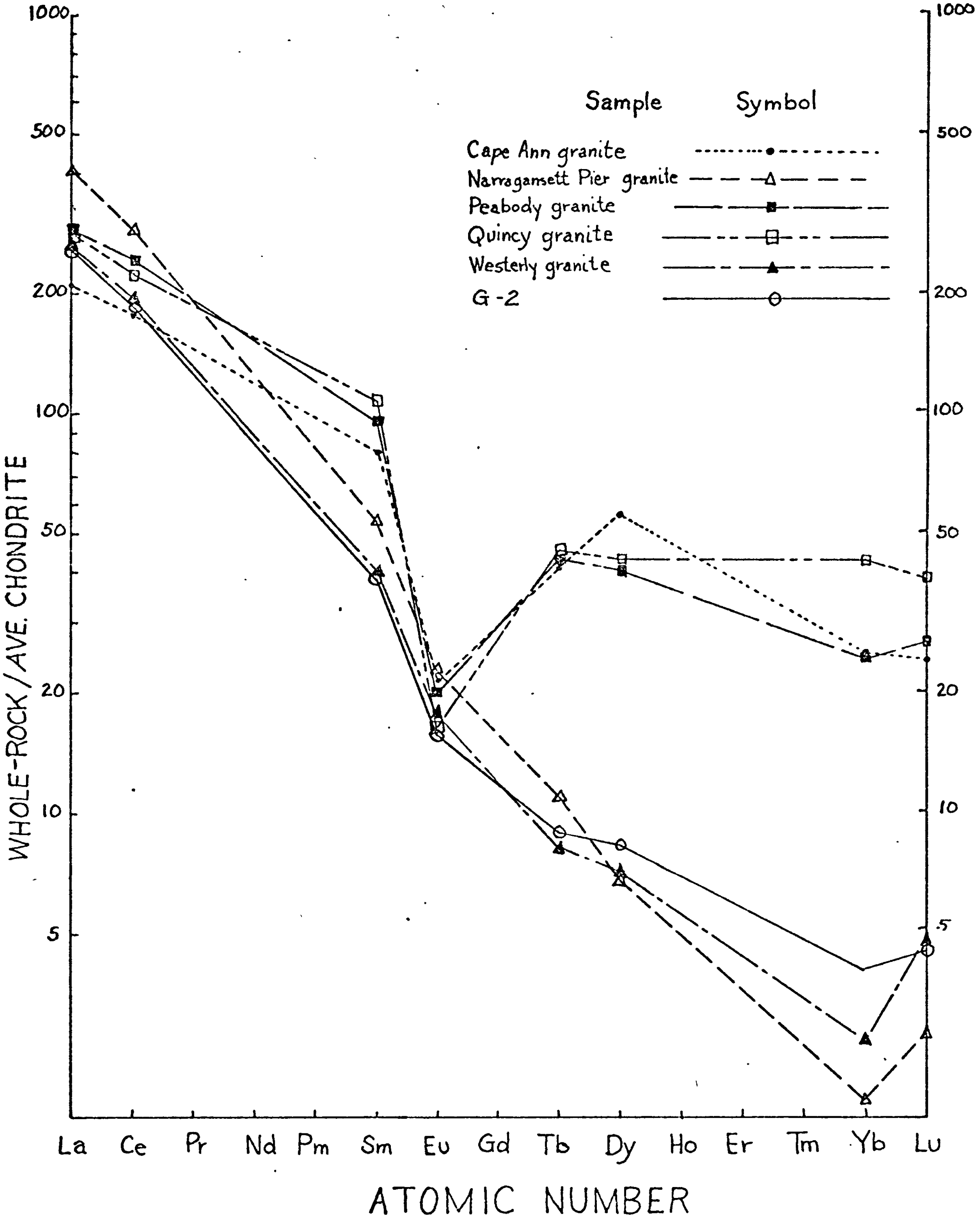


Figure 5 Rare earth abundances of five New England granites normalized to chondrites. (From Buma, 1970, p. 27)

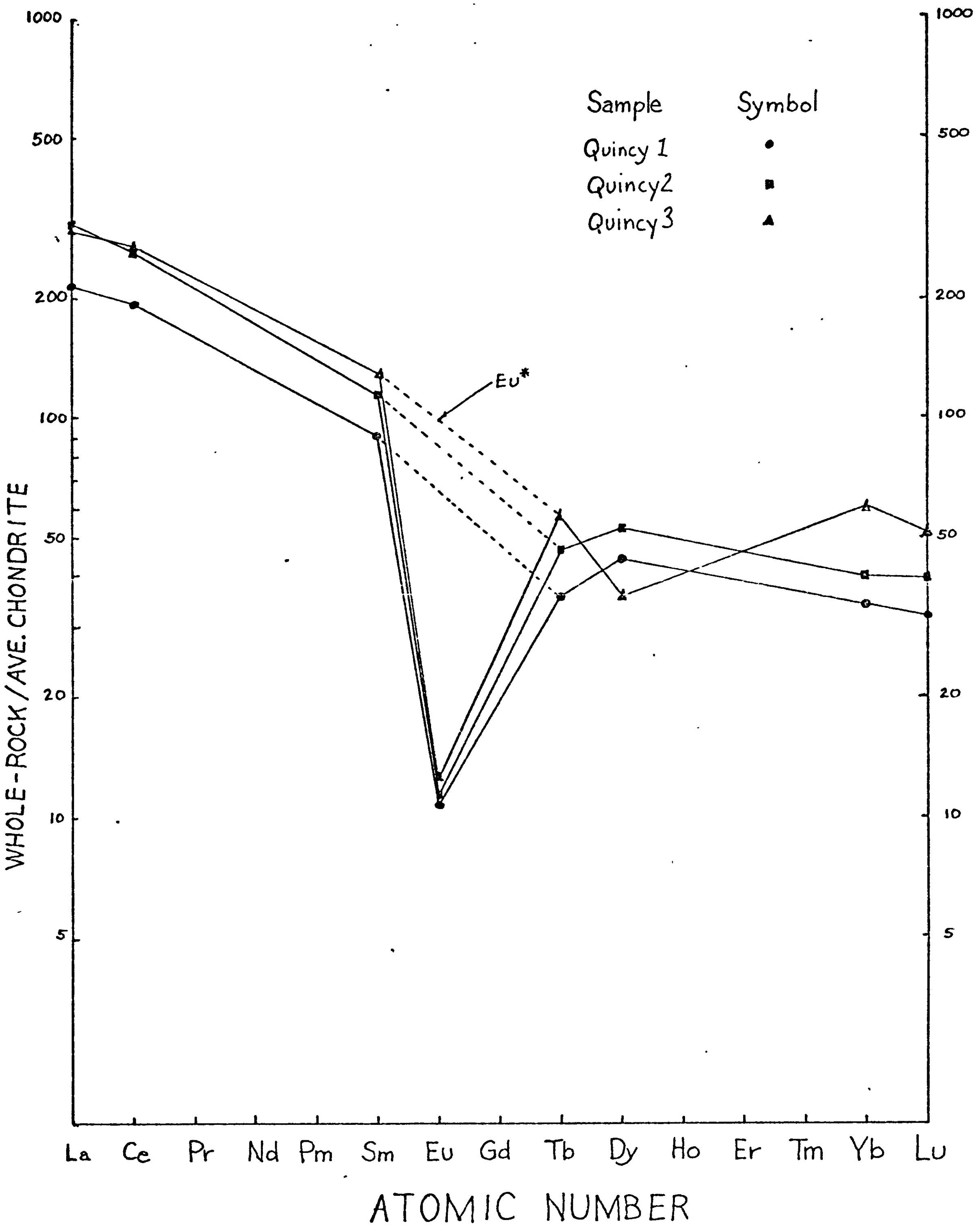


Figure 6 Rare earth abundances of three Quincy granite samples normalized to chondrites.
(Data collected by Buma, F.A. Frey personal communication 1974.)

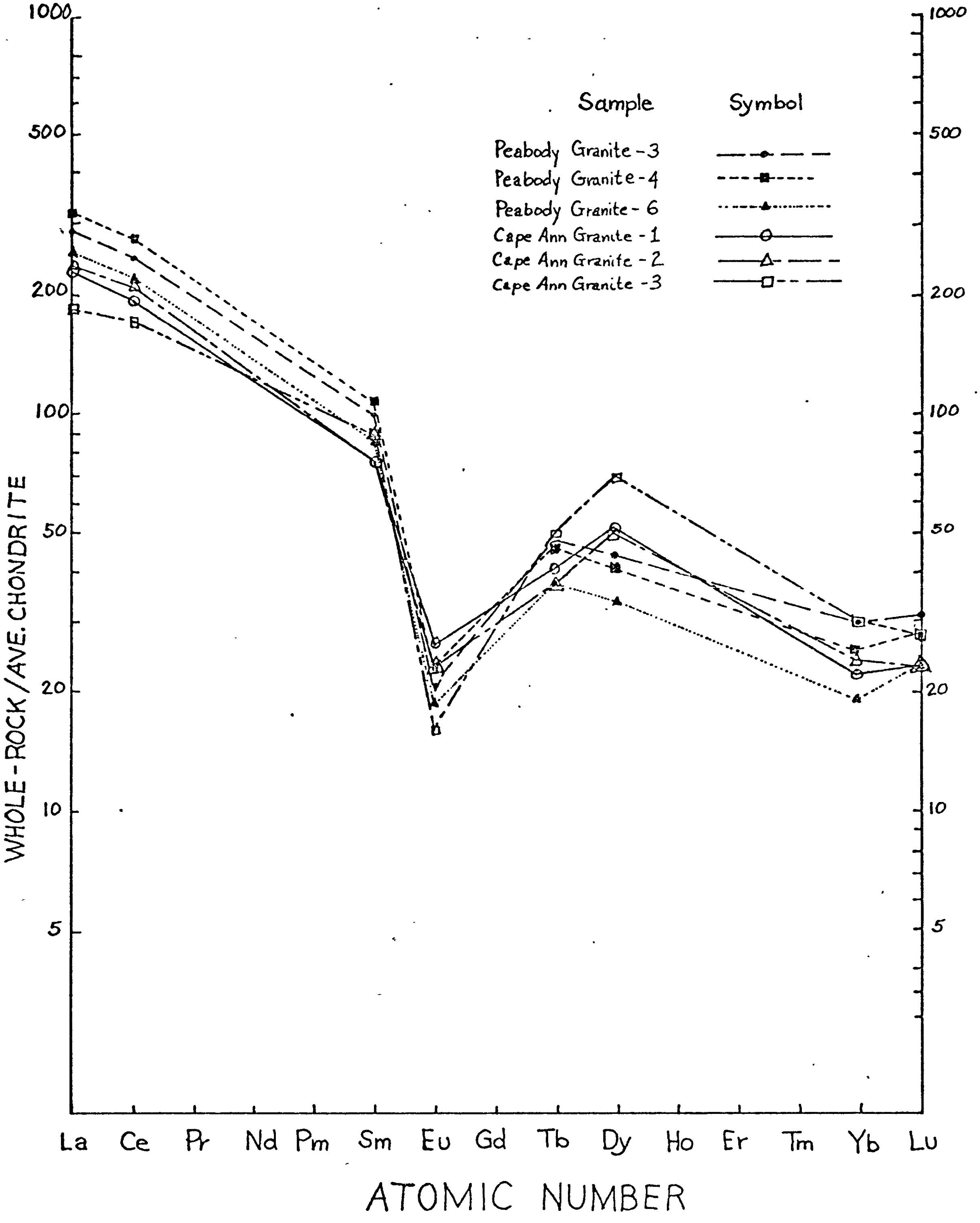


Figure7 Rare earth abundances of three Peabody granite and three Cape Ann granite samples normalized to chondrites. (Data collected by Buma, F.A. Frey, personal communication 1974.)

quartz phenocrysts make up approximately six percent of the rock. The feldspars are greatly altered and probably were a microperthite. Little remains of the feldspars, as they have been sericitized and replaced by calcite. Numerous quartz shards are present. Ilmenite mantled with magnetite has replaced a poikiolitic ferro-magnesian, probably riebeckite. Aenigmatite and augite occur in trace amounts. There is some type of relict bedding. This rock resembles a subaqueous crystal tuff which has been recrystallized.

73-4-2: This is a sample of the BHP from the type locality. It has large euhedral phenocrysts of quartz and feldspar. Feldspar phenocrysts, mostly euhedral orthoclase, and micro- or cryptoperthite are more abundant than quartz. The perthites are rimmed with albite. Both quartz and feldspar show signs of being partially resorbed. The groundmass makes up about fifty percent of the rock and is a fine-grained quartz-feldspar, hypidiomorphic mixture. Riebeckite and poikiolitic aegirine together make up about eight percent of the rock. The riebeckite occurs in tabular masses as well as poikiolitically and the aegirine also occurs as small rods in the groundmass.

73-4-56: This is a typical BHP sample of what Warren (1913) might have called a quartz-feldspar porphyry. It has a finer-grained quartz-feldspar matrix than 73-4-1, but not nearly as fine as 73-4-2.

Feldspar (perthite) phenocrysts occur in larger numbers than quartz phenocrysts. The quartz phenocrysts are subhedral and deeply embayed. Some perthites are broken, and albitization occurs along the fractures. The perthites occur as patchy, braided or string perthites, generally euhedral, but with some rounding.

Broken fragments of partially resorbed quartz occur. A micro-xenolith of granophyric quartz and feldspar is present. Leucoxene occurs as a liberal dusting in the groundmass. Some hematite is present. Ilmenite occurs as granules larger than the quartz-feldspar matrix crystals. Riebeckite is very sparse making up less than one percent of the rock. Astrophyllite and aenigmatite occur as trace minerals.

Sample Preparation

Each of the three samples was crushed, individually homogenized and then split to a few grams and ground into a rock powder. No attention was given to avoiding iron (Fe) contamination as this was not considered a trace element and a few extra parts per million would not affect the Fe content appreciably due to its two percent content already. No mineral separates were made. No duplicate analyses were made.

Estimate of Analytical Accuracy

An estimate for the accuracy of the INAA method used and the standard deviations from U. S. Geological Survey standards can be provided from the analysis of the G-2 data made by L. Lopez (1972, p. 15) and shown in Table 3. Standard deviations are shown in parts per million (ppm). Table 3 shows the data for the analyses for each sample. The Wasson method (Baedecker, P.A., 1971) of calculating the standard deviation for half peak data reduction was used to determine the errors.

The standard deviation for all the elements except scandium (Sc) is less than ten percent. The standard deviation for Sc is thirty-four percent. Samples 73-4-1 and 73-4-56 are very similar and deviate from each other by less than ten percent.

Trends of REE Abundance

Sample 73-4-2 is the BHP geographically closest to the QG. It is also presumably the farthest from any deep weathering zone, as well as being farthest from the surface of the BHP. The general trend of sample 73-4-2 is more nearly similar to the QG than either of the other two samples, as can be deduced from the BHP samples normalized to the three QG analyzed by Buma (see Figures 8a. and 8b.). It shows approximately a fifty-eight percent lower La abundance, and fifteen percent lower Yb and Lu abundance than the other two samples. The 73-4-2 REE curve has the same shape (see Figure 9) as the other two samples but it is shifted approximately twenty-eight percent lower.

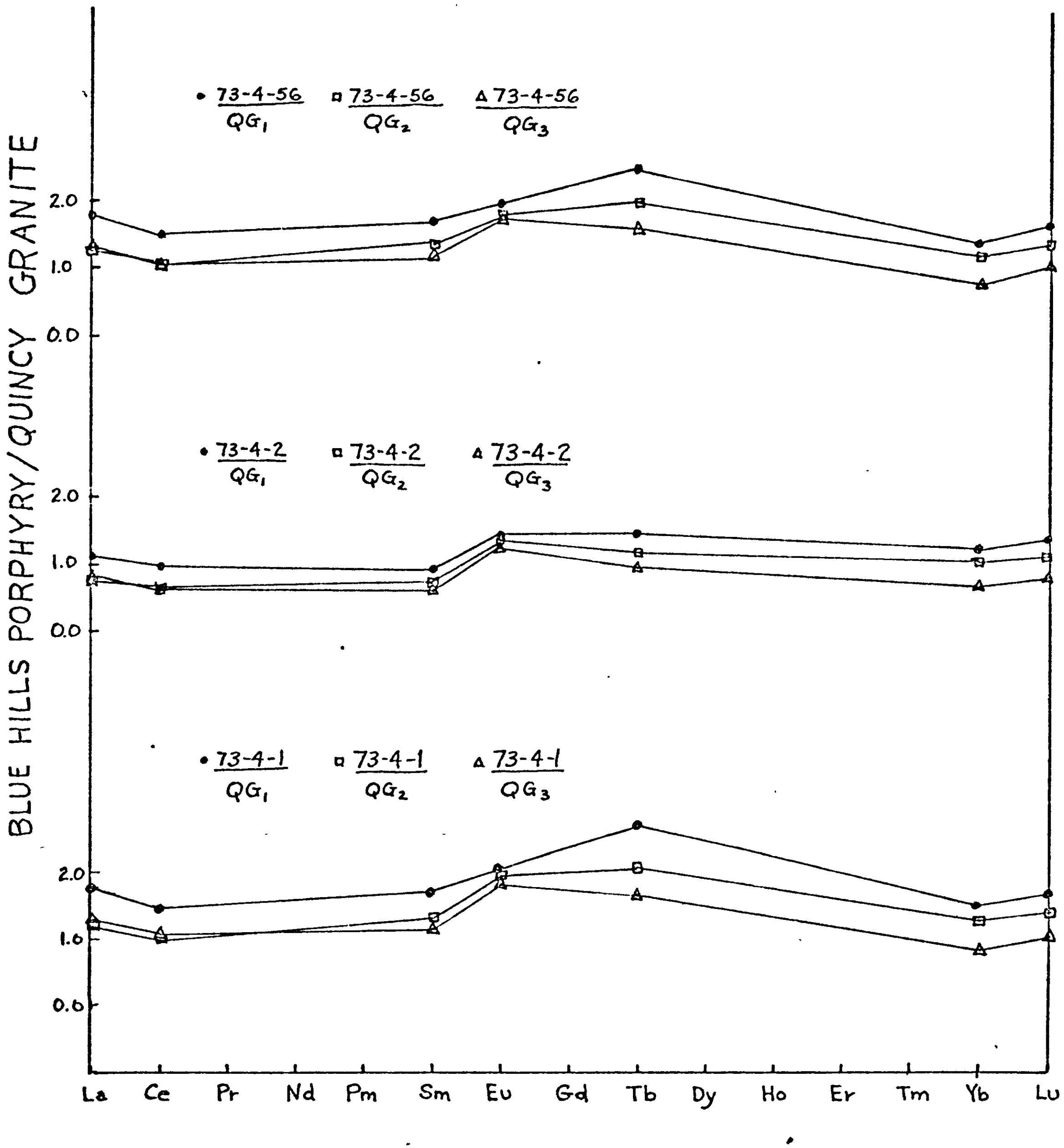


Figure 8a Rare earth abundances of three Blue Hills porphyry samples normalized to Quincy granite rare earth abundance. (Quincy granite data collected by Buma, F.A. Frey personal communication.)

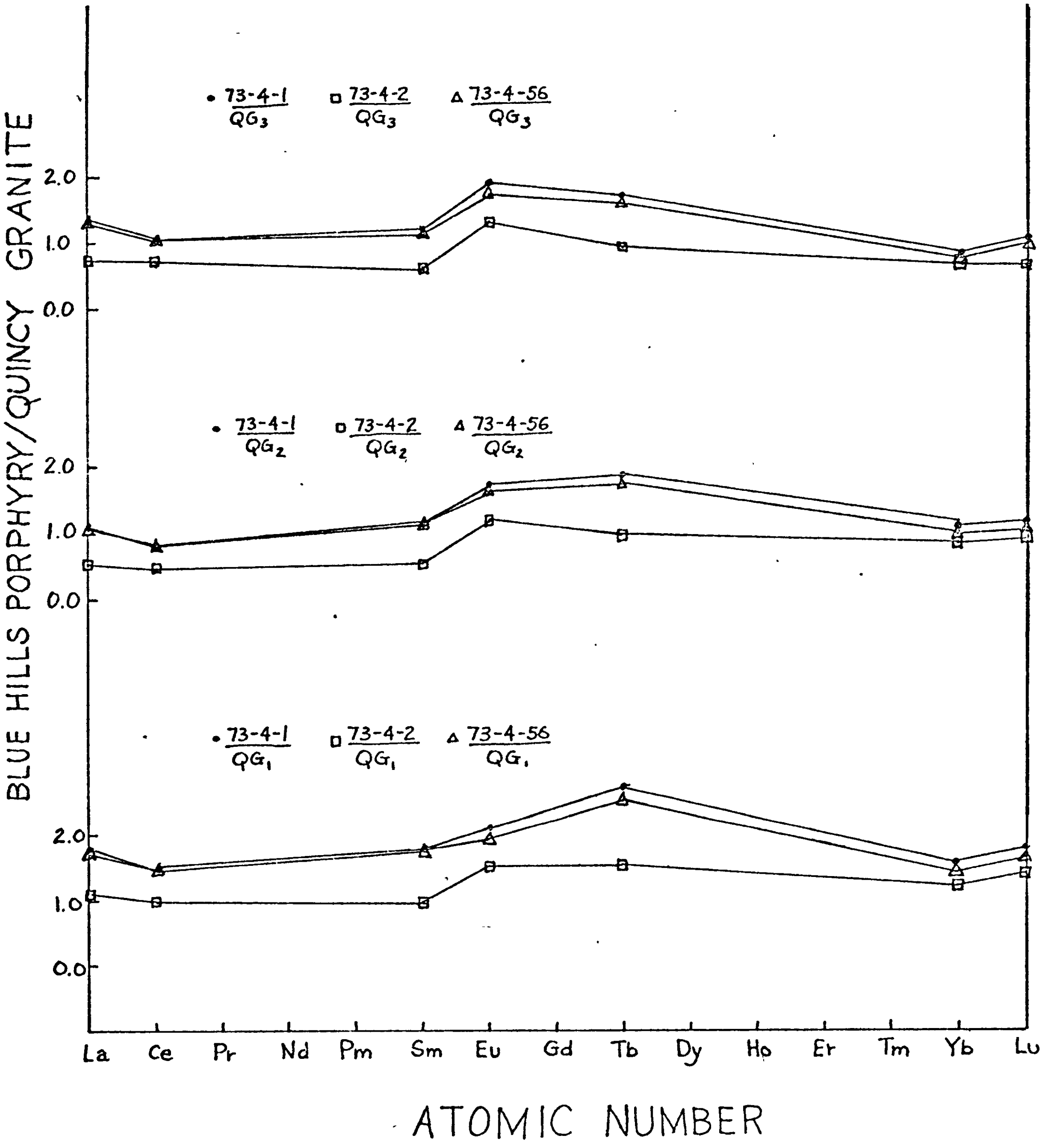


Figure 8b Rare earth abundances of three Blue Hills porphyry samples normalized to three Quincy granite samples. (Quincy granite data collected by Buma, F.A. Frey personal communication.)

All three samples more closely resemble the alkali granites than the subalkaline Rhode Island granites (see Figures 5 and 9).

Results

The results of the INAA show that all three BHP samples are remarkably uniform in their REE trends and follow the trend of the QG to a large extent (see Figures 8a., 8b. and 9).

All BHP samples relative to the chondritic average are enriched in the lighter REE and strongly depleted in europium (Eu), a typical alkali granite trend (Buma and others, 1971).

The heavy REE (Yb and Lu) occur in the same relatively high abundance for granites in both the BHP and the QG. This trend is in contrast to the strong depletion of heavy REE evidenced by the subalkaline granites.

In samples 73-4-1 and 73-4-56, there is a strong sloping trend from Gd to Yb; this trend might be exaggerated due to a problem with obtaining results from the 63 Kev Yb peak. This could not be substantiated by the 283 Kev Yb peak, because of an error made while counting which erased the results of the standard in the neighborhood of the 283 Kev peak.

The error bars for Tb are known to be relatively large (F. A. Frey, personal communication), which might also throw some doubt into the actual abundances of Tb, both in Buma's (1970) results and those of this

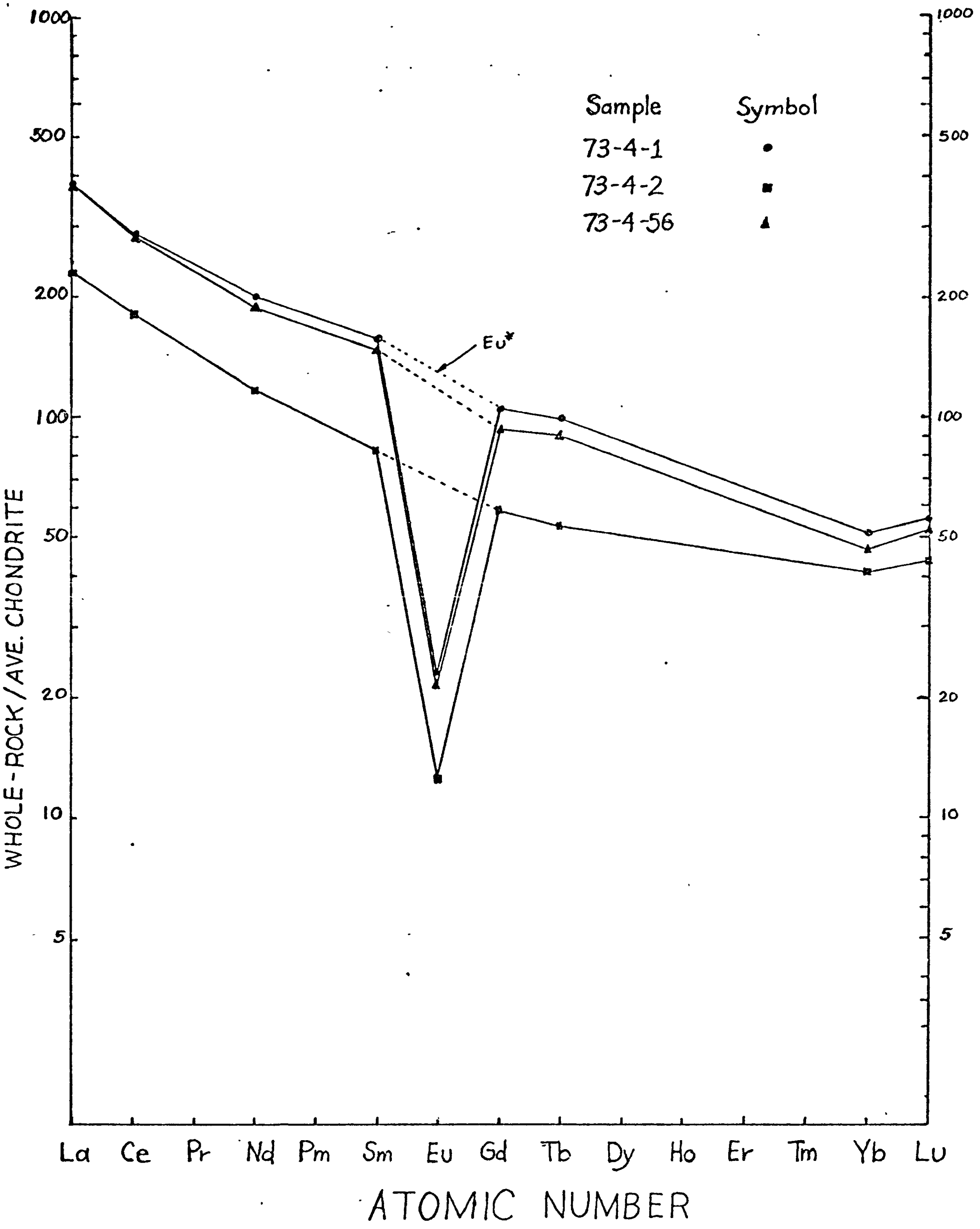


Figure 9 Rare earth abundances of three BHP samples normalized to chondrites.

work.

Sample 73-4-2, as can be seen in Figures 8a. and 8b., more closely approximates the QG REE abundances especially in the Gd, Tb, and Dy area. Again this could be a statistical error as explained in the foregoing paragraph.

The Eu/Eu* values of the BHP indicated in Table 4 show a weaker Eu depletion compared to that found in the QG, but this is not excessive. Eu/Eu* indicates the ratio of the observed Eu abundance to that obtained by interpolating between Sm and Tb abundances on a plot of whole rock/ normalized to chondrite averages versus REE atomic numbers.

The most noticeable difference of the BHP and QG from the other, both alkali and subalkali granites, is the Sc content. The Sc content of the three samples of BHP is less than 1 ppm. This is typical of the QG and is in strong contrast to the other alkali and subalkali granites of the area.

Discussion

The results of the INAA indicate that magmatic conditions of the BHP and QG are similar. The lesser Eu anomaly of the BHP, compared to the Eu anomaly of the QG indicates, that 73-4-1 and 73-4-56 are slightly more primitive (less differentiated) than the QG and might be the chilled border of the QG. The lesser heavy REE depletion of the BHP relative to the QG indicates magmatic conditions more similar to the PG and CA than to the QG.

Buma and others (1971, p. 317) concluded that the QG was more differentiated than either the PG or the CA because :

1) it has a larger Eu depletion;
2) is clearly peralkaline with an agpaitic ratio > 1;
3) the Sc is markedly depleted; and
4) it has higher abundances of elements commonly enriched in liquids (Zr, Yb, Hf, Ta).

In a similar manner,

1) the BHP has a Eu depletion between the QG and PG but closer to the QG;

Table 4

	Eu/Eu*	Eu/Eu*	Eu/Eu*
Blue Hills Porphyry	0.17	0.18	0.17
Peabody Granite	0.26	0.29	0.28
Cape Ann Granite	0.44	0.36	0.22
Quincy Granite	0.17	0.14	0.13

* Eu/Eu* is the observed Eu abundance divided by interpolated abundance in Figures 6, 7, and 9.

2) the BHP has an agpaitic ratio of 1.02, clearly peralkaline;
3) the Sc is markedly depleted in the BHP;

4) Yb, Hf, Ta are present in larger abundances than in the other granites. Zr is present but is quite low compared to the other granites. (Note: Zr data has a large error associated with it due to its low concentration in the standard used, and it might not be at all indicative of the true abundance).

The relatively high Eu content, as shown in Figure 9, seems to indicate that the BHP is more primitive (less differentiated) than the QG. However, the relatively high Hf, Ta, and Th contents relative to the QG indicate a more differentiated magma.

Zr is also quite low in abundance indicating a relatively primitive magma.

The Th abundance ~19 ppm is also slightly higher than average for the QG ~13 ppm, indicating that perhaps the BHP has undergone further differentiation than the QG.

Sample 73-4-2 shows a closer petrogenetic relationship to the QG, as the REE abundances of Gd, Tb, and Dy are more like to QG than the other two BHP samples. In fact, only a few meters to the west of the sample the QG and BHP contact from this locale is gradational in aspect, giving field support to the similar REE trends.

The question of whether the BHP is more primitive or less primitive cannot be answered from the REE abundances. The REE abundances indicate they are very likely to be comagmatic.

CONCLUSION

In conclusion, the INAA disproves the possibility that the BHP could be related to the subalkaline suite of granites, which cuts Carboniferous rocks in Rhode Island. The INAA data indicate the BHP and QG are closely related. This is especially evident by the extremely low Sc abundance in both units, as this feature does not occur in the petrologically similar CA or PG. The low Sc abundance and similar Eu depletion are the strongest reasons for believing the QG and BHP are genetically related.

IV. REVIEW OF ISOTOPIC STUDIES OF THE BLUE HILLS COMPLEX

(Reterence to Table 5 might prove helpful)

SUMMARY OF ISOTOPIC WORK

Quinn, Jaffe, Smith and Waring (1957) determined lead-alpha Pb-ages on zircon and monazite from the "Quincy" granite, and obtained an age of 270± 7 MY. This result gave impetus to the theory of those who believed the BHIC was Carboniferous, and post-Acadian. However, their "Quincy" granite is from Peabody, Massachusetts and is not related to the BHIC. Furthermore, errors in the method used have been found and the data are only of historical interest.

Hurley, Fairbairn, Pinson, Faure (1960) attempted to measure potassium-argon (K-Ar) and rubidium-strontium (Rb-Sr) mineral ages for the QG. They were unable to determine an Rb-Sr age for the QG. They determined a minimum K-Ar age of 280± 15 MY for the QG.

Bottino (1963a) determined Rb-Sr ages on the QG, BHP, and AR. Bottino's Rb-Sr ages of the QG (325± 15 MY) are substantially older than those of the nearby and presumably related BHP (245± 10MY). The results also suggested that the AR (248± MY) was apparently similar in age to the BHP.

Bottino (1963a) did no independent field work but noted that the isotopic results were incompatible with field relationships as reported by Warren (1913), Crosby (1900), and Chute (1940).

TABLE 5 ISOTOPE AGES OF THE BLUE HILLS IGNEOUS COMPLEX ROCK UNITS

ROCK UNIT	Amphibole K-Ar	Whole-rock Rb-Sr	$\left({}^{87}Sr/{}^{86}Sr\right)_0$	$\left({}^{206}Pb/{}^{238}U\right)$	$\left({}^{207}Pb/{}^{235}U\right)$	$\left({}^{207}Pb/{}^{206}Pb\right)$	$\left({}^{208}Pb/{}^{232}Th\right)$	Reference
Quincy Granite	430 - 458	313±22*	0.731	413±8 MY	416± 15 MY	437±32	422± 16	Zartman and Marvin (1971)
Quincy Granite		365±7	0.703±0.004					Bottino and others (1970)
Blue Hills Porphyry		282±8	0.717±0.002					Bottino and others (1970)
Aporhyolite		420–235	0.705					Bottino and others (1970)

* Includes two Blue Hills porphyry samples.

Zartman (1967) determined a K-Ar age of 442± 22 MY for the QG latest radiometric work. Zartman (1969) presented the results of zircon (Pb-U) and K-Ar dating on the QG. Zartman (1969) determined a K-Ar age of 430-457 MY and a Pb^{207}/Pb^{206} zircon age of 450± 50 MY. Zartman said Bottino's (1963a) Rb-Sr data showed considerable scatter and questioned the usefulness of the Rb-Sr method on the BHIC.

Bottino, Fullagar, Fairbairn, Pinson and Hurley (1970) analyzed ten additional BHP, four AR and one QG whole-rock samples for Rb-Sr ages. These data were combined with Bottino's previous (1963a) data with the correction of a systematic mass spectrometer error. The QG yielded an isochron age of 365± 7 MY with an $(Sr^{87}/Sr^{86})_o$ ratio (elsewhere denoted as Sr_o) of 0.703± 0.004. The BHP yielded an isochron (283± 8 MY) with an Sr_o of 0.717±0.002. The AR results plotted on an isochron diagram showed considerable scatter and only an envelope with an age range of 235 MY to 420 MY could be drawn about the points.

Bottino and others (1970) concluded that the QG and BHP probably acted as an open system after crystallization. They correlated the 365 MY isochron age of the QG with a widespread metamorphic period of 360 MY ago (Hurley and others,1960). They suggested that the age recorded by the BHP, is either a younger igneous episode--a partial response to late Paleozoic metamorphism--or a localized hydrothermal event.

Zartman and Marvin (1971) reviewed all the radiometric ages determined for the BHIC. They introduced ten new Rb-Sr whole-rock ages for the BHP and QG, a zircon age for the QG, and six K-Ar ages. Their zircon and K-Ar ages for the QG agreed at 437± 32 MY and 430-458 MY respectively. The Rb-Sr age determined was 313± 22 MY with an Sr_o of 0.731. This age is lower than the age determined by Bottino and others (1970) and the Sr_o much higher (see Table 5). The Rb-Sr data had two BHP points on it. A single K-Ar age was determined for the BHP. Zartman and Marvin (1971) concluded the QG was emplaced about 450± 25 MY ago and that the Rb-Sr ages have been altered and might record some younger post-crystallization event.

DISCUSSION

Zartman and Marvin's (1971) radiometric work, Chute's (1969) field map and Bottino and others' (1970) Rb-Sr whole-rock isochrons do not provide consistent data to advance a suitable theory for the age of the BHIC and its internal relationships.

Zartman and Marvin's (1971) K-Ar and Pb-U ages suggest that Bottino and others' (1970) Rb-Sr ages are too young; however, Bottino and other's (1970) Rb-Sr isochrons are too straight to dismiss arbitrarily and suggest to others (D. R. Wones, personal communication) that there is a possibility of more than one igneous event being recorded in the Blue Hills and the young Rb-Sr ages might have all been collected from the younger unit.

Many of Bottino's (1963a) samples used for Rb-Sr age dating were collected years earlier and were not intended for isotope studies. It is also possible that they are not representative of the unit in which they were collected. The samples were collected for petrographic work and different standards are required for age dating. Thus criteria need to be established to eliminate marginal data that might cause scatter in the Rb-Sr results.

It has been suggested (P. M. Hurley, personal communication) that the K-Ar ages of Zartman and Marvin (1971) may be somewhat high because of inherited Ar in the samples. The K-Ar method of age dating assumes no Ar in the mineral is inherited during crystallization. This assumption is not always valid (Hayatsu, 1972).

Zartman and Marvin (1971) calculated the effects of pyroxene contamination and decided that it affects the ages of the riebeckite by less than two percent. However, they neglected the effect of inherited Ar in the riebeckite structure itself. The effect of inherited Ar in riebeckite is probably not large but might help give old looking ages, and agreement with zircon ages might be fortuitous (R. S. Naylor, personal communication).

The single zircon age determined by Zartman and Marvin (1971) falls along the flattest portion of the Concordia diagram (see Figure 10).

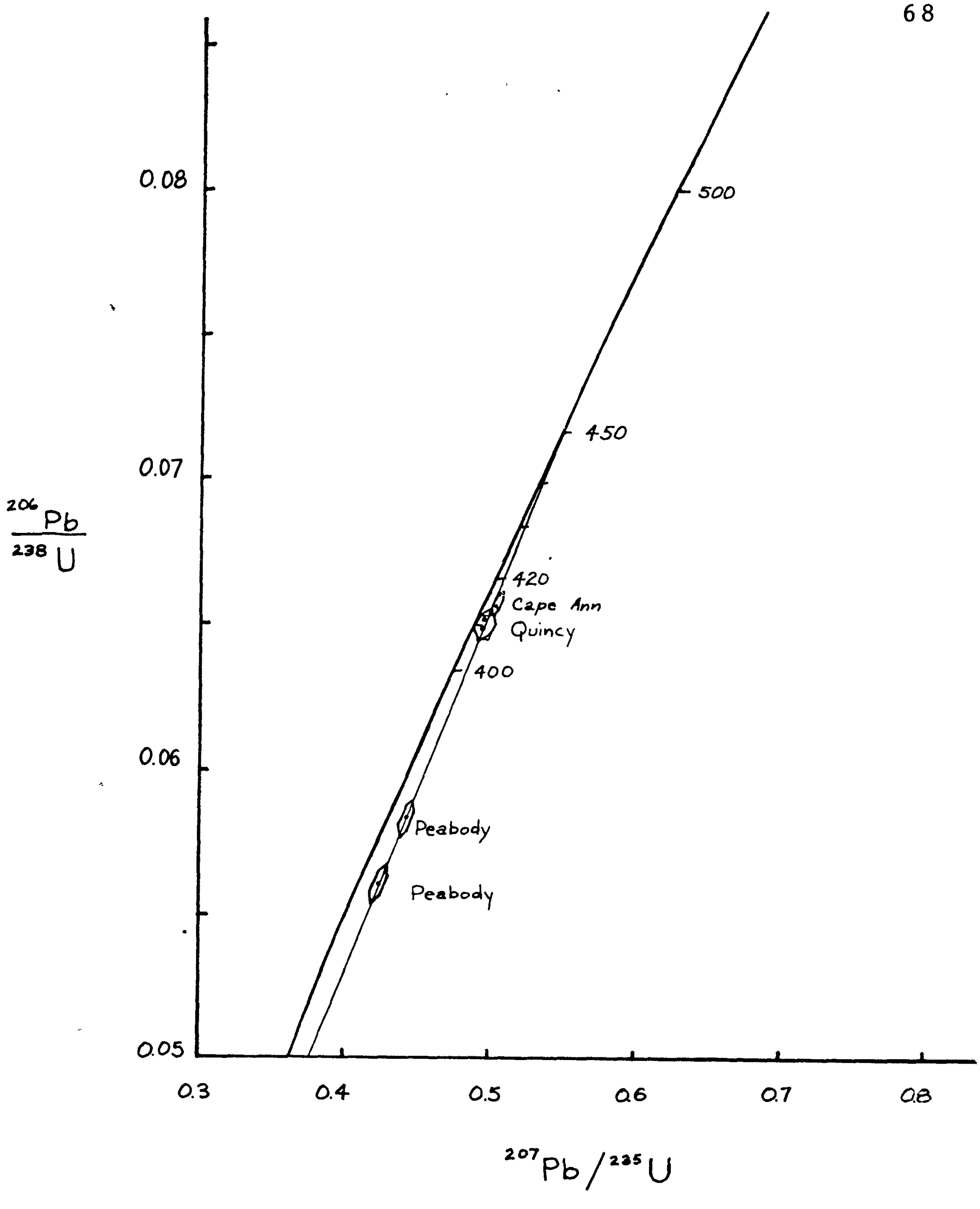


Figure 10 Concordia diagram for zircon from the Cape Ann, Quincy and Peabody granites from eastern Massachusetts. The fine line is a linear-regression fit to all samples. (Figure adapted from Zartman and Marvin, 1971.)

Just a slight shift in the data could shift the age by several million years. Zartman and Marvin (1971) called on a 450 MY kinship between the Cape Ann, Peabody and Quincy granites for their diffusive or episodic lead-loss chord intercept on the Concordia diagram. As the correlation of the alkali granites in New England is becoming more uncertain, because of Foland and others' (1971) White Mountain studies, Zartman (R. S. Naylor, personal communication) would be less inclined to relate the granite. Zartman (1969) also stated that the common lead correction for the QG zircon is large and introduced a large uncertainty.

It has also been suggested that randon loss in the decay scheme of U to Pb might cause a preferential loss of Pb^{206} resulting in an anomalous $^{207}Pb/^{206}Pb$ age. This was not evaluated by Zartman and Marvin (1971).

As isotopic age dating has not proved to be conclusive so far, it should be examined more carefully. In the following section, the uncertainties in the three geochronological methods are examined to determine the most reasonable age for the BHIC. The localities of the samples are shown in Figure 11.

The decay constant for Rb-Sr used in all cases is $\lambda = 1.39 \times 10^{-11} yr^{-1}$. The use of $\lambda = 1.45 \times 10^{-11} yr^{-1}$ would reduce the ages by six percent and cause an even larger discrepancy with K-Ar and zircon ages.

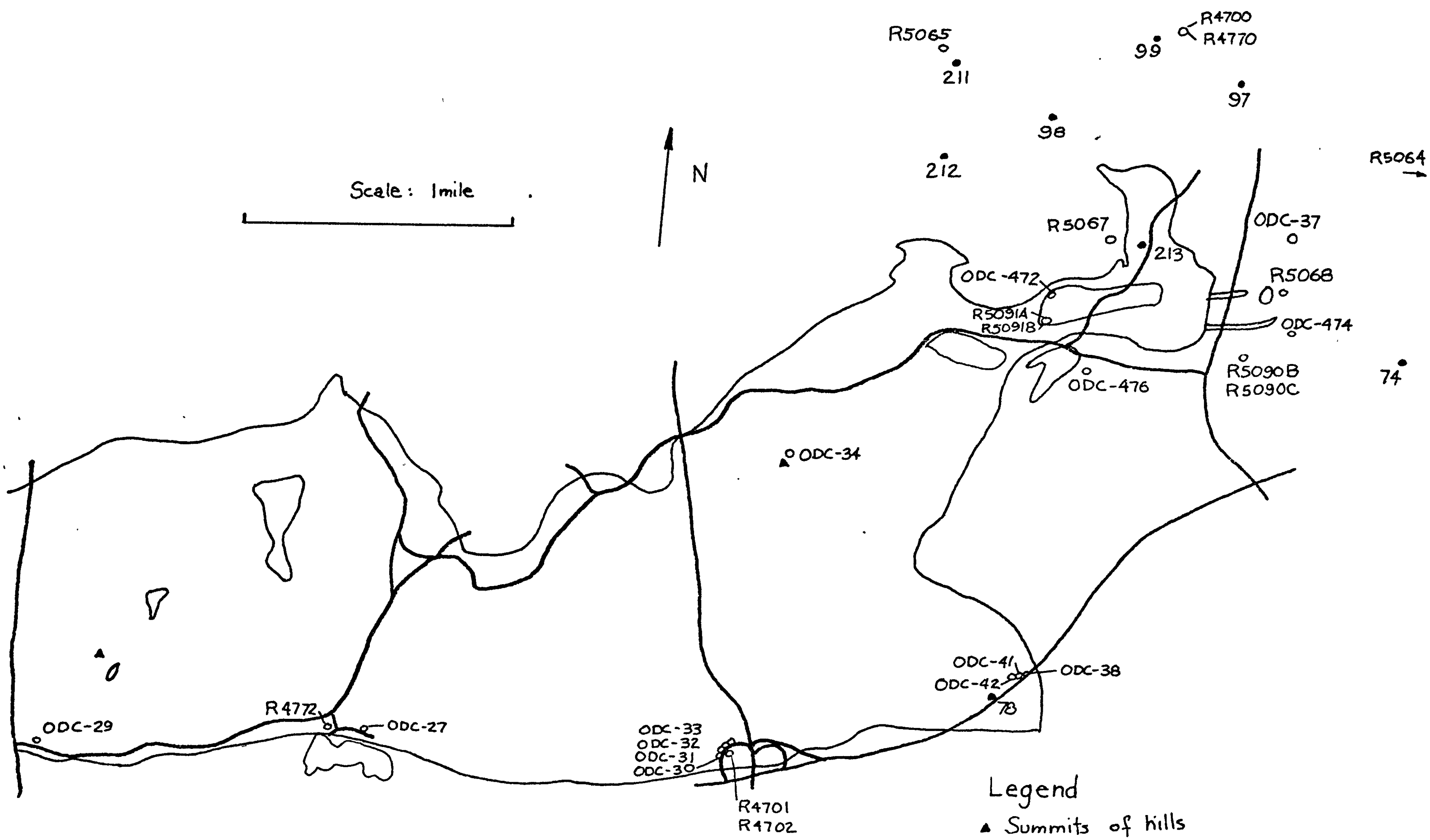


Figure 11 Sample Localities for Rubidium-Strontium Isotopic Analyses

Legend

▲ Summits of hills

● Zartman and Marvin, 1971, sample locality

○ Bottino and others, 1970, sample locality

— outline of ponds ━ roads

━ outline of Blue Hills porphyry

EVALUATION OF Rb-Sr DATING

Quincy Granite Results

In Figure 12, Zartman and Marvin's (1971) eight data points and Bottino and others' (1970) six data points for the QG are plotted. The solid line is a least squares fit (Bevington, 1969) to all fourteen QG points. The linear correlation coefficient is 0.99718, the Sr_o is 0.723±0.005, and the age is 326 MY. Bottino and others' (1970) cubic least squares fit (York, 1966) to their six points is the short-dashed line. The long-dashed line is Zartman and Marvin's (1971) least squares regression (McIntyre and others, 1966) fit to their data.

In Figure 13, only those rock samples collected specifically for age dating and with good reproducibility are included. This deletes R-4770 which did not have good reproducibility, R5064, R5065, and R5067. The computed least squares fit is shown. It yields an age of 319 MY with an Sr_o of 0.725± 0.006, and a linear correlation coefficient of 0.99669.

Blue Hills Porphyry Results

In Figure 14, eighteen data points, sixteen from Bottino and others (1970), and two from Zartman and Marvin (1971) are plotted. The solid line is a computer generated least squares fit. The linear correlation coefficient is 0.99337, the Sr_o is 0.729± 0.006, and the

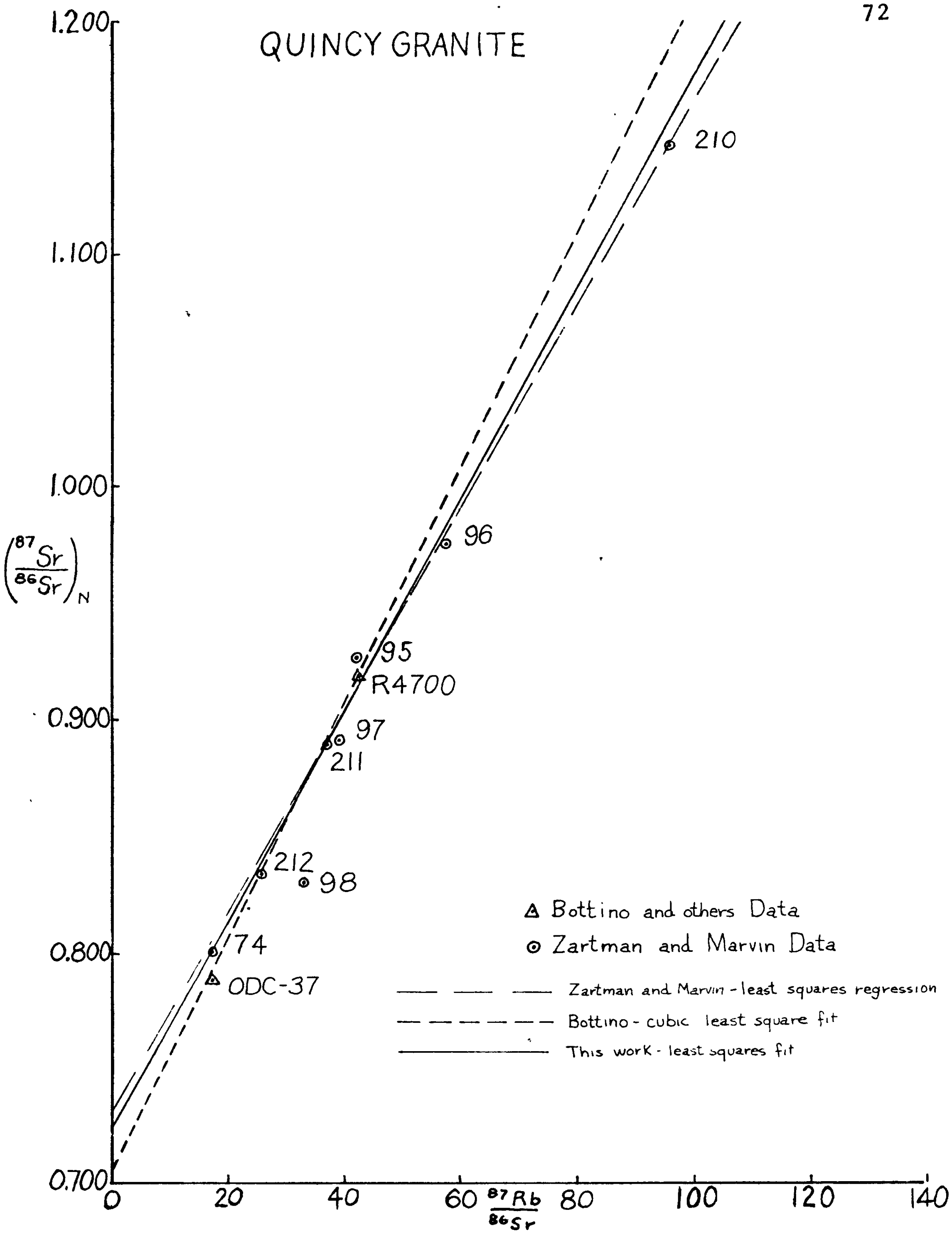


Figure 12 Whole-rock Rb-Sr isochron diagram for Quincy granite. (Data from Bottino and others, 1970, and Zartman and Marvin, 1971.)

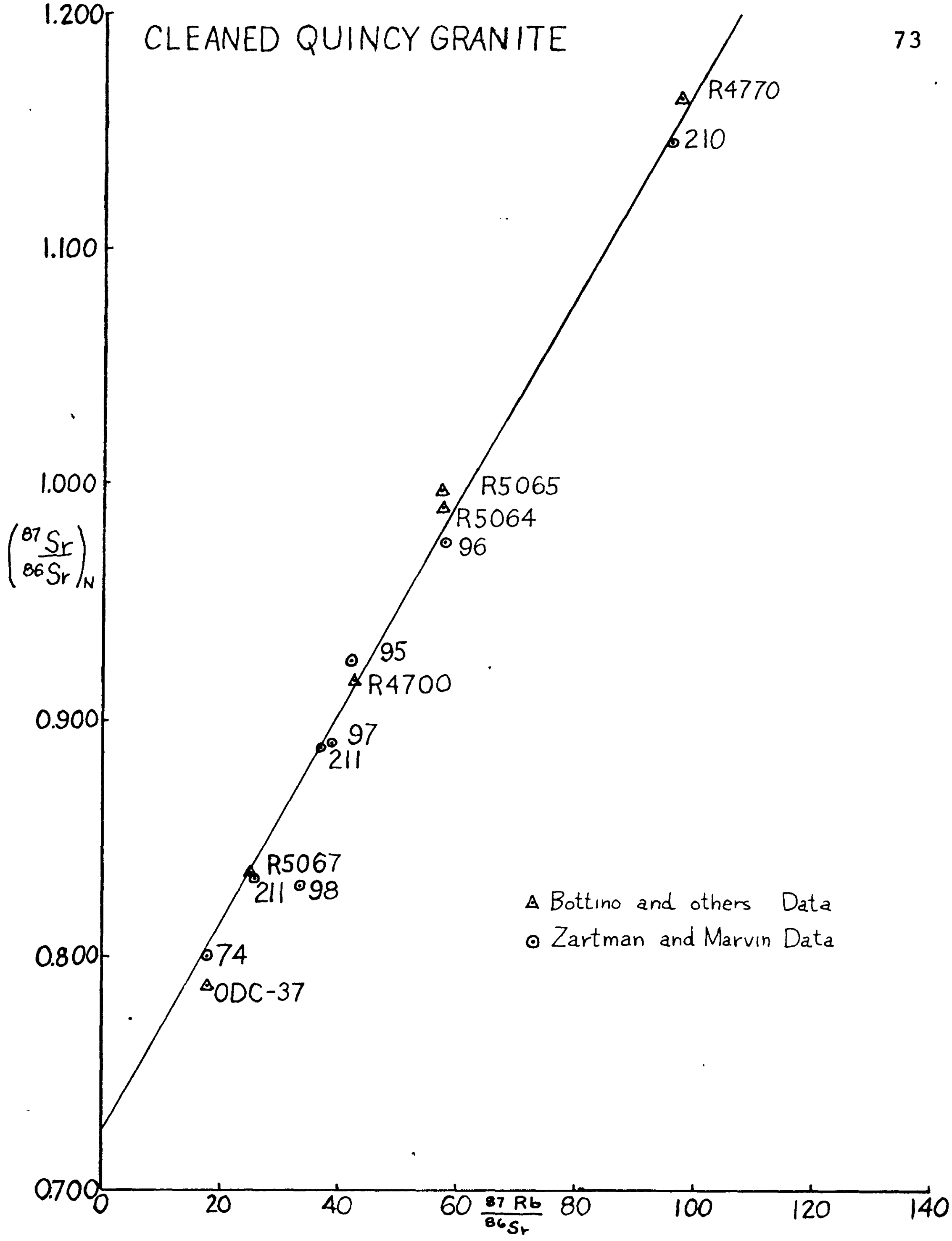


Figure 13 Whole-rock Rb-Sr isochron diagram for cleaned Quincy granite. (Data from Bottino and others, 1970, and Zartman and Marvin, 1971.)

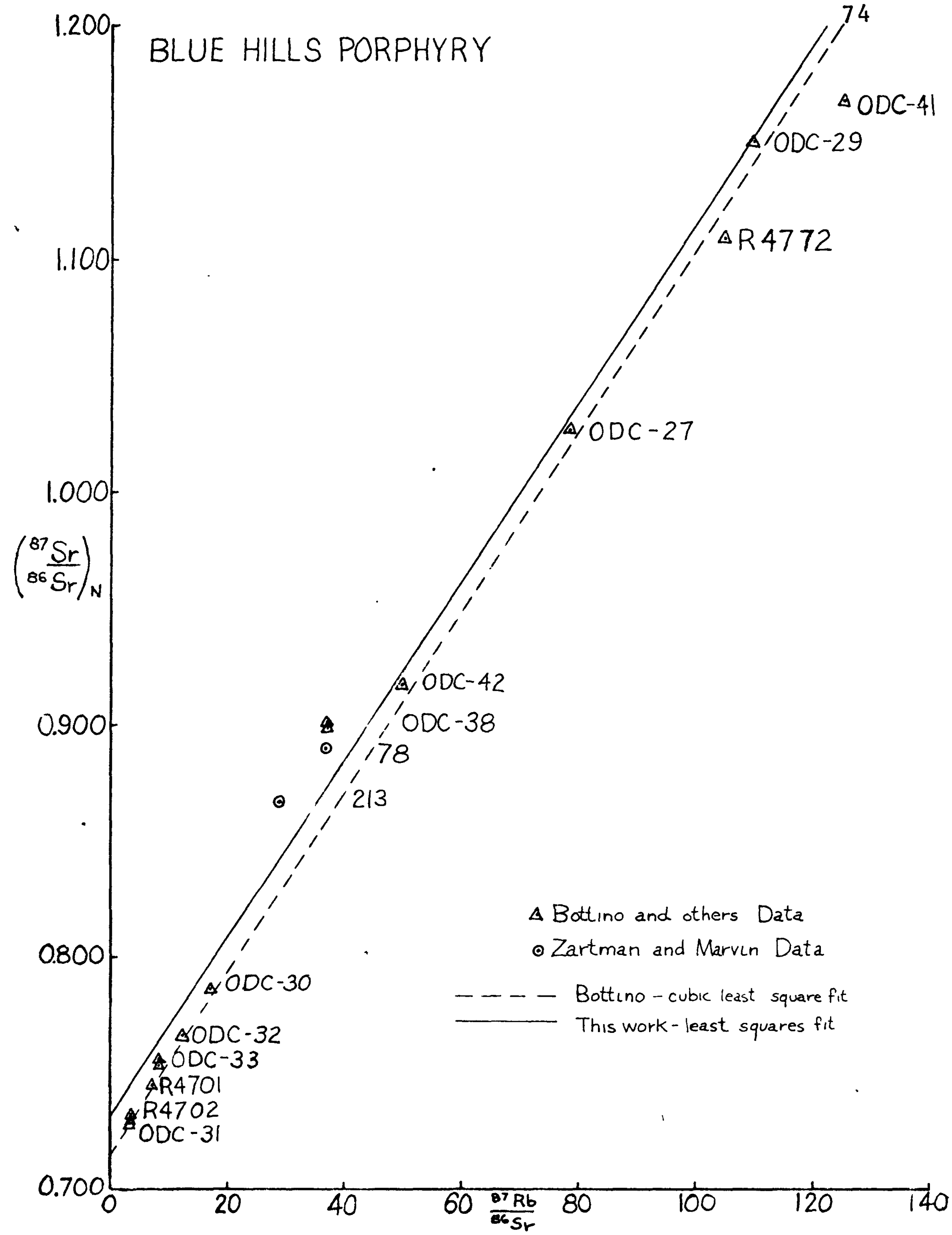


Figure 14 Whole-rock Rb-Sr isochron diagram for Blue Hills porphyry. (Data from Bottino and others, 1970, and Zartman and Marvin, 1971.)

age is 269 MY. The dashed line is Bottino and others' (1970) cubic least squares fit to their sixteen points, yielding a 282± 8 MY isochron with an Sr_o of 0.714.

Figure 15 is a plot of "cleaned" points. The criteria used for cleaning are (1) the rock samples were specifically collected for age dating, (2) they were not near an altered zone in the road cut intersecting Southeast Ridge (see Figure 11), and (3) the data were reproducible. This deletes R4701, R4702, R4772 (poor reproducibility), ODC-38, ODC-41, ODC-42 and 78. A least squares fit to the cleaned data yields an age of 281 MY, the Sr_o is 0.722± 0.006, with a linear correlation coefficient of 0.99709.

Figure 16 is a plot of those samples collected near the southern contact of the BHP with the PC (see Figure 11). The least squares fit yields an age of 273 MY and an Sr_o of 0.718± 0.002. These points are plotted to determine if the southern edge of the BHP might be a unit of a different age. The ages do not show any marked departure from the cleaned or total data points isochron.

Aporhyolite Results

Figure 17 is a plot of all Rb-Sr data on the AR. There is a great deal of scatter. No isochron is plotted; however, an envelope of ages is shown.

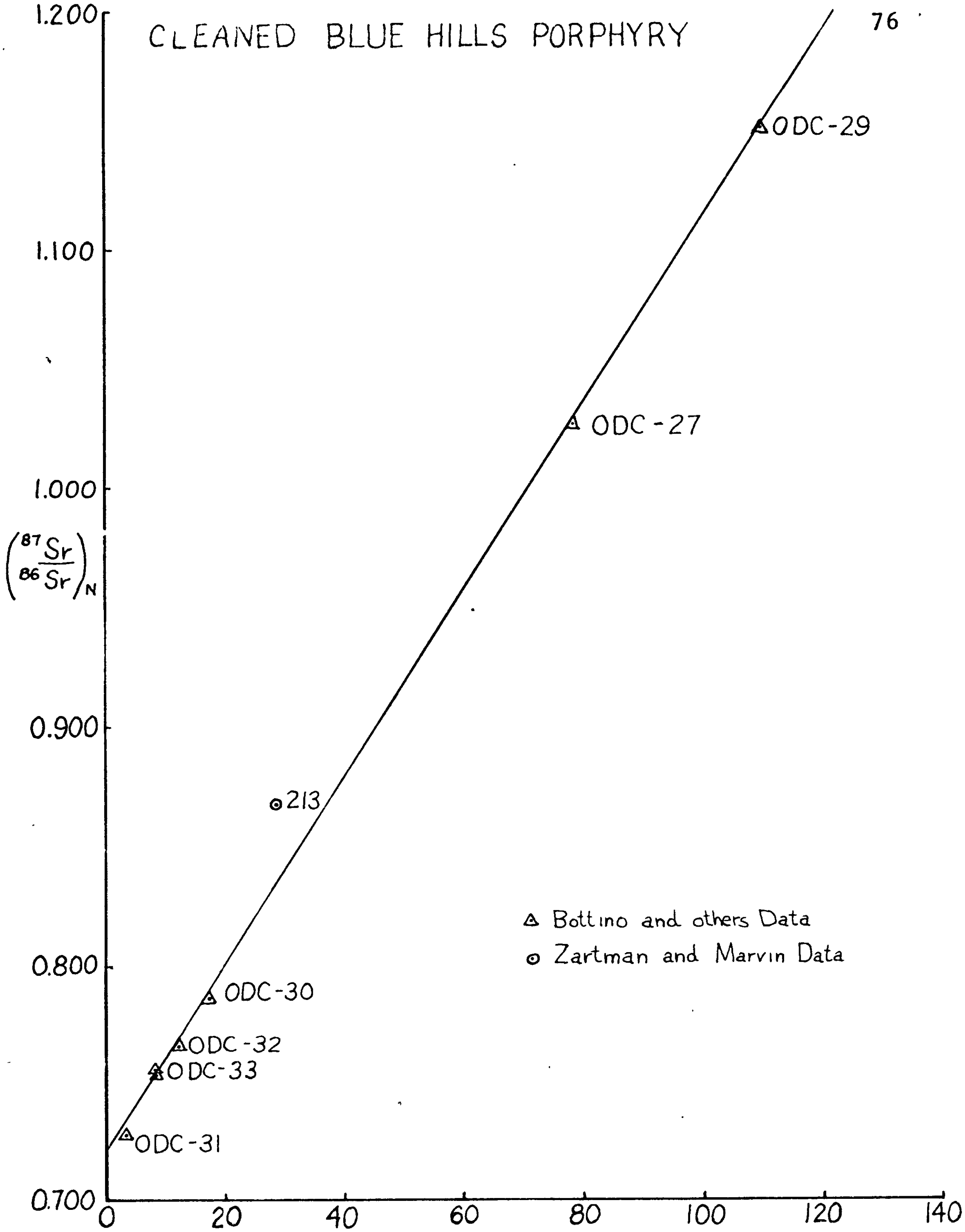


Figure 15 Whole-rock Rb-Sr isochron for cleaned Blue Hills porphyry. (Data from Bottino and others, 1970, and Zartman and Marvin, 1971.)

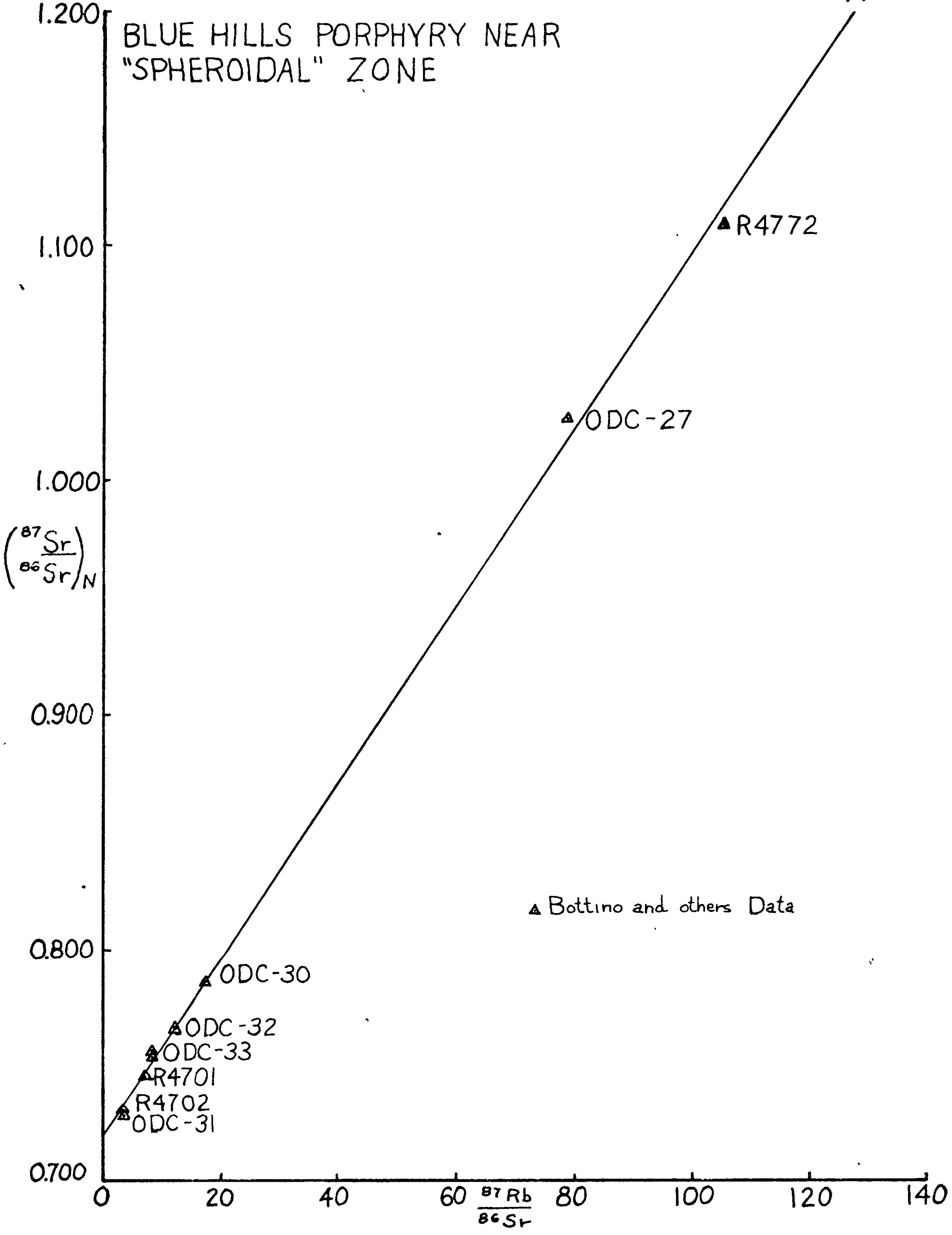


Figure 16 Whole-rock Rb-Sr isochron diagram for Blue Hills porphyry along the southern contact with the Pondville Conglomerate. (Data from Bottino and others, 1970.)

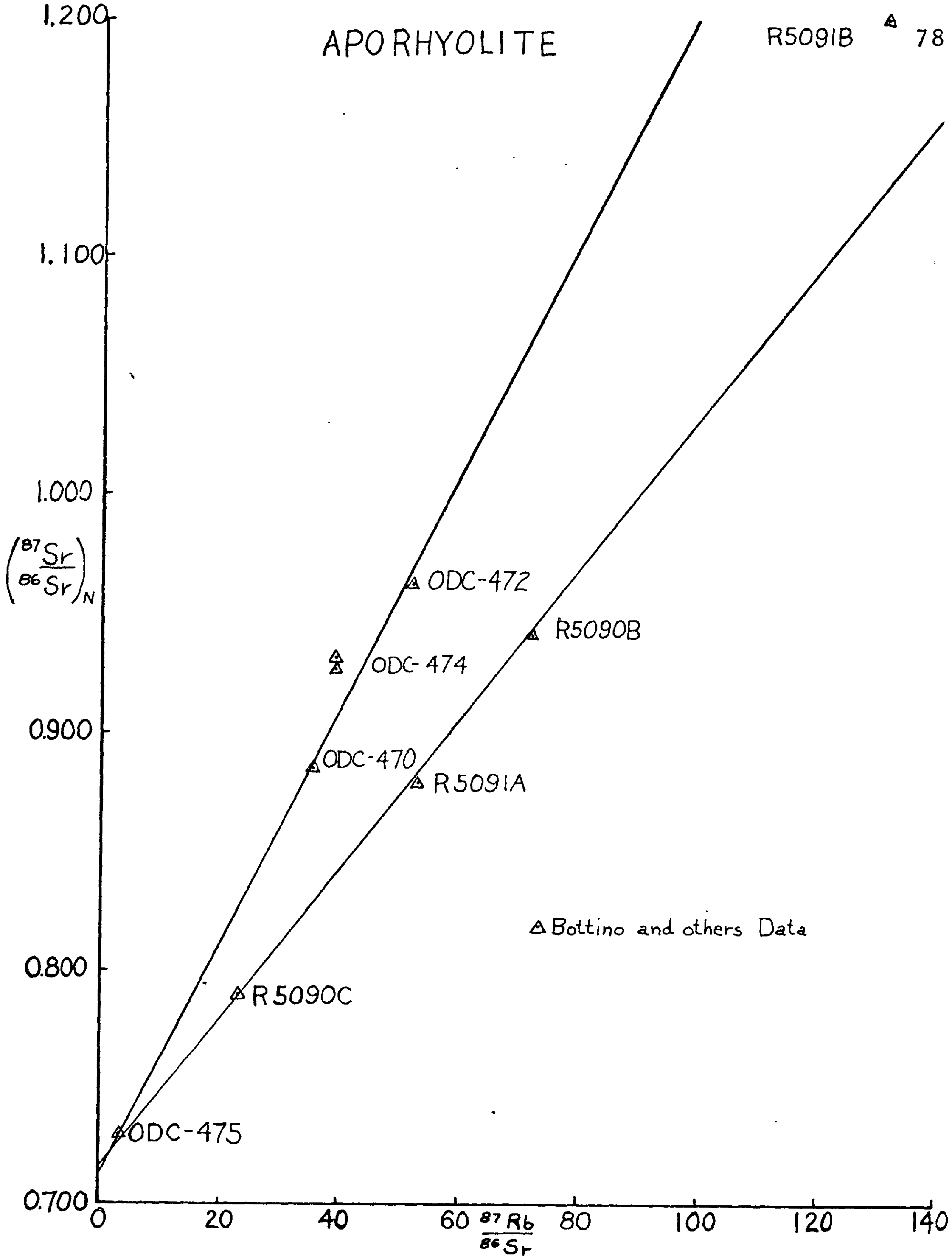


Figure 17 Whole-rock Rb-Sr isochron diagram for Aporhyolite. (Data from Bottino and others, 1970.)

Figure 18 shows a plot of the cleaned AR data. The points were cleaned by including only those which were collected specifically for age dating.

The cleaned AR data yield an age of 361 MY with an Sr_o of 0.716± 0.018, and a linear correlation coefficient of 0.98673.

Discussion of Rb-Sr Systematics

The Rb-Sr pattern for all the units shows considerable scatter. With the exception of the AR, cleaning the isochrons does not reduce the scatter, nor does it change the ages.

The Sr_o of all the units is very high (see Table 6), suggesting that the isochrons have been rotated (Bence, 1966; Faure and Powell, 1972; and Hedge and Walthall, 1963). The rotation must be due to a systematic redistribution of Sr or Rb to keep the isochrons as straight as they are. The most reasonable guess would be a redistribution of Sr. The low Sr content of the rocks makes them sensitive to Sr exchange or contamination.

The raised Sr_o values indicate, however, that the samples with low Rb/Sr ratios may have absorbed some of the radiogenic Sr. One mechanism for explaining the rotation of the isochrons is suggested by the observation that the Rb and Sr in these rocks are contained in a single phase -- the alkali feldspar. This phase favors Rb over Sr, hence Sr will be released during a disturbance. More normal granites

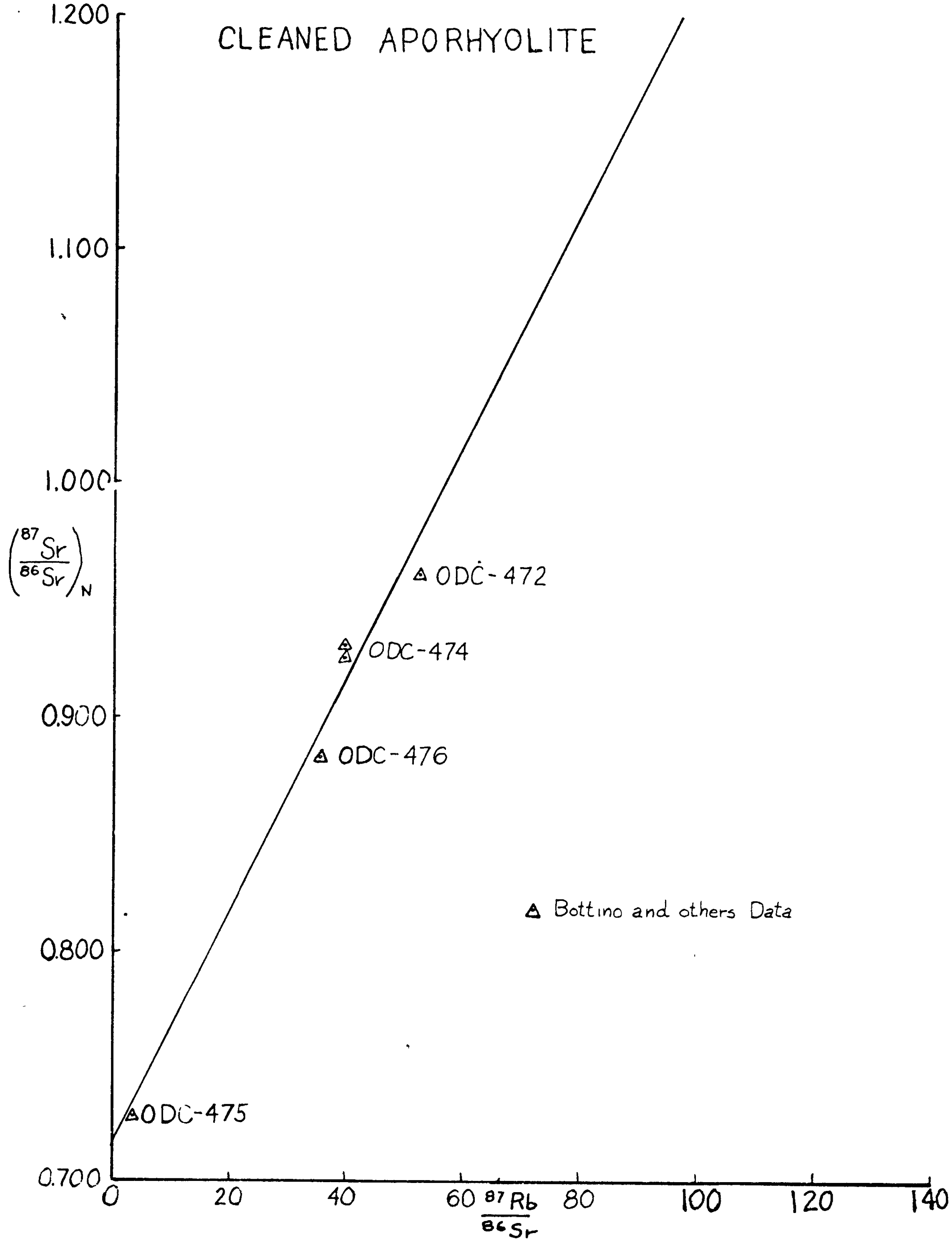


Figure 18 Whole-rock Rb-Sr isochron diagram for cleaned Aporhyolite. (Data from Bottino and others, 1970.)

TABLE 6

Summary of Rb-Sr Ages for Figures in this Work

Rock Unit	Figure	Age	Sr_o	Number of Points	Reference
Quincy granite	12	326	0.723±0.005	14	This work
	12	365	0.703±0.004	6	Bottino and others (1970)
	12	313	0.730	10	Zartman and Marvin (1971)
"cleaned" Quincy granite	13	319	0.725±0.006	10	This work
Blue Hills porphyry	14	269	0.729±0.006	18	This work.
		282	0.714	18	Bottino and others (1970)
"cleaned" Blue Hills porphyry	15	281	0.722±0.006	10	This work
Blue Hills porphyry near southern contact	16	273	0.718±0.002	10	This work
Aporhyolite	17	247	0.743±0.026	9	This work
"cleaned" Aporhyolite	18	361	0.716±0.018	5	This work

contain minerals (calcium plagioclase, apatite, and epidote) which absorb the Sr near where it is released. This may be why the whole-rock samples appear to have closed-system behavior. The QG and BHP lack Sr-acceptor sites, hence the Sr, once released from the parent mineral, may migrate large distances before being absorbed -- distances large enough to redistribute Sr throughout the bulk of the pluton. Loss of Sr from the rock with no resorption could systematically lower the slope of the isochron (lower the apparent age) but would not change the Sr_o value. The anomalously high Sr_o values show that some of the radiogenic Sr has been absorbed by samples with low Rb/Sr ratios.

It is doubtful that Rb is the element effecting the disturbance in the ages. If Rb were the element causing the disturbance, it would have had to have been added. This is doubtful as the Rb content of the units is lower than in normal rocks (Bottino and others, 1970). Also, the addition of the Rb does not account for the raised Sr_o values. It is not likely Rb was added in proportion to the Sr in the rocks so as to produce such straight isochrons.

POTASSIUM-ARGON DATING

Zartman and Marvin (1971) determined potassium-argon (K-Ar) ages of 430-458 MY on six samples of riebeckite from the QG and 301 MY on one sample of riebeckite from the BHP. They used as clean a sample of riebeckite as little affected by alteration as possible.

They also determined the K-Ar age of a pyroxene sample to enable them to quantify the effect a few percent of pyroxene impurity would have on the age of a riebeckite sample. They measured an age of 934± 28 MY indicating that excess Ar is present and calculated that this alters the age of the riebeckite by two percent or less. They did not correct their ages for the pyroxene as it is within the experimental uncertainty of the method. For example, the riebeckite in sample 211 (see Table 7) yielded an age of 437 MY; if this were corrected for six percent pyroxene contamination, it would yield an age of 426 MY.

No attempt was made by Zartman and Marvin (1971) to account for any inherited Ar in the riebeckite structure itself. The effect of inherited Ar is greater in minerals of low K content, and would have a large effect in riebeckite if it were retained. There have been no definitive studies on the ability of riebeckite to retain Ar, but the possibility must not be ruled out (Dalrymple and Lanphere, 1965). From a cursory look at the data the riebeckite with low K content does not produce an age older than one with a higher K content (see Table 7), hence the inherited Ar effect is probably slight.

Zartman and Marvin (1971) determined the age on a single riebeckite sample from the BHP and felt the age was low due to the altered nature of the rock and poikiolitic feldspar included in the riebeckite. The feldspar might have accounted for the high K_2O content and might

TABLE 7

Potassium-Argon Ages of the Quincy Granite and Blue Hills Porphyry*

Rock Unit	Sample No.	Sample Mineral	K_2O%	Age MY
Quincy granite	95	riebeckite	0.931	430 ± 13
	96	riebeckite	0.768	458 ± 14
	97	riebeckite	0.953	444 ± 13
	98	riebeckite	0.612	437 ± 13
	211	riebeckite	0.962	437 ± 13
	211	pyroxene	0.192	934 ± 28
Blue Hills porphyry	213	riebeckite	1.876	301 ± 9

* Data adapted from Zartman and Marvin, 1971, p.943

have contaminated the K_2O of the riebeckite.

ZIRCON DATING

Quincy Granite

The zircon method of age dating has generally been the most successful in "seeing through" more recent thermal or metamorphic events. It has proved useful even in cases where K-Ar or Rb-Sr systems have been reset (Doe, 1970; Steiff, 1959).

Three independent ages (U^{238}/Pb^{206}, U^{235}/Pb^{207}, Th^{232}/Pb^{208}) and one dependent age (Pb^{207}/Pb^{206}) for a single sample may be determined from analysis of thorium (Th), uranium (U), and lead (Pb) isotopes. The method does not require more than one sample from a given pluton; however, because of possible post-crystallization Pb diffusion from the zircon, it is preferable to plot all cogenetic zircons on a Concordia diagram and determine a regression chord whose upper intercept yields the best age for the suite of cogenetic zircons.

Zartman and Marvin (1971) analyzed only one zircon fraction from the QG. They plotted their U-Pb data for the QG on a Concordia plot along with zircon data from the nearby Cape Ann and Peabody granites which they assumed to be cogenetic with the QG. A chord fitted to these points yielded a primary Concordia intercept of 450± 25 MY which Zartman and Marvin interpreted as the best measure of the age for the three granites.

For this paper it is important to estimate an age for the QG alone without introducing the assumption it is cogenetic with the other granites; thus, a discussion of how to estimate an age from a single zircon analysis follows.

A unique age determination from a single zircon fraction cannot be made using the episodic Pb loss model of Wetherhill (1956). Assuming reasonable dates for post-crystallization disturbance episodes, the following primary ages may be derived: a 400 MY episode (possible emplacement of AR) yields a primary age of 680 ± 25 MY; a 360 episode (Acadian orogeny) yields 520 ± 20 MY (Lyons and Faul, 1968; Quinn and Moore, 1968); and a 260 MY episode (emplacement of post-Carboniferous granites) yields 450 ± 20 MY (Zartman, Hurley, Krueger and Gilletti, 1970). All primary ages by this model are older than the Pb^{207}/Pb^{206} age.

The two cogenetic zircons from the Peabody granite have a lower Concordia intercept of 200 ± 20 MY (Zartman and Marvin, 1971), showing no sign of episodic disturbance at any of the times indicated above.

One can use various Pb diffusion models (Tilton, 1960; Wetherhill, 1963) to estimate possible regression lines through a single datum point.

The family of radiation damage diffusive Pb loss models (Wasserburg, 1963) yields slightly younger primary ages than the constant diffusive Pb loss model of Tilton (1960). Wasserburg (1963) has shown that for nearly concordant zircons the ages from these different models agree to the first order, and that these ages are only slightly older than the Pb^{207}/Pb^{206} age. Hence, Zartman and Marvin's (1971) Pb^{207}/Pb^{206} age of 437± 32 MY probably gives a good estimate of the minimum age of the QG zircon. The error bracket of ± 32 MY is large, due to the uncertainty in the common Pb correction for this particular analysis (Zartman and Marvin, 1971).

Radon loss could make the Pb^{207}/Pb^{206} age anomalously old but does not appear to be a major effect. The interpretations discussed above assume no intermediate daughter loss, but this is at least a possibility in the QG which has probably never been "sealed" by deep burial (P. M. Hurley, personal communication). Radon loss is explained in the following paragraph.

An intermediate step in the decay process from U to Pb for both U isotopes as well as Th is radon (Rn) -- a gas. If the system is subject to Rn leakage, either through crystal damage due to radioactive breakdown of the parent or to elevated temperature in the parent rock, the daughter product will then be lost. This loss of daughter product will produce an erroneous age. In the Pb^{207}/Pb^{206} age determination, the two daughter products have different intermediate half lives. The U^{238} to Pb^{206} chain has Rn^{222} with a half life of 3.8 days, the U^{235} to Pb^{207} chain includes Rn^{219} with a 3.9 second half life. Thus, a system open to Rn leakage would have a better chance of retaining the Pb^{207} than Pb^{206}.

Because of the above reasons, U^{238}/Pb^{206}, U^{235}/Pb^{207}, Th^{232}/Pb^{208} will yield lower ages. The Pb^{207}/Pb^{206} age on the other hand will be too old. Thus an age intermediate between the three low ages and one high age (Pb^{207}/Pb^{206}) would yield the most accurate age by this model.

Zartman and Marvin (1971) analyzed two zircon fractions from the Peabody granite for their U-Pb isotope content. A normal Tilton (1960) model regression line for diffusive Pb loss fits the two Peabody points with negligible evidence of any Rn loss having occurred. Thus, diffusive Pb loss clearly dominates the isotope data with only a slight chance of any Rn loss having occurred. The QG lies within analytical uncertainty on the same chord as the zircon fractions from the PG and would probably also be dominated by diffusive Pb loss with minimal evidence of Rn loss.

There is no suggestion from the isotope data or the morphology of the zircons that xenocrystic zircons are present. For this reason, it is doubtful that any anomalously old U-Pb age could be obtained due to older zircon contamination.

Blue Hills Porphyry

A seventy kilogram sample of BHP was collected and processed for zircon (Pb-U) age dating to determine if the zircon age would also yield an older age than the Rb-Sr method for the BHP. However, insufficient zircon was obtained for analysis.

EVALUATION OF ALL ISOTOPIC WORK

Quincy Granite Results

The zircon (Pb-U) ages and K-Ar ages of the QG are in agreement and yield ages ranging from 413 to about 458 MY. At first, the results of Rb-Sr work on the QG and BHP appear to be too good to be dismissed arbitrarily and were, therefore, examined carefully. The Rb-Sr ages of the QG are younger than the K-Ar or zircon ages by at least 50 MY.

The results of the Rb-Sr isochron method on the QG yield ages that range between 313 and 365 MY for computer analyzed results in apparent disagreement with both the K-Ar and zircon ages. This indicates that either both the zircon and K-Ar ages are anomalously old by the same amount (a most improbable occurrence), or else the Rb-Sr system has been reequilibrated after crystallization. The Rb-Sr system records an age that is a partial response to a late Palezoic disturbance.

Blue Hills Porphyry Results

The BHP yields Rb-Sr ages that are younger than the Rb-Sr, K-Ar and zircon ages of the QG. This disagrees with the observed field relationships pointed out in Chapter II. Thus, it is assumed the Rb-Sr ages for the BHP are altered as well.

The BHP whole-rock Rb-Srisochron of Bottino and others (1970) yields a 282± 8 MY age with an Sr_o of 0.717± 0.002.

Cleaning the BHP points, plus including Zartman and Marvin's (1971) data, does not reduce the scatter at all from the isochron of Bottino and others' (1970). The original isochron yielded an age of 283 MY and the cleaned isochron, 281 MY. The isochron for the BHP near the contact with the PC shows the least scatter of any BHP isochron, the age of 273 MY not having changed appreciably. The points not used for the last isochron (see Figure 16) do not produce any isochron at all. There is no evidence that the BHP can be broken into two units from the Rb-Sr data so far obtained.

The BHP must have had its Rb-Sr lowered by the same mechanism which affected the QG, and which was discussed in the preceding pages. The effects which lowered the age are more prominent in the BHP which is possibly due to its more surficial location.

A second reason, such as later hydrothermal activity (which may have lowered the age), is suggested by some altered rock along the roadcut at the base of Southeast Ridge.

Aporhyolite Results

The AR shows the largest scatter in Rb-Sr points of any of the three units under consideration. Its data points define no isochron, either cleaned or using all available points. The uncleaned data yield a 247 MY age with a large standard deviation. The best fit to the cleaned isochron yields a 365 MY age, the latter agreeing with the Devonian paleomagnetic poles reported for the Mattapan volcanics (L. D. Schutts, personal communication) which may suggest that disturbances did occur at that time.

Some of the AR samples appear to be older than both the QG and BHP as they have a higher Sr_o for the corresponding Rb^{87}/Sr^{86}. Other ages are lower, no doubt, due, among other things, to the event which caused the pyritization and faulting along the Route 128 - Route 3 interchange just southwest of Pine Hill.

The AR is composed of a series of acid extrusives; thus, ash and block flows, tuffs, volcanic breccias, and rhyolite flows are all incorporated into the AR unit. It is not surprising that such a varied unit should yield varied ages. The possibility of younger volcanics occurring in the area cannot be ruled out on the basis of geochronology, petrographic work, and field work.

CONCLUSION

It is my opinion, based on Zartman and Marvin's (1971) data, that the QG was emplaced between 422 and 437 MY ago. This age is early Silurian or late Ordovician by many time scales (Faul, 1960; Bottino and Fullager, 1966; Fullager and Bottino, 1968; Edwards, et al., 1959) and is not in conflict with observed field relationships. It later either underwent a metamorphic event, which reequilibrated the Sr throughout the rock, or continuously lost radiogenic Sr due to weathering. The lower ages recorded by the AR and BHP are probably the result of some Permo-Carboniferous hydrothermal activity related to the Wamsutta volcanics.

V. DISCUSSION

PETROLOGY AND GEOLOGY OF THE BLUE HILLS PORPHYRY

The Blue Hills porphyry (BHP) is found to be a single unit despite the large textural variation. The texture varies from an aphanitic, through a porphyritic, to a "granitic" one. These varieties or facies have already been noted by Crosby (1900), Warren (1913), and by Chute (1940, 1969) but could not be shown on geological maps due to their rapid variations.

The BHP is a shallow intrusion as is evident from the gradational changes in texture resulting from variable cooling conditions and proximity to the margin. The presence of low pressure, high temperature, bipyramidal, quartz pseudomorphs, is another indication that the BHP is a shallow intrusion.

A third indication of the proximity of the surface is the vertical gradation of the texture. The BHP is aphanitic at elevated areas near the contacts with the aporhyolite, which may or may not have been preserved. It grades into a granite porphyry in the topographically lower areas of some notches.

The BHP and Quincy granite (QG) have not been deeply eroded because little QG or BHP detritus is seen in the Boston or Norfolk

Basins (Crosby, 1900, p. 462; Pollard, 1965). The BHP has only recently been unroofed. The outer margin of the BHP is indicated by the fine-grained variety and is still evident on top of hills. This shows that it is unlikely that the much discussed outcrop at the Route 128-28 intersection is a spheroidally weathered area.

Field investigations show that the QG is younger than the BHP, as was previously determined by Crosby (1900), Warren (1913), and by Chute (1940) (see Table 8).

Dikes, which intrude the BHP on Chickatawbut and Kitchamakin Hills, are believed to be a part of the QG. The QG is slightly chilled against the BHP on Rattlesnake Hill, as shown by a slightly porphyritic zone developed at the contact. The QG magma is chilled in other places forming the fine-grained riebeckite granite.

Chute (1969) may have been influenced by Bottino's (1963a) isotopic age dating and may have reinterpreted his 1940 observations so that they agree with the resultant ages (Chute, 1966, p. 92). The features at some of the contacts in the Chickatawbut Hill area are indistinct, but the size and shape of the granite bodies point to the conclusion that they are dikes.

From the first conclusion that the BHP is a single, albeit variable unit, and from the second conclusion that the BHP is older than the QG, the Wones and Riley hypothesis that part of the BHP may be a Carboniferous volcanic unit (as discussed in the Introduction), is precluded.

The other major units in the Blue Hills area are believed to have occurred in essentially the same order given by Chute (1969). At one time, the AR was believed to have been the youngest of the units (Crosby, 1900), but Warren (1913) demonstrated that the BHP is indeed younger than the AR. Most recent workers have agreed with Warren's interpretation for reasons cited in Chapter II.

GEOCHEMICAL AFFINITY OF THE BLUE HILLS PORPHYRY AND QUINCY GRANITE

The QG and BHP are related igneous intrusives. Previous investigators have believed that the QG and BHP are comagmatic. They cite similarities in major element chemistry, mineralogy, petrology, and field relationships in support of their tenets. The BHP and QG have the same type of feldspar, alkali hornblende, and pyroxene, as well as the same trace minerals, astrophyllite and aenigmatite. The BHP and QG have the same major element compositions; they both are low in Ca, and have a similar agpaitic ratio.

The unusually low Sc content (0.2 ppm) identical for both the BHP and QG strongly contrast with 1.3 to 3.3 ppm characteristic of other alkali granites of eastern Massachusetts. The europium anomalies, and the rare earth element abundances of both units normalized against the rare earth element abundance of chondrites, are nearly identical.

Similar abundances of trace elements in both units offer strong support to the long-held belief that the BHP and QG may be magmatically correlated.

RADIOGENIC AGES

Previous published isotopic age determinations show unusually large scatter which are difficult to interpret. A single zircon age of 422± 16 MY to 437 ±32 MY approximates the best age for the onset of crystallization in the QG. The K-Ar ages determined correlate well with the zircon age but might be slightly old due to inherited Ar. It is unlikely that the QG is younger than the U^{235}/Pb^{206} of 413± 8 MY.

The Rb-Sr ages determined for the QG are much younger than the K-Ar and zircon ages. The Rb-Sr ages measured for the BHP (Bottino and others, 1970 ; Zartman and Marvin, 1971), although within the stratigraphic limitations, are not compatible with the field relationships presented in Chapter II, the K-Ar and zircon dates of Zartman and Marvin (1971), or the results of Crosby (1900), of Warren (1913) and Chute (1940). The Rb-Sr ages of the BHP afford no help in trying to refine the age relationships within the BHIC or with its surroundings.

Because of the obvious discrepancy between the Rb-Sr ages of the BHP with the zircon and K-Ar ages of the QG, it must be concluded that the Rb-Sr system of the BHP and QG has been open to post-crystallization Sr migration. It is likely, then, that the Rb-Sr whole-rock ages of the QG are also anomalous as the mineralogy, petrology, and location of the QG are so similar to those of the BHP. This is suggested by the scatter of Rb-Sr data for the QG and AR, and the extremely high Sr_o of 0.725 ± 0.006 for the "cleaned" QG isochron.

The disturbance of the Rb-Sr system is probably the result of a variety of effects; a mechanism to preserve the apparent linearity of the isochrons is described on page 79. Nonetheless, the effect of other post-crystallization events might be superimposed on that of isochron rotation.

The BHP and QG systems show the same disturbance mechanism. Hence, the mechanism operating in the BHP is probably similar to that acting in the QG. The more pronounced disturbance on the Sr system in the BHP might be accounted for by the more limited presence in the BHP than are in the QG of trace minerals (i.e., apatite, epidote, monazite, allanite), capable of reabsorbing radiogenic Sr.

There is no basis, either field petrological, mineralogical, or chemical, for separating a younger BHP from the main BHP. Nevertheless, an attempt was made to separate two isochrons from the available isotopic data. The results of Rb-Sr isotopic age dating on the BHP cannot be split to yield two "clean" isochrons. No matter how the data are manipulated, the age always varies systematically about 280 MY. This age is not recognized as belonging to any tectonic or metamorphic event in the area and thus must be due to a partial reequilibration at some younger period, or due to a continual Sr loss.

APPENDIX A

SUMMARY OF PREVIOUS WORK ON THE BLUE HILLS IGNEOUS COMPLEX (BHIC)

The purpose of this section is to review the evolution of the geological thoughts about the Blue Hills Igneous Complex (BHIC), particularly the Blue Hills porphyry (BHP) since the first field studies made by Crosby (1900).

Since eastern Massachusetts lacks fossil localities to cross-correlate the stratigraphic column, the ages assigned to the individual units depend largely upon complex arguments, based on subjective interpretation of field relationships. These correlations are sometimes difficult to follow as they commonly include previously published information that has not been critically reviewed. Therefore, it has proved necessary to document the evolution of ideas of earlier workers and evaluate the validity of current theories. Reference to Table 8 in the following discussion may prove helpful.

Nomenclature

The names are sometimes difficult to follow as they have evolved

Geologic Age	Crosby (1896)	Warren (1913)	Emerson (1917)	Billings (1929)	LaForge (1932)	Bell (1948)	Chute (1969)	This work (1974)
early Permian				Roxbury Conglomerate				
Pennsylvanian	PONDVILLE CONGLOMERATE		Pondville conglomerate Roxbury conglomerate interstratified with Mattapan volcanics + Wamsutta volcanics	PONDVILLE CONGLOMERATE	Wamsutta volcanics	Wamsutta volcanics	Wamsutta volcanics	Wamsutta volcanics Pondville conglomerate
Mississippian			Quincy granite fine grained riebeckite granite	Mattapan volcanics				
early Mississippian	aporhyolite Quincy granite including Dedham granodiorite fine-grained riebeckite granite Blue Hills porphyry rhombporphyry	Quincy granite fine-grained riebeckite granite Blue Hills porphyry rhombenporphyry aporhyolite	Blue Hills porphyry rhombporphyry aporhyolite = Mattapan		Quincy granite fine-grained riebeckite granite Blue Hills porphyry aporhyolite		Roxbury Conglomerate	
late Devonian				Quincy granite fine grained riebeckite granite Blue Hills porphyry aporhyolite rhombporphyry			Blue Hills porphyry Quincy granite fine-grained riebeckite granite	
Devonian		Dedham granodiorite	Dedham granodiorite		Roxbury conglomerate	Quincy granite Blue Hills porphyry fine-grained riebeckite granite aporhyolite = Mattapan = Lynn interstratified with Roxbury + Newbury rhombporphyry		
early Devonian			Newbury volcanics	Dedham granodiorite	• Mattapan = Lynn = Newbury volcanics Dedham granodiorite		Mattapan = aporhyolite rhombporphyry Newbury volcanics	Roxbury conglomerate
Silurian								Newbury volcanics ? Lynn Quincy granite fine-grained riebeckite granite Blue Hills porphyry ? aporhyolite = Mattapan ? Lynn rhombporphyry
late Ordovician						Dedham granodiorite		
Ordovician								
middle Cambrian	BRAINTREE ARGILLITE							
Pre-Cambrian							Dedham granodiorite (?)	Dedham granodiorite (?)

Table 8 Comparison of geologic interpretations of the Blue Hills Igneous Complex by various geologists since Crosby.

over the course of a century of study. For coherence, this author has tried to adopt modern nomenclature, based on that of Chute (1940, 1966, 1969) and use this as consistently as possible throughout the text. The original descriptive terminology is placed in quotation marks and other names used, in parentheses; brackets indicate editorial inserts.

PREVIOUS WORKERS

W. O. Crosby

The earliest available work on the BHIC is that of Crosby (1900), who first described and interpreted many of the critical outcrops.

Crosby recognized that the BHIC, composed of the Quincy granite (QG), aporhyolite (AR) (Mattapan Volcanics), and Blue Hills porphyry (BHP) (Blue Hills Granite Porphyry), is younger than the middle-Cambrian Braintree argillite and older than the Carboniferous Narragansett sediments (Crosby and Barton, 1880).

From chemical analyses (Crosby, 1900, p. 362; Washington, 1896) of the units in the BHIC, Crosby, among others, concluded that all of the units were comagmatic with the surrounding plutons. Thus, the rhombporphyry (RP) (Crosby's (1900) terminology "basic quartz porphyry"), Dedham granodiorite "biotitic normal granite", Sharon syenite "diorite or basic granite" and Salem gabbrodiorite "diorite or granodiorite" were more basic than differentiates of the same magma from which the QG, BHP, AR and fine-grained riebeckite granite (FGRG) were derived. Crosby (1900) noted the RP had thirteen percent less SiO_2 than the other units and some of his units, including the RP, were more calcic. He utilized these findings in his discussion of the differentiation of the magma and never considered the possibility of different parent magmas. (The BHIC and environs were considered a classic example of magmatic differentiation by the nineteenth century geologists).

Crosby's (1900) ideas were developed from observations of field contacts. The following summarizes his field observations of contacts of the units:

1) the QG "hornblendic normal granite" intrudes the Braintree argillite at various localities (Crosby, p. 395);
2) QG contains argillite inclusions (Crosby, p. 395);
3) QG contains FGRG inclusions (Crosby, p. 369);
4) QG contains RP inclusions (Crosby, p. 367, 368, 370);
5) The BHP grades into fine granite and then to granite (Crosby, p. 362, 365, 357-358, 366);
6) Fragments of porphyry are included in the fine granite (Crosby, p. 366, probably RP and FGRG, his descriptions are difficult to interpret);

7) No macroscopic flow texture is evident along contacts of BHP (he did note microscopic flow texture) (Crosby, p. 361);

8) "Fine-grained granite of intrusive character passes into microgranite then quartz porphyry (BHP) .... occurs as dikes cutting through the normal granite both hornblendic (QG) and biotitic" (Crosby, p. 347). Another source of misunderstanding is that Crosby has three aporhyolites, three quartz porphyries, and two fine-grained granites. Here he is referring to an acid fine-grained granite younger than the QG);

9) FGRG occurs as a contact zone of QG and is older and more basic (Crosby, p. 347). This is no doubt the FGRG which occurs as xenoliths in item 3 and is not the fine-grained granite in item 8 because the fine-grained granite in item 8 is younger than the QG and the fine-grained granite in item 3 is older than the QG;

10) FGRG continues as a persistent zone between QG and BHP (Crosby, p. 350);

11) Generally the AR is absent in the QG and BHP;

12) The BHP occurs as boulders in the basal conglomerate of the Carboniferous;

13) The contact of the BHP and QG is not exposed on Pine Hill (Crosby, p. 380);

14) An apophysis of AR seems to intrude the BHP (Crosby, p. 382 on Pine Hill);

15) AR (felsite) is nowhere found in contact with the QG (Crosby, p. 386);

16) A continuous band of subacid porphyry (BHP?) separates the AR and QG (Crosby, p. 382);

17) "A large part of the area mapped as quartz porphyry .... is a blending patchwork of aporhyolite porphyry (BHP) and granite porphyry" (p. 367). Note: According to Moor house (1959), the older usage of quartz-porphyry meant a metamorphosed felsite orrhyolite and Crosby (p. 357) states that he uses quartz-porphyry rather than porphyritic aporhyolite. ;

18) The mottled porphyry "remarkable uniformity of material - only variation noted consists of two angular inclusions of red jasper or fine quartzite" (p. 474);

19) Crosby noted that the quartz-porphyry is not a later intrusion of surface flow over the granite because (1) the porphyry gradually passes into granite; (2) inclusions of fragments of porphyry in fine granite fine granite is the border phase of the QG ; and (3) the entire absence of flow structure in the porphyry (Crosby, p. 366).

Crosby's initial assumptions were that all the igneous bodies were comagmatic and the Braintree argillite occurs as roof pendants in the batholith. His theory needed a thick sequence of sediments in place. Convection currents would homogenize the magma, and upon cooling it would differentiate into the variety of igneous rocks now exposed. Because of the thick sequence of sediments he needed, he thought the BHIC was late Devonian or early Carboniferous. His ages for the rocks from the youngest to the oldest are as follows:

Triassic	Later trap dikes
Pennsylvanian	Wamsutta Formation Pondville conglomerate (basal giant conglomerate)
Carboniferous	Period of deep erosion forming the "spheroidal" zone
Late Devonian or early Carboniferous	Aporhyolite Quincy granite Fine-grained riebeckite Granite Blue Hills porphyry rhombporphyry
Devonian Silurian Ordovician	Thick deposits of sediments now eroded (Crosby, p. 390)
Post-Braintree Pre-Quincy	Older trap dikes
Middle-Cambrian	Braintree argillite

G. F. Loughlin

Loughlin (1911) briefly summarized the geology of the area. He incorporated recent work of others, i.e., he reported Clapp (1910) showed that the alkali granite series is distinctly younger than the "biotite granite" of the Boston area.

Loughlin said geologists believed the Boston and Norfolk Basins were contemporaneous and younger than the QG, but no QG has been found in either basin. He noted Mansfield's (1906) failure to identify BHIC rocks in the PC or Roxbury conglomerate. Loughlin undertook a petrographic study and confirmed the existence of "Quincy type granite porphyry" (BHP) in the basal conglomerate of the PC (Loughlin, p. 240).

He also described the contact of the northern boundary fault of the Quincy block from a newly exposed roadcut.

The only change from Crosby's ideas Loughlin made was to separate the biotite granites from the hornblende granites (BHIC).

C. H. Warren

Warren (1913) published a petrographic and chemical study of the BHIC. He had done field work under Crosby's supervision. Warren clarified some of Crosby's terminology and redefined the units.

APORHYOLITE - Crosby's aporhyolite units were numerous and included some of the BHP. Warren classified Crosby's terminology and defined the unit we now call AR.

RHOMBPORPHYRY - Warren distinguished the RP as being distinct from the porphyritic QG and the BHP.

QUINCY GRANITE - Warren (1913, p. 224, 214) described four variations in the QG and noticed a protoclastic structure of the QG. He also noticed an inconspicous porphyritic border of the QG (p. 207).

BLUE HILLS PORPHYRY - Warren (1913) described the BHP in detail, both in the field and under the microscope. His work should be referred to for petrographic descriptions (p. 243, 249).

Warren broke the BHP into two distinct, major types: (1) granite porphyry, and (2) quartz-feldspar porphyry, and several lesser varieties. He could not map them separately due to transitions of one into the other, to their irregular distribution and only minor textural differences hidden by heavy lichen cover.

GRANITE PORPHYRY - Warren (1913, pp. 238, 240) considered the granite porphyry the most important rock in areal distribution and volume. He said it is holocrystalline, resembling a fine-grained granite for which it is usually mistaken. It has abundant phenocrysts of alkali feldspar and quartz embeeded in a finely granular groundmass with numerous irregular specks of black mineral. Feldspar phenocrysts outnumber the rounded, smaller quartz.

QUARTZ-FELDSPAR PORPHYRY - According to Warren (1913, p. 240) the granite porphyry grades into quartz-feldspar porphyry of lesser areal extent. Warren describes the quartz-feldspar porphyry as having a groundmass which is a little finer, darker and more varied in color than the granite porphyry groundmass. A dark mineral (riebeckite-arfvedsonite?) is distributed about the groundmass making it quite dense in appearance. This grades into a phase with a truly dense groundmass (p. 240). The phenocrysts are less abundant and quartz forms rounder and more prominent grains than in the granite porphyry.

Warren (1913, p. 240) said the quartz-feldspar porphyry is a unit of "heterogeneous structure" which occurs in blotches and streaks and the arrangement of the "streaks and fragments show a pronounced flow structure". It resembles a breccia or tuff with contact features even in areas of the Blue Hills not near a contact (pp. 239-240). He believed "that the contacts were at most only a short distance from the present surfaces of the rocks as now exposed, and that erosion has removed very little of the intrusive rock, a point that seems to be entirely borne out by the notable scarcity of rocks of the alkaline type in the conglomerate ... of later age" (p. 240).

Warren (1913, p. 258) said the streaked porphyry is not due entirely to weathering, as was supposed by Crosby , since it is not homogeneous to start with. Warren noticed flow structure in the BHP parallel to the contact with the AR.

BLUE HILLS PORPHYRY CONTACT FEATURES - Warren (1913, p. 225) found a sharp contact of BHP with QG on Rattlesnake Hill. He could not find the gradational contact between the QG and BHP noticed by Crosby (1900, p. 365) in the notches just east of Chickatawbut Hill but did find "numerous sharp contacts", which he believed were QG dikes in the BHP.

On Pine Hill, Warren (1913, p. 259) noticed a gradation between the BHP and a granite he believed to be the QG. Warren (p. 255) said "a characteristic of the porphyry (BHP) near the contact is the presence of what looks like inclusions or of streaks and spots of different color and texture from the matrix. ... Some of the streaks show evidence of much recrystallization, and seem to be drawn out and recrystallized fragments". "The porphyry of the contact zone may ... be regarded as possessing a somewhat modified taxitic structure" (p. 256).

Warren (1913, p. 241) noticed chilled features of the BHP against the AR. The "immediate contact ... is a dense quartz-porphyry type". Paraphrasing Warren (1913, pp. 253-255), the amount of matrix in the BHP increases and the quartz and feldspar phenocrysts decrease. The matrix becomes finer, almost isotropic, and the feldspar less albitized. Quartz, some showing a dihexahedral habit, increases relative to feldspar.

Warren (1913, p. 256) said:

> "In fact, it is often impossible without microscopic preparations to tell when one is dealing with the aporhyolite and when with the porphyry. The similarity is increased by the fact that the porphyry at the contact, here as elsewhere, is much brecciated, giving rise not only to the appearance of flow structure but also to that of small apophyses of dense material running into the porphyry, and these might easily be mistaken for apophyses of the aporhyolite cutting the porphyry. Such they were supposed to be by Crosby."
>
> Footnote: "To illustrate how natural was this mistake regarding the nature of this contact the writer may say that he collected several suites of specimens illustrating as he supposed the succession of types across the contact, only to find, when they were sectioned, that they were all of the porphyry and that the aporhyolite had not been reached".

SUMMARY OF WARREN'S WORK - Warren's major disagreement with Crosby was finding that the AR is older than the BHP. Warren described the BHP in great detail and believed it is a slightly older member of the same magma from which QG crystallized. He noticed no xenoliths of one in the other. He discovered a previously unknown sharp contact on Rattlesnake Hill, and a sharp contact between the BHP and what he believed to be a QG dike where Crosby (1900) had seen a gradational contact. He said that the QG develops a porphyritic texture near its border, and he also noticed gradational features between the QG and BHP on Pine Hill.

B. K. Emerson

Emerson (1917) summarized the geology of Massachusetts and Rhode Island. His work gives us a datum of what geologists then believed.

The QG, BHP, and AR were all assumed to be related. The BHIC was younger than the middle-Cambrian Braintree argillite and older than the Pennsylvanian PC. It was also considered younger than the "Devonian" Dedham granodiorite because the BHIC related volcanics were extruded on the Dedham in several localities.

Emerson (1917, p. 194) assigned the AR to the Mattapan volcanic complex because of the following reasoning: "It [the AR] is assigned to the Mattpan volcanic complex because it was first regarded as probably effusive and younger than the Blue Hill granite porphyry (BHP), but Warren has since shown rather convincingly that it is more probably older than the porphyry, but comagmatic with it and probably a remnant of the outermost shell and first-cooled part of the invading magma."

The Mattapan is "the floor upon which a considerable part of the sedimentary rocks of the [Boston] basin was deposited" (Emerson, p. 186).

The only fossils found in the Roxbury conglomerate were "a few obscure tree trunks, possibly Cordiates" (Emerson, p. 58). "The age of the beds is assumed from what appear to be the most reasonable correlations with the formations of the Narragansett Basin" (Emerson, p. 58). Thus, Emerson (1917, p. 202) correlated the volcanics of the Narragansett Basin, which are intercalated in the Carboniferous Wamsutta formation, with the Mattapan volcanics. According to Emerson (1917), the Newbury volcanic complex was originally correlated with the Mattapan and Lynn volcanics. However, because Silurian or Devonian fossils were found in the Newbury volcanic complex, Emerson (1917, p. 164) preferred not to correlate the Newbury with the Mattapan but chose to believe the Mattapan volcanics are contemporaneous with the Carboniferous Wamsutta voncanics. His reason for deciding that the Mattapan volcanics are Carboniferous, is that they could be the Boston Basin analogue to the interstratified basalt and rhyolite in the Carboniferous Wamsutta formation (Emerson, p. 202). Emerson (1917, p. 186) believed "Carboniferous time was another period of eruptive activity. These rocks are characterized by being more alkali, rich in sodium... They are in part older than the Carboniferous strata and part inbedded with them".

Emerson (1917) separated the Siluro-Devonian Newbury volcanics from the "Carboniferous" Mattapan and Lynn, placing them with the QG and related rocks in the Carboniferous era.

M. P. Billings

Billings (1929) wrote an article on the structural geology of the Boston Basin. In his article he stated the Mattapan volcanics were probably Pennsylvanian and the "Quincy batholith" or BHIC, including the AR, was probably Devonian in age (Billings, p. 102). Billings (1929, p. 103)"restricts the term Mattapan to the group of volcanics which underlie the Roxbury conglomerate . . . but which rest on the eroded surface of the Dedham granodiorite and contain pebbles of it". He considered these Mattapan volcanics to be Pennsylvanian and he did not group the AR and Mattapan as one unit. Billings (1929, p. 106) correlated the Roxbury conglomerate with the Dighton conglomerate of the Narragansett Basin, thus giving a late Pennsylvanian or early Permian age to the Roxbury conglomerate.

L. LaForge

LaForge (1932, p. 28) divided the igneous rocks into two general groups: one, the older - chiefly volcanics of the Lynn, Newbury and Mattapan complexes; the other, somewhat younger - Quincy related rocks. LaForge called the Mattapan volcanics Silurian or Devonian and correlated them with the Newbury. The Lynn and Mattapan were presumed to be of equal age as they are deposited on identical terrain. The field appearance, mineralogy, degree of alteration, lithological types and chemical similarities indicate they belong to the same volcanic cycle. The Newbury was correlated with the Lynn on structure, geography and field appearance. LaForge did not correlate the Mattapan volcanism with that in the Wamsutta Formation (LaForge, p. 29).

LaForge (1932, p. 33) treated the Brighton melphyre as a separate, younger intrusion from the Siluro-Devonian Mattapan. He did not like a Permian age for the Roxbury and placed it, with its interbedded Brighton volcanics, in the late Devonian.

LaForge (p. 35) believed the BHIC was either Devonian or early Carboniferous and was "the final stage of a Devonian igneous cycle of which the volcanic [Newbury, Lynn, and Mattapan] eruptions were the initial stages".

K. G. Bell

Bell (1948) called the QG lower Devonian based on its consanguinity with the Mattapan volcanics. He correlated the Mattapan and the Lynn; the Lynn with the Newbury volcanics with its interbedded lower Devonian fossils.

He did not correlate the basalt and rhyolite flows in the Narragansett and Norfolk Basins with similar flows in the Boston Basin. He called the Roxbury Devonian, partially based on the fossils of questionable (but possible) Devonian age, and partially because it was deposited upon a basement of lower Devonian volcanics (i.e., Mattapan-Lynn-

Newbury).

Bell (1948) stated the Dedham granodiorite had to be at least as old as early Devonian or late Silurian, as it had a deeply weathered fossil soil developed on it before the Mattapan volcanics were deposited in lower Devonian time.

N. E. Chute

BLUE HILLS PORPHYRY-QUINCY GRANITE RELATIONS-1940 - Chute mapped the Blue Hills Quadrangle for the U. S. Geological Survey in the late 1930's and published a preliminary report in 1940 (Chute, 1940, p. 12). Chute reported two dikes of QG which cut the BHP (Chute, 1940, pp. 11-12). He said the QG is younger than the BHP but that the two are related.

He quotes his Devonian or lower Carboniferous age for the BHIC from LaForge. Chute upheld Warren's conclusions that the AR is the oldest unit as he found "numerous inclusions along the AR contact with the BHP on the northwest side of Hemenway Hill that appear to be fragments of the aporhyolite" (Chute, 1940, p. 14). He also reported that "On Pine Hill, the fine-grained granite [FGRG?] appears to grade into granite porphyry BHP; and therefore may be regarded as another contact facies of the Quincy granite" (Chute, 1940, p. 13).

QUINCY GRANITE-BLUE HILLS PORPHYRY RELATIONSHIPS - 1969 - Chute's (1969) final quadrangle map stated that there was "new evidence" favoring the interpretation that the QG was older than the BHP. Chute reported that he had seen large irregular inclusions of QG in the BHP -- not dikes as previously reported.

From the localities noted on Chute's 1969 bedrock map of the Blue Hills Quadrangle, these "large inclusions" were what Warren called "dikes" and Crosby interpreted as "Quincy granite" grading into BHP.

CONCLUSIONS

The previous workers have all agreed that the AR, QG, and BHP are related and have called them the BHIC. The absolute age of the BHIC has changed considerably, but it remains between middle-Cambrian and upper Carboniferous. The age can be readily shifted up and down within this slot and still fit the relationships.

Although the relationships of the BHP and QG are non-conclusive, Crosby (1900), Warren (1913), and Chute (1940) believed the BHP was slightly older but contemporaneous with the QG. Chute (1969) reversed this for reasons not clearly stated, allowing the BHP to assume any age between the Quincy and Pondville. The AR has been established as being older than both units. The relationship of the AR to the Mattapan volcanics is not certain. The volcanics of the area have been and can be variously correlated depending on what age they need to be to fit various hypotheses.

APPENDIX B

BLUE HILLS PORPHYRY
AND
PONDVILLE CONGLOMERATE CONTACT

This appendix describes in detail the units present along the southern margin of the Blue Hills porphyry (BHP). The section showing the best exposed relationships of the units occurs on the northern side of the Route 128-28 overleaf. Figure 19, a projection of this outcrop, accompanies this appendix and is referred to in the text.

As is shown in Figure 19, the outcrop is divided into three zones: the BHP on the north, the "spheroidal" zone, and the Pondville conglomerate (PC) on the south. The "spheroidal" zone separates the two distinctive rock types and will be dealt with later.

A. BLUE HILLS PORPHYRY

A. 1 Type Locality

The BHP type locality is on the southeast flank of Rattlesnake Hill. The BHP here is holocrystalline, light-bluish grey with phenocrysts of microperthite and quartz in a fine-grained hypidiomorphic matrix. Poikiolitic riebeckite-arfvedsonite, and aegirine also occur. The feldspars are euhedral to subhedral and are generally more abundant and

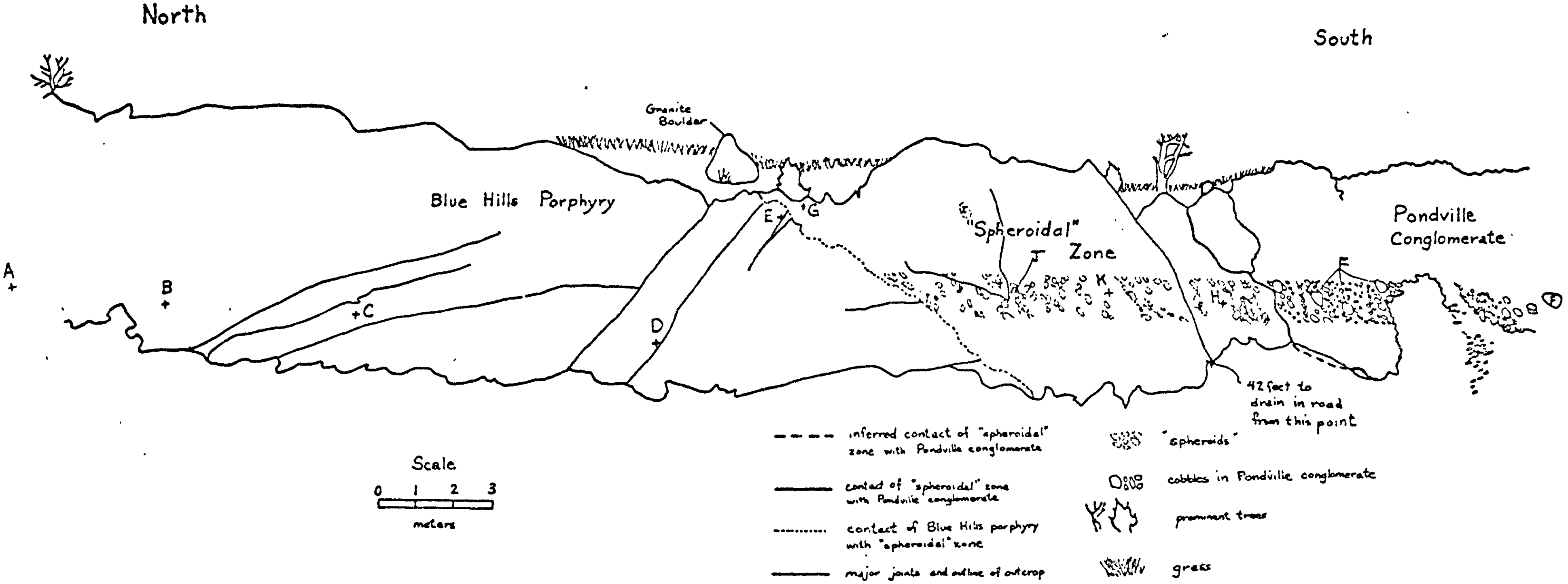


Figure 19 Schematic of contact of the Blue Hills porphyry with the Pondville conglomerate at Route 28-128 interchange.

and larger than the rounded quartz phenocrysts.

A.2 Route 128-Route 28 Roadcut

On the northernmost part of the roadcut at Routes 128-28 (not shown on Figure 19) the BHP is a dark-bluish purple. Riebeckite is developed along joints and weathers to a rust color. En echelon quartz stringers are evident.

The groundmass is a dark, dense aphanitic purple. The purple color probably results from disseminated hematite in the quartz and feldspar matrix. Dark purple, cloudy, subhedral microperthite phenocrysts with a cock's comb fracture are more abundant and larger than the clear, rounded dihexahedral, embayed quartz phenocrysts. The quartz shows undulatory extinction. The feldspars are sericitized and contain minute crystallites of a mafic mineral, probably alkali hornblende or aegirine. Sericite and muscovite together constitute about five percent of the rock. Trace amounts of brown amphibole and pyroxene are present but are not as abundant as at the type locality. Astrophyllite is present in trace amounts.

Position A: [granite porphyry of Warren, 1913] The quartz phenocrysts are more abundant here, the microperthite phenocrysts are less prominent. At Position A, the groundmass is quite dense, and the rock shows evidence of shearing and low grade (chlorite) metamorphism. This shearing, as well as low grade metamorphism, occur elsewhere in the Blue Hills. This rock has a granophyric groundmass with the feldspars totally altered to sericite. This is probably similar to the paisanite of Warren (1913, p. 242). Trace amounts of brown pyroxene and hornblende are present. Magnetite, leucoxene and hematite are present as alteration products.

Position B: Further south at Position B, the feldspars have almost regained their former predominance. The quartz phenocrysts are slightly larger but less abundant. Riebeckite (as an alteration product) has formed along the joints but in the groundmass seems to be altering to limonite.

Position C: Two prominent fractures occur at Position C. The rock is slightly sheared in between them. Areas of hematized rock seem to characterize the rock for approximately one meter about Position C. The hematite veins or zones appear as though they are crossbedded.

Position D: Further south along the roadcut, the hematite veins diappear. Approximately eight meters south of Position C, at Position D, is the ledge from which INAA sample 73-4-1 was taken. This rock is described in Chapter IV [quartz-feldspar porphyry of Warren, 1913] . It is predominantly a light-purplish grey with a greenish-hue. The quartz is conspicuous, occurring in grains up to 4 mm in diameter. The quartz has an equidimensional, dihexahedral habit, embayed and rounded.

The feldspars are smaller and far less numerous than in most of the BHP. They occur as if they are "skeletonized". Part of the feldspars are missing, leaving voids, and the remainder appears as a "honeycombed" structure. From thin section observations, some of these voids are occupied by calcite, the remaining feldspar is albite. The groundmass is granophyric, a micrographic quartz-feldspar intergrowth with the feldspar totally altered to sericite. The groundmass has very fine-grained leucoxene and hematite dust (see page 48for a more detailed petrographic description).

Leaving Position D and continuing toward the contact of the "spheroidal" zone and the BHP, the BHP remains light purplish-grey with prominent quartz phenocrysts and an aphanitic matrix. Feldspar phenocrysts are small and are barely recognizable in hand-specimens.

Position E: A metamorphosed hematite and clay clastic dike fills in a fracture three meters about the base of the outcrop at Position E. It begins abruptly below the "spheroidal" zone and dips north for about 2.5 meters before it pinches out along with the fracture it fills.

Pyrolusite is developed along some of the joint surfaces giving the rock a blocky outline. The pyrolusite staining seems to derive from the joints but it appears on flat surfaces as well. It is inferred to be the lowest part of the "spheroidally weathered" zone by those who prefer this hypothesis.

The BHP is generally massive with few joints, and it weathers to a light green or buff color. The contact between the "spheroidal" zone and the BHP occurs diagonally across the surface projected onto the figure. Below the contact, the BHP is a light green with pyrolusite staining. Above the contact, the "spheroidal" zone has both light green and red units and the pyrolusite staining is not developed. The "spheroidal" zone will be dealt with later in greater detail.

B. PONDVILLE CONGLOMERATE

The Pondville conglomerate (PC) crops out along the southern border of the Blue Hills for over six kilometers. It varies in thickness from an estimated 160 meters at the intersection of Routes 128 and 28 to about 500 meters further west at its maximum width (Chute, 1969).

It contains rounded clasts up to 1.3 meters in diameter. The largest boulders are composed of a fine-grained pinkish-purple to green riebeckite granite (F's in Figure 19), probably the same fine-grained riebeckite granite (FGRG) occurring as xenoliths in the QG. The majority of the cobble-sized clasts are white, buff, pink or green rhyolite. Some angular rhyolite fragments occur as well as the rounded ones. Other cobbles include dark shale, grey quartzite, and near the base of the formation a few scarce boulders of a purplish-grey porphyritic rock with quartz stringers. The porphyry boulders have a greenish rim with a purple interior and are probably BHP.

The matrix shows some stratification indicating the rocks dip nearly vertically. The elongated clasts were deposited with their long axes parallel to the stratification. They generally rest on each other with matrix filling in the voids.

No QG has ever been observed in the PC. The BHP clasts are not present above the base of the PC. The PC has been searched for clasts that might be derived from the "spheroidal" zone but none were found.

B.1 Matrix of the Pondville Conglomerate

The matrix of the PC is generally a light-greenish grey or reddish arkose that grades into a shale. The red coloring is due to hematite, and the greenish-grey to leucoxene. The arkose is very indurated, poorly sorted and contains angular lithic fragments generally of rhyolite. The matrix contains quartz, feldspar, some clay mineral, and a carbonate.

Layering is evident in both hand-specimen and thin section. The quartz-feldspar matrix is coarser than the matrix in the BHP or "spheroidal" zone. The matrix of the PC is characterized by rounded equant quartz and feldspar grains, somewhat sutured, and containing an appreciable amount of sericite in the matrix.

Fractures and joints pass around the clasts through the matrix and do not pass through the clasts. This is a significant feature of the PC which does not occur in the "spheroidal" zone.

B. 2 Contact with the Wamsutta Formation

The contact between the PC and the Wamsutta Formation lying directly above it is gradational. The clasts in the PC become progressively smaller and rarer toward the top of the PC, and the beds of shale become progressively thicker and more numerous.

B. 3 Contact with the "Spheroidal" Zone

The contact between the PC and the underlying "spheroidal" zone is abrupt. It is outlined on Figure 19. It angles across the plane of Figure 19. The contact between the PC and the "spheroidal" zone is placed at the point where the aphanitic matrix of the "spheroidal" zone disappears and lithic fragments and sand occur in the matrix. The matrix of the PC has an heterogeneous composition with angular lithic fragments. It is distinguishable by the naked eye from the even-textured matrix of the "spheroidal" zone. The contact also corresponds to where the clasts are distinct from the matrix and "pop out" on the weathered surface of the conglomerate. In the "spheroidal" zone the clasts are as well indurated as the matrix and do not "pop out".

C. "SPHEROIDAL" ZONE

This zone has initiated many discussions as to the mode of its origin. The favored hypothesis is, that it is an ancient soil formed upon the BHP

(Warren, 1913; Crosby, 1900; Chute, 1940, 1964, 1966, 1969). A second hypothesis has been recently espoused by Wones and Riley (personal communication) stating that the zone is an agglomerate either related to the BHP, or a non-related post-BHP agglomerate of Carboniferous age that is interstratified with the basal member of the PC.

Other hypotheses include (1) the BHP was intruded into the PC and, therefore, would be late Carboniferous in age, (2) a porphyry sill intruded along the BHP and PC unconformity. These hypotheses were discredited (deBruynkop, 1968; Nichols, 1968).

The characteristics of the two models hypothesized for the origin of this unit are described below, in order that definitive characteristics of the two hypothesized modes of formation may be recognized.

C. 1 Characteristics of Pyroclastic Units

The characteristics of a pyroclastic deposit are many, depending on the composition of the material, the manner of deposition, the nature of the vent material and country rock, the amount of volatiles in the parent magma, etc. They can be layered or unlayered, sorted or unsorted, composed of one rock type or of many. The volume of the deposit can vary widely; the oxidation state of the iron can vary as well as the habit and abundance of phenocrysts (Ross and Smith, 1961; Smith, 1960).

C.2 Characteristics of Fossil Soil Horizons

A characteristic of saprolites, noted by Ollier's (1969) book on rock weathering, is that they are commonly enriched in SiO_2, Ni, Co, Cu, and Fe and Mn-oxides. In known fossil soil zones, spheroids are largers, less altered, and more angular near bedrock. In the upper portions of the mantle, the spheroids appear further apart, do not rest on one another and are more rounded. Regular spacing and distribution are characteristic of this type of unit but may not necessarily be present (C. A. Kaye, personal communication). In spheroidally weathered terrain, the spheroids fade out and disappear in the proximity of sound bedrock.

In some cases, spheroids are "case-hardened". A more resistant, siliceous rim forms around the spheroids and the interior becomes more weathered than the rim. The conditions under which this occurs are not well known.

C.3 General Description of the "Spheroidal" Zone

This zone is 11 meters wide and contains elements common to both the PC and BHP. It has a remarkable structure with spheroid-shaped bodies of various sizes and little orientation that resemble a conglomerate. However, the entire zone, matrix and spheroid, is composed of a porphyry unit that looks like the BHP. The "spheroidal" zone is probably some type of igenous extrusive deposit of granitic composition.

The "spheroidal" zone is remarkably uniform in lithology. No xenoliths were found. The porphyry in the unit varies only in the size and abundance of feldspar phenocrysts and in the amount and distribution of the alteration products -- hematite and leucoxene.

The "spheroids" are green porphyry, with feldspar and quartz phenocrysts, surrounded by a matrix of reddish-purple porphyry, with feldspar and quartz phenocrysts. The greenish color is due to leucoxene, and the reddish color to hematite disseminated throughout the matrix. No augite or riebeckite-arfvedsonite is seen in either matrix or "spheroids". Magnetite is altered to hematite in the majority of the rock.

The rock in this zone can be broken into four types:

Type One: A purplish-red aphanitic rock resembling an ash which only occurs in the matrix;

Type Two: A purplish-red aphanitic rock with quartz phenocrysts generally in layers resembling an ash fall which occurs in the matrix;

Type Three: An aphanitic quartz porphyry. This is an extremely fine-grained rock with a matrix of quartz and feldspar and rounded, bipyramidal quartz phenocrysts. The matrix is sprinkled with hematite or leucoxene dust. This appears to be a chilled margin of Type Four;

Type Four: Quartz-feldspar porphyry. This is a fine-grained quartz-feldspar rock with highly broken and fractured albitized feldspars and quartz fragments. Type Four can be red or green and occurs both as matrix and as "spheroid".

None of the above four types corresponds to the BHP from the type locality. Types Three and Four are found elsewhere in the Blue Hills and are not just local varieties. They appear to be Warren's (1913) quartz-feldspar porphyry. Types One and Two have only been found at this roadcut.

Near the top of the roadcut at Position G, there is a definite contact between the BHP and the "spheroidal" zone. Here, the "spheroidal" zone gives the distinct impression of being pyroclastic because of its blotchy, streaked appearance caused by elongated, stretched masses of quartz-feldspar (Type Four) porphyry in a matrix of Type One. Upon closer inspection, gradational features at the contact between the "spheroidal" zone and the underlying BHP are not as dominant as the sharp features.

C.4 Matrix of the "Spheroidal" Zone

The matrix material seems to occur in one of two textures: an aphanitic ash-like unit (Types One and Two) or a porphyritic granophyric texture (Types Three and Four).

Types One and Two: This fine-grained matrix can either be free of quartz phenocrysts (Type One), or it can contain a few percent of these phenocrysts, both euhedral and broken (Type Two). Zones of quartz-free aphanitic red matrix (Type One) are interbedded with an aphanitic matrix with numerous quartz phenocrysts (Type Two). If the matrix does contain quartz phenocrysts, they generally occur in a layered fashion, but they also occur randomly. The quartz phenocrysts are usually equidimensional, bipyramidal, rounded and embayed.

Type Three: Type Three matrix is porphyritic and was emplaced in a liquid state. Its groundmass is aphanitic, either greenish (leucoxene present in larger amounts than hematite), or reddish (hematite more predominant than leucoxene). Type Three has large quartz phenocrysts up to 5 mm in diameter, of dihexahedral shape, but embayed and rounded. The smaller quartz phenocrysts are often broken, rounded and/or embayed. Type Three is not as abundant as Types One or Four. It appears to be a chilled Type Four.

Type Four: This porphyry has the same quartz phenocrysts characteristics of Type Three. The distinctive feature of Type Four is the badly altered, brokenperthitic feldspars albitized along fractures. These range in size from minute broken fragments up to fractured and albitized perthites larger than the quartz phenocrysts. The feldspars occur locally in the "skeletonized" or "honey-combed" fashion described on page121.

One to two percent carbonate is found in Type Four porphyry of the matrix of the "spheroidal" zone at two localities 2.6 km apart, suggesting that perhaps the whole zone was subaqueously emplaced.

C.5 General Characteristics

Equidimensional, dihexahedral quartz phenocrysts are ubiquitous, occurring in varying percentages. In Type Three "spheroids", quartz occurs as the most abundant phenocryst with broken feldspar crystals of minor importance.

A diligent search was made for any structures which might pass through the matrix and "spheroids" alike, but no such structure was found.

Type Two matrix shows no evidence of the quartz phenocryst layers passing through the "spheroids", and in areas the phenocryst layers are not even continuous on the other side of the "spheroids". Type Two generally does not occur in the vicinity of the "spheroids" but occurs more often in areas barren of "spheroids" and showing a more homogeneous, massive, aphanitic texture.

In the "spheroidal" zone composed of Types Three and Four, the matrix and "spheroids" generally grade into each other, the only difference being in color. Upon close inspection, some of the Type Four matrix contains angular or rounded"micro-spheroids" of varying colors bounded by minute amounts of Type Three. Because TypesThree and Four are gradational, the boundary between them is not definable making it difficult to notice some of the "spheroids".

C.6 "Spheroids"

The majority of the "spheroids" are a greyish-green Type Three or Four porphyry. Types One and Two do not occur as "spheroids", probably because they are recrystallized ash and would not have formed blocks prior to the deposition of this unit. The most abundant "spheroids" are Type Four with feldspar phenocrysts which are larger and more abundant than the quartz phenocrysts. All the feldspar occurs as perthite, some of it in the "honey-combed" manner already described, others as normal perthite. The feldspars are generally broken and albitized. "Spheroids" adjacent to Types One and Two have a definite contact.

Other "spheroids", such as I and J,are clearly distinguishable from afar. They are yellow, deeply weathered centers which grade outward into a greenish less weathered rim. No specimen of this type could be inspected under the microscope due to the location and attitude of this type of "spheroid", but it appears to be badly altered Type Four porphyry.

These altered "spheroids" (I and J) do not occur in layers but are randomly scattered. The greenish rim appears to grade into the red matrix with little suggestion of a boundary. I and J do not seem to be a different rock type than the surrounding Type Four "spheroids"; however, they do appear more altered.

C. 7 General Features

There does not appear to be any pattern associated with the "spheroidal" zone that might be related to a fracture system. No gradation in size of the "spheroids" from the top of the zone to the bottom of the zone occurs. The shape of the "spheroids" may vary somewhat, however, round "spheroids" occur both near the top of the unit and near the bottom. Angular "spheroids" do not appear to be as common near the top of the unit, but this may be deceiving because more frequent and thicker beds of Types One and Two matrix occur.

The majority of medium and large sized "spheroids" are subrounded, but between such "spheroids" are subangular blocky "spheroids". The majority of these large "spheroids" are Type Four and can have Type Three or Type Four matrix in between. Type Two and One matrix appear more often as units by themselves, such as at Positions H and K.

Joints cut across the "spheroids" and matrix alike, although a few "spheroids" seem to have cracks rimming them. Joints cutting across the two colors or four porphyry types are more frequent than joints separating them.

The "spheroids" tend to be subangular in shape, some are elliptical, others are trapezehedral or flat-iron shaped. "Spheroids" almost half a meter in diameter occur which are quite rounded. Angular ones occur both in centimeter size as well as ones close to half a meter long.

There is some evidence of flow structure in the "spheroidal" zone (at Position G). Faint stratification or layering appears in the matrix and is especially evident in the area under the large overhanging block of PC near Position H.

Only rarely do "spheroids" actually rest on one another. There is usually some matrix present between the "spheroids". Locally the unit is eutaxitic. It is streaked and blotchy with bands not only of leucoxene or hematite-rich matrix, but it also contains some small microxenoliths of a fine-grained recrystallized ash or rhyolite (Type One or Two). Under the microscope, these recrystallized fragments have a coarser texture, interlocking equidimensional feldspar and quartz crystals. The matrix of the eutaxitic rock appears streaky and dirty with no well defined crystals.

No glass shards were recognized. Microxenoliths (Type One or Two) of either recrystallized tuff or ash fall origin were recognized. Spherulites are absent from the zone.

D. DISCUSSION

The microxenoliths, quartz fragments and embayed, rounded quartz phenocrysts, as well as the eutaxitic structures, indicate some type of pyroclastic material.

The BHP below the "spheroidal" zone has abundant hematite and pyrolusite (a Mn-oxide) staining. Quartz, a detrital mineral, is present in the "spheroidal" zone matrix (Type Three) when feldspar is not. The groundmass (all types) is so fine-grained that it is difficult to determine what minerals do occur. There are abundant clay minerals, hematite, and sericite. The abundance of Ni, Co, and Cu was not determined. The possibility that some of the Type Four "spheroids" with yellow interiors and less weathered borders could be the result of a "case-hardening" phenomena was also examined. However, no outstanding weathering features were found, and this possibility was eliminated.

CONCLUSION

The contact of the "spheroidal" zone with the overlying PC is sedimentary. The features found in the "spheroidal" zone, as well as the PC-BHP contact, are not truly distinctive. Not all characteristics of an agglomerate are present in the "spheroidal" zone. There is no evidence of xenoliths, spherulites, or glass.

There are some clues, however, as to the nature of the unit. The base of the "spheroidal" zone is probably sharper and more easily defined than a BHP- fossil soil contact would be. The presence in the outcrop of microxenoliths, fragmental quartz, and the high temperature/ low pressure bipyramidal embayed quartz, favor the agglomerate hypothesis. Faint layering parallel to both upper and lower contacts in the Type Two matrix may indicate that this deposit is a welded block or ash fall.

Traditionally, the unit has been called a spheroidally weathered zone. The lack of size gradation in the "spheroids", their angularity, and the lack of pattern disfavor the weathering hypothesis. The occurrence of a rounded spheroid, such as "I", so close to the unaltered bedrock where one would expect to find more angular boulders, is unusual for a weathered zone but would not be unusual for a pyroclastic deposit.

At Position G, where one would expect to find spheroidally weathered rock resting on other rock, one finds a layered matrix and "spheroids" unsupported by other "spheroids". Any "spheroid" this close to sound bedrock should be supported and should not show sedimentary layering parallel to the contact.

Identical composition and texture of "spheroid" and matrix would probably not occur in a spheroidally weathered zone. Some elements would be leached and others enriched. It is possible that Type Two could developed by advanced rock decay of Type Three or Four, but Type One could not.

Whatever the lithology of the "spheroidal" zone, it is further obscured by low grade chlorite metamorphism. Sheared and slickensided surfaces occur ubiquitously in the Boston area and this outcrop is not an exception. Recrystallization of the entire unit has occurred, hiding the identity of the original matrix of the "spheroidal" zone.

The nature of the "spheroidal" unit is still questioned, although the microxenoliths and shard nature of some of the quartz strongly suggest a subaqueous extrusive deposit.

APPENDIX C

PEAKS USED IN INAA DETERMINATION OF REE ABUNDANCES

ELEMENT	PEAK IN KEV	DAY COUNTED	DETECTOR
Sc	889.3	16 d.	18cc.
La	328.4	16d.	18cc
La	486.8	16d.	18cc
Ce	145.4	16d.	18cc
Nd	91.4	8d.	LEPS
Nd	531.	16d.	18cc
Sm	103.2	5d	LEPS
Sm	103.2	8d.	LEPS
Eu	1085.8	16d	18cc
Eu	1467.9	16d	18cc
Gd	97.5	8d	LEPS
Tb	298.6	16d	18cc
Tb	879.3	16d	18cc
Tb	~ 1178.	16d	18cc
Yb	63.3	8d	LEPS
Lu	208.4	16d	18cc
Lu	208.4	8d	LEPS
Hf	136	16d	18cc
Hf	343.6	16d	18cc
Hf	482.2	16d	18cc
Zr	724.0	16d	18cc

APPENDIX D - Abbreviations Used in Text

Abbreviation	Name
Ab	Albite
An	Anorthite
AR	Aporhyolite
BHIC	Blue Hills Igneous Complex
BHP	Blue Hills porphyry
CA	Cape Ann granite
FGRG	Fine-grained riebeckite granite
G-2	U.S.G.S. standard rock
INAA	Instrumental Neutron Activation Analysis
MY	million years
NP	Narragansett Pier granite
PC	Pondville conglomerate
PG	Peabody granite
ppm	parts per million
QG	Quincy granite
REE	Rare Earth elements
RP	Rhombporphyry
Sr_0	$(^{87}Sr/^{86}Sr)_0$ ratio
W	Westerly granite

REFERENCES CITED

Baedecker, P.A., 1971. Digital Methods of Photopeak Integration in Activation Analysis; in Activation Analysis in Geochemistry and Cosmochemistry; Ed. Brunfelt, A.O., and Steinnes, E., p. 175-182.

Bell, K.G., 1948. Geology of the Boston Metropolitan Area. Ph.D. Thesis, M.I.T., Cambridge, Mass.

Bence, A.E., 1966. The Differentiation History of the Earth by Rb-Sr Isotopic Relations: Ph.D. Thesis, M.I.T., Cambridge, Mass.

Bevington, P.R., 1969. Data Reduction and Error Analysis for the Physical Sciences: McGraw-Hill, N.Y.

Billings, M.P., 1929. Structural geology of the eastern part of the Boston Basin: Am. Jour. Sci. 5th Series 18, 97-137.

Bottino, M.L., 1963a. Whole-rock Rb-Sr Studies of Volcanics and some related Granites: Ph.D. Thesis, M.I.T., Cambridge, Mass.

_____, 1963b. Whole rock Rb-Sr Studies of Volcanics and some Related Granites: in Hurley, P.M., and others, Variations in Isotopic Abundances of Sr, Ca, and Ar, and Related Subjects: U.S. Atomic Energy Comm. Commission, 11th Ann. Prog. Rept. for 1963, M.I.T., NYO-3943 Contract At (30-1) 1381, 65-84.

_____, 1966. Whole-rock Rubidium-Strontium age of the Silurian-Devonian boundary in northeastern North America: Bull. Geol. Soc. Am. 77, 1167-1175.

_____, 1968. Rb-Sr study of the Blue Hills Igneous complex and the Wamsutta Formation rhyolite, Mass.: Abs. for 1968, Geol. Soc. Am. Special Paper 121, 423. (Abs.)

Bottino, M.L., Fullagar, P.D., Fairbairn, H.W., Pinson, W.H., Jr., and Hurley, P.M., 1970. The Blue Hills Igneous Complex, Mass.: Whole-rock Rb-Sr open systems: Bull. Geol. Soc. Am., 81, 3739-3746.

Bottino, M.L., Pinson, W.H., Jr., Fairbairn, H.W., and Hurley, P.M., 1963. Whole-rock Rb-Sr ages of some paleozoic volcanics and related granites in the northern Appalachians. (Abs.): Am. Geoph. Un. Trans. 44, 111.

Bruynkop, de, J., 1968. Geology of the eastern Blue Hills area, Mass.: Term Paper, Harvard University, Cambridge, Mass.

Buma, G., 1970. Trace element distributions and the origins of some New England granites: M.S. Thesis, M.I.T., Cambridge, Mass.

Chute, N.E., 1969. Bedrock geologic map of the Blue Hills Quadrangle Norfolk, Suffolk, and Plymouth Counties, Mass. U.S. Geol. Surv. Quad. Map GQ-796.

_____, 1966. Geology of the Norwood Quadrangle, Norfolk and Suffolk Counties, Mass. U.S. Geol. Surv. Bull. 1163-B.

_____, 1964. Trip G. Geology of the Norfolk Basin Carboniferous sedimentary rocks, and the various igneous rocks of the Norwood and Blue Hills Quadrangles. (Mass.), in N.E.I.G.C., 56th Ann. Mtg., Chestnut Hill, Mass. Oct. 2-4, 1964. Guidebook to field trips in the Boston Area and vicinity: 91-114.

_____, 1950. Bedrock Geology of the Brockton Quadrangle, Mass.: U.S. Geol. Surv. Quad. Map GQ-5.

_____, 1940. Preliminary report on the geology of the Blue Hills Quadrangle, Mass.: U.S. Geol. Surv. and Mass. D.P.W. Coop. Proj., 1.

Coomaraswamy, Ray, 1954. Geology of the Hoppin Hill Area in North Attleboro, Mass.: Term paper, HarvardUniversity, Cambridge, Mass.

Clapp, C.H., 1910. Igneous rocks of Essex County, Mass. Geology Ph.D. Thesis, M.I.T., Cambridge, Mass.

Crosby, W.O., 1905. Genetic and structural relations of the igneous rocks of the Lower Neponset Valley, Mass.: Am. Geol. 35, 34-47, and 69-83.

_____, 1900. Geology of the Boston Basin: The Blue Hills Complex. Boston Soc. Nat. Hist. Occ. Papers 4, 1, pt. 3, 289-563.

_____, 1880. Contributions of the geology of eastern Mass.: Boston Soc. Nat. Hist. P. 55-63, 267-268.

Crosby, W.O., and Barton, G.H., 1880. Extension of the Carboniferous formation in Mass.: Am. Jour. Sci. 3rd Ser. 20, 416-420.

Dale, T.N., 1923. The commercial granites of New England: U. S. Geol. Surv. Bull. 738, 315-332.

Dalrymple, G. B., and Lanphere, M.A., 1969. Potassium-Argon Dating: W. H. Freeman and Company, San Francisco. Gilluly, J., and Woodford, A. O., Eds.

Doe, B.R., 1970. Lead Isotopes: Springer-Verlag, 137, New York.

Dos Santos, E. R., 1960. The Newbury Volcanics: M.S. Thesis, M.I.T., Cambridge, Mass.

Eaton, H.N., 1925. Structural relations of the igneous rocks of the Wamsutta red beds, Mass.: (abs.) Bull. Geol. Soc. Am. 36 165-166.

Edwards, G., Henle, W.K., Osmund, J.K., and Adams, J.A.S., 1959. Further progress in absolute dating of the middle-Ordovician: Geol. Soc. Am. (abs.) 70, p.1596.

Emerson, B.K., 1917. Geology of Massachusetts and Rhode Island: U. S. Geol. Surv. Bull. 597.

Fairbairn, H.W., Moorbath, S., Ramo, A. O., Pinson, W.H., Jr., and Hurley, P.M., 1967. Rb-Sr age of granitic rocks of southeastern Massachusetts and the age of the Lower Cambrian at Hoppin Hill: Earth and Plan. Sci. Let. 2, 321-328.

Faul, H., 1960. Geologic time scale: Bull. Geol. Soc. Am. 71, 637-644.

Faure, G., and Powell, J.L., 1972. Strontium Isotope Geology: Springer-Verlag, New York.

Foland, K.A., Quinn, A. W., and Giletti, B.J., 1971. K-Ar and Rb-Sr Jurassic and Cretaceous ages for intrusives of the White Mountain Magma Series, northern New England: Am. Jour. Sci. 270, 321-330.

Fullagar, P. D., and Bottino, M.L., 1968. Geochronology of Silurian and Devonian age volcanic rocks from northeastern North America: Intern. Ceol. Congr., 23, Proc. Section 6, Geochemistry, 17-32.

Gordon, G. E., Randle, K., Goles, G., Corliss, J., Beeson, M., and Oxley, S., 1968. Instrumental activation analysis of standard rocks with high resolution gamma ray detectors:Geochim. et Cosmochim. Acta, 32, 369-396.

Hawes, G.N., 1908. Tenth Census, U.S., *10*.

Hayatsu, A., 1972. On the basic assumptions in K-Ar dating Method: Comments on Earth Sci.:Geophy. *3-3* 69-74.

Hedge, C.E., and Walthall, F. G., 1963. Radiogenic Strontium-87 as an index of geologic processes: Sci. *140*, 1214-1217.

Hurley, P.M., Fairbairn, H.W., Pinson, W.H., Jr., and Faure, G., 1960. K-Ar and Rb-Sr minimum ages for the Pennsylvanian section in the Narragansett Basin: Geochim. et Cosmochim. Acta *18*, 247-258.

Kaktins, U., 1969. *Stratigraphy and Petrography of the Ignimbrite Flows of the Blue Hills area, Massachusetts*: Syracuse University, Syracuse, N.Y. M.S. Thesis

Knox, A.S., 1944. A Carboniferous flora from the Wamsutta Formation of southeastern Massachusetts: Am. Jour. Sci., *242*, 130-138.

LaForge, L., 1932. Geology of the Boston area, Massachusetts: U.S. Geol. Surv. Bull. *839*.

______, 1909. Correlations of the rocks of the Boston region. Sci. *29*, 945-946.

Lopez Escobar, L., 1972. *Appalachian Rhyolites: Geochemical Data Concerning Their Origin*: M.S. Thesis., M.I.T., Cambridge, Mass.

Loughlin, G. F., 1911. The structural relations between the Quincy granite and the adjacent sedimentary formations: Am. Jour. Sci. 4th Ser. *32*, 17-32.

Lyons, J.B., and Faul, H., 1968. Isotope Geochronology of the Northern Appalachians: in *Studies of Appalachian Geology:Northern and Maritime*: Intersci. Publ. John Wiley and Sons, N.Y.

Lyons, P. C., 1969. *Bedrock Geology of the Mansfield Quadrangle, Mass.* : Ph.D. Dissertation, Boston University Graduate School.

Lytton, G.B., 1941. *The Geologic Structure of the Igneous and Sedimentary Rocks of South Attleboro, Mass.*: M. S. Thesis, Brown University.

Mansfield, G.R., 1906. The Origin and structure of the Roxbury Conglomerate; Bull. M.C.Z. 49, Geological Series 8 No. 4, 91-271.

McIntyre, G.A., Brooks, C., Compston, W., and Turek, A., 1966. The statistical assessment of Rb-Sr Isochrons: J. Geophys. Res., 71, 5459-5468.

Morgenstern L., 1970. The evolution of some rocks west and South of Boston, Mass. Ph.D. Dissertation, Boston University.

Moorhouse, W.W., 1959. The study of rocks in thin section: Harper and Row Publ. N.Y. and Evanston. p. 514.

Nichols, J.B., 1968. Geology of the Eastern Blue Hills Area, Mass. Term Paper, Harvard University, Cambridge, Mass.

Ollier, C., 1969. Weathering. Oliver and Boyd, Ltd. Edinburgh.

Page, L., 1968. Devonian Plutonic rocks in New England in Studies of Appalachian Geology Northern and Maritime, Interscience Publishers, New York, J. Wiley & Sons, p. 311-384.

Pollard, M., 1965. Age, origin and structure of the Post-Cambrian Boston Strata, Mass. G.S.A. Bull. 76, 1065-1068.

Quinn, A.W., 1971. Bedrock geology of Rhode Island. U.S.G.S. Bull. 1295.

Quinn, A.W., Jaffe, H.W., Smith, W.L., and Waring, C.H., 1957. Lead-Alpha Ages of Rhode Island Granitic Rocks Compared to Their Geologic Ages. Am. Jour. Sci. 255, 547-560.

Quinn, A.W., and Moore, G.E., Jr., 1968. Sedimentation, Tectonism and Plutonism of the Narragansett Basin Region: in Studies of Appalachian Geology, Northern and Maritime, Interscience Publishers, New York, J. Wiley & Sons, p. 269-286.

Quinn, A.W., and Oliver, W.A., Jr., 1962. Pennsylvanian Rocks in New England, Pennsylvanian System in the U.S. A symposium of AAGP Tulsa Okla. ed. Branson, C.C., Pt. 3, 60-73.

Rodgers, J., 1967. Chronology of Tectonic Movements in the Appalachian region of Eastern North America. A. Jour. Sci., 265, 408-421.

_______, 1952. Absolute ages of radioactive minerals from the Appalachian region: Am. Jour. Sci. 250, 411-427.

Ross, C.S., and Smith, R.L., 1961. Ash-flow tuffs; Their origin, geologic relations and identifications: U.S. Geol. Surv. Prof. Paper 366.

Shaler, N.S., and Woodworth, J.B., and Foerste, A.F., 1899. Geology of the Narragansett Basin: U.S. Geol. Surv. Mono. 33.

Smith, R. L., 1960. Ash flows: Bull. Geol. Surv. Am. 71, 795-842.

Steiff, L. R., 1959. Tables for the calculation of lead isotope ages: U.S. Geol. Surv. Prof. Paper 334-A.

Taylor, S.R., 1965. The application of trace element data to problems in petrology: Phys. Chem. Earth 6, 133-213.

Tilton, G. R., 1960. Volume diffusion as a mechanism for discordant ages in zircons: Jour. Geophy. Res. 65, p. 2923-2934.

Toulmin, P., 3rd, 1961. Geological significance of Pb-α and isotopic age determinations of "alkalic" rocks of New England: Bull. Geol. Soc. Am. 72, 775-780.

_______, 1960. Composition of feldspars and crystallization history of the granite-syenite complex near Salem, Essex County, Massachusetts, U.S.A.: Intern. Geol. Congr. 21, pt. 13, 275-286.

Towe, K. M., 1959. Petrology and source of sediments in the Narragansett Basin of Rhode Island and Massachusetts: Jour. Sed. Pet. 29, n. 4, 503-512.

Wadsworth, M.E., 1883. Descriptive catalogue of American and foreign rocks: Boston Soc. Nat. Hist. Proc. 27, n. 7, 431-432.

_______, 1882. Notes in geology and lithology: Harvard University Bull. 22, 359-360.

_______, 1878. Notes on the petrography of Quincy and Rockport: Bos. Soc. Nat. Hist. Proc. 19, 309-316.

Warren, C.H., 1913. Petrology of the alkali granites and porphyries of Quincy and Blue Hills, Mass., U.S.A.: Am. Acad. Arts and Sci. Proc. 49, 203-331.

_______, 1909. Note on the occurence of an interesting pegmatite in the granite of Quincy, Mass.: Am. Jour. Sci. 4th Ser. 28, 449-452.

Warren, C. H., and Palache, C., 1911. The pegmatites of the riebeckite-aegirite granite of Quincy, Mass. U.S.A.;Their structure, minerals and orgin: Am. Acad. Arts and Sci. Proc. 47, 125-168.

Washington, H. S., 1899. Jour Geol. 7, 53-64, 105-121, 284-294, 463-482.

_______, 1898. The petrographical province of Essex County, Mass.: Jour. Geol. 6, 787-808.

_______, 1896. Am. Jour. Sci. 3rd Series 156, 181.

Wasserburg, G.J., 1963. Diffusion processes in lead-uranium systems: J. Geophy. Res. 68, 4823-4846.

Wetherill, G.W., 1963. Discordant uranium-lead ages: J. Geophy. Res. 68, 2957-2965.

_______, 1956. Discordant uranium-lead ages, I: Trans. Am. Geophy. Union 37, 320-326.

White, T. G., 1897. A contribution to the petrography of the Boston Basin: Proc. of the Boston Soc. Nat. Hist. 28, 117-156.

Woodworth, J. B., 1894. Carboniferous fossils in Norfolk County Basin: Am. Jour. Sci. 3rd Ser. 48, 145-148.

Woodward, H. P., 1957. Chronology of Appalachian folding. Bull. Am. Assoc. Petr. Geol. 41, 2312-2327.

York, D., 1966. Least-squares fitting of a straight line: Canadian Jour. Physics 44, 1079-1086.

Zartman, R.E., 1969. Early Paleozoic plutonism near Boston, Massachusetts: Abst. with Prog. for 1969, Pt. 1, Geol. Soc. Am. p. 66.

_______, 1967. K-Ar ages of the Quincy granite: U.S. Geol. Surv. Prof. Paper 575-A, A-166.

Zartman, R.E., Brock, M., Heyl, A.V., and Thomas, H.H., 1966. K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern U.S.: Geol. Soc. Am. Spec. Paper 87, 190-191. (abst.)

Zartman, R.E., Hurley, P.M., Krueger, H.W., Giletti, B.J., 1970. A Permian disturbance of K-Ar radiometric ages in New England: Its occurence and cause: Bull. Geol. Soc. Am. 81, 3359-3374.

Zartman, R. E., and Marvin, R. F., 1971. Radiometric age (Late Ordovician) of the Quincy, Cape Ann, and Peabody granites from eastern Massachusetts: Bull. Geol. Soc. Am. 82, 937-958.

Zartman, R.E., Snyder, G., Stern, T. W., Marvin, R.F., and Bucknam, R.C., 1965. Implications of new radiometric ages in eastern Connecticut and Massachusetts: Geol. Surv. Res. 1965, U.S. Geol. Surv. Prof. Paper 525-D, D1-D10.