

GEOLOGY OF THE BOTTLE LAKE COMPLEX, MAINE,

by

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Geological Sciences

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May, 1982

Blacksburg, Virginia

ACKNOWLEDGEMENTS

I am grateful to my assistants,

for their dedication. Special thanks are extended

to who introduced me to the problems of granite petrogenesis and the geology of Maine. I am greatly indebted to A. K. Sinha, whose steady criticism and pursuit of analytical excellence encouraged me throughout the study. I thank for helping during data collection and reduction, and contributing in many stimulating discussions. I am especially grateful to my colleagues

for their encouragement and help.

I appreciate the support and talent of for drafting the map, and of for typing the manuscript.

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Chapter 1

BEDROCK GEOLOGY OF THE BOTTLE LAKE COMPLEX, MAINE

INTRODUCTION

The Bottle Lake Complex is located between the towns of Topsfield and Lincoln in one of the favorite recreational areas of east-central Maine. The region is characterized by low relief, numerous lakes and swamps, and abundant glacial debris. Several hills are high by eastern Maine standards, attaining heights close to 500 m (for example, Passadumkeag Mountain, Duck Mountain, Getchell Mountain, and Almanac Mountain). The Madagascal and the Passadumkeag Rivers, the major streams, dominate the drainage patterns in the area and connect extensive swamps within the Complex (for example, 1000 Acre Heath). Tracts of pine, spruce, and white birch forests are found throughout the region, together with thick brush and peat deposits.

Tourism and logging are the most important industries in the area. Hunting and fishing camps are especially common in the village of Grand Lake Stream although many tourists prefer the solitude of the many townships without permanent residents. The logging industry is actively harvesting and processing paper pulp and continuously expanding the trails within the Bottle Lake Complex.

Mining and prospecting are notably absent in the region despite the concentration of pegmatites in several areas and the enrichment of sulfide minerals in the contact aureole between state route 6 and the northern contact of the plutons (Doyle and others, 1961; Kleinkopf, 1960).

Recent work in the area indicated anomalously high contents of molybdenum, arsenic, tungsten and bismuth in stream sediment samples near the granite-country rock contact in the Tomah Mountain area (Nowlan and Hessin, 1972; Post and others, 1967). In conjunction with these reports, molybdenite in granite bedrock was also reported. Subsequent work by Otton and others (1980) observed anomalously high concentrations of uranium and thorium in stream sediment samples, and concluded that U-Mo mineralization was likely to exist as a result of vein or contact-metasomatic processes.

The purpose of this report is to demonstrate that the Bottle Lake Complex is a composite Paleozoic batholith consisting of at least two granitic plutons which intruded the core of the Merrimack synclinorium (Ayuso, 1979). The following sections present the results of studies of the field relations and petrography of these granites. Additionally, this report stresses the constraints placed by detailed mapping on the relative sequence of intrusion and magmatic evolution of these plutons. A brief summary of the results obtained from geochronologic, isotopic, and geochemical studies is also presented because they clearly complement the field observations.

METHODS OF STUDY

Because of limited access into the area, most of the fieldwork consisted of pace-and-compass traverses to hilltops either from logging roads or from lakeshores. Hilltops are shallowly covered by glacial debris or vegetation and outcrops are common. Many of the lakes also exhibit extensive outcrops along their shores. In general, granites

containing abundant mafic minerals have fewer exposures because of their extreme weathering and disaggregation. These rocks are concentrated on the western lobe of the Bottle Lake Complex. Rocks of lower color index are predominantly associated with the eastern lobe of the Complex and form numerous outcrops.

Modal analyses were made of 150 granite samples (Appendix, Chapter 2) stained by the method of Boone and Wheeler (1968) in order to distinguish between plagioclase, quartz, alkali feldspar, and total mafic minerals (biotite, hornblende, sphene, allanite, etc.). Mafic minerals were apportioned by examination of appropriate thin sections. Routine point counting consisted of selecting at least one slab per sample with minimum dimensions of 20 x 20 cm and counting 1000-2000 points using mainly a 3 x 3 cm grid. This spacing was adequate for most rocks, especially the equidimensional granitoids. However, some of the slabs were smaller than statistically permissible for very coarse-grained rocks. The best estimate of the uncertainty in the modal analyses is $\pm 2\%$ using the method of Van der Plas and Tobi (1965), depending on the size of the slab, grid size, and number of points counted. Mineral chemistry was obtained using an automated 9-channel electron microprobe. Seventy samples were analyzed for feldspar, biotite, amphibole, oxide minerals, sulfides, apatite, allanite, and sphene. Twenty alkali feldspar concentrates were homogenized (sanidinized) and analyzed by X-ray powder diffraction techniques to estimate their bulk composition and structural state.

Details of the results and analytical procedures of the X-ray fluorescence study of 90 samples are given in Chapter 2 (this study), as

are the details and techniques concerning the geochronology and isotopic work on the Bottle Lake Complex.

PREVIOUS WORK

This area of east-central Maine was mapped in reconnaissance by Larrabee and others (1965). These workers established the extent of the granitic plutons and attempted a regional correlation of the country rocks. Contacts between the plutons and country rocks are generally better established for the northern contact based on aeromagnetic (Doyle and others, 1961; Boucot and others, 1964) and geologic studies (Larrabee and others, 1965; Auyso, 1979) compared to the more inaccessible and swampy southern contact.

Ludman (1978a, 1978b) built on the pioneering effort by Larrabee and his coworkers and this resulted on better understanding of the metamorphic rocks in the region.

He concentrated on the area to the northeast and east of the BLC. Detailed field work by Olson (1972) and reconnaissance mapping by Cole (1961) worked to the southwest and north of the Bottle Lake Complex, respectively.

FIELD RELATIONS OF THE BOTTLE LAKE COMPLEX

Introduction

The granitic plutons of the Bottle Lake Complex are exposed in an area of about 1100 sq. km. in the Waite, Scraggly Lake, Springfield, Winn, Wabassus Lake, Nicatous Lake, and Saponac 15-minute quadrangles. The outline of the Complex is two overlapping subcircular bodies

arranged along an east-west trend, except for an extension of the eastern body (Topsfield facies) which is elongated to the northeast.

The plutons of the Bottle Lake Complex are from east to west, the granite of Whitney Cove and the granite of Passadumkeag River. The Topsfield facies is considered part of the granite of Whitney Cove because of the absence of internal contacts and similarity in petrographic characteristics. However, the Whitney Cove and Passadumkeag River granites exhibit conspicuous mappable features intrinsic to each pluton. This petrographic contrast is expressed by their different textures, mafic mineralogy (especially the biotite to amphibole ratio), abundance of pegmatites and aplites, and by the abundance and types of inclusions (Ayuso, 1979).

The intrusives are characterized by generally coarse-grained granites that consist of two feldspars, biotite and quartz, with primary sphene, magnetite, ilmenite, zircon, apatite, allanite, and pyrite. Hornblende is an essential and abundant mineral only in the granite of Passadumkeag River, where it is primarily associated with rocks of high color index also containing numerous mafic xenoliths.

Reconnaissance mapping by Larrabee and others (1965) made no petrographic distinctions between the granitoid rocks of the Complex, except for the possibility of an internal contact between the Topsfield facies and the main mass of the Whitney Cove pluton. Petrographic variation in the granitoids was ascribed to secondary processes, principally resulting from different degrees of country-rock assimilation. In contrast, Ayuso (1979) suggested the presence of two separate intrusive granitoid plutons.

Another conclusion resulting from detailed mapping and routine petrographic studies is that each pluton within the Bottle Lake Complex exhibits reverse zonation. This feature contrasts with typical mineralogic and geochemical zoning trends in which higher color index and more mafic rocks form the outer rim and envelope the more felsic rocks of the interior (for example, see Pitcher, 1977, 1979).

Many of the features indicative of the relative age of emplacement in composite igneous bodies are absent in the Bottle Lake Complex. However, despite the lack of sharp internal contacts, apophyses, dikes and inclusions of previously crystallized plutons in younger rocks, the relative emplacement age can be determined from mapping lithologic types and the cross-cutting relationships of faults. Additional constraints are placed by geochronologic studies using zircon U-Pb systematics (Chapter 2, this study).

Age Relations

A thick section of interbedded silts and shales of Silurian age (Osberg, 1980) generally characterizes this part of the Merrimack synclinorium. However, contiguous to the Bottle Lake Complex, a Cambrian-Ordovician (?) section was first recognized by Larrabee and others (1965) and later confirmed by Ludman (1978b). The youngest and most common country rocks cut by the plutons are Silurian-Devonian (?) in age (Ludman, 1978b). This age is based on regional correlation and stratigraphic similarity with fossiliferous rocks studied by Ruitenberg (1967) in southern New Brunswick. The Whitney Cove granite is cut by the Norumbega fault zone which disturbed Pennsylvanian sediments in

southern New Brunswick (Wones and Stewart, 1976). Structural and stratigraphic control on the emplacement of the Whitney Cove granite suggests that it must be older than the Pennsylvanian sediments in the fault zone and younger than the Silurian to lower Devonian country rocks. Previous geochronologic work on the Bottle Lake Complex by Faul and others (1963) indicated ages of 380 m.y. by Pb-alpha and 370 m.y. by K-Ar techniques for the granite of Whitney Cove. Recent work by Zartman and Gallego (1979) indicates a zircon Pb/Pb age of 400 ± 4 m.y. for the Whitney Cove pluton (Topsfield facies). Additional study of zircons from the main mass of the pluton also suggests an age of 404 ± 5 m.y., (Chapter 2, this study). A reasonable conclusion from geochronologic and stratigraphic observations is that the Whitney Cove pluton is Lower Devonian in age.

Samples from the Passadumkeag River granite were dated by Pb-alpha and K-Ar techniques and the ages ranged from 410 m.y. to 342 m.y. respectively (Faul and others, 1963). Zircons from this pluton suggest a Pb/Pb age of 396 ± 4 m.y. similar to the ages obtained from zircons separated from a mafic xenolith enclosed by the granite. Despite the large spread in radiometric ages, however, zircon Pb/Pb ages suggest that the pluton of Passadumkeag River is the youngest intrusive within the Bottle Lake Complex. Additional support for this suggestion is given by two field observations: 1) the granite of Passadumkeag River cuts a fault zone which transects the Whitney Cove pluton; 2) rock types characteristic of the Passadumkeag River pluton cross cut rocks typical of the granite of Whitney Cove (Ayuso, 1979). Although the age of the fault cutting the Whitney Cove pluton is unknown, it places the sequence

of emplacement in perspective and argues that intrusion of the pluton of Whitney Cove preceded that of Passadumkeag River (Ayuso, 1979). In conclusion, the granite of Passadumkeag River is of Lower to Middle Devonian age and marks the closing stages associated with the emplacement of the Bottle Lake Complex.

The Granite Of Whitney Cove

Field Relations

The granite of Whitney Cove covers an area of 400 sq. km. and is characteristically granitic in mineralogy (IUGS classification of Streckeisen, 1973). This pluton is easily recognized in the field because of its relatively low abundance of ferromagnesian minerals and lack of amphibole. Other typical features include the relative abundance of aplites and pegmatites and scarcity of mafic xenoliths in most outcrops. Three units are included in this pluton: 1) Topsfield facies, 2) rim facies, and 3) core facies.

The geologic map of the Whitney Cove granite does not separate the Topsfield from the rim facies because of the gradual change between the two. The best exposures of the Topsfield facies are on Tomah Mountain, Farrow Mountain, and East Musquash Mountain in the Scraggly Lake and Waite quadrangles. These mountains form a scarp along the western and northern boundaries of the Topsfield facies. As Larrabee and others (1965) noted, the granitic rocks exposed directly to the south of the mountains near the North Branch of Vickery Brook progressively become similar to the gray, coarser-grained rocks typical of the rim facies exposed on Mt. Delight. The Topsfield facies is characterized by severe

shearing and jointing. Most outcrops consist of intensely weathered granitic rocks ranging in color from moderate pink (5R 7/4) to moderate red (5R 5/4), according to the Rock-Color Chart distributed by the Geological Society of America. Grain size is medium- to coarse-grained with a color index generally less than five. Pink alkali feldspar and plagioclase are phenocrysts in a matrix of felsic minerals and biotite. Zircon, apatite, allanite, opaque oxides (magnetite), and pyrite are present but not abundant. Most rocks exhibit aggregates of epidote, chlorite, and opaque oxides instead of primary biotite, while feldspars are commonly replaced by sericite and epidote.

The rim facies of the Whitney Cove pluton typically consists of grayish pink (SR 8/2) to moderate pink (5R 7/4) rocks. Their grain size is medium- to coarse-grained. Hypidiomorphic and seriate textures were developed on rocks of low color index. The most distinctive feature of the rim which separates it from the core facies is its characteristic seriate texture despite the similarity in mineralogy across the pluton. Although two feldspars are present as phenocrysts, alkali feldspar is predominant in size (up to 3.5 cm) and abundance over plagioclase. Euhedral quartz phenocrysts (up to 1 cm) and distinctive pseudo-hexagonal biotite books are characteristic of this facies and of the pluton as a whole. Matrix minerals include two feldspars, quartz, biotite, allanite, sphene, apatite, and zircon. The opaque phases consist of magnetite, ilmenite, and pyrite.

Magnificent outcrops are exposed in the Pineo Mountains in the Scraggly Lake quadrangle and in the Sysladobsis Lake area in the Wabassus Lake quadrangle (Ayuso and Wones, 1980). Many of the outcrops

are characterized by rocks containing aplites, pegmatites, granophyres, and quartz veins. These felsic dikes are variable in attitude and thickness and exhibit a tendency to subdivide and crisscross within individual outcrops.

Modal analyses indicate that the rim facies is uniformly granitic in mineralogy. The average values for alkali feldspar (40%), plagioclase (28%), quartz (28%), and the sum of the mafic minerals (4%) attest to the felsic nature of this rock (Ayuso, 1979). Biotite is the predominant mafic phase and the total abundance of the accessories and opaque minerals is characteristically less than one percent. Secondary minerals consist of chlorite, epidote, and sericite as alteration products after biotite and plagioclase.

The core facies of the Whitney Cove pluton is best exposed along the shores of Whitney Cove in the Wabassus Lake and Scraggly Lake quadrangles. Internal contacts between the core and rim facies are rarely sharp and well-exposed. Instead, a progressive and gradual transformation is expressed from the outer rim facies toward the interior. Large outcrops showing both rock types are exposed near Pork Barrel Lake in the Scraggly Lake quadrangle. Distinction between the two facies strongly depends on the development of the typically porphyritic texture of the core rocks. Other characteristics of this facies include the formation of a fine-grained matrix and the grayish pink (5R 8/2) to grayish orange pink (10R 8/2) color. Large country-rock and quartz dioritic xenoliths are rare, but ovoidal clusters of fine-grained mafic minerals are relatively more common. These clusters are small (up to 5 cm), widely disseminated, and consist principally of

biotite with variable amounts of accessories and plagioclase. Within the core facies biotite, the predominant mafic phase occurs as large pseudo-hexagonal plates or as fine-grained clusters within both matrix and the feldspars. Fine-grained biotite and feldspars impart a conspicuous and easily mappable feature for to this facies.

Modal examination of stained slabs and thin sections indicate the following average mineralogy: alkali feldspar (34%), plagioclase (36%), quartz (26%), total mafic minerals including the opaque and accessory suites (5%). Based on the modal analyses, the core facies is generally as enriched in felsic minerals as the rim. However, despite the overlap in modal abundances across the pluton, the core facies is distinguished by its enrichment in plagioclase and depletion in alkali-feldspar. This is in contrast to the abundance of quartz and total mafic mineral content which show no significant differences.

Petrography

Textural observations and studies focusing on the mineral chemistry of the granites are necessary to define a probable order of crystallization and to constrain the nature of residual and cumulate products. Results from detailed petrographic study of the Whitney Cove pluton are given in Chapter 2 (this study). The present discussion consists of a brief summary of these results.

The Whitney Cove granite contains accessory phases, oxides, and sulfides as subhedral to euhedral grains mainly within biotite, or near small clusters formed by plagioclase and biotite. Apatite is an example of an optically homogeneous but chemically heterogeneous (for example, F

and Mn) phase. This heterogeneity is expressed even within individual grains. Allanite is common as large (up to 1.5 mm), euhedral, optically and compositionally zoned (Ti, Fe, F, Ca, and P) grains typically intergrown with biotite and oxide minerals. Sphene occurs as large primary grains (up to 4 mm) and as a product of biotite breakdown. No clear trend exists in the abundance or mineral chemistry of any accessory phase across the Whitney Cove pluton.

Magnetite and ilmenite form subhedral grains within biotite, plagioclase, and allanite. Intergrowths between biotite and magnetite are also common, as are the anhedral concentrations of magnetite along biotite lamellae. Magnetite abundance shows no trend across the pluton. Compositionally, these magnetites are characterized by low TiO_2 (less than 1.0 wt. %). Pyrite droplets are preferentially found within magnetite grains. Granular ilmenites coexist with magnetite and also form domains (Buddington and Lindsley, 1964) within it. Reequilibration at low temperature (Czamanske and Mihalik, 1972) is indicated by their manganiferous compositions (3.0 to 13.0 wt. %). Compositional variations suggest a trend toward lower manganese in ilmenites of the rim facies of the pluton.

Biotite forms at least two distinct generations recognized by size, habit, number of inclusions, and chemistry. Pseudo-hexagonal biotite phenocrysts and inclusions of biotite in all other silicates attest to its early precipitation in both facies of the pluton. Incomplete reaction of the melt and early crystallized biotite is suggested by the corroded edges of the grains. Comparison of the chemical composition of biotite from the core and rim facies of the Whitney Cove pluton suggests

important contrasts. Biotite from the core facies is lower in the ratio of $\text{Fe}/(\text{Fe} + \text{Mg})$ (0.48 - 0.58) compared to the rim facies (0.61 - 0.71). The core facies also contains biotites with the lowest manganese content. Additionally, the most aluminous and probably the most fluorine-rich biotite is also concentrated in the core. These results indicate that despite a general constancy in abundance from rim to core, biotite shows compositional zoning which readily distinguishes between the two facies.

Plagioclase is the first feldspar to crystallize in this pluton. Several petrographic generations are evident including the following: as phenocrysts, in the groundmass, in clusters with biotite, and concentrated along the edges of other felsic minerals. Phenocrysts are distinguishable by their texture (kind and number of inclusions, associated contiguous mineralogy, resorption features), and optical characteristics (zoning, twinning), even though they show the same range in composition. At least two groups of phenocrysts are present. One group has a mottled appearance (restite according to White and Chappell, 1977), is characteristically blotchy in extinction, and consists of thin, optically continuous rims around cores enclosing many inclusions. These phenocrysts are generally associated with clustering of biotite and contrast with the other phenocryst group, which is randomly distributed in the rock, has a more regular optical and chemical zoning, has wider rims, and tends to show more euhedral habits. The composition of the plagioclase cores across the pluton agrees with the zoning suggested by the composition of biotite. A gradient toward calcic-rich plagioclase exists from rim (An_{20}) to core (An_{55}) facies of the Whitney Cove pluton.

Subhedral grains are representative of plagioclase in the groundmass. Such plagioclase is compositionally more sodic than the phenocrysts and averages about An_{20} . Clusters of ferromagnesian minerals and plagioclase consists of the large, stubby, mottled phenocrysts, and the finer-grained plagioclase which is compositionally similar to the groundmass. The most sodic plagioclase (An_5) is found in the fine-grained matrix of the aplites, and in the grains forming selvages (mortar texture) around other felsic minerals.

Quartz forms inclusions near the rims of plagioclase phenocrysts and as euhedral grains within alkali feldspar. It is also present as subhedral to euhedral grains in the matrix suggesting that it preceded alkali feldspar precipitation. Within the core of the pluton, quartz forms euhedral phenocrysts which in places coalesce to form clusters. Undulose extinction is a characteristic feature except near the faults where much of the quartz is completely annealed.

Alkali feldspar encloses all other phases and this indicates that it crystallized late in sequence. Microcline twins are commonly developed in the pluton and these generally are embayed by perthite patches. Rapakivi (viborgite) texture is usually evident in most exposures, generally forming incomplete rims around anhedral cores. Compositionally, alkali feldspar ranges from Or_{85} to Or_{98} and its structural state resembles maximum microcline according to the scheme of Wright (1968) and Wright and Stewart (1968). Compositional zoning was not detected in the alkali feldspar, although the composition of the albitic rims in the rapakivi texture ranged from almost pure Ab to Ab_{89} . No gradients are evident across the pluton probably because the

consistently high orthoclase content is indicative of substantial deuteritic alteration. Alkali feldspar was also out of equilibrium prior to the deuteritic stage, as indicated by the corroded and embayed alkali feldspar cores, by the intricate intergrowths of alkali feldspar and biotite, and by the irregular widths of the albite rims in the Rapakivi texture. Edges shared by alkali feldspar and plagioclase show myrmekitic textures in which growth proceeded at the expense of plagioclase. Granophyre textures are for the most part constrained between contiguous alkali feldspar grains.

Bulk Chemistry

The preceding sections demonstrated that the granite of Whitney Cove is zoned mineralogically, texturally, and in the composition of its constituent minerals. This zoning is also evident in the bulk composition of the granites from the rim and core facies. A summary of the geochemical characteristics follows in this section, but a more detailed study of the pluton is given in Chapter 2 (this study).

From core to rim CaO, MgO, Fe₂O₃, TiO₂, Al₂O₃, and P₂O₅ decrease as SiO₂ increases from 67.0 to 78.0 wt. %. These marked differences across the pluton take place at a uniform total alkali element abundance. Normative compositions are corundum-poor for the pluton as a whole, but total normative felsic minerals is highest in the rim facies.

Preliminary trace element determinations for U, Th, Pb, Sc, Cr, Ta, Hf, Cs, Ba, Zr, and REE show no gradients within the pluton, except for the strong and consistent variations in Rb, Sr, and Y which support the distinction of each facies and the geochemical zonation from core to

rim. Higher Sr and Y but lower Rb rocks are concentrated in the interior of the Whitney Cove pluton. In agreement with the general clustering in mineralogy and major element chemistry, trace element abundances also fail to show smooth and gradational changes across the pluton.

The Granite of Passadumkeag River

Field Relations

The granite of Passadumkeag River is exposed in an area of about 700 km. sq. showing distinct petrographic zoning from a granitic rim toward rocks of quartz monzonitic mineralogy. Two feldspars, biotite, amphibole and quartz are the essential and varietal minerals in this pluton, while the accessory (zircon, sphene, apatite, allanite) and opaque phase assemblage (magnetite, ilmenite, pyrite) are similar to that of the Whitney Cove granite.

The granite of Passadumkeag River consists of the rim and core facies. Rocks forming the rim facies are grayish pink (5R 8/2) to grayish-orange pink (10R 8/2). They are typically granitic in mineralogy (IUGS classification of Streckeisen, 1973) and show textures ranging from porphyritic to equidimensional. The outcrop pattern of this facies suggests that it is variable in width. Near the area north of Upper Sysladobsis Lake (Springfield quadrangle) the rim facies is at its widest, but its continuation to the west, in the area near No. 3 Pond (Winn quadrangle) is altogether absent. Detailed mapping and subdivision of this facies into different types is also possible using the abundance of amphibole, total ferromagnesian mineral content, and

development of seriate, equidimensional and porphyritic textures (Ayuso and Wones, 1980). Many of these lithologic types are evident in the Springfield and Scraggly Lake quadrangles which contrast with the predominantly amphibole-poor, equidimensional rocks developed elsewhere in the rim facies (for example, in the Nicatous Lake quadrangle).

Additional petrographic heterogeneity in the rim facies is expressed by the progressive changes in fabric and mineralogy away from the granite-country rock contact. Porphyritic rocks associated with aplites and tourmaline-bearing pegmatites are well developed at the contact, but within a few meters toward the interior they become medium-grained and equidimensional granites. Many of these changes are evident in the area of Getchell Mountain and near Almanac Mountain in the Springfield quadrangle.

Forceful intrusion of the pluton is indicated by the sharp contacts exposed north of No. 3 Pond. However, lit-par-lit disaggregation of country rock by numerous aplites and pegmatites is a more common contact type. This is exemplified by outcrops west of Getchell Mountain, where the band of porphyritic rocks developed at the contact is poor in mafic minerals and pinkish gray (5 YR 8/1) to grayish-orange pink (10R 8/2) in color. Amphibole is the only mineral that is uncommon near the contact, although it progressively increases in abundance and grain size toward the interior. Similar changes are documented for the accessory and varietal minerals. Mafic xenoliths are absent at the contact and their change in abundance and size parallels that of amphibole. Although porphyritic rocks are generally massive in fabric, some of the seriate granites are foliated parallel to the contact. Preferred orientation of

the feldspars, biotite and quartz argue for a granitic magma already saturated with respect to these phases during intrusion at this level. Exposures of foliated granitoids are common to the west of Lombard Mountain, and south of Bowers Mountain in the Springfield and Scraggly Lake quadrangles respectively.

Other typical changes occurring within the rim facies as a function of distance from the country rock include the general decrease in Schlieren, amorphous felsic inclusions, and country-rock xenoliths. All of these, except for the felsic inclusions, are aligned with their long dimensions parallel to the contact. Many of the felsic masses show textures and mineralogy similar to the porphyritic band developed at the contact with the country rock.

The average modal composition of the rim facies is as follows: alkali feldspar (30%), plagioclase (39%), quartz (24%), biotite (5%), and amphibole (2%). The sum of opaque minerals and accessories accounts for significantly less than one percent of the mode. The trend in modal abundances within the Passadumkeag River pluton is clearly toward a plagioclase and mafic mineral rich interior facies.

The core facies consists of coarse-grained, very pale orange (10 YR 8/2) to yellowish gray (5 Y 8/1) granitoid rocks that contain numerous mafic xenoliths, and characteristically euhedral, black amphibole prisms (Ayuso, 1979). Color index and plagioclase content attain their highest values in this facies resulting in rocks of quartz monzonitic mineralogy. Although the change across facies is sometimes abrupt as in the area west of Upper Sysladobsis Lake (Springfield quadrangle), the transition is more commonly unexposed.

Textures are predominantly porphyritic and display euhedral alkali feldspar with Rapakivi texture, plagioclase and amphibole phenocrysts in a matrix of mafic and felsic minerals. The average modal composition of this facies is as follows: plagioclase (38%), alkali feldspar (33%), quartz (19%), biotite (6%), amphibole (3%), and the sum of the accessory and opaque suites (1%). Comparison of the modes clearly shows that the core contains about twice the total mafic mineral content of the rim. Further evidence for zonation is exhibited by the reverse correlation of alkali feldspar and quartz with respect to total mafic mineral content and plagioclase. Typical outcrops are exposed west of Sysladobsis Lake (Springfield quadrangle), on Moose Mountain (Winn quadrangle), and around the Chain Lakes (Nicitous Lake quadrangle).

The most significant feature of the rocks within the core facies is their heterogeneity, not only in the regional sense but even within single outcrops (Chapter 2, this study). This results in the absence of smooth and linear trends in the modal abundances across the pluton. Typical core facies rocks consist of randomly distributed, fine-grained quartz-dioritic clusters, rich in mafic minerals which alternate with clusters made up almost exclusively of feldspathic minerals. Similarly, the entire lithological diversity of mafic xenoliths is sometimes exemplified in individual outcrops by a great range in size, shape, and mineralogy. Xenoliths range in size from the randomly oriented small (5 - 10 cm), ovoidal fine-grained, oriented masses of biotite and plagioclase common throughout the pluton, to banded biotite-rich aggregates, and finally to large (up to 1 m) disc-shaped and prominently porphyritic quartz-diorite rocks.

Petrography

Compositional variation of the constituent phases within the pluton exceeds the analytical uncertainty, supports the modal heterogeneity, and argues for distinct chemical differences even within each facies. Detailed studies of the petrography of the Passadumkeag River pluton are reported in Chapter 2 (this study) and Ayuso and Wones (1980). A summary of these results is presented in the following section.

The core facies of this pluton contains more accessories than the rim facies, especially as inclusions within mafic minerals and close to the mafic xenoliths. Zircon and apatite are the earliest phases to crystallize. Apatite shows larger variations in F (from 1.6 to 3.0 wt. %) and Mn (from the limit of detectability to 0.24 wt. %) than in the granite of Whitney Cove. Allanite tends to form euhedral and smaller grains than at Whitney Cove, and these are also optically and compositionally zoned from core to rim. Primary sphene presents euhedral sides to all phases except apatite and zircon, while secondary sphene is generally anhedral and replaces amphibole and biotite.

In this pluton magnetite and ilmenite generally occur as inclusions in mafic minerals, as secondary reaction products in biotite and amphibole, and scattered in the matrix. Pyrite globules are rare and appear to concentrate within magnetite. Magnetite contains less than 1.0 wt. % TiO_2 and shows no differences intrinsic to each facies. The composition of ilmenite is less manganiferous than in the Whitney Cove pluton but ranges up to 7.5 wt. % MnO and suggests reequilibration at low temperature.

Clinopyroxene is an extremely rare phase in the Passadumkeag River pluton, where it is concentrated in the core facies as fine-grained inclusions within plagioclase phenocrysts in only one sample. Although the phenocrysts also enclose amphibole, there are no reaction rims between amphibole with the generally subhedral, monoclinic, and optically unzoned clinopyroxenes.

Amphibole is heterogeneously distributed in this granite and near the granite-country rock contact the ratio of amphibole to biotite approaches zero. This ratio increases in a few areas within the core facies to about one-to-one, but more commonly, amphibole is subordinate in abundance to biotite. Two generations are present in the Passadumkeag River pluton and consist of amphibole formed as phenocrysts and in the matrix. Amphibole phenocrysts (up to 0.7 cm) are black prisms, invariably euhedral to all other silicates except biotite. Although amphibole appears to precede biotite in the crystallization sequence, inclusions of unaligned biotite plates within amphibole suggest a stage of coprecipitation of these two phases. In accordance to the classification of Leake (1978), the amphiboles range from ferroedenites to ferro-edenitic hornblende. The $Fe/(Fe + Mg)$ ratio ranges from 0.53 to 0.74 without a distinct trend from rim to core facies. However, the composition of the iron-rich amphiboles tends to contain less calcium but more manganese and aluminum than the more magnesian amphiboles.

Biotite is the predominant mafic mineral in the Passadumkeag River pluton. Several textural types are present and include phenocrysts, groundmass, biotite, and biotite forming fine-grained clusters with

other mafic minerals and plagioclase. Biotite compositions across the pluton characteristically show major overlap. However, there is a suggestion that the more titanian and magnesian varieties are concentrated in the core facies.

The textural variation shown by plagioclase is significant. Plagioclase occurs forming two petrographic groups of phenocrysts, as groundmass grains, and in fine-grained clusters with mafic minerals. The composition of plagioclase fails to reflect the modal zoning from the granitic rim facies toward the core. Although compositions of An_{46} occur within the inclusion-rich phenocrysts, the average is An_{20-30} and the pluton generally shows large compositional variability within each facies. The only distinction that may be made is that the average composition of plagioclase cores in the rim facies are constrained to less than An_{25} . Plagioclase inclusions within alkali feldspar sometimes represent the most calcic compositions within a sample. Matrix plagioclase shows a range between An_{12} to An_{28} , overlapping the composition of the plagioclase phenocrysts.

The composition of alkali feldspar shows insignificant variations regardless of facies. This probably resulted from deuteric alteration to and reequilibration to compositions of Or_{85-98} . Inclusions of all other phases are commonly enclosed within subhedral alkali feldspar and argue for its late crystallization. Alkali feldspar displays faces only in contact with quartz. Rapakivi texture is uncommon in the Passadumkeag River pluton. However, in contrast with the Whitney Cove granite, this texture is developed in a number of alkali feldspar phenocrysts in most outcrops. Granophyric textures occur close to the

granite-country rock contact and are commonly associated with myrmekitic intergrowths, development of mortar or granulated texture, and deeply embayed, corroded rims of biotite and opaques.

Quartz is concentrated in the matrix, especially within the felsic clusters. Subhedral to anhedral grains with typically undulatory extinction and sutured borders are characteristic of this pluton. Judged from the lack of euhedral faces of quartz in contact with all other phases except alkali feldspar, quartz represents one of the latest phases to precipitate.

Bulk Chemistry

The granite of Passadumkeag River is mineralogically and texturally zoned from rim to core facies. Ayuso and Wones (1980) argued that this zonation is also evident in the major and trace element composition across the pluton. Thus, compared to the rim, the core facies is lower in silica but higher in CaO, MgO, Fe_2O_3 , TiO_2 , P_2O_5 and Al_2O_3 , also the total alkali element content shows no significant enrichment in the more felsic rocks. Silica decreases in a regular gradient from 65.0% to 77.0% from core to rim and is inversely correlated to the other major oxide constituents.

The compositional diversity and field relations of wall-rock xenoliths argue strongly for a minimum degree of interaction with the granitic melt. However, compositional control of the mafic xenoliths on the evolution of the granitic melt is complex and uncertain, partly because of the petrographic diversity evident even within single outcrops. This diversity is also indicated in the spread of

compositions of the mafic xenoliths, as they are only broadly correlated to the trend defined by the granitoids.

Normative composition of this pluton shows that they are slightly corundum normative (less than 2%) and exhibit higher anorthite in the core facies. Similar to the Whitney Cove pluton, normative compositions are not directly correlated to silica abundances.

Preliminary analyses of the same suite of trace elements analyzed in the Whitney Cove pluton confirm the reverse zonation in the Passadumkeag River granite. However, in contrast to the general clustering of data at Whitney Cove, the strontium- and yttrium-rich rocks of the core facies form a continuous band toward the strontium- and yttrium-poor rim facies. Rubidium concentrations also decrease toward the interior of the pluton and suggest more gradual variations than previously encountered at Whitney Cove.

Felsic Dikes

Aplites are relatively uncommon in the Bottle Lake Complex. However, the two plutons differ because the Whitney Cove granite is comparatively richer in felsic dikes (aplites, pegmatites, granophyres) than the granite of Passadumkeag River. Additionally, small miarolitic cavities (1 - 3 mm) are concentrated in the Whitney Cove granite, west of Pug Lake in the Scraggly Lake quadrangle, but appear to be absent in the granite of Passadumkeag River. Aplite bodies are fine-grained leucocratic rocks ranging from a few centimeters to 0.8 m in thickness. They often show diffuse contacts, extreme variation in attitude, and inward mineralogical banding from felsic to thin biotite zones which

culminate in a pegmatitic core. Muscovite is present in some of the aplites exposed within the plutons, especially in the core of Whitney Cove. However, muscovite is best developed in pegmatitic pods near granite-country rock contacts in association with long blades (3 - 5 cm) of black tourmaline. These are exposed west of Almanac Mountain and north of Bowers Mountain in the Springfield and Scraggly Lake quadrangles.

Within the Bottle Lake Complex, felsic dikes are common east of Sysladobsis Lake and along the shores of McLellan Cove in West Grand Lake (Scraggly Lake quadrangle) within the Whitney Cove pluton, and in Getchell Mountain (Springfield quadrangle) and south of Chamberlain Ridge (Nicatorous Lake quadrangle). Felsic dikes are typically impoverished in mafic minerals, accessories, and plagioclase. Compositionally, they represent the most felsic rocks of each pluton and characteristically contain less strontium but more rubidium than associated granitoids (Chapter 2, this study).

Amphibolite Dike

An amphibolite unit outcrops in the Scraggly Lake area, entirely confined within the cataclastic zone. This unit is best exposed in Hasty Cove and on islands near the southern shores of Scraggly Lake. Most amphibolite outcrops are intensely sheared, jointed, and exhibit a strong northeast-trending foliation parallel to that of the granitic rocks. The predominant rock type is a fine-grained, greenish black (5 GY 2/1) unit with sparse plagioclase phenocrysts. Contacts with the granitic rocks of the Whitney Cove pluton are characterized by a hybrid

zone where porphyritic greenish gray (5 G 6/1) rocks are abundant. Felsic dikes cut the hybrid zone and the amphibolite. Mineralogic and size variability characterizes the xenoliths, as they range from mafic to felsic-rich and from a few centimeters to one meter in length.

The mineralogy of the amphibolite consists of plagioclase, amphibole, and biotite with minor amounts of quartz and alkali feldspar. Apatite, allanite, sphene, ilmenite, magnetite, and zircon are also present. However, apatite is the most conspicuous accessory in this rock.

Structures

The generally massive fabric of the Bottle Lake Complex commonly persists up to the granite-country rock contact. However, in the foliated rocks the feldspars are generally aligned parallel to the contact. Extensive outcrops are developed on Lombard Mountain and Getchell Mountain in the Springfield quadrangle. Several areas within the granites also show foliated rocks and these consist of the following: 1) randomly distributed zones within the core facies of the Passadumkeag River pluton; 2) foliated rocks of the rim facies of the Whitney Cove pluton developed in a cataclastic zone; and 3) the randomly foliated rocks within the core facies of the Whitney Cove granite.

The foliation of minerals in rocks within the interior of the Passadumkeag River pluton is aligned to the northeast, but is not accompanied by the strong cataclastic deformation characteristic of most foliated areas in the Whitney Cove pluton. Foliation within the granite of Whitney Cove is generally associated with bands of cataclastic

deformation. The two most important of these are the northeasterly trending fault zones of the Norumbega fault system and the fault zone which diametrically transects the Whitney Cove pluton. Each of these zones is also characterized by foliated granitic rocks preferentially aligned to the northeast, and contrast with the randomly foliated rocks of the core facies.

At least three fault zones are exposed in the Bottle Lake Complex: 1) the wide band of deformation which cuts the Whitney Cove pluton; 2) The Norumbega fault system; and 3) the fault which cuts the Topsfield facies which was mapped by Ludman (1978b). The northeast trending (N40-50°E) cataclastic zone which cuts the Whitney Cove pluton terminates against the Passadumkeag River granite. This zone extends from Orié Lake to Junior Lake in a well-exposed 1.5-3.0 km band in the Scraggly Lake quadrangle. Typical rocks are cataclastically deformed, sheared, and crisscrossed by quartz and epidote veins. Most outcrops show at least one set of mylonite zones to the northeast, although many show significant scatter in attitude. The deformation along the fault zone was a combination of brittle and ductile deformation and was confined to narrow zones of maximum stress. Spindle-shaped quartz grains are common in most exposures. Many outcrops also show evidence for right-lateral motion and up to 50 cm displacement in east-trending fractures. Granitic rocks are pervasively and massively altered. Feldspars are crisscrossed by thin, epidote-rich veins and show extreme alteration, disintegration, shearing, and displacement, especially within once plastic bands of recrystallized quartz and biotite.

The Norumbega fault zone is the major northeast trending right-lateral system in the region and constitutes the southern contact of the Whitney Cove pluton. According to Wones (1980) the amount of displacement along the fault is unknown. Outcrops in Farm Cove of West Grand Lake in the Wabassus Lake quadrangle are good examples of intensely sheared, silicified and mylonitized granitic rocks.

A left-lateral fault mapped by Ludman (1978b) along the southern shores of East Musquash Lake near U.S. Route 6 splits the upper half of the Topsfield facies from the main mass of the Whitney Cove pluton. The fault is oriented along an east-west trend and is characterized by epidotized and intensely sheared red granitic rocks.

Mylonite veins are relatively common near the traces of the fault zones and also as randomly distributed and oriented features within the Whitney Cove pluton. Many of these veins are probably related to the identified faults in the region. However, the preponderance of mylonites showing a pronounced east-west trend is suggestive of a distinct and possibly later deformation unrelated to the identified faults.

Joints and fractures are common in most outcrops throughout the Complex. They often show large variation in attitude even within individual outcrops and show no regional variation or trend within the granitic rocks. Jointing is significantly increased with proximity to the areas of intense cataclastic deformation.

OTHER GRANITIC ROCKS

At least three other Paleozoic granitic plutons in addition to the

Bottle Lake Complex are exposed in the area: 1) the Center Pond pluton; 2) the Lead Mountain pluton; and 3) the Wabassus Lake granite. A brief summary of their characteristics is as follows. The Center Pond pluton was first studied by Larrabee and others (1965) but a more complete description is given in Scambos (1980). Field characteristics are summarized in Ayuso and Wones (1980) where the general similarity between the Passadumkeag River and Center Pond plutons is emphasized. Although this pluton is one of the smallest granites in this area, it exhibits characteristic mineralogic (from amphibole to biotite-rich) and compositional (from quartz diorite to granite) variability which distinguishes the plutons intruding this part of the Merrimack synclinorium (Ayuso and others, 1980). As in the Passadumkeag River pluton, however, the Center Pond granite is cut by a right-lateral northeast trending fault zone. Also, according to Scambos (1980), the Center Pond pluton exhibits strictly linear compositional variation from quartz diorite to biotite granite.

The Lead Mountain batholith constitutes a large (1000 km sq.), composite body in which granites are the predominant rock type. Exposures of this batholith are found directly south of the Bottle Lake Complex, within fault-bounded blocks, and as a large granitic mass extending south toward the Maine coast. Recent mapping suggests that the batholith has an extensive lithological range from amphibole-bearing to biotite granite. Petrographic contrast between the Bottle Lake Complex and the Lead Mountain which lie on either side of the Norumbega fault argue against correlation of the two granites.

The Wabassus Lake granite was first studied by Larrabee and others (1965) and is exposed only within the blocks bounded by the Norumbega fault system (Ayuso and Wones, 1980). Petrographic correlation with the Bottle Lake Complex or with the Lead Mountain batholith is not supported because the Wabassus Lake pluton is finer-grained, more felsic, and texturally different from the other nearby plutons. Preliminary observations suggest that biotite is the predominant mafic phase. This rock is commonly exposed as intensely sheared and deformed outcrops showing only traces of the original mafic mineral and felsic assemblage.

METAMORPHIC ROCKS

The Bottle Lake Complex plutons intrude greenschist facies metamorphic rocks of the Merrimack synclinorium. Country-rocks are consistently low in metamorphic grade and show great differences in lithology and age (Larrabee and others, 1965; Olson, 1972; Ludman, 1978b). The age span represented by these rocks extends from Cambrian (?) to Devonian; with lithologies ranging from almost monomineralic sandstones to andesitic volcanics (Ludman, 1978b). Metasedimentary units generally show primary sedimentary features but are very poor in fossils and difficult to correlate regionally. Numerous faults occur between and within the metavolcanic and metasedimentary sections. However, all of these faults are cut by the Bottle Lake Complex.

The oldest rocks intruded by the plutons are Cambro-Ordovician (?) green and maroon slates, argillaceous quartzo-feldspathic sandstones, and quartz-granite conglomerates. Larrabee and others (1965) suggested the age based on the similarity to the Cambrian Grand Pitch Formation,

and to parts of the Ordovician Tetagouche Group in New Brunswick. Most units are thick-bedded, exhibit penetrative cleavage, and an early episode of isoclinal folding probably pre-Acadian age (Ludman, 1978b). The early folding episode in the area was recognized only within these rocks. Mineral assemblages show zoning as a function of distance from the granite-country rock contact. Detailed traverses at right angles away from the pluton show mappable zones of garnet, cordierite, and biotite hornfels. About one kilometer from the contact, chlorite and white-mica bearing argillaceous quartzo-feldspathic sandstones represent typical country-rock lithologies. All of the rocks have tourmaline, epidote, calcite, sphene, and opaque minerals, as well as two feldspars. Albite showing checkerboard texture and alkali feldspar are subordinate in abundance to quartz and suggest that the source was igneous in character.

The Ordovician (?) or Silurian (?) metavolcanic and metasedimentary rocks form a band to the west of the Cambro-Ordovician section. In addition, Ludman (1978a) also mapped a thinner but similar section south of East Musquash Lake, and north of the Topsfield facies in the Scraggly Lake and Waite quadrangles respectively. Volcanic rocks exposed south of East Musquash Lake consist of hornblende-bearing andesite interbedded with minor sedimentary and volcanoclastic sandstones (Ludman, 1978a), while pelitic to quartzose rocks showing graded and fine-scale bedding characterize the tourmaline-bearing metasedimentary rocks. Mineralogical zoning is also evident in these rocks as noted by Cole (1961) and indicated by the presence of garnet, cordierite, tremolite, and biotite as a function of distance from the plutonic contact.

Garnet-cordierite hornfels are formed closest to the pluton which progressively becomes tremolite-epidote-biotite schists away from the contact. Immediately contiguous to the granite-country rock contact, felsic pods which mineralogically consist of two feldspars, muscovite, quartz, garnet, allanite and biotite are sometimes present. These pods are discontinuous and amorphous in shape, small (10-20 cm), and consistently show similar mineralogy and cuneiform textures. Relict and retrograded aluminosilicate (?) mineral and muscovite are concentrated within alkali feldspar. In contrast to the felsic pods, the country rock consists of finer-grained, garnet-cordierite hornfels which also contain white mica and biotite.

Silurian and Siluro-Devonian (?) rocks are designated as the Vassalboro Formation (Osberg, 1968) and are the most common country rocks intruded by the granites. Ruitenberg and Ludman (1978), Ludman (1978b) and Wones (1980) suggest that the Vassalboro is correlative to the Flume Ridge Formation to the southeast, the Kellyland to the northeast and the Bucksport Formation to the southwest of the Bottle Lake Complex. This section is generally characterized by calcareous siltstones interbedded with pelitic sediments. Changes in bedding-style, calcareous nature, color, and grain size are common in hornfels around the plutonic rocks. In the vicinity of the northern contact, near No. 3 Pond in the Winn quadrangle, the Vassalboro Formation is a pin-striped, shaly, slightly rusty, and intensely jointed rock. The stripes are generally centimeter-sized dark and light bands of contrasting mineralogy. Biotite-rich stripes are dark purple and alternate with light colored stripes consisting of calcite and quartz.

Throughout the rock, the assemblage diopside, amphibole, epidote, and quartz coexists with biotite and calcite. Mineral zoning is also developed in these rocks, as garnet-cordierite-biotite hornfels are formed closest to the contact, but these progressively become lower grade rocks away from the plutons.

GEOLOGIC INTERPRETATION

Field studies indicate that the plutons of the Bottle Lake Complex are mineralogically zoned. In contrast to more common normal zonation (Compton, 1955; Reesor, 1958; Bateman and others, 1965; Cobbing and Pitcher, 1972; Bateman and Chappell, 1979; Halliday and others, 1980), the plutons are mineralogically and chemically reversely zoned. This is evidenced by a mappable interior facies consisting of mafic mineral-rich rocks, commonly associated with precipitation at higher temperatures (Bateman and Chappell, 1979). Compositionally, the more felsic rocks are concentrated in the outer envelope and thus are in direct conflict with the commonly accepted model of progressive crystallization toward the interior (see for example Bateman and Nockleberg, 1978). Ayuso and Wones (1981) concluded that reverse zonation resulted from the process of autointrusion of the more mobile core into each pluton. Felsic cores intruding mafic rims were described by Cobbing and Pitcher (1972), and more recently by Bateman and Chappell (1979) in the Tuolumne Series in California. However, in the Bottle Lake Complex, a more mafic core was squeezed into the felsic rim. The regularity in compositional changes across the plutons suggest that each intrusive represents genetically related magmatic pulses upon which the processes of autointrusion and fractional crystallization were superimposed.

Intrusion of the rim facies of the Whitney Cove pluton was followed by the core and by reactivation of the northeast trending fault zones followed by emplacement of diabase dikes. As in the earlier melting episode, the core facies of the Passadumkeag River intruded after the rim facies. Remobilized core rocks are enriched in ferromagnesian minerals, refractories (zircon, sphene, allanite), mafic xenoliths, and contain several petrographic generations of biotite, amphibole, and plagioclase. Additionally, the textural heterogeneity of the granitic rocks, the persistently coarse grain-size, and the abundance of phenocrysts argue that at the level of emplacement the pluton intruded at an advanced stage of crystallization. The textural and chemical heterogeneity probably reflects processes related to the intrusion and mechanical mixing of different parts of the same crystallizing system. However, especially in the case of the Passadumkeag River pluton, the abundance of alternating mafic and felsic mineral clusters, the relic textures and compositional diversity of the near liquidus phases (biotite, plagioclase, and hornblende), abundance of a complex refractory suite, and the abundance of lithologically and chemically diverse mafic xenoliths suggest that the granite inherited much of its heterogeneity at the source. Concentration by fractional crystallization and gravitational settling of phenocrysts and xenoliths representing relics from a heterogeneous source resulted in the liquid mush representative of the core facies of the Passadumkeag River granite.

Petrographic studies of the Bottle Lake Complex and its contact aureole critically limit the intensive variables during emplacement.

Aluminosilicates are not well developed in the region but the presence of andalusite near the Complex was reported by Ludman (1978b), suggesting a maximum pressure estimate of 5 kb according to the aluminosilicate relations studied by Richardson and others (1969), or about 3.5 kb according to Holdaway, 1971. A more refined pressure estimate results from the application of the experimental granite system (Tuttle and Bowen, 1958; Luth and others, 1964) which indicates a range from 1.5 to 2 kb. The use of biotite equilibria and coexisting feldspars in the granite suggests that the emplacement temperature range is from 675 to 750°C. (see Chapter 2, this study).

The absence of miarolitic cavities and the relatively few felsic dikes within the batholith suggests that most of the crystallization occurred under vapor unsaturated conditions. Comparison of the modally determined order of crystallization with experimental granitic systems studies by Naney (1978) also argue for the generation of a free vapor phase at a very late stage of crystallization. Additionally, petrographic analyses place limits on the oxygen fugacity. The presence of sphene and magnetite suggest oxygen fugacity above the Ni-NiO buffer (Czamanske and Wones, 1973).

Petrographic similarities between the granites of Whitney Cove and Passadumkeag River indicate that they were derived from similar sources. Both granites are alike in their essential mineralogy, key index accessory suite (primary sphene, allanite, zircon, apatite), and lack of aluminous phases. This similarity is also reflected in the major and trace element variations and abundances by a general overlap in composition and trend.

A protolith of igneous character must dominate the source material of the Bottle Lake Complex as indicated by the field relations, accessory mineralogy, and major and trace element composition. This corresponds to the I-type source material in the classification of Chappell and White (1974), and to the magnetite series of Ishihara (1977). Such a source is supported by the composite nature of the Complex, the subcircular shape of the plutons and development of a contact metamorphic aureole, the range in the lithological variety of the granitic rocks, and by the presence of mafic xenoliths. Also in agreement with an I-type source is the presence of primary sphene and the abundance of amphibole.

Comparison of the field relations of granites intruding the Merrimack synclinorium in east-central Maine indicate that the Bottle Lake Complex is characteristic of the plutons emplaced in this part of the synclinorium. All of these plutons (Whitney Cove, Passadumkeag River, Center Pond) have high color indices, compositions ranging from diorite to granite, numerous mafic xenoliths, and few aplites and pegmatites (Ayuso and others, 1980).

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Chapter 2

GEOCHEMISTRY OF REVERSELY ZONED GRANITES OF THE BOTTLE LAKE COMPLEX, MAINE, AND THE EFFECT OF SOURCE HETEROGENEITY

INTRODUCTION

The Bottle Lake Complex is a composite batholith consisting of the Whitney Cove and Passadumkeag River plutons. The granites were emplaced during the Paleozoic in the southern part of the Merrimack synclinorium in east-central Maine and have similar Pb-Pb zircon ages of about 400 m.y. They are distinctively amphibole and biotite-rich plutons and contain primary sphene, magnetite, and abundant mafic xenoliths. These characteristics are especially common in the granite of Passadumkeag River.

Petrographic variations and changes in the mineral chemistry and bulk composition across the granites identify the interior areas as the least differentiated portions within each body. In comparison to Whitney Cove, the pluton of Passadumkeag River is markedly heterogeneous in its petrography, abundance and composition of its mafic xenoliths.

The evolution of the granitic rocks within the Bottle Lake Complex is closely modelled by the process of crystal fractionation of the assemblage plagioclase + biotite + amphibole + apatite. The relationship between the mafic xenoliths and host granitoids is not explained by fractionation or simple unmixing of a homogeneous source. The presence of a heterogeneous source is suggested by the geochemical variation of the xenoliths, recognition of at least two zircon

populations in the granites, and by the petrographic heterogeneity of the plutons.

The granite of Whitney Cove represents two granitic melts derived from a similar source intruded in close succession. The heterogeneous character of the Passadumkeag River suggests an origin from melting a geochemically diverse source which culminated with the generation and emplacement of the mafic xenolith-rich core facies.

The Bottle Lake Complex and the Center Pond pluton are examples of a distinct group of plutons emplaced north of the Norumbega fault system occupying the core of the Merrimack synclinorium. The tectonic setting associated with the granites in this region is not typical of plutonism occurring at destructive margins. Other processes such as production of granitic liquids from long-term storage and passage of basaltic liquid through the continental crust may account for this type of plutonism.

PREVIOUS WORK

Reconnaissance mapping by Larrabee et al. (1965) established the location of igneous contacts and the general stratigraphic relations in the region. However, a more refined understanding of the stratigraphy of the metamorphic rocks resulted from the studies of Ludman (1978a, 1981), Wones (1979), Olson (1972), and Osberg (1968).

Contacts between the Complex and the country rocks were initially determined by aeromagnetic studies (Doyle et al., 1961; Boucot et al., 1964) followed by field mapping (Larrabee et al., 1965; Ayuso, 1979).

FIELD RELATIONS AND PETROGRAPHY: GRANITES AND OTHER ROCKS

This section represents the field relations and petrography of the granites, aplites and xenoliths in the Bottle Lake Complex. A more detailed description of the field relations is given in Chapter 1 (this study), and Ayuso and Wones (1980).

The overall shape of the Complex resembles two superimposed subcircular bodies roughly arranged along an east-west trend with a prominent northeast trending granitic extension (Topsfield facies) off the eastern pluton (Fig. 1). The two individual bodies recognized within the Complex are the granite of Whitney Cove (east) and the granite of Passadumkeag River (west).

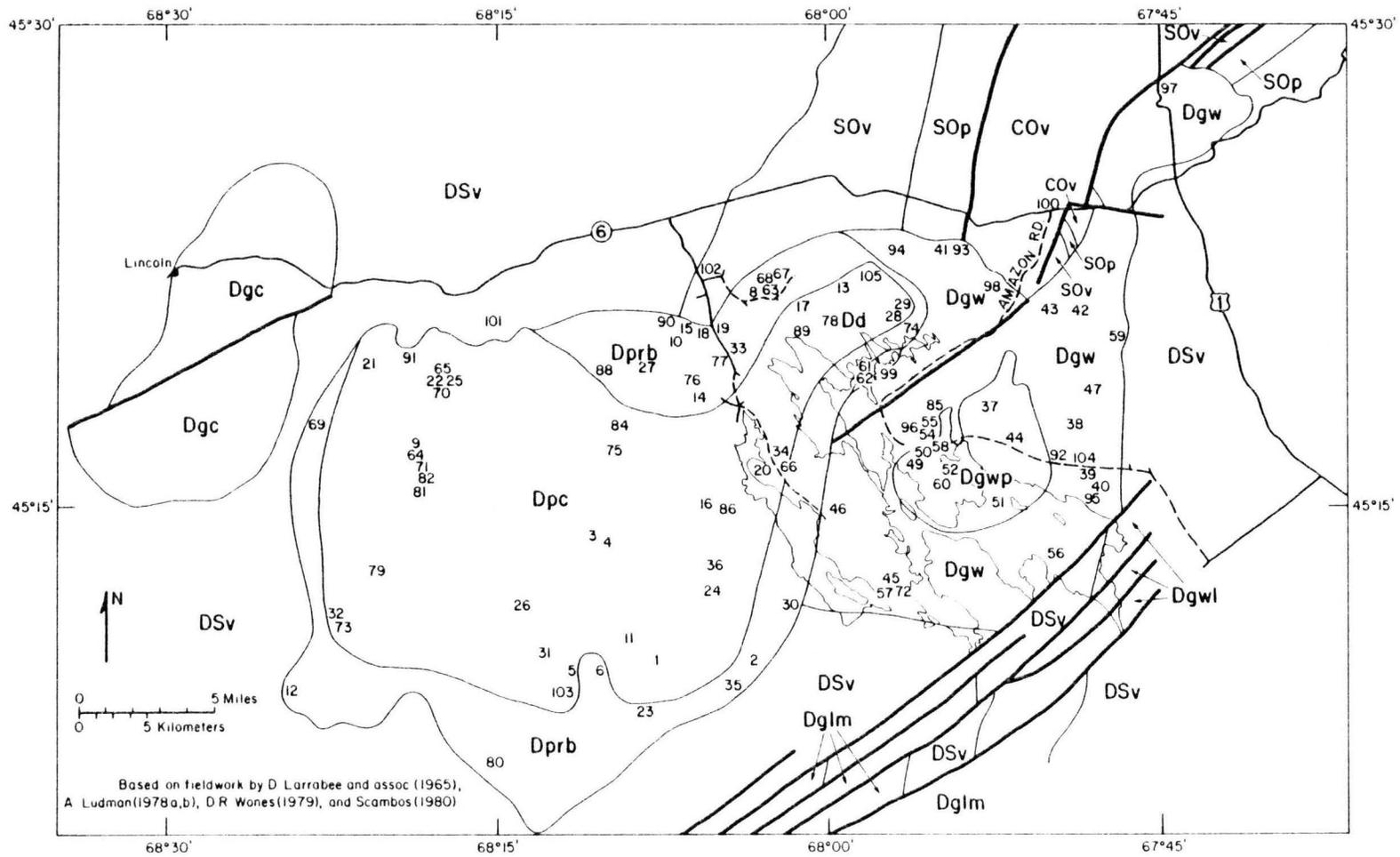
In general, both plutons are characterized by coarse-grained rocks consisting of two feldspars, quartz, biotite, and a similar suite of accessory and opaque phases (sphene, magnetite, ilmenite, zircon, apatite, allanite, and pyrite). Hornblende is abundant only in the Passadumkeag River granite, especially in association with rocks of high color index which also contain abundant mafic xenoliths. Although pyroxene is an extremely rare mineral, its association with mafic mineral-rich rocks is similar to that of hornblende.

Ayuso (1979) concluded that the composite nature of the batholith was expressed by the textural diversity, mafic mineralogy, abundance of pegmatites and aplites, and by the diversity and abundance of inclusions.

A thick section composed mostly of interbedded silts and shales of Silurian age is characteristic of this region in the Merrimack synclinorium (Osberg, 1978). However, Olson (1972), Larabee et al.

FIGURE 1.

Generalized geologic map of the Bottle Lake Complex, Maine. Sample distribution and locations are also shown.



LEGEND

PLUTONIC ROCKS - Bottle Lake ComplexGranite of Passadumkeag River

- Dpc** Coarse-grained biotite-hornblende bearing facies--generally quartz monzonitic composition, high color index, euhedral amphibole prisms, and abundant mafic inclusions
- Dprb** Coarse-grained biotite-hornblende granitic to quartz-monzonitic facies--commonly heterogeneous in texture; quartz forms large mosaic textures, generally poorer in mafic minerals than rocks in the interior

Amphibolite

- Dd** Diabase (?) intruded in cataclastic zone

Granite of Whitney Cove

- Dgwp** Medium- to coarse-grained, biotite bearing facies--homogeneous in composition, typically porphyritic, and low color index
- Dgw** Coarse-grained biotite facies granite--equidimensional texture, low color index, biotite in pseudo-hexagonal books

PLUTONIC ROCKS - Other Granitic Rocks

- Dgc** Granite of Center Pond--medium-grained, granitic rock ranging from diorite to biotite granite; contains abundant hornblende
- Dglm** Undifferentiated granitic rocks, usually coarse-grained, biotite-hornblende bearing rocks
- Dwl** Medium-grained granite found only within Norumbega fault zone, lower mafic-mineral content than Bottle Lake Complex

METAMORPHIC ROCKS

- DSv** Vassalboro Fm (?)--calcareous siltstones and pelites showing prominent mineralogic zonation from contact metamorphic effects imposed by the Bottle Lake Complex
- SOv** Undifferentiated Siluro-Ordovician (?), volcanic rocks, rusty pelitic beds; includes the Ordovician (?) Cemetery Hill Fm. (Olson, 1972)
- SOp** Undifferentiated Siluro-Ordovician (?), pelitic siltstones containing graded beds; includes the Ordovician (?) Greenfield Fm. (Olson, 1972)
- COu** Graywakes, siltstones, slates are the main lithologies of Cambro-Ordovician (?) age

Geology by R. A. Ayuso and assistants (1977, 1978, 1979); based on fieldwork by D. Larrabee and assistants (1965), R. K. Olson (1972), A. Ludman (1978a, b), D. R. Wones (1979), and T. Scambos (1980).

(1965) and Ludman (1978a,b, 1981) identified Cambro-Ordovician rocks adjacent to the Bottle Lake Complex. The youngest and most common rocks intruded by the plutons are Silurian to Lower Devonian in age (Ludman, 1978b).

Characteristic features at the granite-wall rock transition include lit-par-lit and brecciated contacts. Porphyritic rocks generally outcrop at the contact in a narrow (less than 20 m) band which exhibits aplites and pegmatitic pods. Both granites are massive from their cores to their margins. Foliated rocks are, for the most part, constrained either to zones of cataclastic deformation, or within the interior of the plutons distributed in a seemingly random manner. Cataclastically deformed zones are generally less than 3 km in width and are directly associated with the three fault traces mappable in the Complex (Fig. 1): 1) the fault zone cutting through the pluton of Whitney Cove; 2) the Norumbega fault system; and 3) the fault recently mapped by Ludman (1978b) which separates the Topsfield facies from the main mass of the Whitney Cove pluton.

Granite of Whitney Cove

The granite of Whitney Cove is recognizable in outcrop by its strictly granitic (Streckeisen, 1973) mineralogy and low content of ferromagnesian phases (Table 1, Fig. 2). Pegmatites and aplites are usually present in most outcrops and xenoliths are for the most part scarce, except for those derived from the country rock and concentrated near the granite-country rock contact. Field relations indicate that this pluton can be divided into three units: 1) Topsfield facies; 2) rim facies; 3) core facies (Fig. 1).

FIGURE 2.

Modal composition of the Passadumkeag River and Whitney Cove plutons according to their respective facies.

THE BOTTLE LAKE COMPLEX

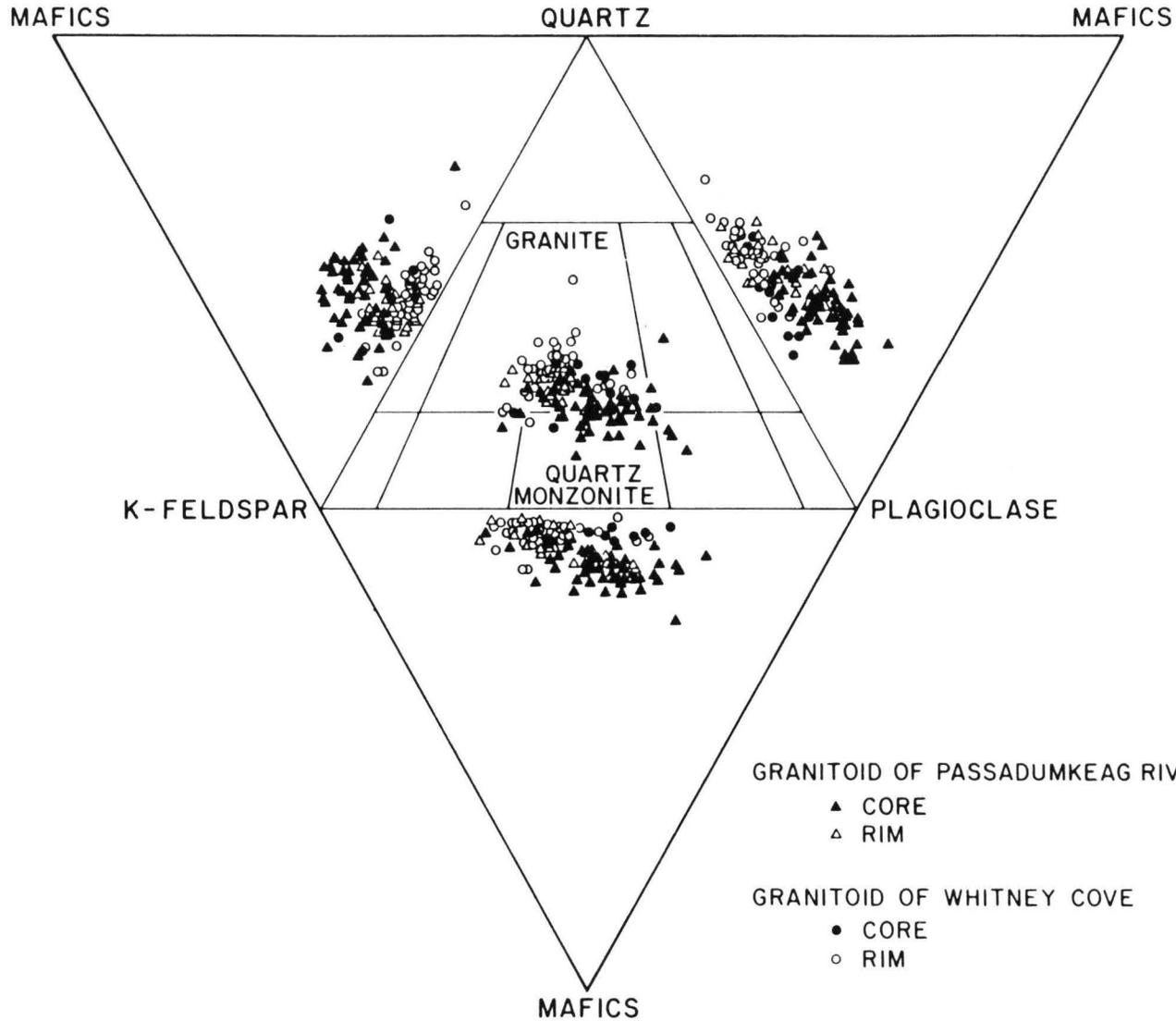


TABLE 1. Average modal composition of the plutons in the Bottle Lake Complex, Maine*.

	Whitney Cove		Passadumkeag River	
	Rim	Core	Rim	Core
Quartz	28.1	25.6	24.0	19.5
Plagioclase	27.5	35.8	30.0	37.7
Alkali feldspar	40.2	33.9	39.0	32.7
Biotite	4.2	4.7	4.9	5.9
Amphibole	0	0	2.1	4.2
Others	0.5	0.5	0.5	0.5

* Complete data set is given in Table 15

The best exposures of the Topsfield and rim facies suggest that both units have similar field relations and mineralogy. They are gradational in petrographic character, and except for the intense shearing and jointing in the Topsfield facies, cannot be distinguished (see Chapter 1, this study).

The rim facies of the Whitney Cove pluton is a pink, coarse-grained rock with hypidiomorphic and seriate textures. Alkali feldspar is predominant in size and abundance over plagioclase. The presence of euhedral quartz and pseudohexagonal biotite together with the relative abundance of aplites, pegmatites and granophyres are characteristic of this facies. Representative average modal analyses are given in Table 1. Biotite is the most important mafic phase because the other mafic phases are characteristically less than one percent in total abundance.

The Whitney Cove pluton, for the most part, exhibits a gradual textural transformation from the rim toward the porphyritic rocks of the core facies. Ayuso (1979) observed that the pattern of total mafic mineral abundance in this pluton showed a well-defined unimodal distribution centered at about 5 percent, reaching levels up to 13 percent in some rocks of the porphyritic facies. Field observations and point-counting of stained slabs support a textural and mineralogic change from typical granular granitic rocks to porphyritic rocks relatively enriched in biotite and plagioclase but depleted in alkali feldspar and quartz (Fig. 2). This is shown in the ternary modal diagrams which suggest that the mineralogic evolution of the Whitney Cove pluton was dominated by subtraction of plagioclase and biotite.

Study of the distribution and abundance of the accessory suite in selected thin sections indicates that the core facies, at least qualitatively, contains more apatite than the rim. No clear trends were detected for allanite, sphene, and zircon.

Mineral Chemistry

Detailed study of the crystallization of the Bottle Lake Complex is given by Ayuso (see Chapter 1, this study). The lithological reverse zonation of the Whitney Cove granite is also expressed by the compositional gradients of the constituent minerals. The importance of biotite and plagioclase in determining the lithological contrast between the two facies of this pluton and effectively controlling the evolution of this pluton was discovered early, on the basis of field studies. This contention is supported by the reverse zonation shown by these minerals in each facies, as compositions associated with higher temperature systems are consistently concentrated in the interior of the pluton.

In the case of biotite, the earliest major mafic phase to crystallize, the Fe/(Fe + Mg) ratio (Table 2, Fig. 3) is consistently lower in the core (0.48-0.58) compared to the rim facies (0.61-0.71). However, Ti shows no consistent trend. In contrast, zoning of octahedral aluminum and fluorine is evident in biotites across the pluton, and higher abundances are characteristic of the interior facies. Individual biotite grains are generally unzoned.

Plagioclase is the first feldspar to crystallize and its core compositions are also zoned in the direction of lower to higher

FIGURE 3.

Biotite composition in the core facies (filled circles) and rim facies (open circles) of the Whitney Cove pluton.

WHITNEY COVE

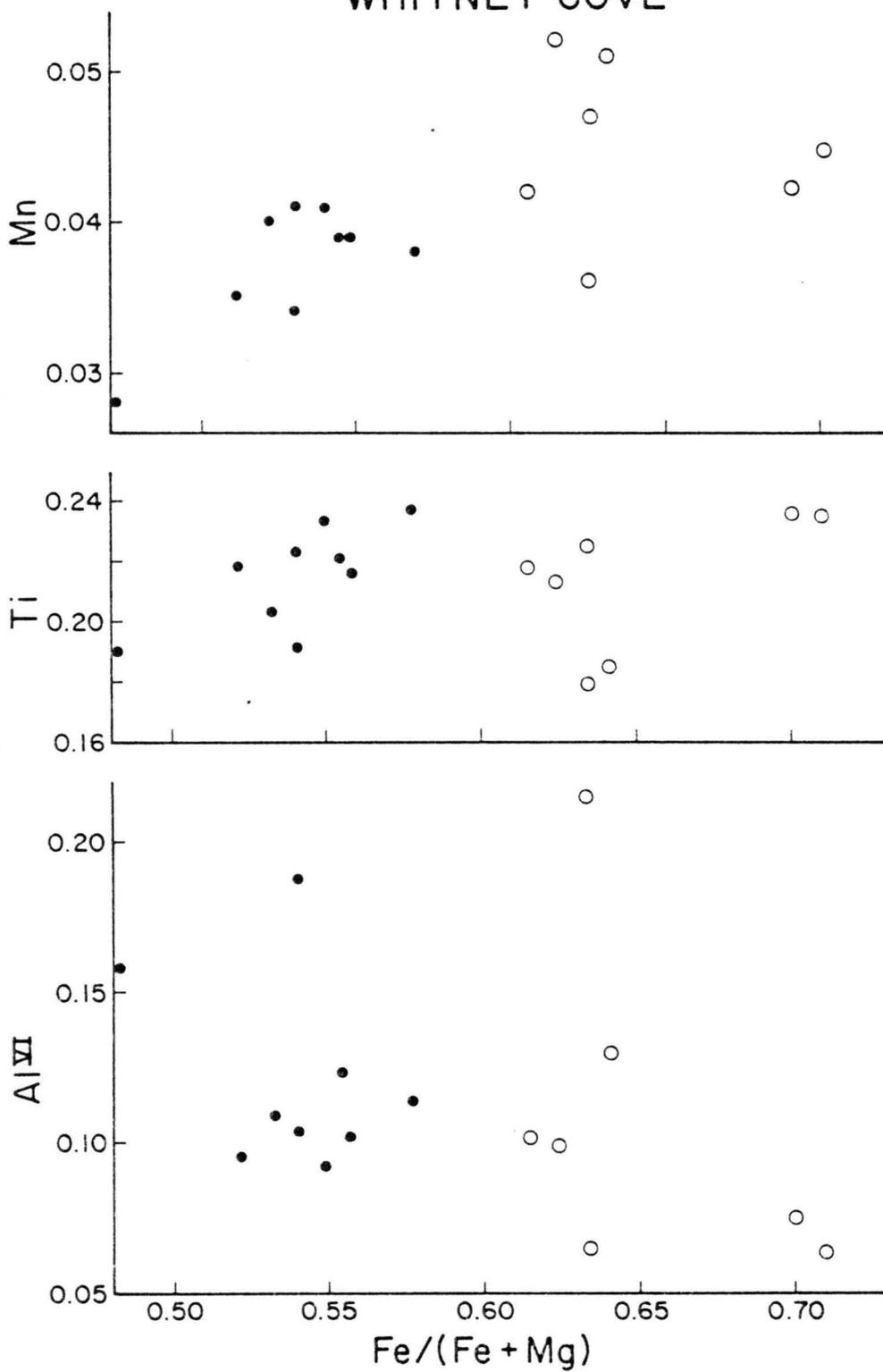


TABLE 2. Electron microprobe analyses and structural formulas* of biotite from the Bottle Lake Complex.

	1	2	3	4	5	6	7	8	9	10
SAMPLE**	57R	41R	44C	58C	13C	78C	79C	10R	8R	80R
SiO ₂	37.23	35.51	37.05	37.57	36.87	35.66	36.55	36.64	36.71	36.51
Al ₂ O ₃	15.23	13.31	14.92	14.14	13.43	13.03	14.13	13.41	13.90	14.16
TiO ₂	3.12	3.94	3.32	3.79	3.71	4.01	3.08	3.46	3.02	3.44
FeO †	23.52	26.02	18.72	21.89	23.33	23.69	26.82	24.76	23.42	22.92
MnO	0.72	0.65	0.43	0.61	0.51	0.42	0.49	0.43	0.45	0.60
MgO	7.61	6.25	11.28	9.72	8.87	8.42	6.79	8.17	8.86	8.38
CaO	0.06	0.04	0.07	0.08	0.06	0.05	0	0.09	0.08	0.05
Na ₂ O	0.10	0.08	0.09	0.11	0.12	0.08	0	0.08	0.12	0.06
K ₂ O	9.43	9.26	9.42	9.45	9.40	11.12	9.76	9.70	9.79	8.87
BaO	0.29	0.20	0.23	0.19	0.05	0.08	0.14	0.17	0.18	0.03
F	0.91	1.10	1.25	1.17	0.86	0.89	0.72	0.87	ND	0.98
Cl	0.09	0.10	0.04	0.05	0.58	0.07	0.05	0.08	0.11	0.07
P ₂ O ₅	0	0	0	0	0	0	0	0	0	0.01
SrO	0	ND	0	ND	0	0	0	ND	ND	0.05
TOTAL	98.29	96.46	96.82	98.74	97.79	97.47	98.53	97.89	96.82	96.13

* Structural formulas calculated for 11 oxygen atoms.

** R and C represent rim and core facies respectively; columns 1-4 from Whitney Cove; columns 5-10 from Passadumkeag River.

† Total iron as FeO.

ND Not Determined.

TABLE 2 (continued). Electron microprobe analyses and structural formulas* of biotite from the Bottle Lake Complex.

	1	2	3	4	5	6	7	8	9	10
SAMPLE**	57R	41R	44C	58C	13C	78C	79C	10R	8R	80R
Si	2.844	2.826	2.819	2.842	2.897	2.809	2.832	2.841	2.829	2.847
Al	1.371	1.249	1.338	1.260	1.222	1.210	1.290	1.225	1.262	1.298
Ti	0.179	0.236	0.190	0.216	0.216	0.237	0.172	0.202	0.196	0.202
Fe	1.503	1.732	1.192	1.383	1.507	1.560	1.738	1.607	1.509	1.492
Mn	0.047	0.043	0.028	0.039	0.033	0.280	0.032	0.028	0.029	0.039
Mg	0.866	0.742	1.279	1.096	1.021	0.988	0.784	0.944	1.017	0.973
Ca	0.006	0.004	0.006	0.006	0.006	0.004	0	0.008	0.007	0.004
Na	0.015	0.012	0.014	0.015	0.019	0.012	0	0.013	0.018	0.010
K	0.919	0.941	0.915	0.912	0.927	1.005	0.964	0.959	0.962	0.880
Ba	0.009	0.007	0.007	0.006	0.002	0.002	0.004	0.005	0.005	0.001
F	0.220	0.276	0.302	0.259	0.209	0.223	0.177	0.214	ND	0.242
Cl	0.012	0.014	0.005	0.007	0.008	0.010	0.008	0.011	0.014	0.009
P	0	0	0	0	0	0	0	0	0	0.001
Sr	0	ND	0	ND	0	0	0	ND	ND	0.003
Fe/Fe + Mg	0.64	0.70	0.48	0.56	0.60	0.61	0.69	0.63	0.60	0.61

* Structural formulas calculated for 11 oxygen atoms.

** R and C represent rim and core facies respectively; columns 1-4 from Whitney Cove; columns 5-10 from Passadumkeag River.

ND Not Determined.

anorthite content from rim to core facies. This supports the argument for reverse zonation (Table 3, Fig. 4). Average core compositions in the rim facies are about An_{21} whereas the core facies contains plagioclase of compositions up to An_{58} . The most calcic average core composition of plagioclase in the Whitney Cove pluton is An_{26} , but single analyses up to An_{33} were also recorded.

The two lithological types of the Whitney Cove pluton are composed of plagioclase coexisting with biotite. A general trend from calcic (An_{24} - An_{56}) plagioclase and more magnesian and aluminous biotite progressively changes into an assemblage consisting of more sodic (An_{18} - An_{25}) plagioclase and more iron-rich biotite in the rim facies (Fig. 4). Plagioclase represents the most important calcium and aluminum-bearing phase controlling evolution of this granite. This is expected at least until alkali feldspar starts crystallizing. In the Whitney Cove pluton the appearance of alkali feldspar was late, and it is probably represented by the inflection at An_{25} in Fig. 4.

Alkali feldspar probably exerted minor compositional control on the evolution of the pluton. Compositionally, this phase ranges from Or_{85} to Or_{98} as determined by the method of Wright (1968) and Wright and Stewart (1968) following sanidinization of the alkali feldspar. On the basis of detailed microprobe traverses, only minor variations were recognized between phenocrysts in comparison to alkali feldspar in the matrix. This was exemplified by slightly higher (0.1 to 0.2 wt.%) Ba in some phenocrysts.

Apatite appears to be modally more abundant in the core facies and this is reflected in the bulk composition of the rocks. However,

FIGURE 4.

Compositional change of biotite and plagioclase in the Whitney Cove granite. Symbols as in Fig. 3, plotted at the average value per sample; horizontal lines show the range in An content in the cores of plagioclase in single samples.

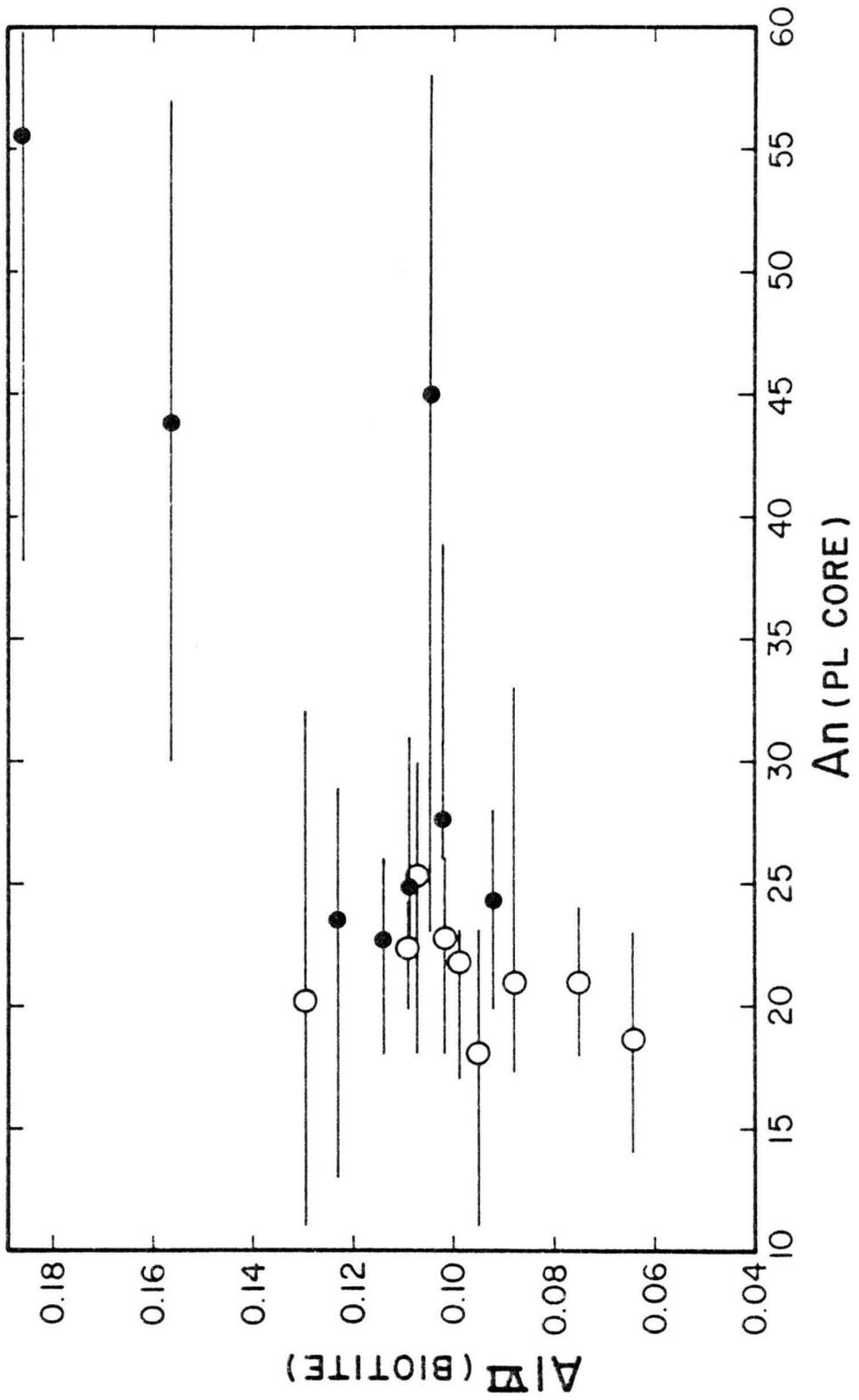


TABLE 3. Electron microprobe analyses and structural formulas* of plagioclase in the Bottle Lake Complex, Maine.

SAMPLE**	92C	58C	44C	93R	43R	20C	34C	75C	88R	10R
SiO	57.87	61.40	61.46	63.73	64.85	56.30	62.43	63.90	61.77	62.74
Al ₂ O ₃	26.31	24.40	24.47	22.67	22.14	28.00	23.26	22.77	23.96	24.75
FeO [†]	0.41	0.14	0.17	0.09	0.12	0.15	0.08	0.07	0.10	0.14
MgO	0.02	0.01	0.01	0	0	0.03	0.04	0.02	0.02	0
CaO	8.11	5.41	5.45	3.69	3.19	9.86	4.87	3.94	5.40	5.94
Na ₂ O	6.65	8.12	8.25	9.54	9.63	5.85	8.95	9.20	8.28	6.34
K ₂ O	0.14	0.14	0.37	0.25	0.25	0.15	0.06	0.13	0.18	0.37
SrO	0.12	0	ND	0.07	0.03	0.14	0	0.12	0.03	0
TOTAL	99.54	99.62	100.18	100.04	100.21	100.48	99.69	100.15	99.74	100.28
Si	2.605	2.731	2.725	2.816	2.852	2.520	2.774	2.817	2.746	2.755
Al	1.396	1.279	1.279	1.180	1.148	1.477	1.218	1.183	1.255	1.281
Fe	0.005	0.005	0.006	0.003	0.004	0.005	0.003	0.002	0.004	0.005
Mg	0.001	0.001	0.001	0	0	0.002	0.003	0.001	0.001	0
Na	0.580	0.700	0.709	0.817	0.821	0.508	0.771	0.786	0.714	0.540
Ca	0.391	0.258	0.259	0.175	0.150	0.473	0.232	0.186	0.257	0.280
K	0.008	0.008	0.021	0.014	0.014	0.009	0.004	0.008	0.010	0.020
Sr	0.003	0	ND	0.002	0.001	0.004	0	0.003	0.001	ND
AN	40.1	26.7	26.2	17.6	15.3	48.0	23.0	19.2	26.3	33.3
AB	59.1	72.5	71.6	81.2	83.3	51.1	76.6	80.0	72.7	64.3
OR	0.8	0.8	3.2	1.2	1.4	1.9	0.4	0.8	1.0	2.4

* Calculated per 8 oxygen atoms.

† Total iron as FeO.

ND Not Determined.

** R and C represent rim and core facies respectively; columns 1-4 from Whitney Cove; columns 5-10 from Passadumkeag River.

apatite is extremely heterogeneous even within individual samples in its content of Mn and F. This relation is also present in other accessory phases in the pluton as they show extreme heterogeneity from sample to sample. In the case of allanite, intragrain chemical zoning is displayed optically and by the content of Ti, Fe, F, Ca, and P. Spene, magnetite, and ilmenite exhibit no compositional gradients. Representative microprobe analyses of selected accessory phases are given in Table 5.

The Granite of Passadumkeag River

The most striking feature of this pluton is its extreme petrographic diversity. Two facies (rim and core) are present, each exhibiting marked textural and mineralogical differences (Chapter 1, this study, Fig. 1). Rocks from the rim facies are characteristically pink, are granitic in mineralogy, and have textures ranging from porphyritic to equigranular.

In a traverse across the pluton the modes of granitic rocks typical of the rim facies progressively become enriched in plagioclase and mafic minerals (Table 1, Fig. 2). Yellowish-gray porphyritic rocks of this facies display numerous mafic xenoliths and euhedral black amphibole prisms. Thus, they are easily distinguished in the field from all other units. A distinct trend from granite to quartz-monzonite lithologies is evident from examination of stained slabs and in the representative modes shown in Table 1 and 15 (Ayuso, 1979; Chapter 1, this study).

In contrast to the total mafic-mineral variation shown in Whitney Cove, this pluton shows a clear bimodal abundance distribution centered

TABLE 5. Electron microprobe analyses of apatite, allanite and titanite from the Bottle Lake Complex

SAMPLE*	1 37C	2 85R	3 86C	4 80R	5 49C ^a	6 49C ^b	7 105C	8 13C
SiO	0.60	0.65	1.06	0.67	31.20	31.54	30.95	29.86
Al ₂ O ₃	0	0	0	0	12.25	2.79	2.05	2.06
TiO ₂	0	0.03	0.01	0	2.39	2.86	33.80	34.35
FeO [†]	0.33	0.04	0.51	0.91	16.80	19.26	2.21	2.05
MnO	0.45	0.11	0.16	0.14	0.53	0.33	0.22	0.19
MgO	0.12	0.21	0.05	0.11	1.14	0.70	0.11	0.07
CaO	52.73	53.84	51.98	52.94	7.12	4.54	27.13	28.25
Na ₂ O	0.11	0	0.08	0.04	0.09	0.06	0.06	0.02
K ₂ O	0.03	0.06	0.05	0.01	0.03	0.04	0.02	0.01
BaO	0	0.06	0	0	0.08	0.04	0.09	0
F	4.32	4.10	4.56	3.90	0.27	0.27	0.80	0.84
Cl	0.02	0	0.01	0.02	0.03	0.03	0.01	0.02
P ₂ O ₅	40.64	40.42	40.52	41.11	0.06	0.05	0.04	0.04
SrO	0.01	0	0.04	0.04	0	0	0	0.04
TOTAL	99.36	99.88	99.03	99.89	71.99	72.51	97.49	99.78

* R and C represent core and rim facies respectively; columns 1-4 are apatite, 5-6 are allanite, 7-8 are titanite.

† Total iron as FeO.

^a Analyses from the innermost zone of grain.

^b Analyses from the outermost zone of grain.

at about 5% for the rim, and 11% in the core. This variation is consistent with the modal trends shown in Fig. 2, which may be summarized to suggest that plagioclase, biotite, and amphibole, in decreasing order of importance, dominate the mineralogical evolution of the Passadumkeag River pluton. Alkali feldspar and quartz are depleted in the core compared to the rim facies. Higher abundance of refractory phases (zircon, apatite, allanite, and sphene) distinguishes the relatively enriched core from the rim facies. Apatite and zircon are especially abundant near the mafic xenoliths.

Mineral Chemistry

Petrographic heterogeneity of this pluton is expressed by the textural variation as well as by the absence of compositional gradients in the minerals across the pluton (Ayuso, Chapter 1, this study). This is shown in the regional sense by the mappable petrographic domains of each facies, and also at the level of single outcrops. Because of this variation and despite the well-displayed lithologic reverse zonation from rim to core facies, the composition of the constituent minerals does not show clear compositional gradients.

The accessory suite represents the products of early precipitation and are especially abundant near the mafic xenoliths, their composition is characterized by granular and intrasample heterogeneity (Table 5).

Among the mafic phases, biotite and to a lesser degree amphibole are the most important minerals crystallized slightly prior to plagioclase. Both show a variety of textures and relative abundance within each facies. Amphibole ranges from euhedral to poikilitic

megacrysts of ferroedenite composition (Leake, 1978), and Fe/(Fe + Mg) ratios from 0.53 to 0.74 (Table 4, Fig. 5). No clear compositional trend is evident across the pluton. Biotite is also texturally heterogeneous and characteristically exhibits compositional overlap from core to rim facies. No trends are suggested to more aluminous (Fig. 6), magnesian and titanian-rich biotites in the interior (Table 3).

Compositional gradients in plagioclase are also absent despite the obvious (Fig. 2) increase in abundance from rim to core facies. The average composition is about An₂₅ to An₃₀ for the entire pluton (Table 4), and suggests that the composition of this phase was not controlled by closed-system fractionation. The average composition of the most calcic core in the rim facies is about An₂₄ although individual analyses as high as An₂₇ were observed. Anorthite-rich compositions up to An₄₆ are present in the core facies, but they show no consistent gradational change in composition toward more sodic plagioclase in the felsic rim (Fig. 5, 6). Plagioclase is the first feldspar to crystallize. The mafic phases and plagioclase control the evolution of the granite.

Alkali feldspar is late in the crystallization sequence and shows insignificant compositional changes across the pluton. The range extends from Or₈₅-Or₉₈.

Xenoliths

Because granitic plutons originate from various sources, it is important to distinguish the petrographic nature of the xenolith suite. Under ideal conditions, xenoliths provide geochemical memory of processes and source materials involved in the production of granites.

TABLE 4. Electron microprobe analyses and structural formulas*
for amphibole from the Bottle Lake Complex, Maine

SAMPLE**	31C	79C	29C	36C	8R	76R
SiO ₂	44.44	42.70	44.08	43.99	44.06	43.69
Al ₂ O ₃	8.22	8.45	7.78	8.28	8.07	8.12
TiO ₂	1.66	1.37	1.71	1.91	1.52	1.54
FeO [†]	22.89	25.22	21.39	22.04	21.93	22.43
MnO	0.70	0.79	0.70	0.72	0.79	0.79
MgO	7.49	5.46	8.35	7.75	7.80	7.44
CaO	10.85	10.50	10.58	10.73	11.02	10.68
Na ₂ O	1.77	1.89	1.81	1.76	1.66	1.80
K ₂ O	0.98	1.05	0.87	1.14	1.13	1.10
BaO	0	0	ND	0.13	0.14	0.11
F	0.37	0.61	0.51	0.40	0.43	0.47
Cl	0.15	0.13	0.11	0.20	0.14	0.18
P ₂ O ₅	0.02	0.01	0.20	0	0	0
SrO	0	0	0	0	0	0
TOTAL	99.54	98.18	98.09	99.05	98.69	98.35

* Calculated for 23 oxygen atoms using the scheme of Czamanske and Wones (1973).

** C and R refer to core and rim facies respectively.

† Total iron as FeO.

ND Not Determined.

TABLE 4 (continued). Electron microprobe analyses and structural formulas* for amphibole from the Bottle Lake Complex

SAMPLE	31C	79C	29C	36C	8R	76R
Si	6.777	6.722	6.846	6.742	6.779	6.759
Al	1.223	1.278	1.154	1.258	1.221	1.241
$\Sigma_{\text{(TET)}}$	8.000	8.000	8.000	8.000	8.000	8.000
Al	0.254	0.290	0.247	0.238	0.243	0.239
Fe	2.853	3.268	2.655	2.772	2.791	2.850
Mg	1.703	1.280	1.902	1.770	1.788	1.716
Ti	0.190	0.162	0.196	0.220	0.178	0.195
Mn	0	0	0	0	0	0
$\Sigma_{\text{(M}_1 - \text{M}_3)}$	5.000	5.000	5.000	5.000	5.000	5.000
Ca	1.722	1.772	1.732	1.762	1.817	1.771
Mn	0.091	0.106	0.090	0.093	0.103	0.100
Fe	0.067	0.053	0.078	0.055	0.032	0.052
Na	0.120	0.069	0.100	0.090	0.048	0.077
$\Sigma_{\text{(M}_4)}$	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.403	0.509	0.435	0.434	0.449	0.463
K	0.191	0.210	0.169	0.222	0.222	0.218
Ba	0	0	0	0.008	0.009	0.007
$\Sigma_{\text{(A)}}$	0.594	0.719	0.604	0.664	0.680	0.688
Fe/Fe + Mg	0.632	0.722	0.509	0.615	0.612	0.628

* Calculated for 23 oxygen atoms using the scheme of Czamanske and Wones (1973).

FIGURE 5.

Compositional change of amphibole and plagioclase in the Passadumkeag River pluton with respect to the core (filled circles) or rim (open circles) facies. Samples are plotted at the average but show the range of An found in the cores of plagioclase.

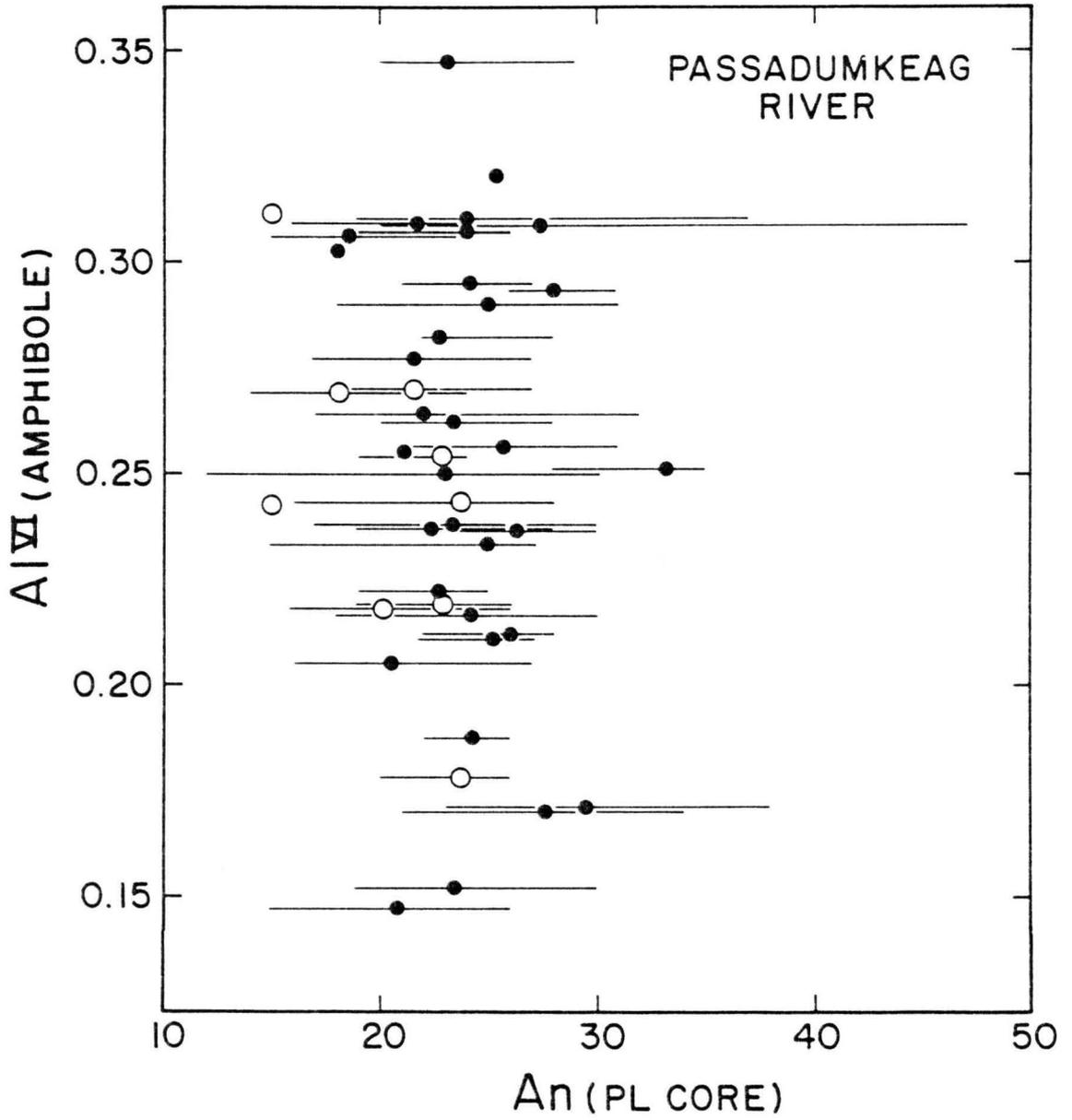
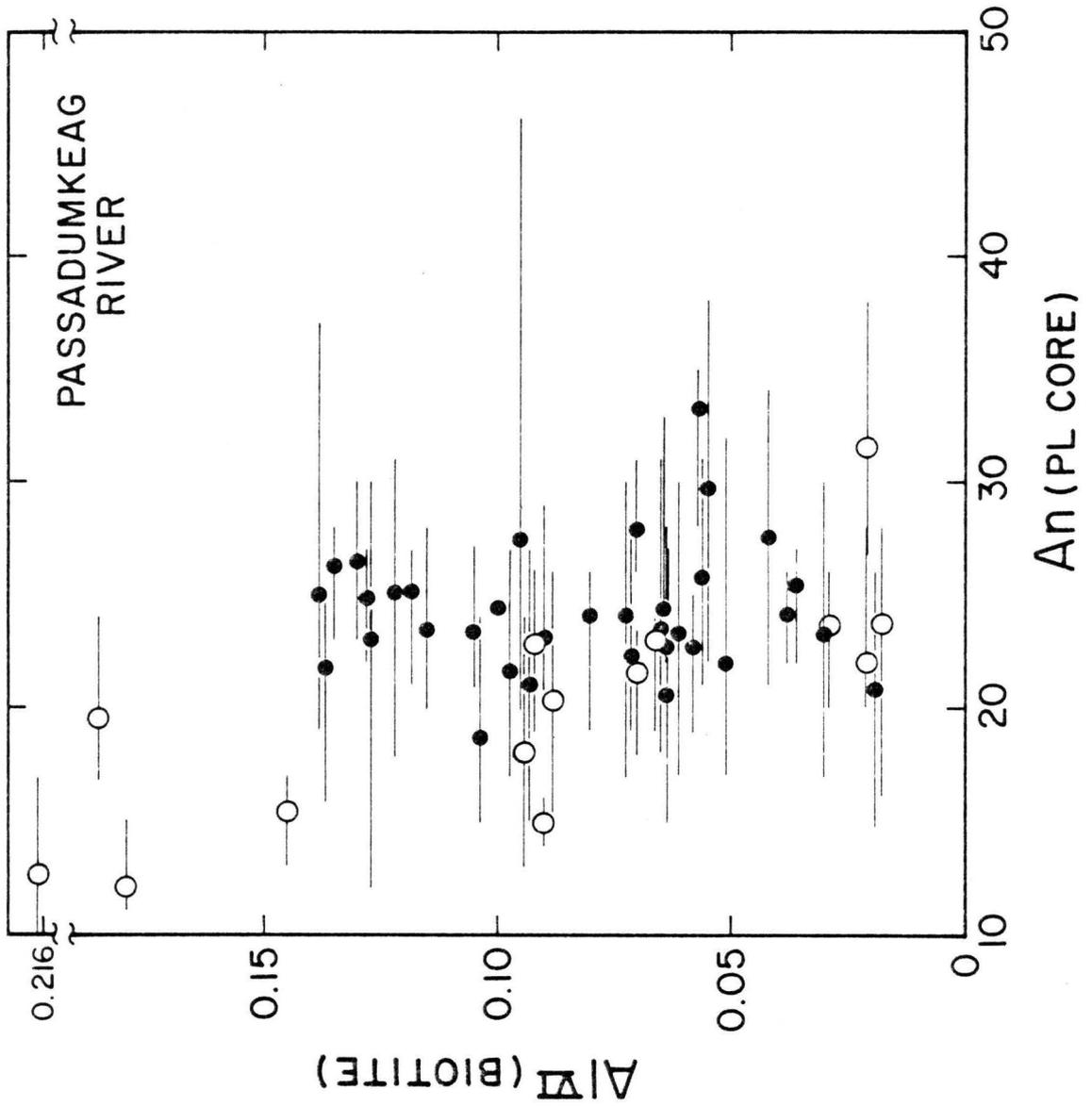


FIGURE 6.

Compositional change of biotite and plagioclase in the Passadumkeag River pluton. Symbols as in Fig. 5.



Although the two plutons of the BLC are geographically closely associated, each encloses different amounts and kinds of xenoliths (Ayuso, 1979). Two categories are recognized in the Complex: 1) metasedimentary and 2) mafic xenoliths.

Metasedimentary inclusions are concentrated near the granite-country rock contact and both their size and abundance decrease toward the interior of the granites. Metasedimentary inclusions also retain characteristic bedding-styles, structural features and petrography that match protoliths in the country rock.

Mafic xenoliths exhibit significant petrographic diversity among themselves as evidenced by their variable grain size, maximum dimension (up to 0.7 m), presence of feldspar megacrysts, and wide range of biotite to amphibole ratios (Chapter 1, this study). This variation is evident even within individual outcrops, although in the regional sense two general petrographic groups are present. The most abundant mafic xenoliths are porphyritic rocks of quartz dioritic mineralogy, fine- to medium-grained matrix, with prominent alkali feldspar and plagioclase megacrysts. Both opaque phases (magnetite and ilmenite) are present, together with abundant sphene and apatite.

This group of xenoliths is randomly distributed throughout the cores of both plutons, but is especially abundant in the Passadumkeag River pluton. They are distinguished from the finer-grained, more mafic, mineral-rich basaltic inclusions found preferentially in the vicinity of the cataclastic zone. However, these xenoliths are not restricted to that zone but are also found in the interior of the pluton.

Most xenoliths are not zoned macroscopically in their textures or mineralogy with proximity to the granite contact. Individual outcrops show a variety of sizes and shapes ranging from small (1 - 2 cm) and circular, to large (up to 0.7 m) inclusions characterized by lensoidal cross sections.

Mineral chemistry

Preliminary studies of the mineral chemistry in the mafic xenoliths (quartz diorite group) determined with the electron probe show that the composition of the mafic minerals are distinguishable from those in the host rock (Ayuso, Chapter 1, this study). This refers especially to biotite and to a less degree to amphibole (Table 4). In contrast, the composition of plagioclase exhibits similar ranges (An_{45} to An_{20}) as those documented in the Passadumkeag River granite (Table 4).

Biotite in the mafic xenoliths is consistently higher in Al but lower in Ti and alkalies (?) compared to biotite in the host rocks. Both groups of biotite, however, show similar $Fe/(Fe + Mg)$ ratios. Production of liquids enriched in Ti and alkalies is expected if the xenoliths represent residual material that underwent incongruent melting of biotite. In migmatitic areas such melting produces a granitic liquid enriched in K, Ti, Fe, and Rb (Martin, 1979). Reaction of titan-phlogopite was suggested to account for the enrichment of K and Ti in orogenic magmas (Forbes and Flower, 1974), and for Ti in highly potassic liquids (Edgar *et al.*, 1976).

Amphibole mimics the compositional change in biotite and supports the change toward higher Ti, Fe, and alkalies, but lower Mg in amphibole

of the granite coexisting with the xenolith (Table 4, 6). The higher Ti and alkalies in amphibole and biotite of the granites is generally in agreement with the proposition of Forbes and Flower (1974) that higher Ti is correlated with higher pressures. Thus, despite reequilibration between the xenoliths and granites, a tentative suggestion can be made regarding the higher P and T recorded in the xenoliths.

ESTIMATE OF INTENSIVE PARAMETERS DURING CRYSTALLIZATION

Estimate of pressure

A combination of textural, chemical and geologic observations may be used to place constraints on P, T, and oxygen fugacity during the crystallization of the Bottle Lake Complex. Among the most difficult parameters to estimate is total pressure. Plutons of the Bottle Lake Complex intruded country rock in the lower greenschist facies, almost certainly within the stability field of andalusite. Ludman (1978) observed only andalusite in metamorphic rocks in the area to the northeast, contiguous to the BLC. Depending on the choice of equilibrium curves, maximum pressure based on andalusite stability range from about 3.5 kb (Holdaway, 1971) to about 5.5 kb (Richardson et al., 1971). Rast and Lutes (1979) estimated a pressure range of 1.5 to 3 kb at the contact of the Pokiok-Skiff Lake granite immediately to the northeast of the BLC through the coexistence of garnet-cordierite-andalusite-biotite assemblages. Similarly, the existence of garnet-cordierite-biotite assemblages in the country rock intruded by the BLC suggest a pressure interval of 1.5 to 4.5 kb (Hess, 1969).

TABLE 6. Electron microprobe analyses* of hornblende, biotite, plagioclase, and biotite from the mafic xenoliths (quartz diorite) in the Bottle Lake Complex

	Hornblende			Biotite		Plagioclase		Apatite	
	1 ^a	2 ^b	3 ^c	4 ^a	5 ^c	6 ^a	7 ^c	8 ^a	9 ^c
SiO ₂	44.24	44.16	44.07	36.19	36.54	61.49	61.02	0.52	0.23
Al ₂ O ₃	7.91	7.78	8.63	14.34	12.99	23.91	24.08	0	0
TiO ₂	0.97	1.75	1.95	3.88	4.36	0.16	0.14	0.03	0.06
FeO [†]	22.51	22.85	23.46	23.84	25.69	0.30	0.18	0.31	0.46
MgO	7.85	6.86	6.72	7.71	7.28	0.04	0.02	0.03	0.06
MnO	0.79	0.92	0.84	0.53	0.48	0.01	0.01	0.14	0.12
CaO	11.62	10.98	10.96	0.09	0.08	5.58	5.92	55.75	55.58
Na ₂ O	1.17	1.62	1.68	0.03	0.24	8.27	8.09	0	0
K ₂ O	0.85	1.11	1.15	9.67	9.54	9.22	0.22	0.06	0.11
BaO	ND	0.16	0.06						
F	ND	2.98	3.39						
Cl	ND	0.01	0						
P ₂ O ₅	ND	40.13	39.09						
TOTAL	97.91	98.03	99.46	96.28	97.20	99.98	99.68	99.81	99.16

* Hornblende (columns 1-3), biotite (columns 4-5) and plagioclase (columns 6-7) from sample 75C; apatite (columns 8-9) from sample 81C.

† Total iron as FeO.

^a Near center of mafic xenolith.

^b Rim of xenolith.

^c In granite matrix.

ND Not Determined.

Rast and Lutes (1979) cite the estimate by Garland (1953) of about 2 kb for the maximum thickness of cover north of the BLC. This is also consistent with the indication of 2 kb for the emplacement of the granite of Center Pond (Scambos, 1980) immediately west of the Complex.

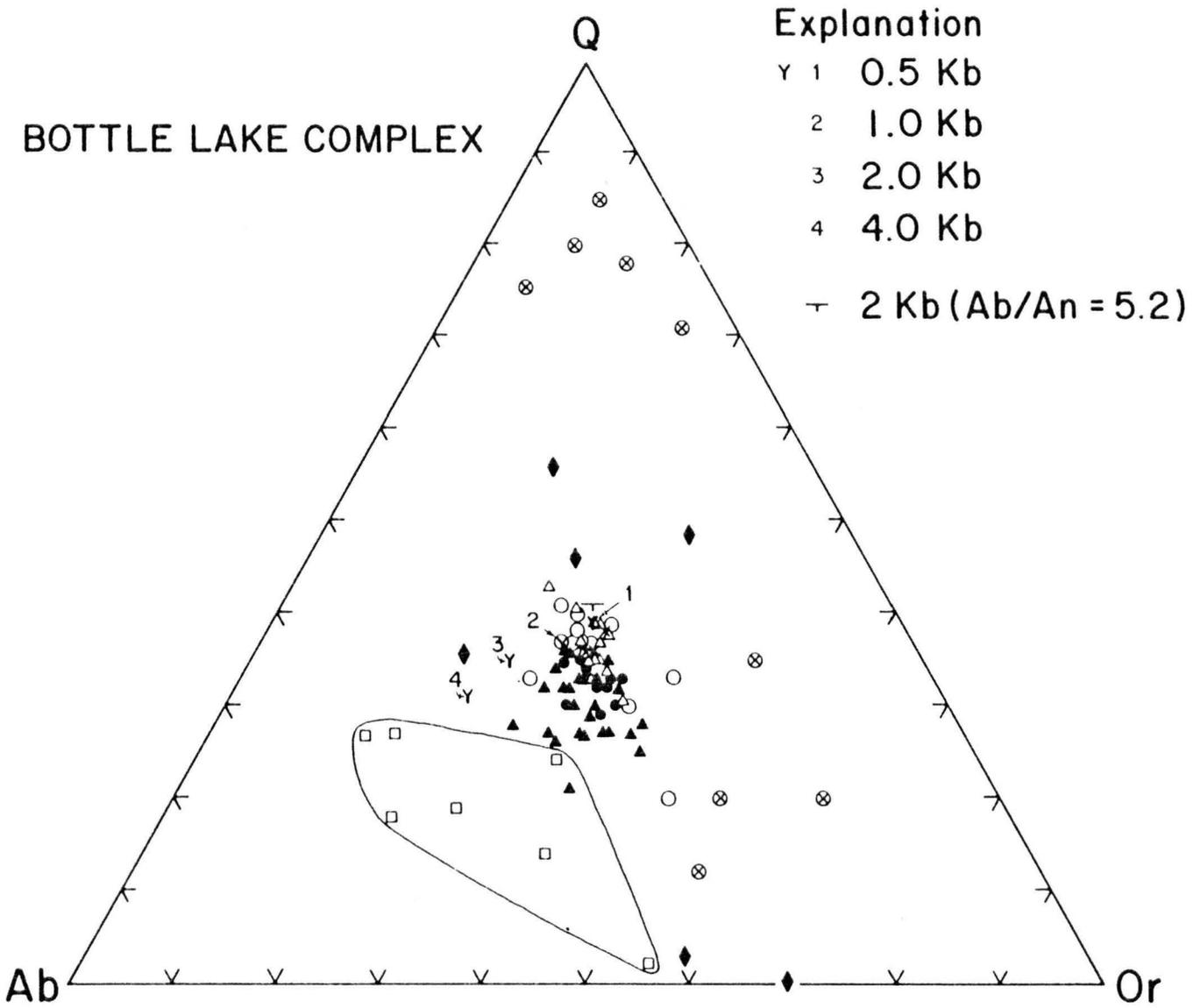
Finally, because felsic minerals precipitated through much of the crystallization sequence, and because of the small number of aplites, pegmatites, and miarolitic cavities in the BLC, the only rocks equivalent to the synthetic Q-Ab-Or-An-H₂O system (Tuttle and Bowen, 1958; Luth, 1969; James and Hamilton, 1969) are the most evolved units. These yield an estimate of pressure during emplacement. On the basis of such analysis, and assuming the $P(H_2O) = P(T)$, a range between 1.5 and 2.5 kb probably existed during emplacement of the BLC (Fig. 7). Assuming that $P(H_2O) = P(T) = 2$ kb and that the ratio of normative Ab/An = 5.2 in the rock, then a temperature of 685°C is estimated from the experimental data for granite minimum melts of von Platen (1965).

Estimate of water content

An estimate water content can be established by comparing the order of crystallization with granodiorite experimental systems obtained by Naney (1978) in conjunction with experimental systems documenting the paragenetic sequence of mafic phases in K₂O-rich magmas (Wones and Dodge, 1977). Early crystallization of euhedral hornblende together with euhedral biotite imposes minimum water contents on these granitic magmas. For relatively high water activity, amphibole precedes phlogopite in the crystallization sequence. Such a sequence is present in the Passadumkeag River pluton supporting the suggestion that water activity was relatively high in this granite.

FIGURE 7.

Normative quartz-albite-orthoclase (Q-Ab-Or) diagram of rocks of the Bottle Lake Complex. Symbols are as follows: Whitney Cove, rim (open circles), core (filled circles) facies; Passadumkeag River, rim (open triangles), core (closed triangles) facies; mafic xenoliths (open squares); country rock xenoliths (closed diamonds); country rocks (circles with crosses). Experimentally derived minima (Tuttle and Bowen, 1958; Luth et al, 1964; Luth, 1969; James and Hamilton, 1969). At 2 kb and using $Ab/An = 5.2$, data is from Von Platen (1975).



Comparison of the mineralogy and order of crystallization observed in the Passadumkeag River granite with pertinent systems studied by Naney (1978) suggests that water saturation occurred only in the latest stages. Water content probably never exceeded 4 wt. %. The order of crystallization established for the Whitney Cove pluton also limits the water content of the magma. In it, vapor saturation occurred relatively late but at an earlier stage than in the Passadumkeag River pluton, after the hornblende temperature stability was exceeded. This pluton probably never exceeded a maximum water content of 5 wt. %. Prominent alkali feldspar megacrysts are present in the core facies of this pluton because they grew faster than plagioclase and quartz (Swanson, 1977). This happened relatively late in the sequence as a result of the undersaturated conditions (Fenn, 1973).

Estimate of T, $f(\text{O}_2)$, $f(\text{H}_2\text{O})$

Although temperature of crystallization may be estimated from the equilibrium distribution of the Ab molecule in coexisting plagioclase and alkali feldspar, this approach is not useful in the case of the BLC as a result of substantial feldspar reequilibration. Sanidization of alkali feldspar and use of powder diffraction techniques (Wright, 1968; Wright and Stewart, 1968) suggest that the bulk composition is in the range Or_{85} to Or_{98} . Application of the feldspar geothermometer (Stormer, 1975) yields a large spread in temperature from 450 to 800°C with most estimates clustered closer to 450-550°C. These temperatures are lower than estimated for a minimum melt at 2 kb (685°C) and reflect the high potassium content of the alkali feldspar. Also, secondary

processes probably affected the geothermometer and resulted in the formation of clay minerals in many feldspar cores, and in the conversion of the mafic phases to chlorite.

Examination of coexisting oxides provide a way of simultaneously estimating $f(O_2)$ and T. Unfortunately, such estimates also yield unrealistically low temperatures (400-500°C?) of equilibration. The composition of ilmenite is enriched in MnO, and as suggested by Czamanske and Mihalik (1972), such ilmenite may not be strictly tractable by the Buddington and Lindsley (1964) scheme. Despite the coexistence of magnetite and ilmenite, the use of the geothermometer yields temperatures probably reflecting secondary processes.

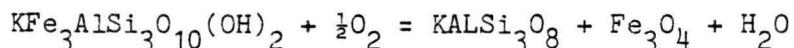
The modal abundance of magnetite and ilmenite in the BLC in a number of areas displays significant variation. In some cases either magnetite or ilmenite is dominant in a sample to the exclusion of the other phase. In at least one sample (94R) in the Whitney Cove pluton inclusions within plagioclase were exclusively ilmenite, while magnetite predominated in the matrix. Within the core of the Passadumkeag River pluton, many samples showed the dominance of ilmenite compared to magnetite and were strikingly in contrast with nearby rocks showing subequal amounts of both phases. As a result of the coarse-grained nature of the granites, however, several samples are usually needed to document significant modal variation in these rocks.

The coexistence of sphene and magnetite in the BLC, essentially throughout its crystallization history, suggests minimum $f(O_2)$ during the evolution of the batholith. Wones (1966) suggested that this equilibrium lies at slightly higher oxygen fugacities than the Ni-NiO

buffer curve (Huebner and Sato, 1970). Because primary hematite is absent, the $\text{Fe}_3\text{O}_4\text{-Fe}_2\text{O}_3$ buffer curve (Eugster and Wones, 1962; Chou, 1978) provides an estimate of the maximum oxygen fugacity during crystallization.

Secondary sphene rims around granular ilmenite and growth of aligned opaques (magnetite and ilmenite) in biotite suggest subsolidus or late changes in oxygen fugacity. These features are common in the Whitney Cove pluton and are also present in the granite of Passadumkeag River. Feathery intergrowths of biotite, ilmenite, magnetite, and extremely fine-grained felsic phases also attest to the effect of secondary changes late in the crystallization history.

The oxidation-dehydration reaction:



can be used to estimate T, $f(\text{H}_2\text{O})$ and $f(\text{O}_2)$ (Wones and Eugster, 1965; Wones, 1972). The most recent description of the curve relating that assemblage is given by:

$$\log f(\text{H}_2\text{O}) = \frac{4819}{T} + 6.69 + 3 \log X_{\text{annite}} - \log a_s -$$

$$\log a_m + \frac{1}{2} \log f(\text{O}_2) - \frac{0.011 (P - 1)}{T}$$

determined by D. A. Hewitt (personal communication, 1980), where X_{annite} is the mole fraction of Fe in octahedral coordination in biotite. The activity of sanidine in the feldspar solid solution (a_s) is assumed to be about 0.6 (Waldbaum and Thompson, 1969), as expected from magmatic compositions prior to the onset of secondary processes resulting in

feldspar reequilibration. The activity of magnetite (a_m) is unity because this phase is nearly pure. Values of $f(\text{H}_2\text{O})$ are from Burnham et al. (1969).

Biotites in the BLC evolved under relatively high $f(\text{O}_2)$ conditions and did not coexist with primary hematite. Nevertheless, the amount of Fe^{3+} in these biotites is unknown and this could considerably extend their calculated stabilities (Wones, 1972). In the same manner, the substitution of F^- or O^{2-} for OH^- as suggested by Czamanske and Wones (1973) may lower the activity of annite and thus increase the stability of biotite. Similar effects may result from the effects of Ti (Robert, 1976) and Al (Rutherford, 1973).

Curves relating oxygen fugacity to temperature may be generated by knowing the composition of the coexisting phases and assuming constant fugacities of H_2O . These curves constrain $f(\text{O}_2)$ and T when plotted against estimates of $f(\text{O}_2)$ made from examination of coexisting assemblages (sphene + magnetite + quartz) and from the stability curves of coexisting oxides (Buddington and Lindsley, 1964). Using this method, the intersection of the average biotite stability curve for each facies and appropriate oxide or buffer curve limits the maximum T and $f(\text{O}_2)$ for that facies at the chosen $f(\text{H}_2\text{O})$.

Biotite stability curves (Fig 8a) show the range of $f(\text{O}_2)$ - T variation found in the Complex. Their intersection with the Ni-NiO buffer curve provides only upper temperature limits because the Fe^{3+} content of the biotite is unknown. Temperatures from 720 to 780°C are indicated, but the range may be lower for oxygen fugacities higher than Ni-NiO and more representative of the assemblage magnetite and sphene.

Typical samples from the core (44C) and rim (41R) facies of the Whitney Cove pluton are separated by almost 1 log unit of $f(\text{O}_2)$. Judged on this basis, higher temperature and $f(\text{O}_2)$ conditions apparently describe the core facies of this pluton in comparison to the rim.

The two representative samples of the Passadumkeag River show that the core (78C) and rim (80R) facies have an equivalent $f(\text{O}_2)$ - T interval. However, the values of $f(\text{O}_2)$ differ between the core samples (78C, 79C) of the Passadumkeag River granite and thus probably indicate that differences are still recorded within single facies.

The variation in $f(\text{O}_2)$ in the Bottle Lake Complex, probably reflects processes or the oxidation conditions of the source materials. Although the Whitney Cove pluton has a larger range in $f(\text{O}_2)$ than the Passadumkeag River granite, the two plutons show a large degree of overlap. Core samples of the Whitney Cove pluton indicated the highest temperature (780°C) while the rim facies showed the lowest (725°C). Core facies samples of the Passadumkeag River pluton show an interval of maximum temperature from 720 to 740°C . However, given the range and variation in $\text{Fe}/(\text{Fe} + \text{Mg})$ of biotite within each facies, together with the assumptions inherent in the calculation of the biotite stabilities, this discrepancy is probably insignificant.

The $f(\text{H}_2\text{O})$ - T relations can be estimated through the use of the biotite stability curves, and the granite minimum melting curve (Tuttle and Bowen, 1958). An approximate range in $f(\text{H}_2\text{O})$ from 760 to 1250 bars, and T from 715 to 750°C is estimated from Fig. 8b. This fugacity corresponds to a pressure ranging from 1 to 1.8 kb (Burhnam *et al.*, 1969). The lowest $f(\text{H}_2\text{O})$ and highest temperature are present in the

core sample of the Whitney Cove pluton, while the highest $f(\text{H}_2\text{O})$ and lowest temperature was obtained from the core of the Passadumkeag River granite.

AGE RELATIONS

The relative age of emplacement within the Bottle Lake Complex can be established by mapping lithologic types singular to each pluton so as to recognize any cross-cutting relations (Ayuso, 1979). Additionally, geochronologic studies employing zircon U-Pb and whole-rock Pb-Pb methods place additional age constraints on the field determined sequence of intrusion.

Relative Age of Emplacement

The Whitney Cove pluton intrudes rocks as young as Siluro-Devonian but it is cut by a trace of the Norumbega fault system (Wones and Thompson, 1979). Because the fault disturbs Pennsylvanian sediments (Wones and Stewart, 1976), emplacement of the Whitney Cove pluton is bracketed between Silurian-Devonian to Pennsylvanian in age.

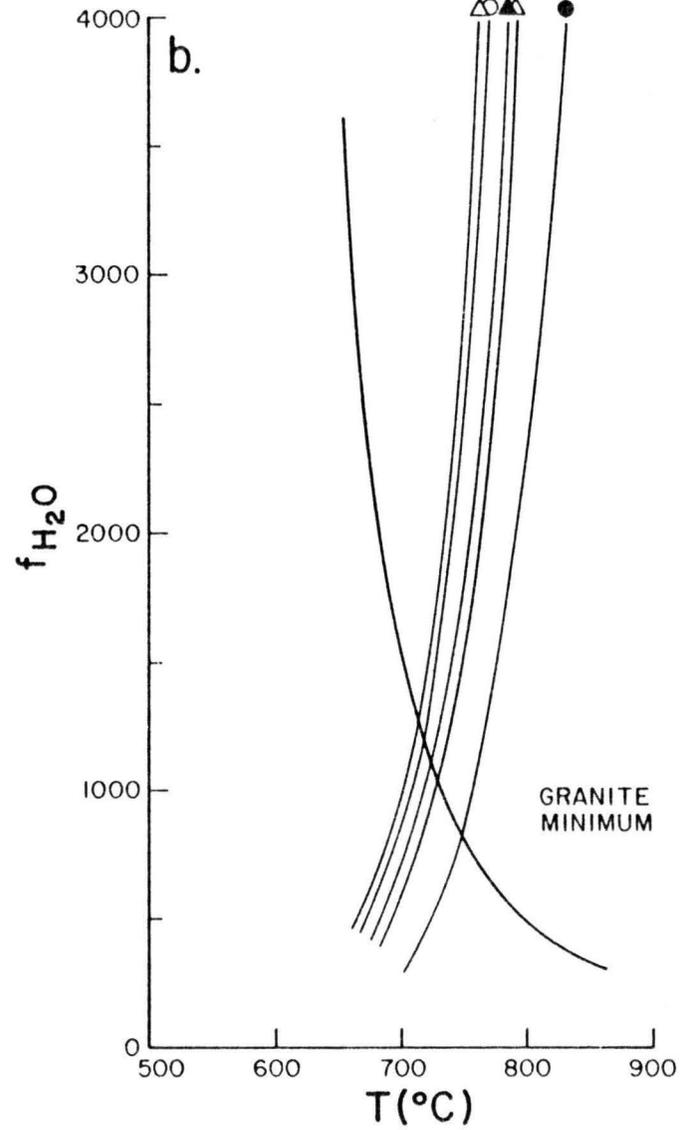
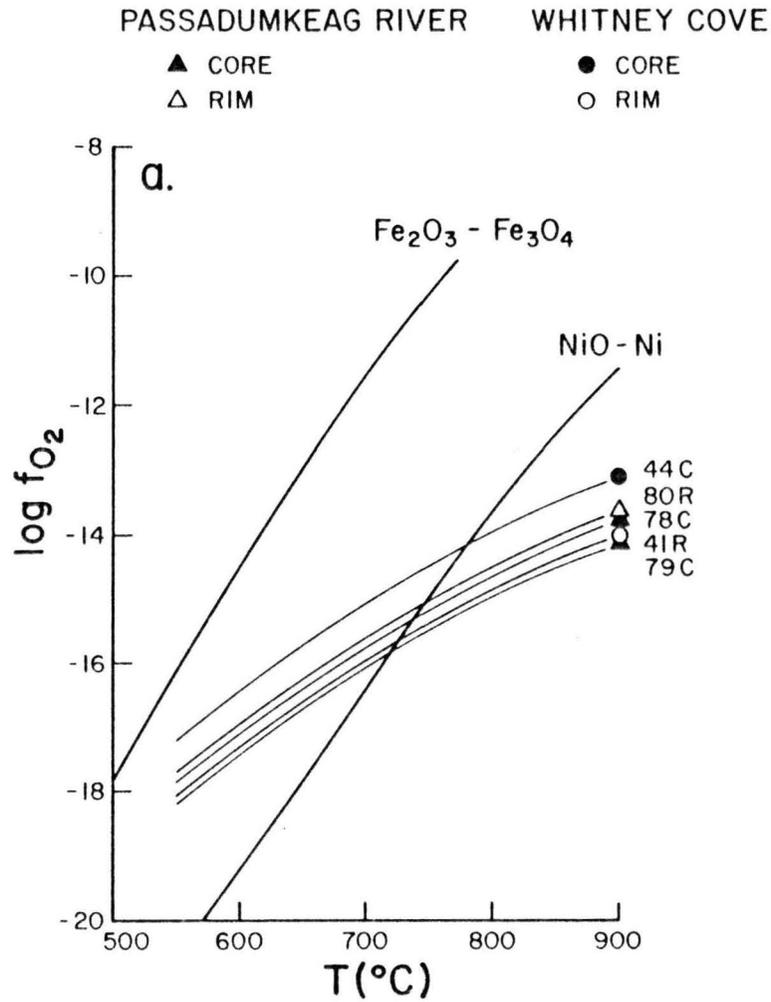
The trace of the fault cutting through the main mass of the Whitney Cove pluton is interrupted by rocks typical of the Passadumkeag River granite. Despite the unknown age of this fault, its presence places the sequence of emplacement in perspective and suggests that the emplacement of the Whitney Cove pluton was followed by the granite of Passadumkeag River. Also, in agreement with such a sequence are the field observations which suggest that the trace and areal extent of lithologic types characteristic of the Passadumkeag River pluton are superimposed on rocks typical of the older granite (Fig. 1).

FIGURE 8.

Biotite from the Bottle Lake Complex;

- A. Whitney Cove and Passadumkeag River biotite plotted on an $f(\text{O}_2)$ - T plot with reference buffer data.
- B. Calculated stabilities of biotite from the Bottle Lake Complex and the Q-Ab-Or minimum melting curve (Tuttle and Bowen, 1958) plotted on an $f(\text{H}_2\text{O})$ - T diagram.

BOTTLE LAKE COMPLEX



Previous Geochronologic Work

The Bottle Lake Complex was dated by Faul et al. (1963) using Pb-alpha and K-Ar techniques. Samples from the granite of Whitney Cove resulted in a range of ages from 370 (Pb-alpha) to 380 m.y. (K-Ar), while those from the Passadumkeag River pluton yielded a spread from 342 to 410 m.y. Because of the variability and inconsistency between the two methods, the age of the Complex remained unknown.

Geochronology and isotopic studies

Sampling

Of five samples dated by U-Pb using zircon separates one from the pluton of Whitney Cove, and four from the Passadumkeag River granite. The latter consisted of three samples from the granitic rocks and one from a mafic xenolith (quartz diorite).

U-Pb geochronology

The isotopic composition (Table 7) and morphology of the analyzed zircons provide important clues concerning the sources of the Bottle Lake Complex as well as the age of emplacement of each pluton. In fact, one of the most critical observations is the existence of at least two zircon populations in the Bottle Lake Complex. The fractions analyzed in the Whitney Cove pluton are dominated by light brown translucent zircons, subhedral to euhedral in habit. Detrital cores, pits and frosting were absent although some of the grains enclosed tiny dark

TABLE 7. U and Pb isotopic compositions, concentrations, and ages of the granitic rocks of the Bottle Lake Complex, Maine.

Sample (mesh size)	Concentration (ppm)		Atom (percent)			Age (m. y.)		
	U	Pb	^{204}Pb	^{206}Pb	^{207}Pb	$\frac{^{206}\text{Pb}}{^{238}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
Mafic xenolith in granite of Passadumkeag River								
66M (100-200)	1041.9	58.15	0.0354	80.90	4.92	320	335	390
66M (325)	983.2	60.48	0.0294	78.01	4.70	387	386	399
66M (200-325)	969.8	57.71	0.0229	79.53	4.65	335	348	382
Granite of Passadumkeag River								
8R (100-200)	796.8	43.12	0.0095	84.27	4.72	324	335	384
8R (200-325)	833.5	46.21	0.0076	82.59	4.64	326	343	404
9C (100-200)	1902.7	86.71	0.0061	85.45	4.71	278	295	372
10R (100-200)	1579.9	55.84	0.0111	82.80	4.66	210	230	385
Granite of Whitney Cove								
47R (100-200)	1060.5	59.99	0.0371	84.20	5.14	336	351	395
47R (200-325)	2223.0	70.86	0.0312	84.56	5.08	193	214	400
97R (150-250) ^a	1864.0	114.6	0.0412	85.45	5.268	379	381	397
97R (250-325) ^b	2019.0	126.5	0.0714	83.88	5.639	377	380	404

^{a, b} Analyzed by Zartman and Gallego (1979)

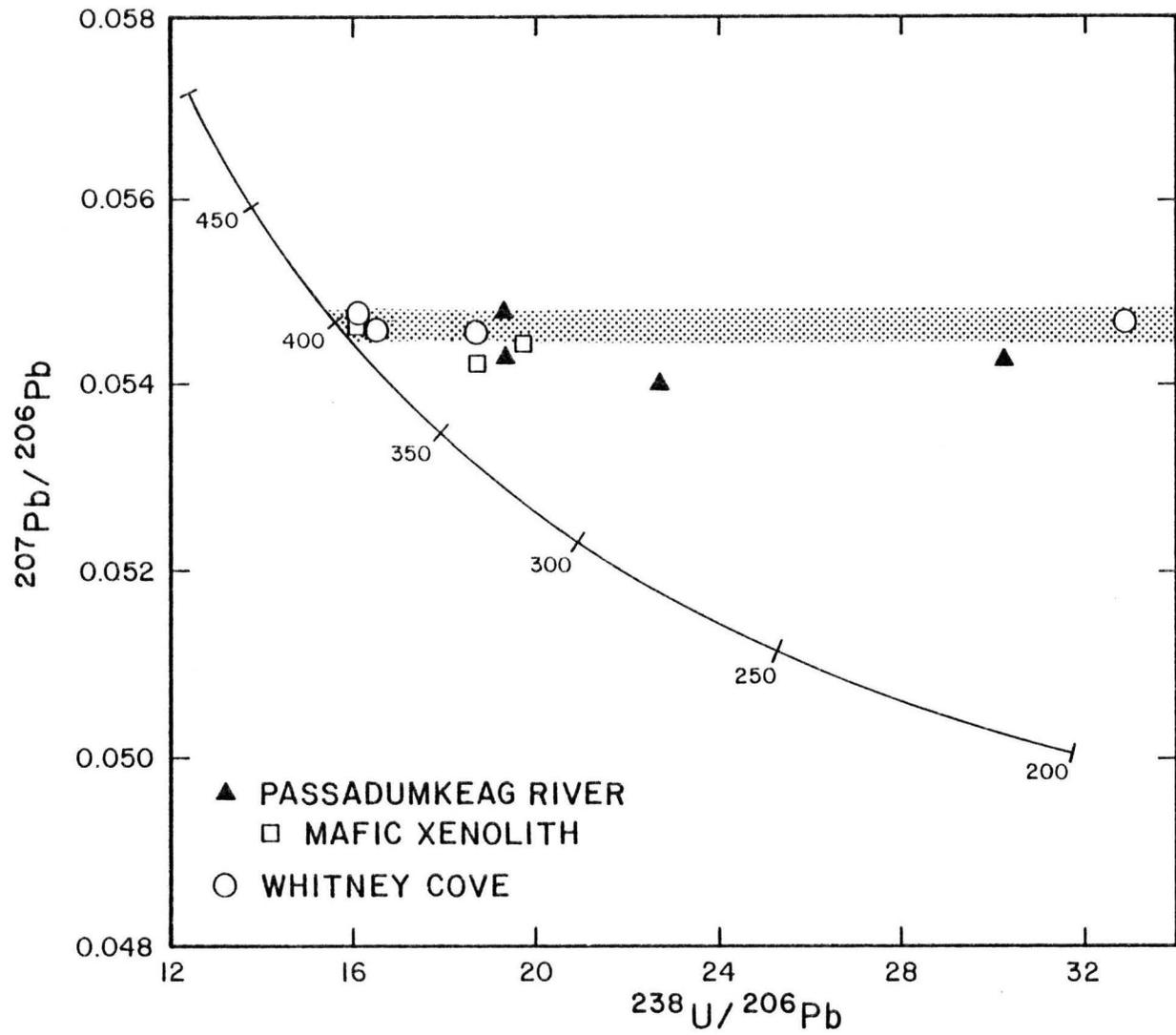
inclusions. This population was clearly the most abundant fraction in the most silicic rocks represented by sample 97R (Topsfield facies). However, zircons from less silicic (47R) rocks (rim facies) of the Whitney Cove pluton progressively contain more of the euhedral population, which attain their highest abundance in the least silicic samples from the core facies of the pluton. Zircon fractions from the interior of the pluton were characterized by heterogeneity in morphology and color.

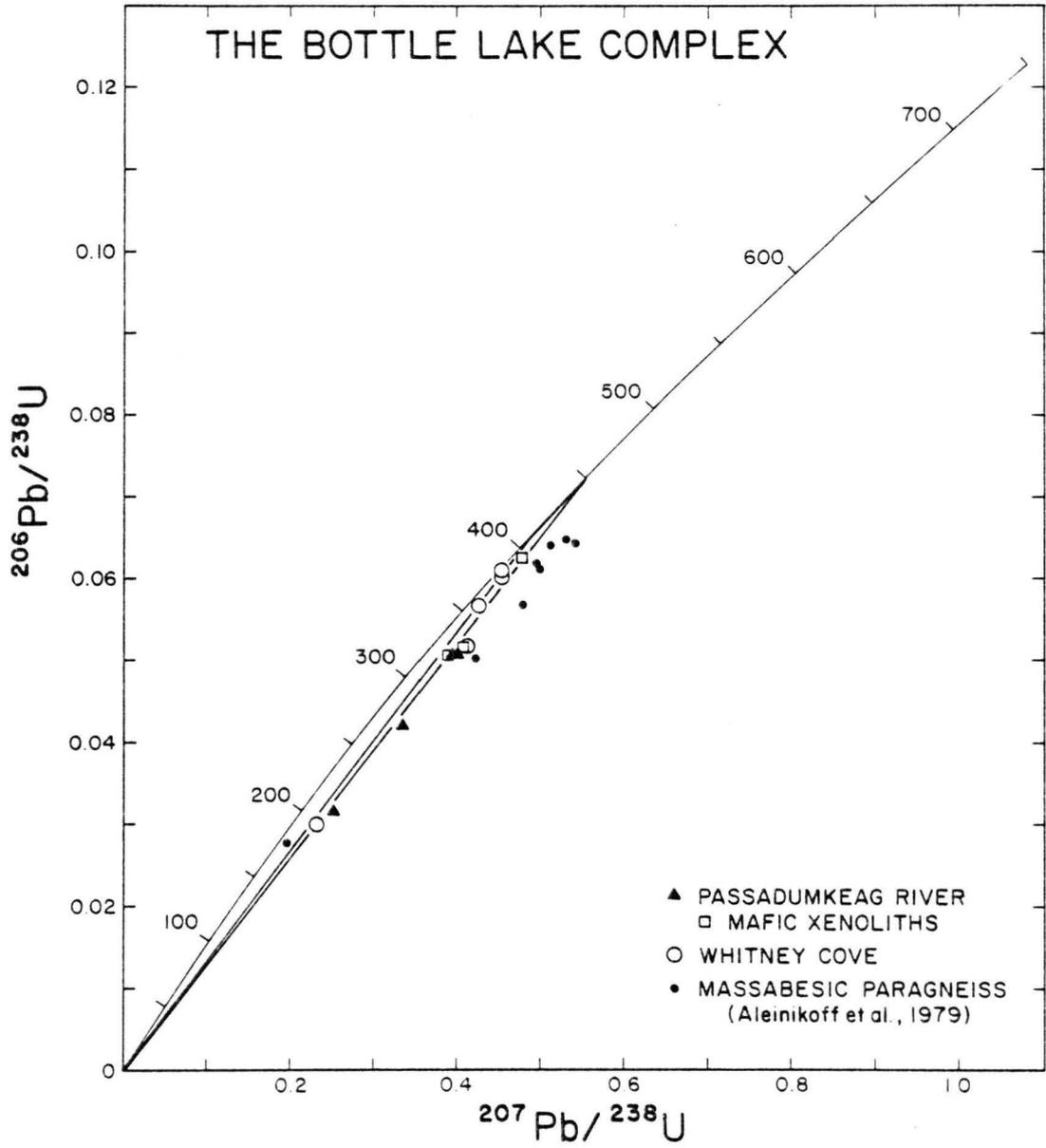
A similar trend from a nearly homogeneous light brown zircon population to another consisting essentially only of the dark brown fraction is present in the granite of Passadumkeag River. In sample 8R, the most silicic sample (rim facies) analyzed the zircons are predominantly represented by light brown. In contrast, sample 9C (core facies) consists almost entirely of dark brown, euhedral zircon with occasional light brown grains. Zircons from a mafic xenolith (sample 66M) belong to the least silicic sample analyzed, but contain more of the light brown zircon population than sample 8R (rim facies).

Results from this study are tabulated in Table 7 and plotted on Fig. 9. They show that U-Pb ages are grossly discordant for the Bottle Lake Complex as a whole. However, a restricted range of Pb-Pb ages is present, especially in the case of the Whitney Cove pluton. Analysis of sample 97R (Topsfield facies) yielded a concordant age of 400 ± 4 m.y. (Zartman and Gallego, 1979). Additional determinations on less silicic samples from the main mass of the pluton of Whitney Cove show a restricted range in Pb-Pb ages from 395 m.y. to 400 m.y. The total spread in Pb-Pb ages for the Whitney Cove granite extends from 395 m.y.

FIGURE 9.

- 9A. Modified concordia diagram showing the isotopic composition of zircons in the Bottle Lake Complex.
- 9B. Concordia diagram for the Bottle Lake Complex.





to 404 m.y. This is shown as an elongated band on a modified concordia (Tera and Wasserburg, 1972) diagram (Fig. 9a). Such a diagram emphasizes the Pb-Pb age and minimizes the effect of secondary processes on U-Pb ages. Because Pb-Pb ages are independent of a radioactive parent, the intersection of the band with the growth curve is presumed to represent the last resetting of the system. This intersection corresponds to about 398 ± 8 m.y. and represents the age of the Whitney Cove pluton.

Samples from the granite of Passadumkeag River have Pb-Pb ages which range from 372 m.y. to 404 m.y. (Table 7, Fig. 9a). Three of the four analyzed fractions have younger Pb-Pb ages than the Whitney Cove samples. However, the oldest age of this pluton is identical to the oldest age obtained in the Whitney Cove pluton. The spread in ages within the Passadumkeag River granite is directly correlated to the abundance of the dark brown zircon population. The youngest Pb-Pb age in sample 9C corresponds to the highest abundance of dark brown euhedral zircons and the least silicic sample, while the oldest age was obtained from sample 8R which represents the most silicic rock dominated by light brown zircons. Because the oldest Pb-Pb age of this pluton (404 m.y.) is similar to that of Whitney Cove, no clear age difference can be strictly postulated. However, the intersection of the band in Fig. 7a suggests that the age of the Passadumkeag River pluton may be slightly younger than the granite of Whitney Cove.

The three fractions analyzed from a mafic xenolith have Pb-Pb ages ranging from 382 to 399 m.y. which are generally similar to the ages of the granitic host (Table 7, Fig. 9a). The ratio of the abundance

between the two zircon populations in the xenolith suggest that both fractions are represented in subequal amounts.

Examination of the U-Pb isotopic composition plotted on a concordia diagram (Fig. 9b) shows the complex history of these zircons. The spread in the Pb-Pb ages probably does not represent episodic (Wetherill, 1956) nor diffusional (Nicolaysen, 1957; Tilton, 1960; Wasserburg, 1963) processes, because zircons from each pluton show a great range in their upper intercepts with concordia. More complex models assuming superposition of more than one lead loss event (Allegre et al., 1974; Gebauer and Grunenfelder, 1979) are adequate to explain the spread in ages.

The Pb-Pb ages of the granites suggest an event at about 400 m.y. This event probably represents the age of the plutons. A modern event resulting in lead loss from dilatancy (Goldich and Mudrey, 1972) during crustal uplift after much of the lead isotopic evolution had taken place is considered to represent this intercept with concordia at 0 m.y. In this manner, an envelope containing the lead isotopic composition of the Bottle Lake Complex is constructed. The intercepts with concordia are at 0 m.y., 400 m.y., and about 450 m.y. These represent the most significant events recorded by the zircon populations.

The intercept at about 450 m.y. suggests that the zircons of the Bottle Lake Complex contain evidence of an older basement. A similar but older (646 m.y.) basement (Massabesic paragneiss) in the core of the Merrimack synclinorium in New Hampshire was previously identified in the zircon isotopic work of Aleinikoff et al. (1979). This older basement possibly represents the source of the dark brown population of

zircons. Following partial melting of this source at about 400 m.y., light brown zircon recrystallized and resulted in an array of isotopic compositions from 400 to about 525 m.y. These remained undisturbed until modern lead loss from a combination of dilatancy (Goldich and Mudrey, 1972) and low temperature annealing (Gebauer and Grunenfelder, 1976) effects.

Whole rock and feldspar lead

Lead isotopic compositions can be used as tracers of the continental crust (see for example Doe, 1970; Doe and Delevaux, 1973; Doe and Zartman, 1979; Allegre and Othman, 1980).

The lead isotopic composition of the Complex is shown on Fig. 10 and Table 8. The spread confirms the complicated history suggested by the zircon studies, and suggests that other processes apart from fractionation must be present. This is the case because crystallization in a closed system is unable to account for isotopic fractionation (Taylor, 1968).

The Pb isotopic composition of these granites suggests sources consisting of varying ratios of $^{238}\text{U}/^{204}\text{Pb}$ ($^{238}\text{U}/^{204}\text{Pb}$). Plotted in respect to the Stacey and Kramers (1975) two stage growth reference line, the isotopic data from the Complex is clustered above a $^{238}\text{U}/^{204}\text{Pb} = 9.74$ intersecting the 400 m.y. isochron at about $^{238}\text{U}/^{204}\text{Pb} = 10.0$. Neither the age of the source nor the age of emplacement is easily interpretable from this data.

Within the Bottle Lake Complex, the Passadumkeag River granite is recognized by its extreme heterogeneity in composition ($^{206}\text{Pb}/^{204}\text{Pb}$:

FIGURE 10.

Whole rock and feldspar isotopic composition of lead in the Bottle Lake Complex and country rock. The Center Pond pluton is also shown. Average orogene and upper continental crust curves are from Doe and Zartman (1979).

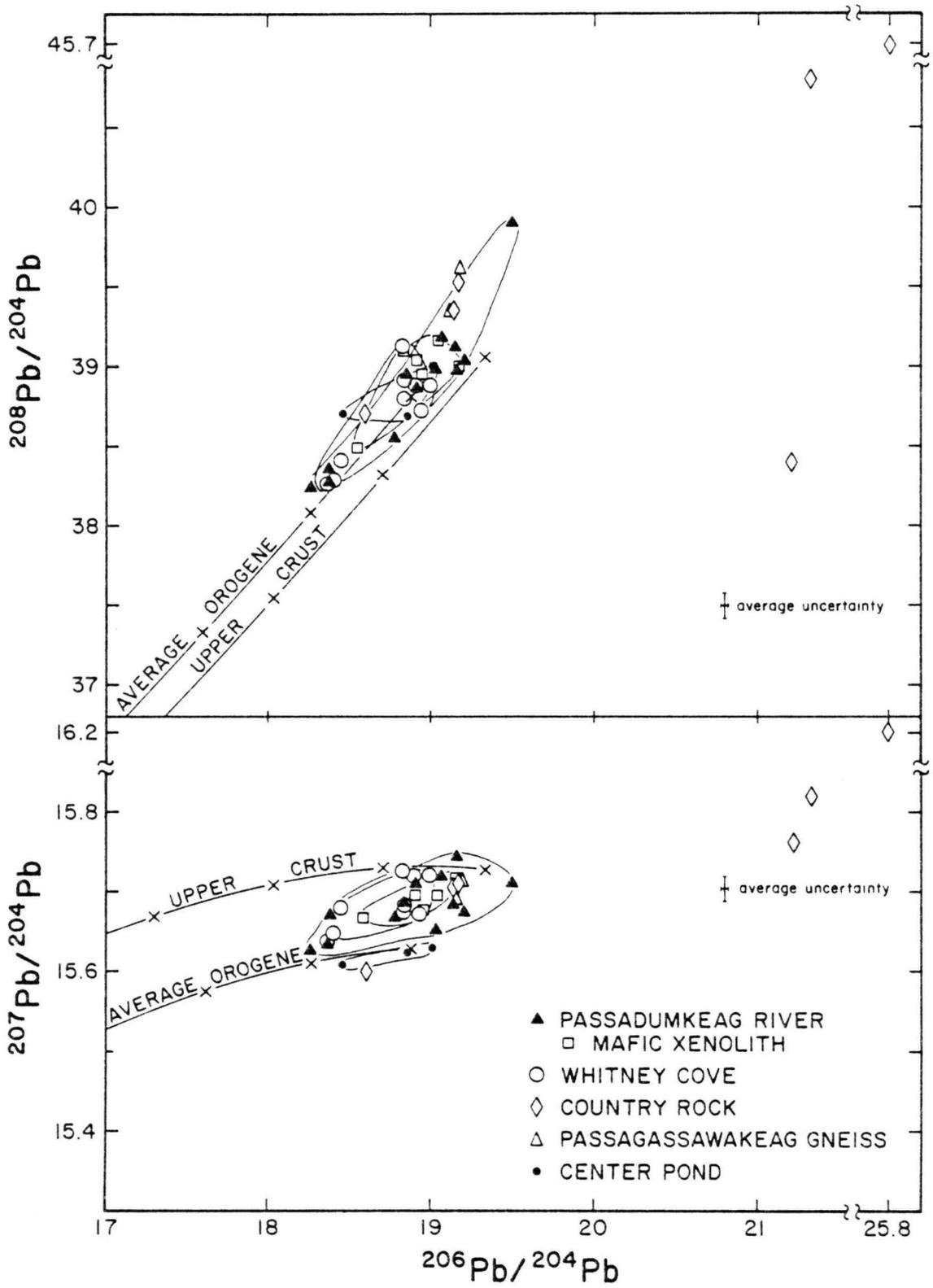


TABLE 8. Lead isotopic ratios and concentration of lead and uranium in the whole rocks and feldspar of the Bottle Lake Complex and its country rock*

Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$	Pb ppm	U ppm
PASSADUMKEAG RIVER					
35C	19.034 (18.426)	15.654 (15.621)	39.985	14.1	1.8
34C	19.160 (18.025)	15.746 (15.686)	38.983	15.3	3.6
36C	19.149	15.686	39.134		
10C	19.065 (18.295)	15.720 (15.678)	39.185	21.2	3.0
29C	18.912	15.708	38.866		
32C	18.841 (18.403)	15.686 (15.662)	38.951	17.2	1.6
66C	19.210	15.676	39.041		
8R	18.779	15.666	38.563		
86C	18.381	15.672	38.367		
FS9C	18.271	15.629	38.245		
9C	19.504	15.712	39.901		
FS105C	18.375	15.638	38.269		
MAFIC XENOLITHS					
65M	18.596 (18.311)	15.672 (15.656)	38.515	28.5	1.7
64M	18.842 (18.289)	15.683 (15.653)	39.108	14.5	1.7
66M	19.175	15.697	39.003		
62M	18.952 (18.335)	15.678 (15.644)	38.957	8.0	1.0
63M	19.047 (18.515)	15.696 (15.667)	39.174	19.8	1.8
61M	18.921	15.703	39.053		
WHITNEY COVE					
58C	18.827	15.726	39.130		
60C	18.842 (18.417)	15.682 (15.659)	38.810	30.1	2.6
FS37C	18.344	15.658	38.277		
47R	18.897 (18.660)	15.722 (15.709)	38.892	31.0	1.5
FS94R	18.454	15.682	38.423		
57R	18.833 (18.633)	15.687 (15.676)	38.924	22.9	1.0
49C	18.406	15.648	38.294		
37C	18.938	15.672	38.730		
COUNTRY ROCK					
103	21.315 (18.372)	15.822 (15.661)	40.799	5.1	2.9
102	21.220	15.763	38.417		
101	18.614	15.603	38.734		
100	25.788	16.247	45.705		
PAS2 ^a	19.182 (18.306)	15.715 (15.667)	39.622	23.1	4.2
PAS1 ^b	19.145 (18.923)	15.686 (15.674)	39.351	18.3	0.7

a, b Samples of the Passagassawakeag gneiss representing the closest possible Precambrian basement.

* Corrected values assuming t = 400 m.y. are shown in parentheses.

18.3 to 19.5) compared to Whitney Cove ($^{206}\text{Pb}/^{204}\text{Pb}$: 18.2 to 19.1). However, the scatter of the data is arranged about a line of similar slope regardless of pluton. This scatter is also present in the mafic xenoliths, although to a lesser degree. Together with the Whitney Cove pluton, the mafic xenoliths are enclosed by the isotopic spread of the Passadumkeag River granite.

The lead evolution diagram (Fig. 10) also shows the nearby Center Pond pluton and emphasized the closeness in isotopic composition of the granites intruding the core of the Merrimack synclinorium. All show the same slope but in the case of the Center Pond pluton, regression through the data intersects the curve of Stacey and Kramers ($^{238}\text{U}/^{204}\text{Pb} = 9.74$) at about 400 m.y.

Comparison of this data with the isotopic fields characteristic of many different environments which are generally characterized by heterogeneous isotopic composition. As suggested by Doe and Zartman(1979), continental arcs show a larger contribution from cratonic sources leading to isotopic compositions with higher $^{207}\text{Pb}/^{204}\text{Pb}$ values. The range in the isotopic composition of the plutons emplaced in the core of the Merrimack agree with the suggestion that involvement of cratonized Precambrian sources was minimal or absent.

WHOLE ROCK CHEMISTRY - MAJOR OXIDES

The Granite of Whitney Cove

Consistent differences in major element abundances exist between the core and rim facies of this pluton (Fig. 7, 11, Table 9). Oxides associated with higher temperature minerals namely CaO , MgO , Fe_2O_3 ,

FIGURE 11.

Variation diagrams of the Whitney Cove pluton showing the core (filled circles) and rim (open circles) facies. The composition of mafic xenoliths (open squares), cataclastically deformed granite (upside down open triangles), aplites (X), and amphibole dike (filled square) are also shown. Inserts show the fields defined by the average composition of plagioclase (filled diamond), biotite (upside down filled diamond) and amphibole (solid triangle on its side), together with the field defined by the mafic xenoliths and a line through the granite analyses.

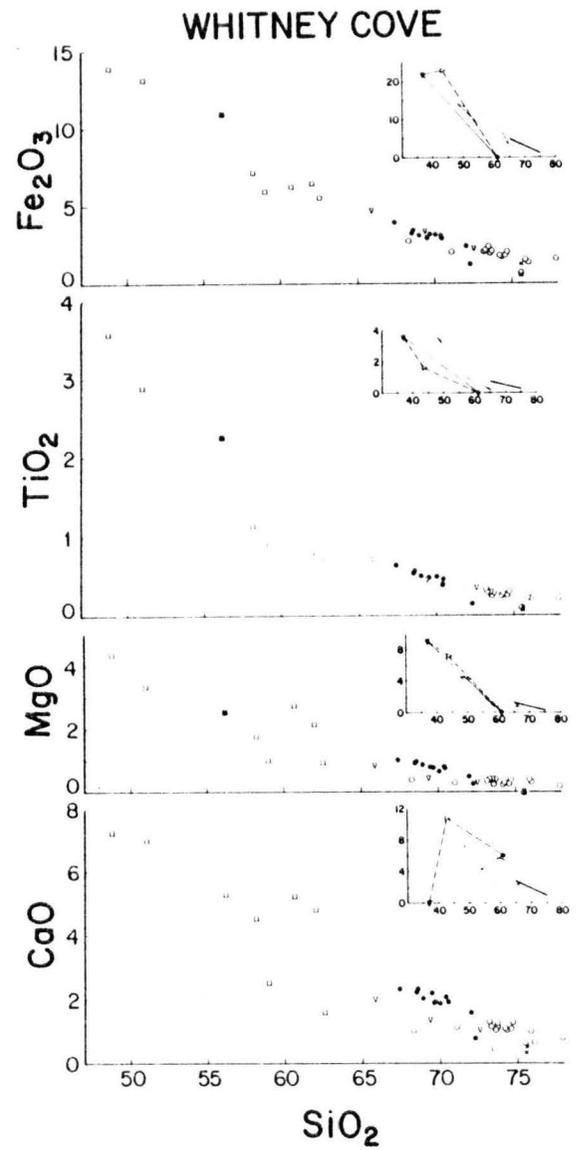
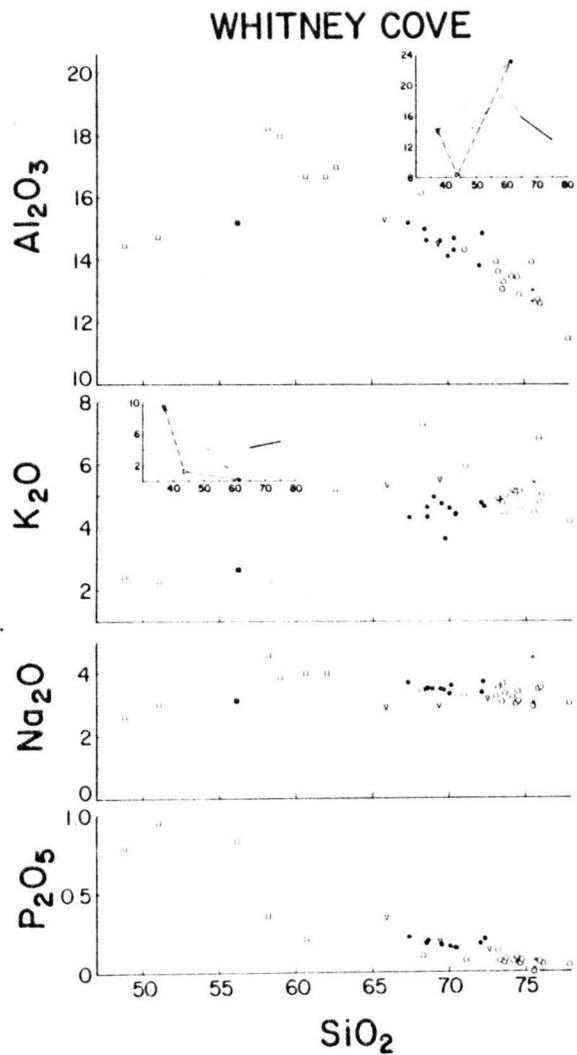


TABLE 9. Representative major and trace element analyses of the granite of Whitney Cove

SAMPLE*	38R	39R	40R	41R	42R	43R	45R	46R	47R	54R	55R	56R	72R	37C	44C	49C	50C	51C	52C	53C	58C	60C	57R	59R	r		
SiO ₂	73.18	74.30	71.12	74.58	73.62	74.20	75.56	75.54	73.46	74.88	73.90	76.09	77.87	70.45	70.05	68.99	70.51	68.51	67.40	68.67	69.50	71.97	73.32	75.89	—		
TiO ₂	0.34	0.20	0.29	0.26	0.25	0.25	0.06	0.06	0.30	0.30	0.29	0.22	0.22	0.47	0.50	0.51	0.49	0.54	0.64	0.57	0.48	0.37	0.30	0.23	-0.907		
Al ₂ O ₃	13.94	13.25	14.34	13.44	13.05	13.46	13.03	13.94	13.60	12.92	13.26	12.59	11.48	14.70	14.14	15.04	14.30	15.00	15.20	14.61	14.64	13.76	13.61	12.65	-0.929		
Fe ₂ O ₃ †	2.11	1.78	2.05	1.84	1.94	1.80	0.50	0.69	2.40	2.00	2.11	1.32	1.64	2.93	3.17	3.17	3.07	3.27	3.97	3.46	2.93	2.42	2.18	1.51	-0.901		
MnO	0.05	0.04	0.05	0.04	0.05	0.05	0.02	0	0.05	0.04	0.03	0.02	0.05	0.10	0.07	0.06	0.07	0.06	0.08	0.06	0.06	0.06	0.06	0.04	-0.708		
MgO	0.37	0.34	0.31	0.28	0.25	0.25	0	0	0.42	0.44	0.47	0.32	0.19	0.77	0.69	0.86	0.81	0.92	1.02	0.97	0.83	0.54	0.42	0.32	-0.905		
CaO	1.30	1.06	1.12	1.07	1.07	1.09	0.34	0.63	1.29	1.29	1.27	0.65	0.79	1.91	1.86	2.04	2.10	2.24	2.32	2.34	2.16	1.60	1.15	1.02	-0.923		
Na ₂ O	3.23	2.97	3.25	3.08	3.63	3.20	4.46	2.88	3.32	3.37	3.31	3.50	3.02	3.23	3.32	2.98	3.57	3.44	3.66	3.50	3.45	3.37	3.50	3.49	-0.074		
K ₂ O	4.94	5.14	5.97	5.18	4.43	5.16	4.47	6.85	4.80	4.67	5.03	5.06	4.20	4.41	4.62	4.97	4.41	4.65	4.31	4.35	4.75	4.82	4.91	4.81	0.249		
P ₂ O ₅	0.13	0.09	0.07	0.05	0.06	0.06	0.07	0	0.08	0.07	0.08	0.05	0.04	0.15	0.16	0.17	0.15	0.18	0.22	0.20	0.17	0.15	0.07	0.06	-0.910		
LOI	0.48	0.44	0.53	0.16	0.52	0.24	0.50	0.28	0.49	0.70	0.84	1.14	0.49	0.44	0.48	0.44	0.92	1.21	1.58	1.33	0.80	0.51	0.87	0.47	ND		
TOTAL	100.07	99.61	99.10	99.98	98.87	99.76	99.01	100.87	100.21	101.30	100.59	100.92	99.99	99.56	99.06	99.23	100.40	100.02	100.58	100.06	99.73	99.57	100.93	100.49	—		
<u>NORMATIVE COMPOSITIONS</u>																											
Q	32.49	34.97	26.95	34.28	33.43	33.38	32.30	30.95	32.55	35.86	33.02	35.63	42.37	30.10	28.77	27.68	27.67	24.42	23.97	26.10	26.63	31.95	32.11	37.78	—		
C	1.23	1.09	0.67	0.94	0.49	0.77	0.41	0.64	0.79	0.59	0.45	0.54	0.63	1.51	0.69	1.47	0.18	0.42	0.82	0.37	0.44	0.87	0.80	0.82	—		
OR	29.17	30.49	35.60	30.62	26.48	30.57	26.68	40.13	28.31	27.68	29.83	30.00	24.82	26.18	27.56	29.60	26.19	27.77	25.77	26.04	28.38	28.83	29.19	28.56	—		
AB	27.31	25.23	27.75	26.07	31.07	27.14	28.12	24.16	28.03	26.31	27.09	28.44	25.56	27.45	28.36	25.41	30.45	30.70	31.42	30.00	28.84	26.72	28.86	25.42	—		
AN	5.60	4.69	5.15	4.78	4.97	5.03	1.24	3.10	5.87	5.96	5.80	2.91	3.66	8.53	8.26	9.08	9.49	10.04	10.19	10.44	9.71	7.04	5.28	4.69	—		
EN	0.92	0.85	0.78	0.70	0.63	0.62	0	0	1.04	1.10	1.18	0.80	0.47	1.93	1.74	2.16	2.03	2.32	2.57	2.45	2.09	1.36	1.05	0.80	—		
HM	2.11	1.79	2.07	1.84	1.96	1.80	0.51	0.68	2.40	2.01	2.12	1.32	1.64	2.94	3.20	3.20	3.09	3.30	4.02	3.51	2.96	2.45	2.19	1.52	—		
IL	0.11	0.09	0.11	0.09	0.11	0.11	0.04	0	0.11	0.09	0.06	0.04	0.11	0.22	0.15	0.13	0.15	0.13	0.17	0.13	0.13	0.13	0.13	0.09	—		
TN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	—		
RU	0.28	0.16	0.24	0.22	0.20	0.19	0.04	0.06	0.24	0.26	0.26	0.20	0.16	0.36	0.43	0.45	0.41	0.48	0.56	0.51	0.42	0.31	0.23	0.19	—		
AP	0.31	0.21	0.17	0.12	0.14	0.14	0.17	0	0.19	0.17	0.19	0.12	0.10	0.36	0.38	0.41	0.36	0.43	0.53	0.48	0.41	0.36	0.17	0.14	—		
<u>TOTAL</u>																											
<u>TRACE ELEMENTS (ppm)</u>																											
Rb	158	163	195	169	166	183	ND	169	154	127	128	148	144	205	166	214	162	152	166	144	151	163	172	162	-0.344		
Sr	168	148	164	100	96	136	ND	90	140	134	138	107	88	285	218	289	234	263	264	287	258	202	122	104	-0.902		
Y	ND	35	ND	ND	ND	33	ND	ND	31	23	23	18	ND	23	37	31	40	37	45	38	33	32	37	30	-0.566		
Ba	572	ND	ND	ND	ND	574	ND	ND	ND	ND	ND	ND	ND	729	503	ND	ND	697	518	ND	587	478	458	384	-0.517		
Zr	164	ND	ND	ND	ND	160	ND	ND	ND	ND	ND	ND	ND	154	189	ND	ND	208	251	ND	198	163	208	142	-0.741		

* R and C refer to rim and core facies respectively.

† Total iron as Fe₂O₃.

ND Not determined.

r Represents the correlation coefficient with SiO₂.

TiO_2 , Al_2O_3 , and P_2O_5 are inversely correlated with silica, but the alkali elements remain essentially unchanged.

Reverse zonation is clearly exhibited in a trend from rim to core, because more felsic and silica-rich rocks progressively become more mafic and silica-poor toward the interior (Fig. 7, 11). Especially in the variation plots for CaO and K_2O , the Whitney Cove pluton exhibits consistent clustering with respect to silica. This contrasts with the better correlation shown by the decreasing abundance of TiO_2 , Fe_2O_3 , and Al_2O_3 in the more felsic rocks of the rim facies.

The Granite of Passadumkeag River

A reverse zonation from the felsic rim toward the more mafic rocks of the interior characterizes this pluton. In contrast to the tendency toward clustering by facies in the Whitney Cove granite, the Passadumkeag River pluton is characterized by consistently decreasing CaO, MgO, Fe_2O_3 , TiO_2 , P_2O_5 and Al_2O_3 with increasing silica (Table 10, Fig. 7, 12). The core facies consists of silica-poor (64 to 71 wt. %) rocks which progressively grade into silica-rich (70 to 76 wt. %) rocks of the granitic envelope.

Xenoliths

The composition of mafic and country rock xenoliths are plotted on the granite variation diagrams (Figs. 7, 11, 12) for comparative purposes. Representative analyses are given in Table 9.

Although wall-rock xenoliths may exert control over the chemistry of a pluton, their assimilation by granitic liquids of the Bottle Lake Complex resulted primarily in dilution of granitic components. This is

FIGURE 12.

Variation diagrams of the Passadumkeag River granite showing the core (filled triangles) and rim (open triangles) facies. Other symbols and fields in the insert are as in Fig. 9.

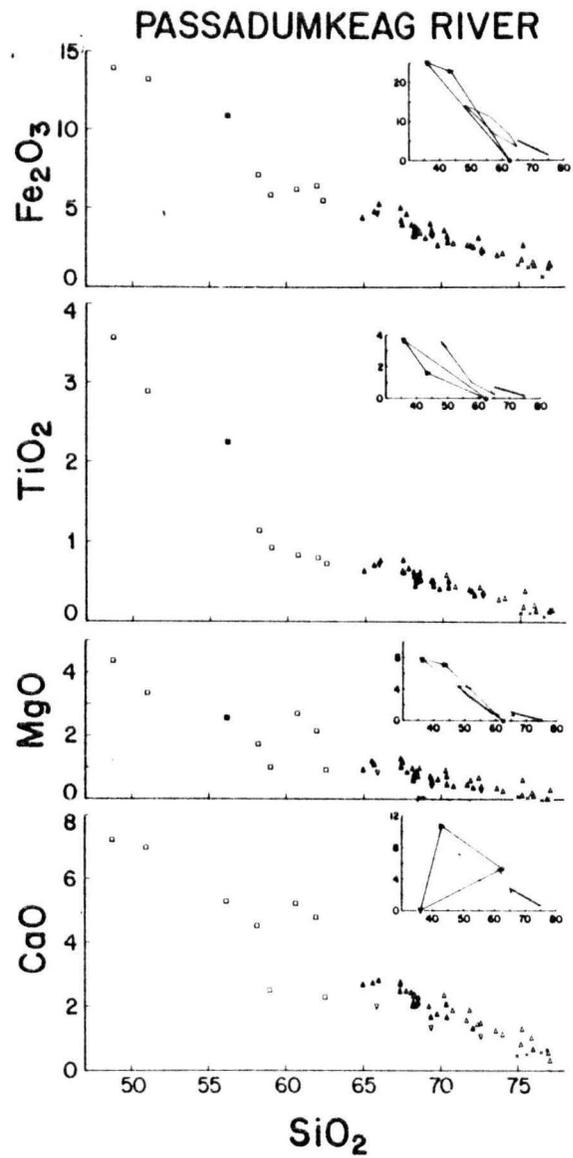
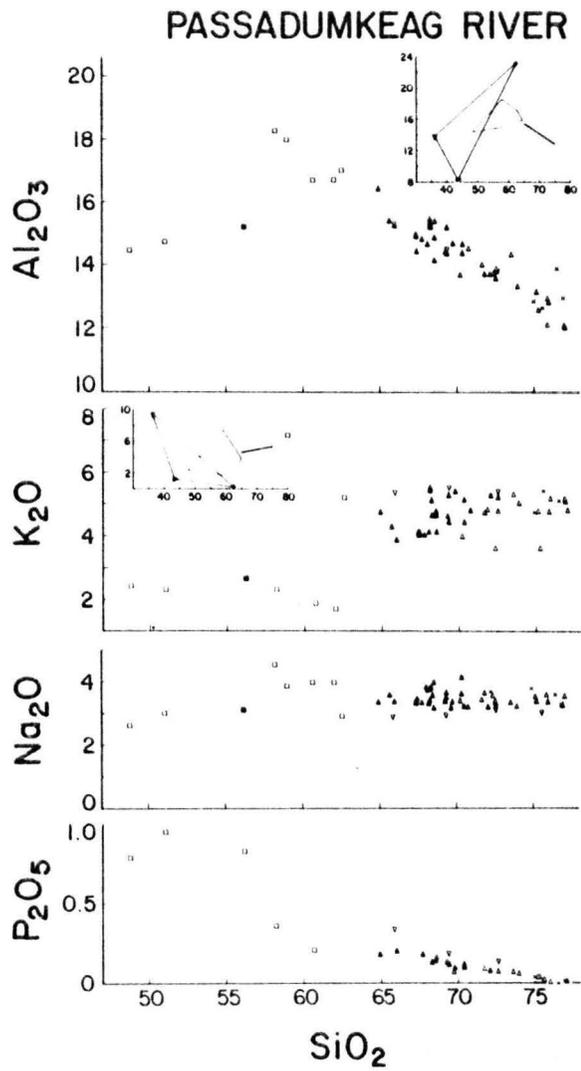


TABLE 10. Representative major and trace element analyses of the granite of Passadumkeag River

SAMPLE*	1R	2R	6R	8R	10R	14R	15R	18R	19R	28R	27R	30R	35R	74R	3C	4C	5C	9C	11C
SiO ₂	76.91	75.17	71.72	70.25	70.79	76.98	76.00	75.31	73.59	75.93	72.59	77.11	71.87	72.41	64.95	66.02	69.39	67.46	70.43
TiO ₂	0.12	0.19	0.41	0.58	0.44	0.16	0.14	0.39	0.28	0.21	0.36	0.15	0.39	0.44	0.64	0.77	0.51	0.62	0.43
H ₂ O ₃	12.96	13.15	14.04	13.66	14.53	12.12	12.81	12.58	14.33	12.92	13.56	12.03	13.70	13.73	16.42	15.26	14.39	14.44	14.68
Fe ₂ O ₃ [†]	1.18	1.72	2.81	3.59	2.78	1.50	1.39	2.66	2.00	1.58	2.32	1.49	2.68	3.16	4.40	5.37	3.37	3.96	2.84
MnO	0.02	0.06	0.05	0.06	0.03	0.03	0.03	0.06	0.04	0.04	0.03	0.02	0.05	0.04	0.09	0.11	0.05	0.07	0.04
MgO	0.04	0.15	0.46	0.89	0.67	0.06	0.11	0.63	0.36	0.24	0.38	0.31	0.56	0.70	0.94	1.20	0.67	0.16	0.48
CaO	0.67	0.81	1.55	2.35	1.87	0.54	0.69	1.27	1.21	1.04	1.17	0.46	1.44	1.46	2.67	2.83	2.01	2.76	1.68
Na ₂ O	3.29	3.52	3.41	3.36	3.19	3.30	3.35	3.37	3.33	3.29	3.24	3.54	3.63	3.58	3.34	3.37	3.51	3.44	4.13
K ₂ O	5.18	4.80	4.73	3.98	4.77	5.13	5.18	3.62	5.31	4.75	5.22	4.82	4.84	4.78	4.74	3.86	4.42	4.09	5.16
P ₂ O ₅	0.02	0.04	0.09	0.16	0.11	0.02	0.01	0.04	0.07	0.08	0.08	0.02	0.12	0.11	0.18	0.20	0.12	0.18	0.10
LiO	0.39	0.41	0.31	0.47	0.45	0.44	0.33	0.17	0.29	0.37	0.33	0.77	0.73	0.47	0.48	0.45	0.45	0.93	0.10
TOTAL	100.78	100.02	99.58	99.35	99.63	100.28	100.04	100.10	100.81	100.45	99.28	100.72	100.01	100.88	98.85	99.44	98.89	99.11	100.07
NORMATIVE COMPOSITIONS																			
Q	36.23	34.47	30.16	30.64	25.97	36.86	35.06	38.27	30.72	36.09	31.14	38.87	29.04	29.18	21.01	25.00	27.40	25.78	22.91
C	0.77	0.79	0.71	0.13	0.03	0.20	0.46	0.90	1.06	0.66	0.65	0.78	0.21	0.27	1.39	0.88	0.47	0	0
OR	30.37	28.36	28.07	23.81	28.26	30.23	30.60	21.37	31.13	27.94	31.07	28.60	28.82	28.00	28.34	22.94	26.41	24.64	30.47
AR	27.62	29.78	28.98	27.76	31.98	27.85	28.34	28.49	27.95	27.71	27.62	27.10	30.69	30.03	28.59	28.68	30.03	28.82	34.92
AN	3.17	3.76	7.13	10.75	8.58	2.54	3.36	6.03	5.50	4.62	5.32	2.16	6.41	6.47	12.21	12.81	9.29	12.57	6.27
EN	0.10	0.37	1.15	2.24	1.67	0.15	0.27	1.57	0.89	0.60	0.95	0.78	1.41	1.73	2.37	3.01	1.69	2.95	1.20
HM	1.17	1.72	2.82	3.64	2.79	1.50	1.39	2.66	1.98	1.57	2.34	1.50	2.70	3.13	4.45	5.4	3.41	4.04	2.84
IL	0.04	0.13	0.11	0.13	0.06	0.06	0.06	0.13	0.09	0.09	0.07	0.04	0.11	0.09	0.20	0.24	0.11	0.15	0.09
TN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.94
RU	0.10	0.12	0.36	0.52	0.41	0.13	0.11	0.32	0.23	0.16	0.33	0.13	0.34	0.39	0.55	0.65	0.46	0.50	0
AP	0.05	0.1	0.21	0.38	0.26	0.05	0.02	0.10	0.16	0.19	0.19	0.05	0.29	0.26	0.43	0.48	0.29	0.44	0.24
TOTAL																			
TRACE ELEMENTS (ppm)																			
Rb	216	235	125	124	142	220	172	127	214	169	153	157	163	166	149	139	115	175	113
Sr	31	47	136	172	147	20	29	94	105	104	100	25	134	122	257	201	176	242	141
Y	ND	ND	ND	32	30	ND	21	ND	ND	34	28	19	31	36	38	ND	32	39	ND
Ba	ND	ND	ND	553	ND	ND	88	ND	ND	ND	343	ND	459	ND	777	ND	574	445	ND
Zr	ND	ND	ND	322	ND	ND	119	ND	ND	ND	200	ND	280	ND	257	ND	256	260	ND
* R and C refer to the rim and core facies respectively.																			
† Total iron as Fe ₂ O ₃																			
ND Not Determined																			
r Correlation coefficient with SiO ₂																			

TABLE 10 (continued).

SAMPLE*	12C	13C	16C	17C	20C	21C	22C	24C	25C	26C	28C	29C	31C	32C	33C	34C	36C	r
SiO ₂	73.98	69.82	68.52	68.27	67.81	72.12	69.32	68.24	69.41	67.44	68.31	68.36	68.14	68.31	68.63	67.43	65.66	—
TiO ₂	0.29	0.41	0.52	0.50	0.67	0.33	0.51	0.45	0.47	0.77	0.55	0.58	0.63	0.57	0.53	0.63	0.71	-0.934
H ₂ O ₃	13.34	14.69	14.89	15.46	14.81	13.70	14.42	15.97	15.21	14.95	15.20	15.28	14.68	15.38	15.36	14.92	15.40	-0.923
Fe ₂ O ₃ [†]	2.12	2.65	3.61	3.21	4.66	2.57	4.03	3.26	3.64	5.03	3.63	3.65	3.97	3.79	3.48	4.27	4.80	-0.927
MnO	0.04	0.05	0.06	0.06	0.11	0.05	0.07	0.07	0.06	0.11	0.04	0.05	0.08	0.07	0.06	0.09	0.11	-0.761
MgO	0.26	0.62	0.73	0.70	0.87	0.36	0.70	0.58	0.54	1.28	0.78	0.86	0.97	0.82	0.87	1.03	1.13	-0.881
CaO	1.11	1.75	2.02	2.10	2.47	1.28	1.99	2.00	1.66	2.73	2.02	2.38	2.42	2.37	2.16	2.47	2.74	0.958
Na ₂ O	3.20	3.35	3.55	3.30	3.31	3.09	3.36	4.20	3.56	4.02	3.63	3.88	3.90	3.39	3.96	3.35	3.59	-0.334
K ₂ O	5.05	5.40	4.76	5.53	4.03	5.27	4.61	5.43	5.28	3.91	5.11	4.64	4.12	4.66	4.60	4.11	4.26	-0.333
P ₂ O ₅	0.06	0.10	0.14	0.13	0.18	0.08	0.13	0.13	0.11	0.22	0.14	0.16	0.16	0.15	0.15	0.19	0.24	-0.934
LiO	0.22	0.47	0.56	0.38	1.15	0.27	0.45	0.45	0.47	0.28	0.39	0.36	0.84	0.60	0.47	0.61	0.71	ND
TOTAL	99.67	99.31	99.36	99.64	100.07	99.12	99.59	100.78	100.41	100.74	99.80	100.20	99.91	100.11	100.27	99.37	99.35	—
NORMATIVE COMPOSITIONS																		
Q	33.56	25.45	24.79	22.82	27.03	31.20	27.31	18.19	24.35	21.99	22.59	22.10	23.86	22.27	21.93	25.40	21.04	—
C	0.74	0.40	0.56	0.54	0.94	0.78	0.60	0	0.88	0	0.36	0	0	0.07	0.13	0.69	0.25	—
OR	29.94	32.13	28.31	32.80	23.80	31.42	27.35	31.84	31.07	22.94	30.26	27.36	24.58	27.55	27.21	24.62	25.48	—
AB	27.17	28.54	30.23	28.03	27.99	26.38	28.55	35.26	30.00	33.77	30.78	32.77	33.31	32.51	34.39	30.02	31.95	—
AN	5.13	8.08	9.17	9.60	11.07	5.88	9.06	8.62	7.49	11.12	9.13	10.55	10.48	10.79	9.75	11.16	12.17	—
EN	0.65	1.56	1.83	1.75	2.17	0.91	1.75	1.43	1.34	3.16	1.95	2.14	2.44	2.04	2.17	2.60	2.85	—
HM	2.13	2.67	3.63	3.22	4.66	2.59	4.05	3.24	3.63	4.99	3.64	3.64	4.01	3.79	3.48	4.33	4.86	—
IL	0.09	0.11	0.13	0.13	0.24	0.11	0.15	0.15	0.13	0.23	0.09	0.11	0.17	0.15	0.13	0.20	0.24	—
TN	0	0	0	0	0	0	0	0.27	0	0.63	0	0.13	0.41	0	0	0	0	—
RU	0.25	0.36	0.46	0.43	0.55	0.28	0.43	0.26	0.40	0.38	0.51	0.47	0.38	0.49	0.46	0.54	0.59	—
AP	0.14	0.24	0.33	0.31	0.43	0.19	0.31	0.31	0.26	0.52	0.33	0.38	0.38	0.36	0.36	0.46	0.58	—
TOTAL																		
TRACE ELEMENTS (ppm)																		
Rb	183	160	175	143	148	218	194	159	162	134	145	133	117	135	179	160	188	0.437
Sr	83	163	162	197	195	132	143	183	133	217	184	209	180	182	196	203	222	-0.955
Y	ND	ND	ND	ND	43	ND	ND	36	43	48	37	34	42	39	35	47	45	-0.746
Ba	ND	ND	ND	ND	481	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	514	602	-0.867
Zr	ND	ND	ND	ND	304	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	302	323	-0.725

* R and C refer to rim and core facies respectively

† Total iron as Fe₂O₃

ND Not Determined

r Represents the correlation coefficient with SiO₂

suggested by the broadly calc-alkaline nature of the Complex compared to the strongly silicic and peraluminous compositions of most country rocks. Also, the variation from more mafic to felsic rocks in the plutons follows a generally well-defined trend despite the wide range of lithologies representative of the country rocks. In agreement with the petrographic diversity of the mafic xenoliths, their bulk compositions also exhibit significant spread (Figs. 7, 11, 12, Table 11). In general, mafic inclusions found near the cataclastic zone are silica- and alumina-poor compared to other inclusions and host rocks. They are also richer in Fe_2O_3 , TiO_2 , MgO , CaO , and P_2O_5 .

Comparison of the composition of the xenoliths with basalts from different tectonic settings results in ambiguous associations, partly because of the effects of reequilibration. In general, the major element compositions resemble the high-alumina andesite (calc-alkali series) of Irvine and Baragar (1971). This resemblance is also present in the Ordovician volcanic rocks of north-central Maine (Island Falls) studied by Hynes (1976). Consideration of the immobile elements (Zr, Ti, Y) as proposed by Pearce and Norry (1979), however, shows that the xenoliths overlap the field of within plate basalts.

An origin for the xenoliths in granites as representative of quenched basaltic material in silicic chambers was proposed by Eichelberger (1975). He envisions that basaltic magmas provide both the heat required for melting in the lower crust as well as a component for mixing. In contrast, study of mafic xenolith and granites led Bateman et al. (1963), Presnall and Bateman (1973) and Chappell and White (1974) to suggest that xenoliths represent residues (restites) from the

TABLE 11. Representative major and trace element analyses of mafic xenoliths and country-rock inclusions

SAMPLE*	71M	61M	62M	63M	64M	65M	66M	67CR	68CR	69CR	70CR	r
SiO ₂	60.71	51.07	48.83	58.24	62.03	59.01	62.57	74.27	52.56	47.86	57.76	—
TiO ₂	0.83	2.89	3.57	1.14	0.80	0.92	0.73	0.77	1.10	1.07	0.84	-0.981
Al ₂ O ₃	16.70	14.72	14.45	18.26	16.69	17.96	17.03	9.73	20.29	22.13	17.77	0.774
Fe ₂ O ₃ †	6.26	13.22	13.93	7.15	6.47	5.85	5.56	5.64	9.88	10.92	8.13	-0.970
MnO	0.11	0.23	0.22	0.14	0.12	0.10	0.10	0.06	0.16	0.22	0.25	-0.948
MgO	2.74	3.35	4.37	1.76	2.16	1.03	0.93	1.32	2.17	5.47	4.04	-0.817
CaO	5.22	7.00	7.24	4.51	4.80	2.50	2.55	0.30	1.31	2.80	5.69	-0.799
Na ₂ O	3.99	3.02	2.01	4.55	4.39	4.04	4.32	1.64	2.59	2.33	2.62	0.916
K ₂ O	1.86	2.31	2.42	2.32	1.68	7.28	5.21	5.23	8.49	4.92	1.77	0.247
P ₂ O ₅	0.21	0.95	0.79	0.36	0.17	0.25	0.21	0.07	0.11	0.14	0.14	-0.952
LOI	0.53	0.58	1.16	0.51	0.52	0.57	0.61	0.52	1.07	1.84	1.35	ND
TOTAL	99.16	99.34	98.99	98.94	99.83	99.51	99.81	99.55	99.73	99.70	100.36	
NORMATIVE COMPOSITIONS												
Q	16.35	9.30	9.80	11.75	17.47	1.78	11.27	42.49	0	1.73	17.86	
C	0	0	0	0.94	0	0	0.15	1.00	4.73	8.24	1.53	
OR	11.08	13.74	14.45	13.86	9.94	43.23	30.84	31.05	50.31	29.16	10.42	
AB	34.05	25.72	17.18	38.91	37.21	34.35	36.62	13.94	21.98	19.78	22.09	
AN	22.35	19.91	23.50	20.24	20.91	9.42	11.30	1.04	5.80	13.02	27.22	
EN	6.88	8.40	11.00	4.43	5.39	2.58	2.32	3.30	2.98	13.66	10.03	
HM	6.31	13.31	14.07	7.23	6.48	5.88	5.57	5.67	9.91	10.95	8.10	
IL	0.24	0.50	0.48	0.30	0.26	0.22	0.21	0.13	0.34	0.47	0.53	
TN	1.68	6.20	5.34	0	1.29	0.99	0	0	0	0	0	
RU	0.03	0.12	1.18	0.99	0.14	0.41	0.62	0.71	0.92	0.83	0.56	
AP	0.50	2.27	1.89	0.86	0.40	0.60	0.50	0.17	0.26	0.33	0.33	
FO	0	0	0	0	0	0	0	0	1.71	0	0	
TRACE ELEMENTS (ppm)												
Rb	140	92	97	122	126	261	180	246	370	355	106	0.519
Sr	275	248	377	193	230	227	200	72	160	345	486	-0.704
Y	26	52	44	67	ND	65	61	ND	39	ND	ND	0.150
Ba	158	377	360	182	ND	ND	429	ND	884	ND	ND	-0.303
Zr	164	391	345	655	ND	ND	514	ND	159	ND	ND	0.141

* M refers to mafic xenolith; CR refers to country rock inclusion

† Total iron as Fe₂O₃r This is the correlation coefficient with SiO₂ of the mafic xenoliths

ND Not Determined

granite source. Mafic xenoliths and a felsic component are related by a process of unmixing which results in granitic rocks (Chappell, 1978). This scheme necessarily limits the composition of the source to lie along the mixing line shown in variation diagrams. Departures from the mixing line are envisioned to result primarily from the process of fractionation (Bateman and Chappell, 1979). However, Cramer (1979) showed that because of the effect of diffusion, a restite may deviate from the mixing line of the host rocks. In any case, homogeneous sources result in consistent compositional gradients from xenoliths to host granitoids in variation diagrams. In the case of the Bottle Lake Complex, preliminary data on the mafic xenoliths show significant scatter along the regression lines defined by the granites (Fig. 7, 11, 12). Regardless of the ultimate origin of the xenoliths, their range in composition cannot be adequately explained by a homogeneous parent.

Xenoliths in other batholiths also exhibit a great range in compositional scatter even within single plutons. This is evident in granites that share many of the geochemical characteristics of the BLC, as in Australia (Chapell and White, 1976; Griffin et al., 1976; Hine et al., 1978), French-Spanish Pyrenees (Debon, 1980), and the British Caledonides (Halliday et al., 1980). The inescapable conclusion is that unless the process of generation and emplacement of granitic magmas is simple, the geochemistry of the source and identification of the process involved are difficult to discern without careful study of the xenolith suite.

Xenoliths representing a heterogeneous source but remaining in contact with granitic liquid are likely to achieve equilibrium because

of the process of assimilation (Bowen, 1928). Under ideal conditions complete assimilation of homogeneous material results in straight lines in variation diagrams (Wilcox, 1979; McBirney, 1979). The resulting pattern resembles mixing of two liquids for the major elements. Mineralogically, assimilation is expressed by emphasizing the fractionating scheme and resulting in a change of the final crystallizing assemblage (Bowen, 1928). For the Bottle Lake Complex, complete assimilation and equilibration with the heterogeneous suite of xenoliths did not occur. This is shown by the significant departures from linearity in the major oxides and by the isotopic variability of the xenoliths and host rocks.

Because of this feature, the composition of the source cannot be constrained accurately. Other processes apart from fractionation such as incomplete assimilation, and mixing are necessary to account for the evolution of the batholith.

Comparison of the Granites

Compositional differences between the main intrusives of the BLC are minor, as they show similar ranges in their oxide variation and trend with increasing silica concentration. Toward the interiors, both granitoids display progressive enrichment in oxides typically associated with higher temperature assemblages or less fractionated rocks (e.g., TiO_2 , Fe_2O_3 , MgO , CaO , P_2O_5). Comparison between the two core facies indicates the generally higher concentration of mafic constituents in the Passadumkeag River granite. However, the variation present in the rim facies in both plutons makes them indistinguishable.

The regular gradient from low to high silica rocks supports the argument that the facies within each pluton are broadly cogenetic. Vance (1961) suggested such an origin for plutons exhibiting normal zonation by the process of fractionation from one magma.

Because of the scatter in the abundance of the alkali elements, the calc-alkali indexes for the Bottle Lake plutons are roughly constrained between 53 to 57. The range is lower than expected from calc-alkaline suites (60-64) and it is equivalent to the range of extensional suites (50-56) defined by Petro et al. (1980).

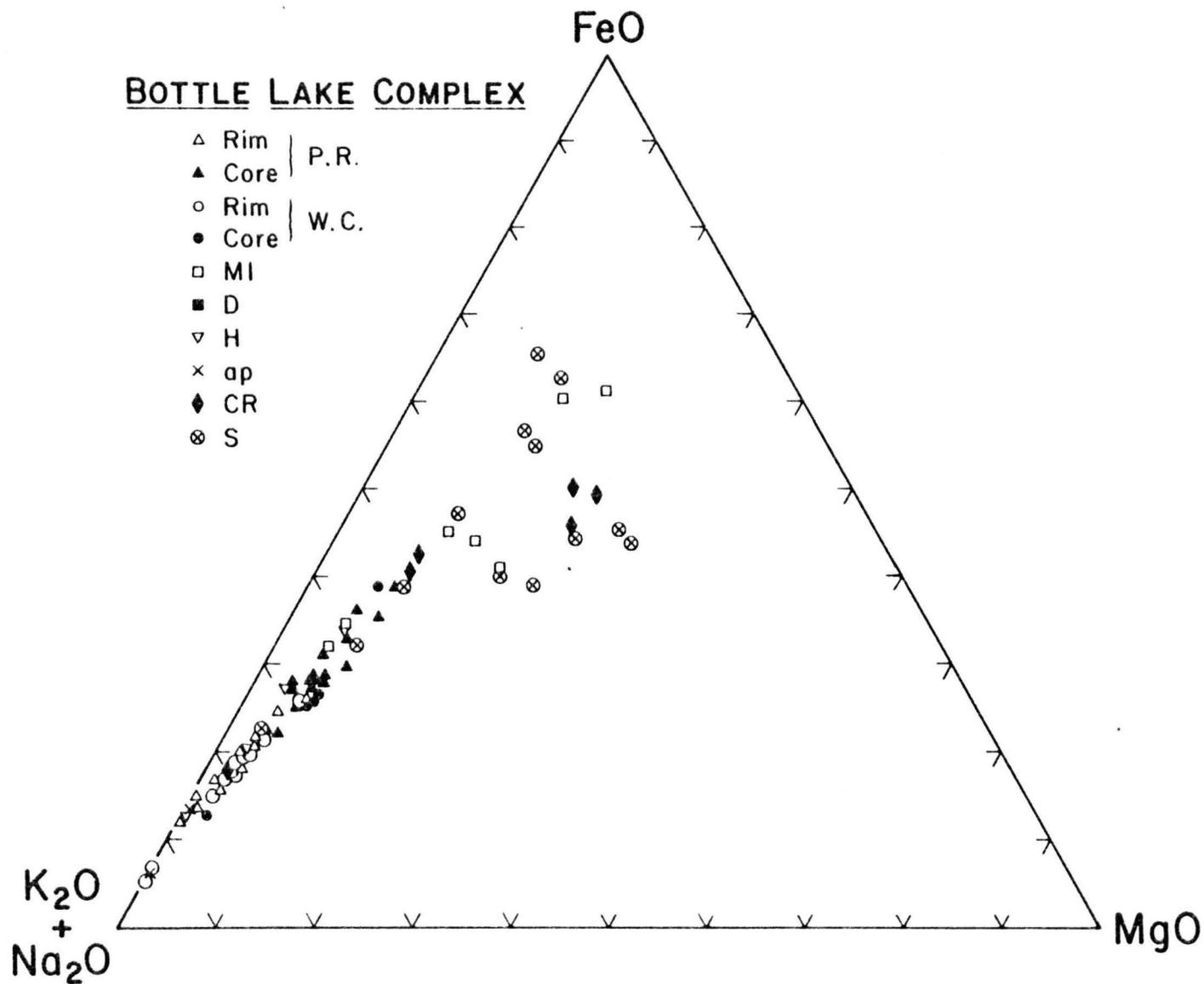
Plotted on an AFM diagram, the composition of the BLC defines a band trending away from the FeO-MgO sideline toward the alkaline apex (Fig. 13). This suggests a broadly calc-alkaline trend but no distinction is possible between the two plutons. Wall rock xenoliths are distinct from this trend, while mafic xenoliths are generally aligned in agreement with the plutons and plot closer to the FeO-MgO sideline.

A feature common to the BLC granites is their low (2%) corundum normative values. This is consistent with the absence of aluminous minerals (garnet, cordierite, aluminosilicates, etc.). No correlation exists between normative corundum and SiO_2 .

The gradual change from diopside to corundum-normative rocks in calc-alkaline sequences results from the crystallization of hornblende in hydrous magmas according to Cawthorn and Brown (1976). Their study also indicated that at higher ratios of $\text{Na}/(\text{Na} + \text{K})$ (0.6) amphibole fractionation was dominant over mica. The Bottle Lake Complex granites are restricted to ratios lower than 0.45 in agreement with precipitation of both amphibole and mica.

FIGURE 13.

AFM diagram showing the Bottle Lake Complex, the mafic xenoliths, amphibolite rocks of the cataclastic zone, hybrid granitoids of the cataclastic zone, aplites, country rock xenoliths (crosses inside circles), and representative analyses of the country rocks (solid diamonds). Other symbols are as in previous figures and as shown on the key.



RARE EARTH AND TRACE ELEMENTS

Rare Earth Elements

Preliminary analyses of representative samples of the BLC are shown in Figures 14, 15, and Table 12. In general, all samples are mildly enriched in the light rare-earth elements (LREE), have europium anomalies, and show chondrite normalized La concentrations of 45-217 ppm, Yb of 12-22 ppm, and La/Yb ratios of 4-14. The compositional patterns consistently have the same shape but vary by about a factor 3 to 4 in their absolute REE content. A small decrease in the heavy rare earth element (HREE) group with respect to the middle rare earth elements (MREE) is also characteristic of these granites. This results in a convex upshape of the normalized pattern.

In the Passadumkeag River pluton, rim samples which are also the most felsic rocks tend to have lower concentrations of the HREE compared to the core facies (Fig. 14). The least fractionated pattern (sample 8R) is the poorest in its total abundance of REE and the most siliceous of the rocks analyzed. In contrast to the range in compositions shown by the rim facies, rocks from the interior are similar in their LREE and MREE, but show a range in their HREE.

The composition of the Whitney Cove pluton shows characteristics similar to those of the Passadumkeag River (Fig. 15). Sample 95R belongs to an aplite from the rim facies and is the most REE enriched of all the analyzed samples. Also, it shows the largest europium anomaly in the Bottle Lake Complex. In contrast to the Passadumkeag River granite, no clear trend exists between the silica content and HREE

FIGURE 14.

Chondrite-normalized rare-earth element composition of samples from the Passadumkeag River granite.

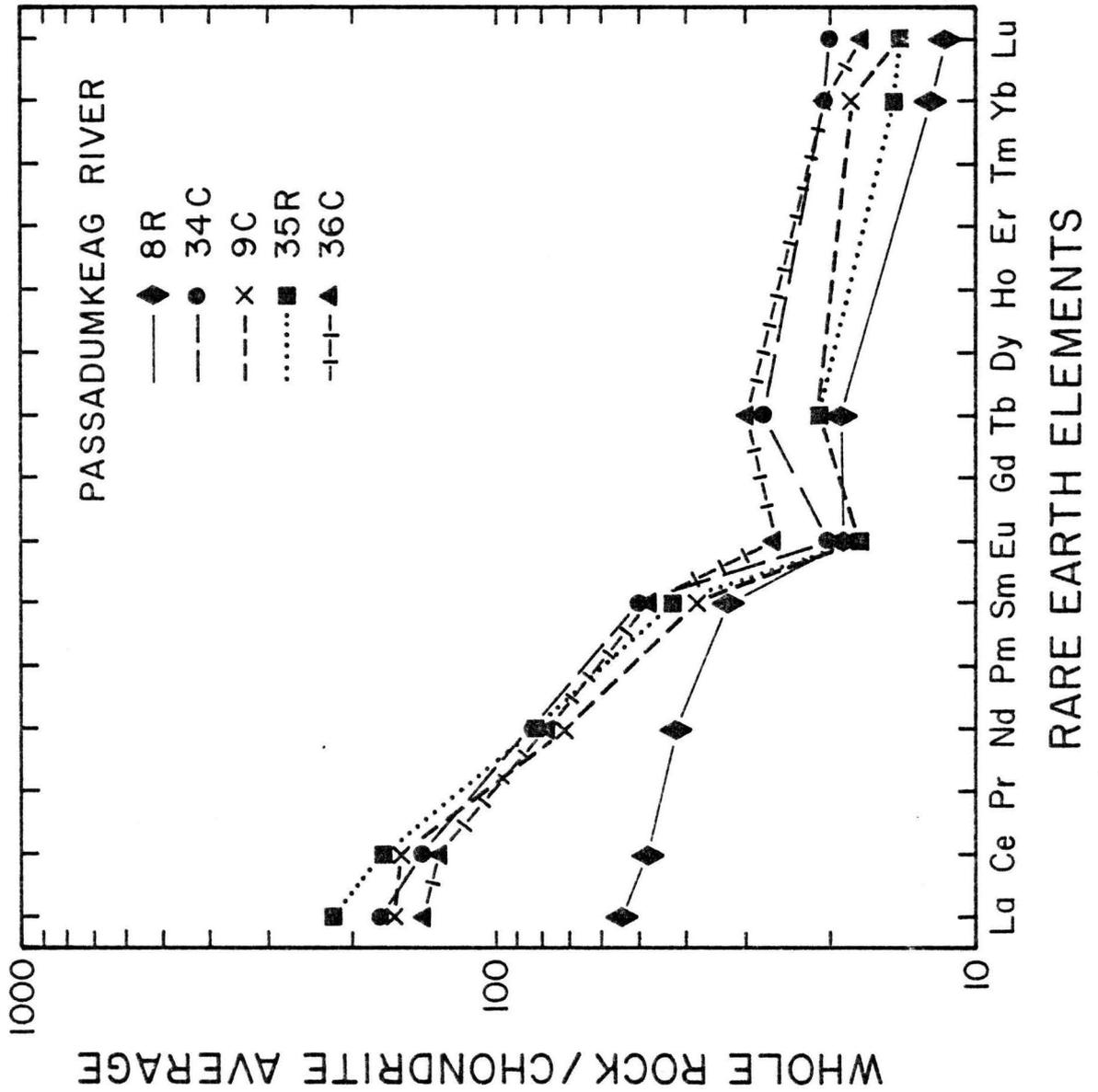


FIGURE 15.

Chondrite-normalized rare-earth element composition of samples from the Whitney Cove granite.

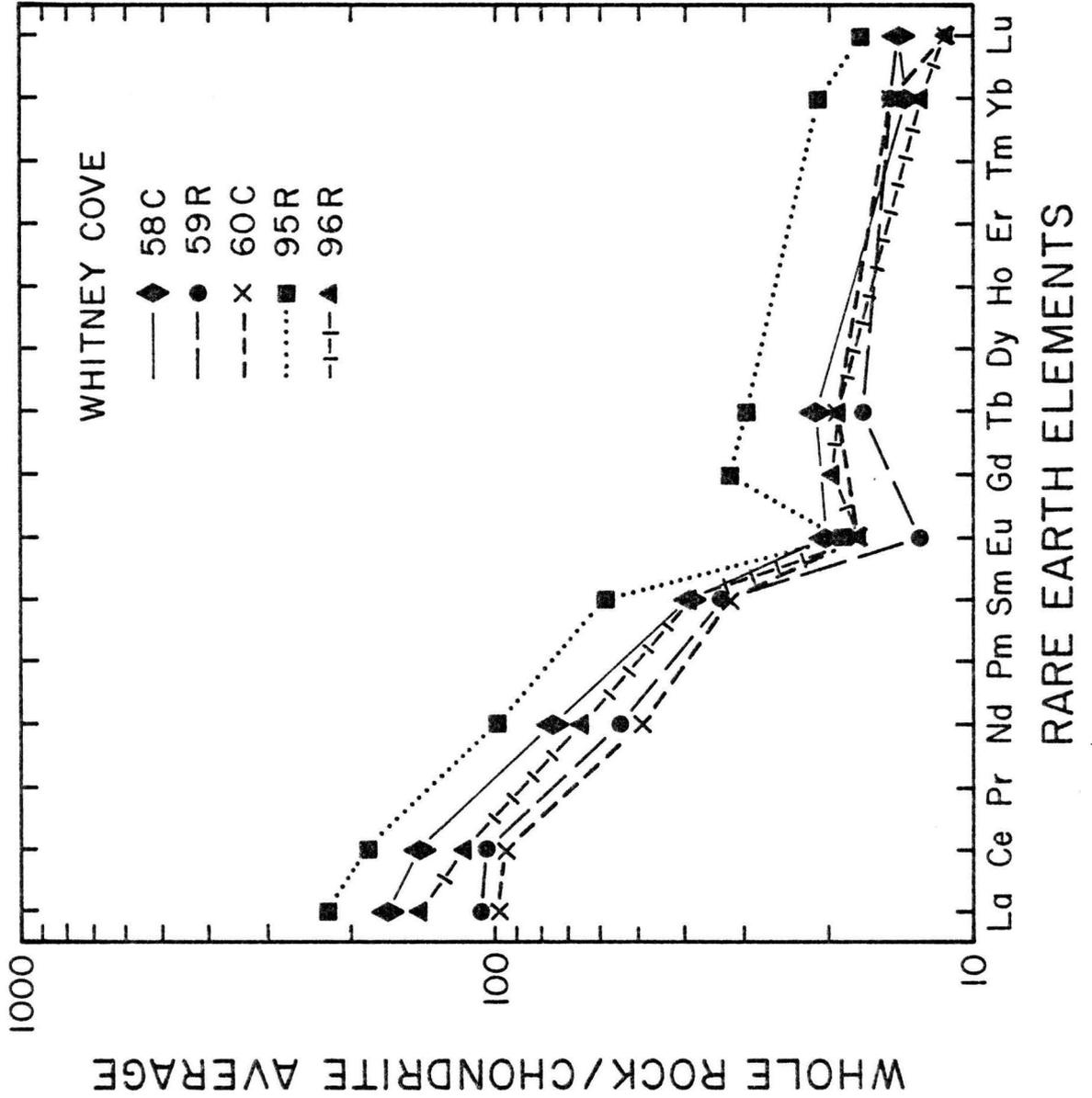


TABLE 12. Rare earth element concentrations in the Bottle Lake Complex, Maine

<u>Sample</u>	1 [*] <u>58C</u>	2 <u>59R</u>	3 <u>60C</u>	4 <u>95R</u>	5 <u>96R</u>	6 <u>8R</u>	7 <u>34C</u>	8 <u>9C</u>	9 <u>35R</u>	10 <u>36C</u>
La	54.7	34.7	32.1	73.3	46.7	17.7	56.9	53.8	71.5	46.2
Ce	115.0	82.9	76.0	147.8	92.5	38.8	114.0	126.0	138.0	105.0
Nd	43.0	31.0	28.0	56.2	37.2	24.0	48.0	41.0	47.0	44.0
Sm	7.3	6.2	6.0	11.0	7.2	6.1	9.3	7.1	8.0	8.9
Eu	1.4	0.9	1.2	1.3	1.2	1.3	1.4	1.2	1.2	1.8
Gd	N.D.	N.D.	N.D.	8.2	5.0	N.D.	N.D.	N.D.	N.D.	N.D.
Tb	1.0	0.8	0.9	1.4	0.9	0.9	1.3	1.0	1.0	1.4
Yb	2.9	3.1	3.1	4.4	2.7	2.6	4.3	3.8	3.1	4.3
Lu	0.5	0.5	0.4	0.6	0.4	0.4	0.7	0.5	0.5	0.6

* Columns 1-3, 6-9 represent samples analyzed at the Massachusetts Institute of Technology with data reduction by M. C. Loisellet at VPI & SU; columns 4-5 represent samples analyzed at the U.S. Geological Survey. Columns 1-5 represent the granite of Whitney Cove; columns 6-10 represent the granite of Passadumkeag River.

N.D. Not Determined.

enrichment in these samples. Instead, they are best described by criss-crossing in the patterns of the HREE.

The general shape of the chondrite-normalized REE abundances, their concentric nature, and parallelism suggest that the rocks of the Bottle Lake Complex are closely related. Because of their strong similarity, the nature of the residual phases must also be similar. Modal and petrographic studies identified plagioclase and biotite in the Whitney Cove pluton, and plagioclase, biotite, and amphibole in the Passadumkeag River granite as the controlling phases in the progressive change from rim to core facies. The presence of plagioclase in the residue is supported by the negative europium anomalies, but because of its low coefficient for all other REE, other phases must also be residual. Among the possibilities are biotite, hornblende and the accessories.

The effect of biotite on the granitic melt is minor due to its low affinity for the REE (Hanson, 1980; Arth and Hanson, 1975). In contrast, hornblende has REE affinities that are compositionally controlled and lead to depletion of the middle and light REE, as well as a positive Eu anomaly in the melt. In a qualitative sense, both hornblende and biotite may remain as residues in the Bottle Lake Complex. However, the assemblage plagioclase, amphibole and biotite is inadequate to explain the REE distribution and fractionation. As a result, the effect of the accessory suite on the liquid must be explored.

Modal studies reveal the core facies rocks to be enriched in the accessory suite. In the Whitney Cove pluton, apatite shows more euhedral habits and higher abundance than sphene, zircon and allanite.

Thus, on purely petrographic grounds, the assemblage plagioclase, biotite and apatite should account for the REE distribution.

A more complicated assemblage including plagioclase, biotite, amphibole, and apatite must be present in the residue of the Passadumkeag River pluton. As will be shown in a later section, however, the fractionating assemblage must be supplemented by other accessory phases (zircon, sphene, allanite), by additional geologic processes (vapor loss?) or both to account for the most differentiated compositions.

In comparison to the calc alkaline granites from the Sierra Nevada (Frey et al., 1978) and the Saudi Arabian peninsula (Dodge, 1979), the BLC plutons are generally higher in the LREE, show larger negative Eu anomalies, and have higher abundances of the HREE. The shape and REE concentrations of the BLC plutons show more striking contrasts with the REE-enriched peralkaline granites of Nigeria (Bowden and Whitley, 1974) which are also characterized by large negative Eu anomalies.

TRACE ELEMENTS

Sr, Rb

The granite of Whitney Cove. In accordance with the petrographic and major oxide distinctions within the Whitney Cove granite, the core facies is clearly enriched in Sr compared to the rim (Table 7). This enrichment is best displayed in Figure 16 as the high Sr (200 pm) and low SiO₂ (72 wt.%) values are concentrated within the interior and contrast with the low Sr (170 pm) and high SiO₂ of the rim. Compared to the rim facies, rocks of the interior are more constant in Sr.

FIGURE 16.

Variation of Sr with SiO_2 showing the core and rim facies of the Whitney Cove. Other symbols are as in Fig. 9.

The variation of Sr in the mafic xenoliths define a different slope and it is not colinear with the trend of the pluton.

Rubidium abundances across Whitney Cove are generally similar (Table 9) and are not strongly correlated with Sr (Figure 17). Aplites are typically lower in Sr than the granites because they characterize fractionated systems which have undergone significant crystallization of feldspar (Hon and Noyes, 1977).

Crystallization of typical phases results in characteristic liquid paths (McCarthy and Hasty, 1976; McCarthy and Groves, 1979). Inserts in Fig. 17 (after Walsh et al., 1979) show the effect of fractionation on the composition of the liquid. These are calculated by the Rayleigh fractionation law distribution coefficients summarized by Arth (1976). The distribution of compositions shown by the felsic rim may be related to the core by a complex fractionation sequence involving at least two stages. This is consistent with control of the liquid path by fractionation of plagioclase. In addition to plagioclase, however, subtraction of minor amounts of a mafic-phase is necessary to provide for the observed scatter.

The granite of Passadumkeag River. The Sr concentration and variation with respect to silica are given in Table 10 and Figure 18. Unlike the Whitney Cove pluton, the variation of Sr across this granite forms an overlapping and generally continuous band from core to rim facies. As in the Whitney Cove granite, the reverse zonation is clearly exhibited because the core rocks are enriched in Sr (130 ppm) and depleted in SiO₂ (72.5 wt. %). The general continuity and regularity of the trend supports the contention that it represents a genetically related sequence.

FIGURE 17.

Variation of Rb with Sr in the Whitney Cove pluton. Symbols area as in Figs. 9 and 11. Insert shows the path of the liquid depending on the fractional crystallization of a phase.

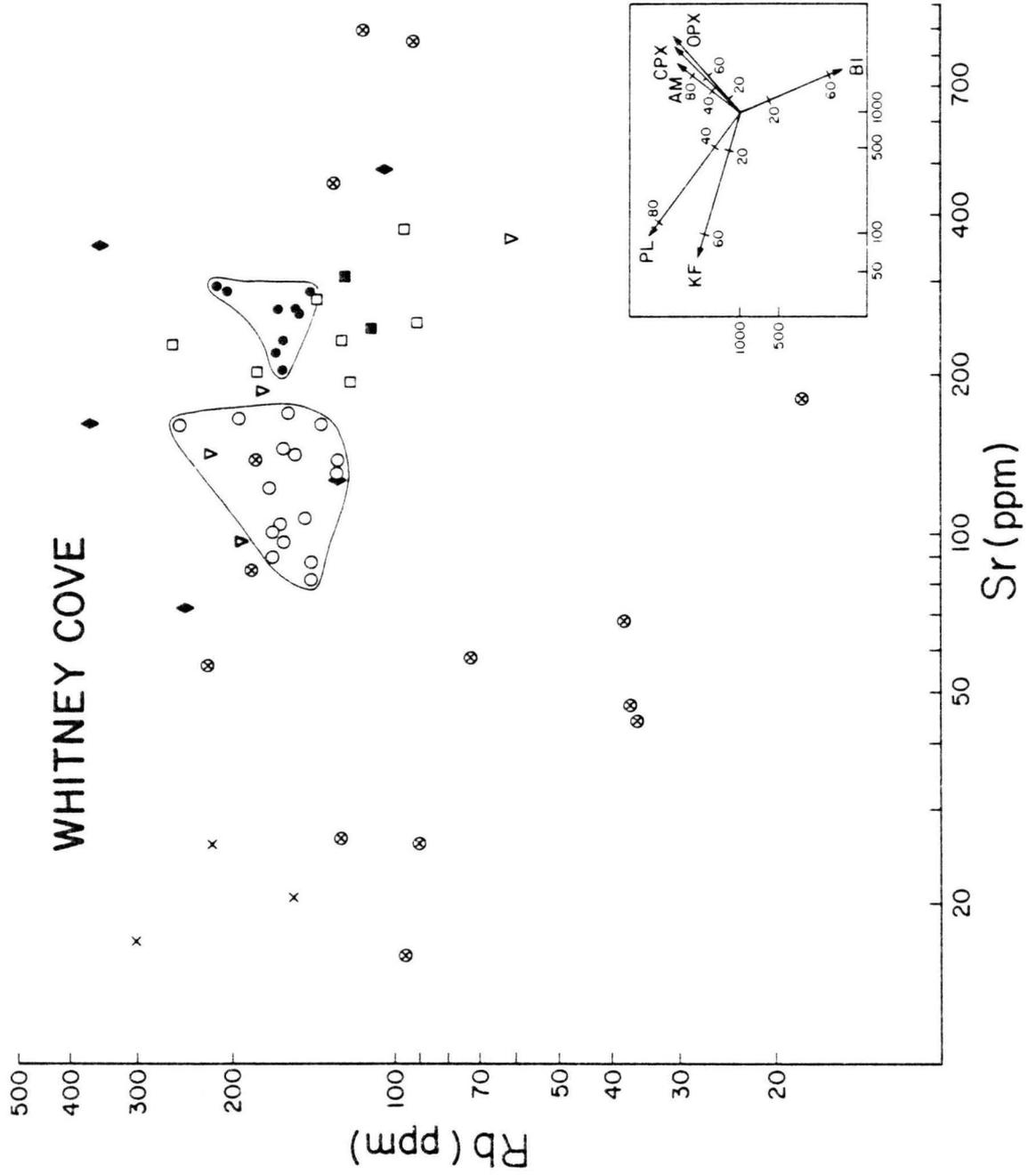
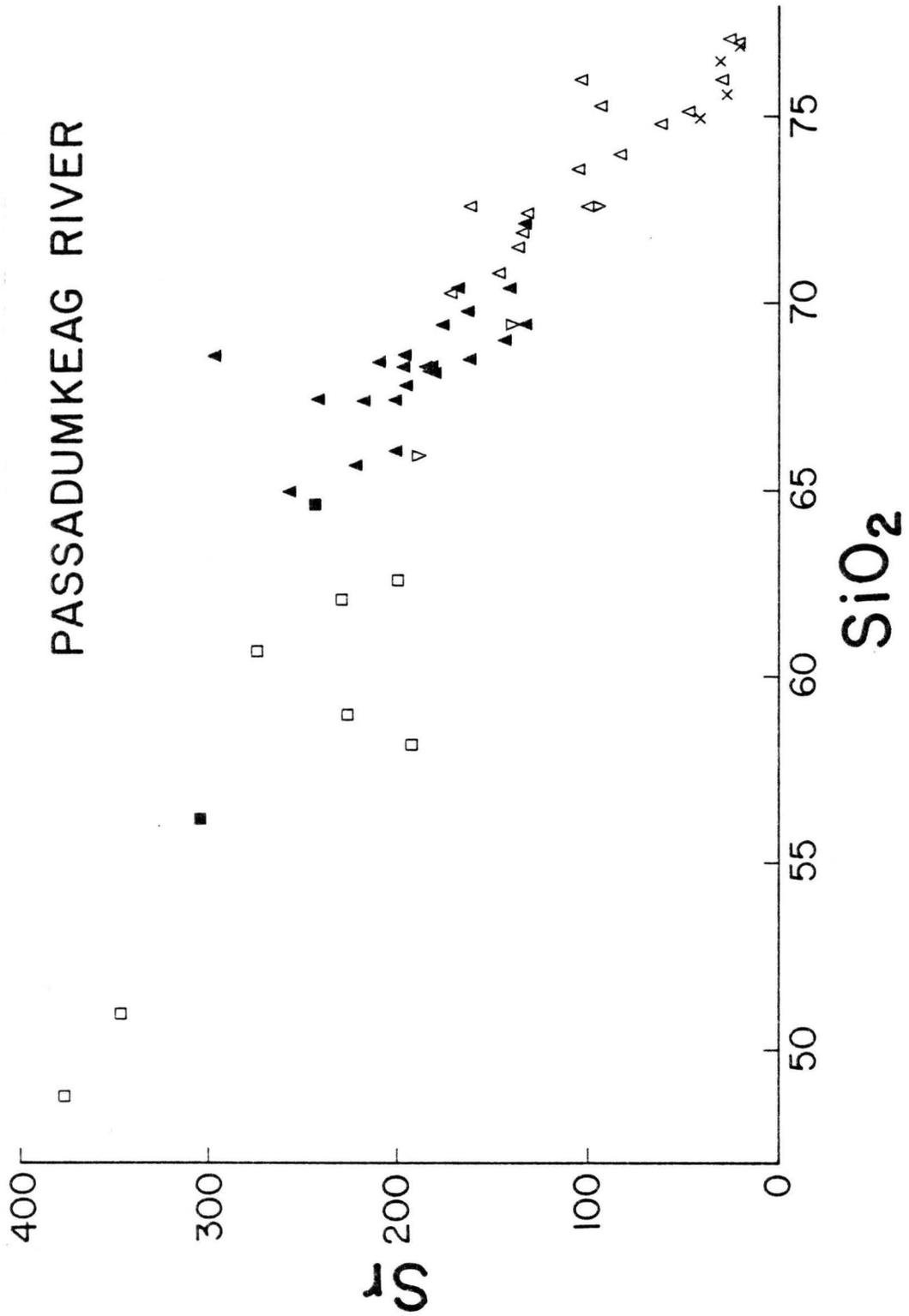


FIGURE 18.

Variation of Sr with SiO_2 showing the core and rim facies of the Passadumkeag River pluton. Other symbols are as in Figs. 9 and 14.



In contrast to the Whitney Cove pluton, Rb and Sr are better correlated and this is shown in Figure 19. However, as expected, the pluton is characterized by major scatter in Rb at a given Sr value. This overlap and scatter prevents clear distinction between the core and rim facies.

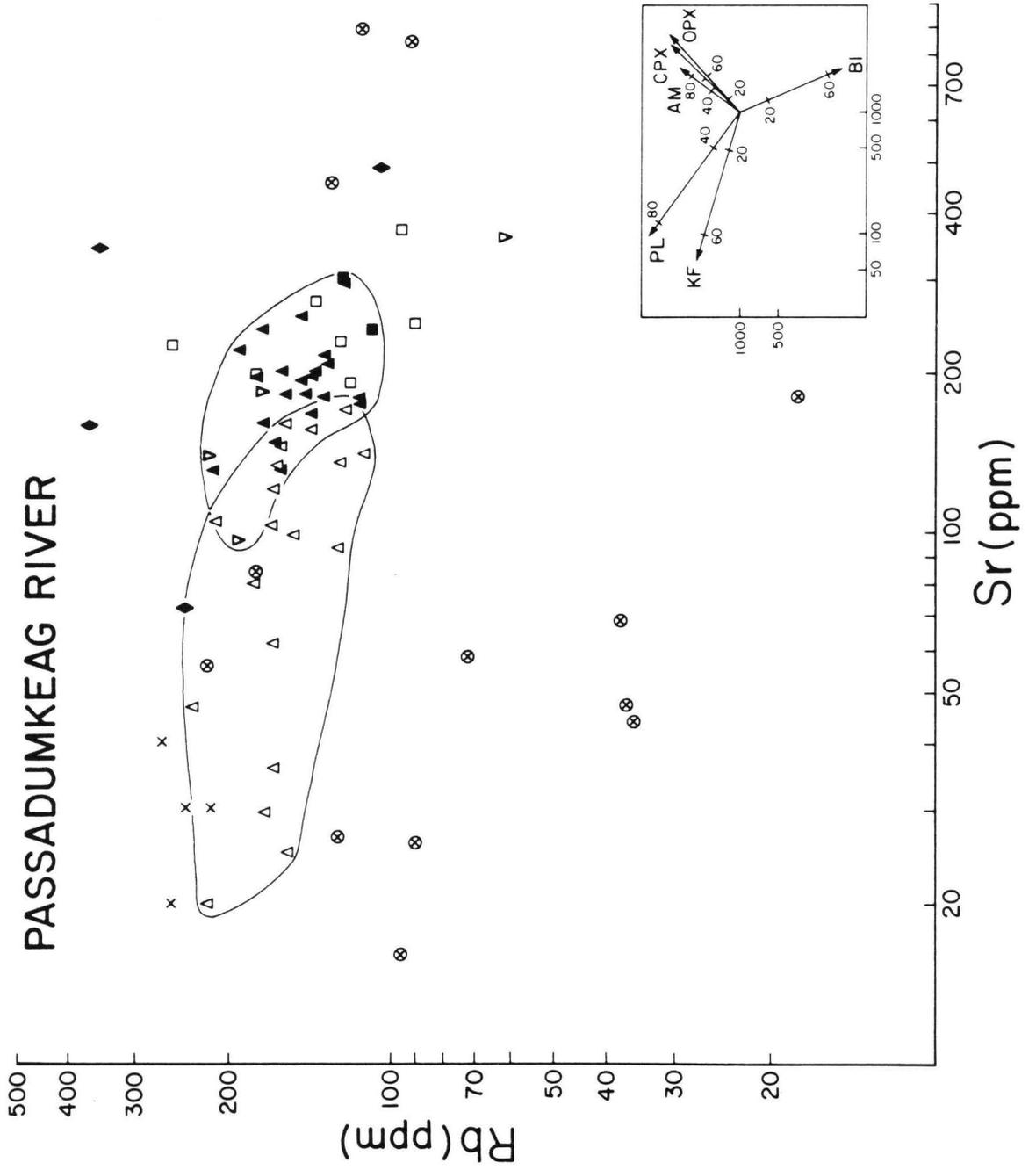
Aplite and rim facies rocks tend to have higher Rb and lower Sr concentrations. This feature suggests that fractionation of major silicate phases account for some of the chemical diversity. Fractionation of amphibole, biotite, and plagioclase is consistent with the broad scatter of composition.

Mafic xenoliths are characteristically heterogeneous in composition and show enrichment in Sr and depletion in Rb. Sr abundances range from about 190 to 380 ppm and are inversely correlated with SiO_2 (Fig. 18, 19). Xenoliths generally display Sr concentrations equivalent to the granite but in some cases they have lower Sr than the more felsic granitic host rocks. No simple fractionating scheme accounts for the compositional change from the mafic xenoliths to the host granitoids.

The enormous heterogeneity shown by the country rock inclusions and wall rocks argues against their control over the composition of the pluton (Fig. 13). Even if reactions between felsic magma and wall rock occurred, these were of minor importance in determining the observed abundances. This is suggested by the clustering of each facies regardless of the composition of the wall rock.

FIGURE 19.

Variation of Rb with Sr in the Passadumkeag River pluton. Symbols are as in Figs. 9 and 11. Insert as in Fig. 15.



Y, Ba, Zr

Preliminary analyses of Y, Ba, and Zr in the Bottle Lake Complex are consistent with the zonation of the granites (Table 9-11). All of these elements are enriched in the interiors compared to the rim facies of each pluton (Fig. 20-22).

Yttrium shows a sympathetic variation with Ca and supports the presence of a fractionating phase other than plagioclase and biotite. As previously suggested from petrographic and REE arguments, both apatite and hornblende are candidates that have the potential for concentrating this element (Lambert and Holland, 1974).

Barium variation in the plutons is also in agreement with reverse zonation (Fig. 21), but it is significantly more scattered than Y and Zr. Much of this scatter probably results from secondary effects on alkali feldspar and biotite, as these phases probably represent the primary recipients of Ba in the Bottle Lake Complex.

Zirconium variation in the batholith supports the qualitative observation concerning the relative enrichment of zircon in the core facies of the plutons (Fig. 22). However, neither pluton shows distinct trends on the basis of these analyses.

The compositions of the mafic xenoliths are significantly more scattered than the host granitoids especially in the case of Ba (Fig. 21), but also for Zr (Fig. 22) and Y (Fig. 20). Because of the variation in composition, differentiation trends and mixing lines are difficult to evaluate graphically.

FIGURE 20.

Variation of Y with SiO_2 in the Bottle Lake Complex. Symbols as in Figs. 9 and 11.

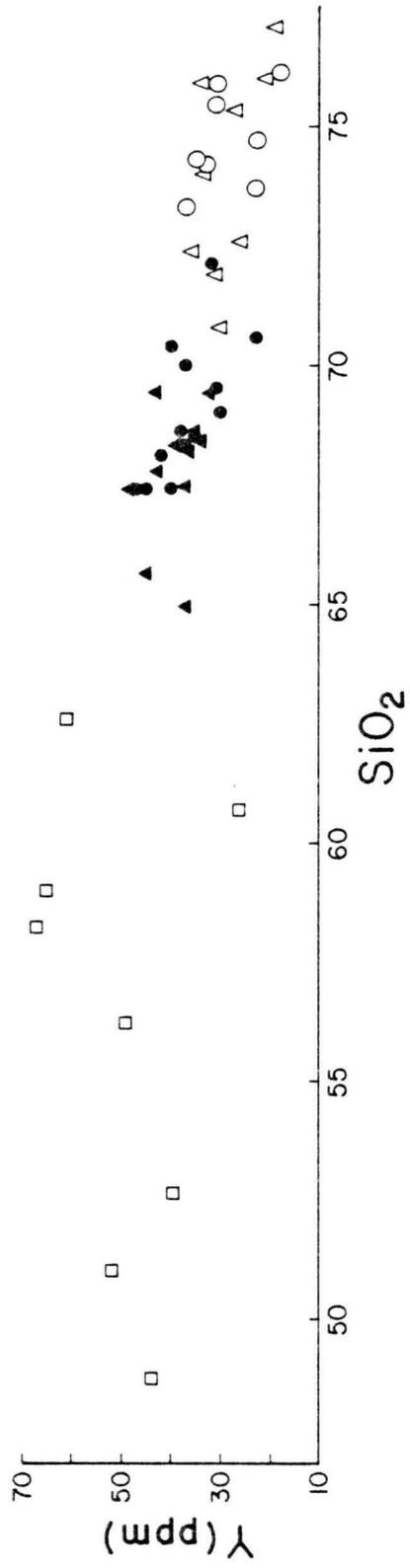


FIGURE 21.

Variation of Ba with SiO_2 in the Bottle Lake Complex. Symbols as in Figs. 9 and 11.

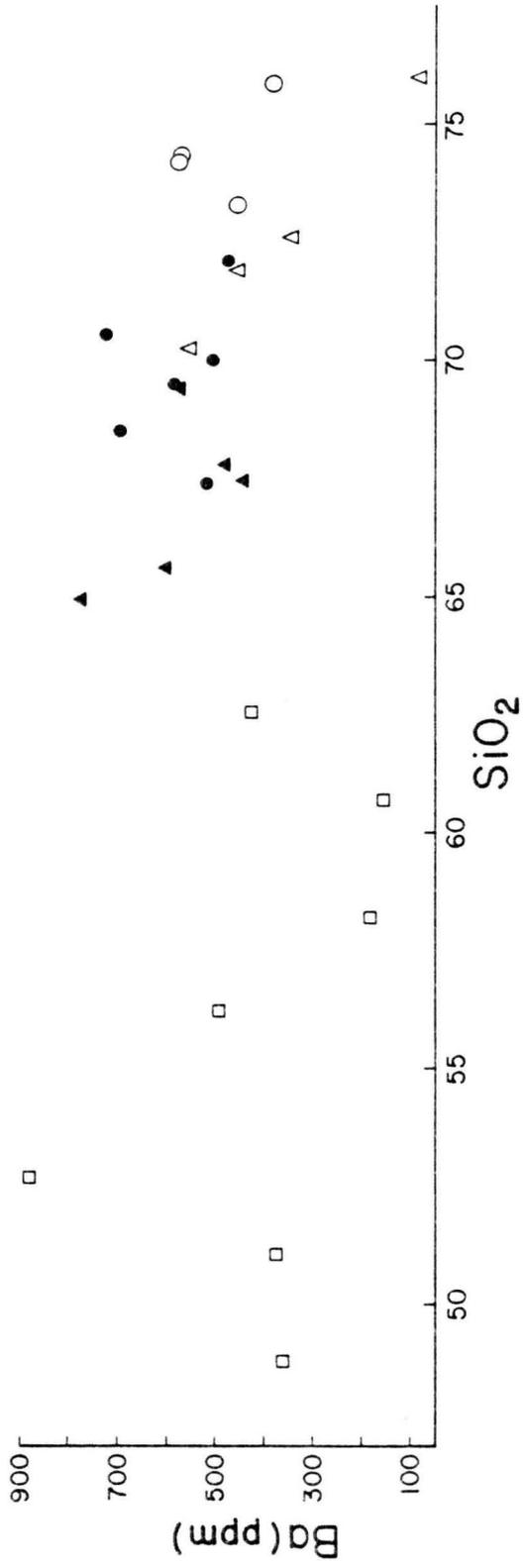
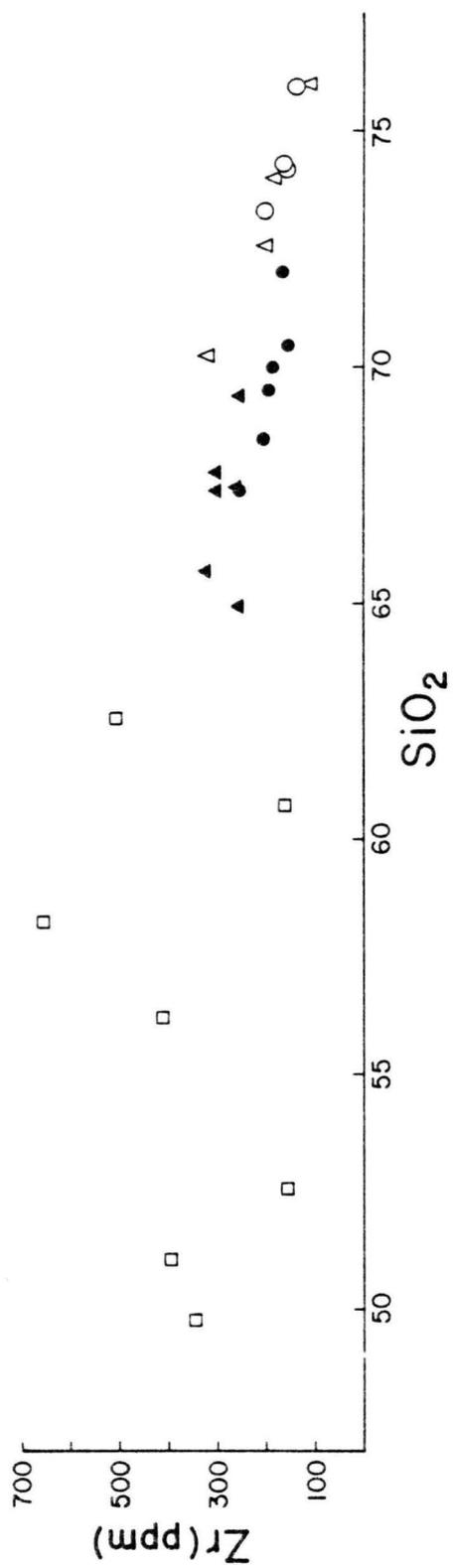


FIGURE 22.

Variation of Zr with SiO_2 in the Bottle Lake Complex. Symbols as in Figs. 9 and 11.



FRACTIONATION AND MIXING CALCULATIONS

Major Elements

This section presents the results of calculations using the least squares computer program of Wright and Doherty (1970) to evaluate the processes of fractional crystallization and mixing on the evolution of the Bottle Lake Complex. These results are followed by calculations using a computer program by J. G. Arth (U.S. Geological Survey) in order to identify and quantify the fractionating assemblage using selected trace and rare earth elements.

The most difficult decisions from the application of computer modelling schemes are made on geological grounds. This is invariably the case because of the subjectivity in choosing a parental rock and crystallizing assemblage. Modelling of major element fractionation in the Bottle Lake Complex was pursued following two approaches: 1) by considering the average composition of each facies; and 2) by stepwise fractionation from the most mafic to the most felsic rocks in each pluton. Both of these approaches were successfully followed by Erikson (1977) when he considered the fractionation of the Mt. Stuart batholith.

The results on Table 13 suggest that most of the major oxide variation from core to rim facies in each pluton is a result of fractional crystallization. Fractionation of the average core facies sample toward the average rim in Whitney Cove pluton explains the geochemical variation of the pluton (Table 13). This result is duplicated if fractionating schemes from individual core rocks to rim rocks are performed, or if the fractionating scheme is done stepwise

TABLE 13. Results of fractionation from core to rim facies and mixing in the Bottle Lake Complex

		FRACTIONATION						
		FRACTIONATING MINERALS					REMAINING LIQUID	LARGEST RESIDUAL
		PL (plagioclase)	BT (biotite)	HB (horn- blende)	AP (apatite)	MT-IL (magnetite- ilmenite)		
Average, Whitney Cove, core facies	Average, Whitney Cove, rim facies	13.0	5.0	0	0.5	0.5	81	+0.30 CaO
Average, Passadumkeag River, core facies	Average, Passadumkeag River, rim facies	17	8.0	0	0.5	0	75	+0.28 K ₂ O
62M	63M	0	8.0	24.0	2.6	3.5	62	+1.04 MgO
63M	66M	34.0	1.0	14.0	0	1.0	51	+0.56 Na ₂ O, K ₂ O
66M	36C	16.0	8.0	0	0	0	76	+1.17 K ₂ O

		MIXING					LARGEST RESIDUAL
		PARENT				HYBRID	
		62M	63M	66M	59R	= 52C (Whitney Cove, core)	-0.22 Na ₂ O
Solution		2%	22%	27%	49%	= 100%	-0.22 Na ₂ O
		62M	63M	66M	59R	= 36C (Passadumkeag River, core)	-0.24 Na ₂ O
Solution		7%	21%	31%	41%	= 100%	-0.24 Na ₂ O

from least to most siliceous rocks. Residuals are invariably less than 0.30 and are in general attributed to excess CaO or alkalis.

Crystallization of about 19% of the liquid in equilibrium with 13% plagioclase, 5% biotite, 0.5% apatite, and 0.5% magnetite-ilmenite account for the variation from the core to rim facies.

The results from the Passadumkeag River pluton (Table 13) suggest a more complicated process. About 75% of the liquid remains after crystallization of 17% plagioclase, 8% biotite, and 0.5% apatite if averages of the core and rim are evaluated. However, on calculations involving individual rocks from each facies the proportions of each phase varies several percent (1-5%) as does the fraction of the liquid. This is in agreement with the petrographic heterogeneity of the pluton and demonstrates the overall variability of samples from individual facies. The most important result from these calculations is the identification of plagioclase, biotite, and apatite as the controlling assemblage in the petrological evolution of the plutons.

However, a central problem in the petrogenesis of the Bottle Lake Complex is the selection of geologically reasonable parental magma. This problem is closely related to the genesis of the mafic xenoliths in the batholith. Stepwise fractionation of the mafic xenolith suite (Table 11) and the granite of Passadumkeag River consistently yields high residuals.

Results of mixing the composition of mafic xenoliths (samples 62M, 63M, 66M) with the most felsic sample assumed to represent a minimum granitic melt (sample 59R) yields hybrid magmas representative of the core facies (samples 52C, 36C) of each pluton (Table 13). Residuals are typically less than 0.25 and are usually accounted by Na_2O .

Hybrid rocks in the Whitney Cove pluton differ from those in Passadumkeag River primarily on the importance of the most mafic xenolith (sample 62M) and the most felsic composition (sample 59R) in the mix. Calculations using two component mixing between any mafic xenolith and sample 59R, three component mixing or four component mixing other than the successful ones yield inadequate solutions (Table 13). Five component mixing, including the correct four components, provide solutions with high residuals but eventually converge on the correct four components previously identified.

The calculations support the argument that for mixing to yield low residual solutions it must include the most mafic xenolith (62M) representative of the basaltic group, the most mafic xenolith of the quartz-diorite group (63M), the most silicic xenolith (66M), and the granite minimum melt (59R). Addition or subtraction of extra mixing components yields high residual solutions. In this manner, the composition of parental rocks in the core facies of each pluton is successfully approximated by mixing of mafic xenoliths with the assumed composition of a minimum melt.

Trace and Rare Earth Elements

Modeling of the fractionating assemblage using coefficients for Rb, Sr, and the rare earth elements summarized by Arth (1976), yielded solutions generally in agreement with those obtained from major element calculations (Table 14). This was especially obvious in the case of the Whitney Cove pluton and resulted in the assemblage: 67% plagioclase, 30% biotite, and 3% apatite, by fractional crystallization of about 25%

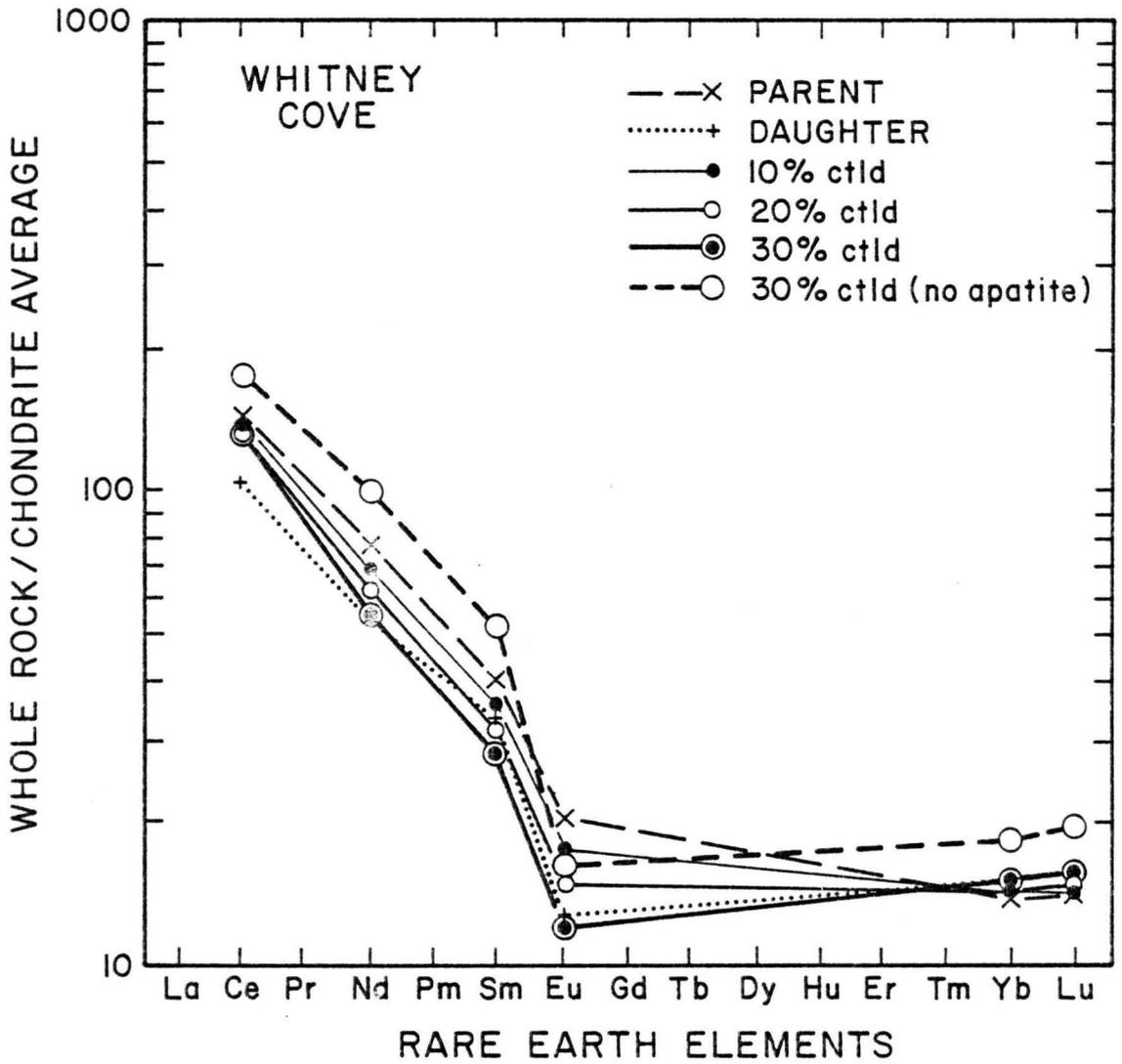
TABLE 14. Results of fractional crystallization of two mineral assemblages in the Bottle Lake Complex.

WHITNEY COVE								
Sample	58C	Fractional Crystallization					59R	
	Parent	(0.67 PL + 0.30 BI + 0.03 AP)			(0.69 PL + 0.31 BI)		Daughter	
		20%	30%		30%			
Rb	147	157	164		162			155
Sr	231	147	112		110			100
Ba	570	355	268		258			384
Ce	115.0	107.0	103.0		148.4			82.9
Nd	43	34.9	30.7		56.5			31.0
Sm	7.3	5.8	5.0		9.8			6.2
Eu	1.4	1.0	0.8		1.1			0.9
Yb	2.9	2.9	3.0		3.9			3.1
Lu	0.5	0.5	0.5		0.7			0.5

PASSADUMKEAG RIVER								
Sample	Parent	Fractional Crystallization					8R	35R
		(0.70 PL + 0.23BI + 0.3 HB + 0.04 AP)			(0.72 PL + 0.24 BI + 0.04 HB)		Daughters	
		20%	30%	50%	30%	50%		
Rb	138	146	150	162	148	159	124	163
Sr	222	207	189	179	196	173	172	134
Ba	577	656	774	860	704	848	553	460
Ce	105.0	94.2	81.9	75.0	145.0	196.0	38.8	138.0
Nd	44.0	32.5	22.0	17.2	61.1	83.3	24.0	47.0
Sm	8.9	6.3	4.0	3.0	12.4	16.9	6.1	8.0
Eu	1.8	1.6	1.4	1.3	2.3	3.0	1.3	1.2
Yb	4.3	4.3	4.2	4.2	6.0	8.1	2.6	3.5
Lu	0.6	0.6	0.6	0.6	0.8	1.1	0.4	0.5

FIGURE 23.

Rare-earth element variation in the granite of Whitney Cove assuming the assemblages of Table 14 at different degrees of fractional crystallization.



of the liquid represented by sample 52C (Fig. 23). Despite the heterogeneity in the rare-earth and trace element compositions, fractionation of sample 52C to sample 59R (presumed to represent a granite minimum melt) reproduces the lower MREE content, the crossing of the HREE, and the concentrations of Rb and Sr.

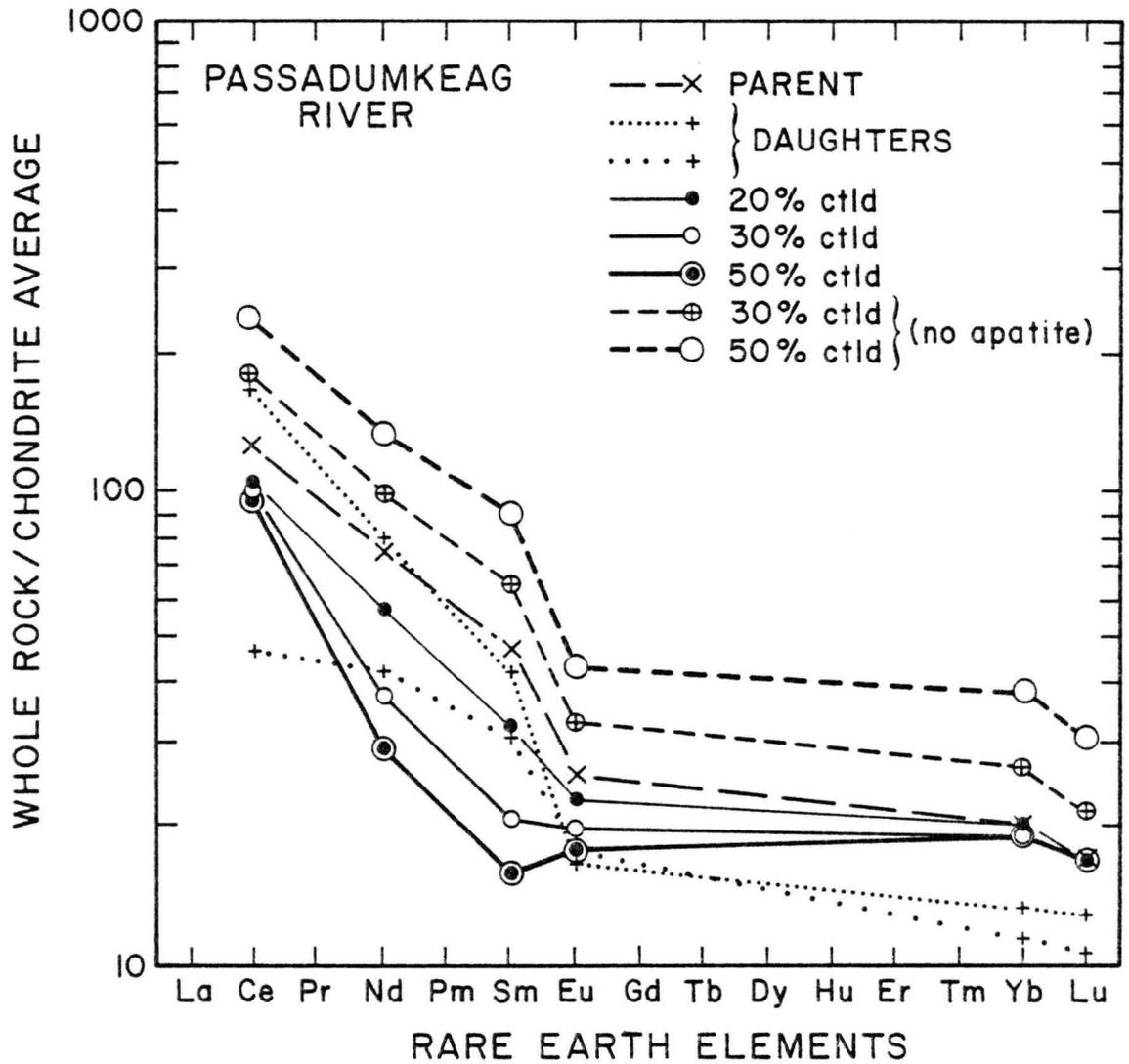
Another phase is suspected to effect the drop in the normalized chondrite pattern for the LREE (allanite?). A process such as loss of a REE-enriched vapor phase is also considered likely because similar variations were observed in granites from Alaska (Hudson and Arth, 1981). The significant effect of the volatile phase on REE, especially the HREE depletion in subalkaline granites and its relation to pegmatite formation was discussed by Buma, et al. (1971).

One of the most interesting observations in the study of the BLC is the importance of apatite in dropping the absolute concentration of REE and rotating the pattern from one characterized by LREE-enrichment to a less fractionated pattern culminating in the crossing of the HREE. This is demonstrated by the shape of the composition of the resulting liquid if apatite were excluded from the assemblage (Fig. 23).

Results from fractional crystallization in the Passadumkeag River granite of sample 36C representative of the mafic core, to sample 8R belonging to the most silicic sample analyzed from the rim, are generally equivalent to the assemblage at Whitney Cove. Crystallization of 30% of liquid by subtraction of 72% plagioclase, 19% biotite, 5% apatite, 3% hornblende, and 1% zircon yield patterns similar in their depletion of the MREE, and unfractionated nature of the HREE (Fig. 24). However, as in the Whitney Cove pluton, the drop in the LREE suggests

FIGURE 24.

Rare-earth element variation in the Passadumkeag River pluton assuming the assemblages given in Table 14. Note the range of compositions shown by the daughters and the results of different degrees of fractional crystallization.



that another phase, possibly allanite, accounts for that effect. The dramatic importance of adding apatite to the assemblage is demonstrated in Fig. 24. However, in the Whitney Cove pluton, the drop in the LREE probably reflects the presence of allanite. In a study involving the relationship between granites and their aplites, Hon and Noyes (1977) discovered that removal of allanite in Sierra Nevada granites resulted in a similar drop in the LREE.

EVOLUTION OF THE BOTTLE LAKE COMPLEX

Nature of the Source

The Bottle Lake Complex results from a complicated evolutionary process which started with the generation of granitic melts from a heterogeneous source, probably as this source was heated by basaltic liquids. However, evidence for substantial interaction of basaltic and granitic liquids is absent in the Complex.

The predominance of continental crust in comparison to mantle-like material in the evolution of granites was shown in the isotopic studies of Allegre and Othman (1980) and Hamilton et al. (1980). In the BLC the Pb isotopic signature is more reminiscent of upper continental material in contrast to the environment characterized by the lower continental crust. Lead isotopic studies are critical in distinguishing the input of cratonized crust which characterizes the lower continental crust. The lead isotopic composition of the BLC is consistent with materials that accumulated lead in environments with higher U/Pb ratios than are typical in granulite facies terranes. Preliminary Rb/Sr work

in the BLC suggests that the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio is about 0.705 (Ayuso and Wones, 1980a).

Additional clues suggestive of the type of source are evident from the mineralogy and composition of the batholith. The general type of source is classified as igneous (I-type) in the manner of Chappell and White (1974) or as belonging to the magnetite-series of Ishihara (1977). However, the geochemical heterogeneity of the mafic xenoliths, presence of a mixed zircon population, and isotopic heterogeneity of granites and xenoliths support the existence of a heterogeneous source for the batholith.

Xenoliths in the BLC are not related to the granites by closed system fractionation. Instead, they suggest a multiple source. Variability in the geochemistry of xenoliths studied from many granitic plutons suggests that heterogeneous sources may be the rule rather than the exceptions. Hanson (1980) suggested that even for small granitic intrusions the volume of partial melting of the source is likely to include a collection of rock types. The importance of a heterogeneous source to explain the geochemistry of granitic rocks in the Central Pyrenees was demonstrated by Michard-Vitrac et al. (1980), and in the Scottish Caledonides by Halliday et al. (1980).

On the basis of the heterogeneity expressed by the BLC, its evolution is compatible with derivation from older volcanoclastic deposits (Ayuso et al., 1980b). Such deposits are characterized by a wide range in lithologic types, and degrees of alteration (Williams and MacBirney, 1979). Wones (1981) noted that granitic rocks emplaced in congruent plate margins are characteristically oxidized, as are the

volcanic rocks from island arc environments studied by Ewart (1979). Melting of a source consisting of volcanic materials and sediments from the continents represents the most adequate source of the plutons in the BLC. It is possible that the difference between the sources of the granites within the BLC lies perhaps on the increased role of sediments in the Whitney Cove pluton.

Origin of the Bottle Lake Complex

The origin of the Bottle Lake Complex probably involves the following: 1) production of granitic liquids through melting of the source materials; 2) pooling and mixing of liquids derived from melting of the source rocks; and 3) fractionation and ascent into the upper crust. In this model, the concentration of calcemic constituents in the interior of the plutons is derived primarily from the process of fractional crystallization. However, the most notable difference between the granites in the Bottle Lake Complex depends on whether the magmatic system represented by each pluton was thoroughly mixed as new batches of liquid were added prior to large scale fractional crystallization (Whitney Cove), or during fractionation (Passadumkeag River).

In the case of the Whitney Cove pluton, melting of a heterogeneous source (volcaniclastics and sediments) produced granitic liquids which at first were probably, but not necessarily, minimum melts. Heat was provided from the passage and storage of basaltic liquids in the granitic source region, but without significant interaction by mixing of basaltic liquid and granitic melts. Continued melting of the

heterogeneous source resulted in the production of liquids progressively more removed from minimum melt composition. Pooling and thorough mixing of the system ensued and was followed by the onset of fractionation. Emplacement of the core facies of the Whitney Cove pluton was preceded by the more felsic rim facies, perhaps by the process of autointrusion of remobilized refractory material (Ayuso and Wones, 1980).

In contrast with the "closed" and thoroughly mixed system described for the pluton of Whitney Cove, the Passadumkeag River granite represents a magmatic system characterized by periodic replenishment and feeding of granitic liquids simultaneously with crystallization and fractionation. Even allowing for major geochemical similarities between the batches of liquid, it is reasonable to suggest that each new batch added to the system altered the existing liquid-crystal equilibrium and resulted in reequilibration of the crystallized minerals.

Despite the tendency to achieve equilibrium in the liquid-crystal mush, perhaps due to kinetic and mechanical factors, complete homogenization was not achieved. This explains the geochemical and mineralogic heterogeneity of the pluton in contrast with the more regular geochemical gradients present in the Whitney Cove granite. The mafic xenoliths in the Passadumkeag River pluton represent residual material inherited from the source and their geochemical heterogeneity is a reflection of the diversity of materials available for melting. These xenoliths were carried upward, probably in granitic liquids derived from high degrees of melting, and delivered into a fractionating system. However, total disaggregation and equilibrium was not reached in the system as numerous xenoliths of contrasting composition still

remain within the core facies. Because of the successive addition of melt and of a xenolith-laden mush into a fractionating system, equilibrium between liquid and crystals was more difficult to attain than previously described in the Whitney Cove pluton. Subsequent fractionation and concentration of refractories followed. As in the Whitney Cove granite, the resurgent core was remobilized and intruded into the carapace formed by the rim facies.

COMPARISON WITH NEARBY GRANITES

The plutons emplaced in the core of the Merrimack synclinorium are the Bottle Lake Complex and a small intrusion known as Center Pond. These granites are petrographically (Ayuso and Wones, 1980) and geochemically similar (Ayuso et al., 1980a; Loiselle and Ayuso, 1980; A. Andrew, pers. comm., 1981). The Center Pond pluton has many of the attributes of the Passadumkeag River granite and its origin was associated with the process of unmixing (Chappell and White, 1974) by Scambos (1980). Because of its petrographic and major element similarity with the Passadumkeag River granite, coupled with its Pb isotopic homogeneity, an origin by mixing liquids and assimilation followed by emplacement is also possible. The striking colinearity of major oxide variations may have resulted from gradual but complete equilibration by interaction of a minor and compositionally fixed endmember (basaltic) with granitic liquid. Fractional crystallization was unimportant, as suggested by the highly regular variation of the major elements (Scambos, 1980).

Acadian plutons emplaced along a traverse through the Merrimack synclinorium (Katahdin, Seboeis, Center Pond, Bottle Lake, Lucerne, Lead Mountain, Cranberry Lakes) are distinguishable in their major element composition (Loiselle and Ayuso, 1980) and Pb isotopic makeup (Ayuso et al., 1980) with respect to whether they intrude north or south of the Norumbega fault system (Fig. 1). Plutons intruded in the core of the synclinorium belong to the group north of the fault. Granites south of the fault (Lucerne and Lead Mountain) are enriched in K_2O and have higher K_2O/Na_2O ratios. These plutons are also characterized by higher values of $^{206}Pb/^{204}Pb$ at a given $^{207}Pb/^{204}Pb$ in comparison to the granites north of the fault.

Because of the absence of geochemical variations commonly associated with plutonism along subduction zones, plutons in east-central Maine contrast with the Sierra Nevada batholith (Bateman and Dodge, 1970) and argue against an origin from similar processes (Wones, 1980). Similar studies discussing the geologic evolution of the Caledonian plutons in the British Isles (Brown et al., 1979) suggested that the correlation between plutonism and plate subduction was unclear.

Other studies in the northern Appalachians recognized that the granitoid plutonic rocks of Newfoundland exhibited geochemical variations which could not be ascribed to subduction as in the circum-Pacific (Strong, 1980). Instead, Strong (1980) recognized geochemical variation in tectonic zones independent of gradient. Many of the plutonic types in Newfoundland are also recognizable in New Brunswick (Fyffe et al., 1980), although in the latter, tectonic zones are not evident. Geochemical comparison of these plutons led Fyffe et al.,

(1980) also to doubt a direct correlation of plate subduction to the origin of Acadian plutonism in New Brunswick.

Recognition of tectonic basements or zones in Australia (White et al., 1976) and southeast Asia (Beckinsale, 1979) resulted from classification of the granites into S (sedimentary) or I (igneous) type of sources. A similar approach in east-central Maine yields the recognition of three general groups. The northernmost plutons (Katahdin, Seboeis), the granites in the core of the synclinorium (Bottle Lake Complex, Center Pond), and those across the Norumbega fault (Lucerne, Lead Mountain, Cranberry Lakes). A broadly similar three-fold distinction of basement types was proposed by Osberg (1978) on the basis of stratigraphy and isotopic ages. Although he distinguishes two different basements under central and southern Maine no distinction is made between the core and northern limb of the Merrimack synclinorium.

Regardless of the process involved, the geochemical variation of the plutons indicates the existence of different granitic sources across the synclinorium. Continuous volcanism in New England, at least from the Cambrian to the Devonian (Hynes, 1976; Moench and Gates, 1976) appears to be the rule (Wones, 1980), and granitic liquids probably resulted from heat transfer from basaltic magma long after closure of the Ordovician ocean.

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APPENDIX

Modal Determinations

Modal analyses of 150 granite samples were made after slabbing and staining the feldspars by the method of Boone and Wheeler (1968). Representative samples are shown in Fig. 1 and Table 15. Each slab had minimum dimensions of 20 x 20 cm. Routine point counting of 1000-2000 points using mainly a 0.3 x 0.3 cm grid was employed to distinguish the feldspars, quartz, and the total of the mafic minerals. Examination of appropriate thin sections was used to apportion between biotite, amphibole, and the accessory minerals.

A few of the slabs were smaller than statistically permissible for very coarse-grained rocks. According to the method of Van der Plas and Tobi (1965), the best estimate of the uncertainty in the modal analyses is $\pm 2\%$ depending on slab size, grid size, and the number of points counted.

Mineral Chemistry

Seventy samples were analyzed using an automated ARL 9-channel microprobe and a variety of silicate and oxide standards. In most cases analyses were made with operating conditions of 15 KV (voltage) and about 150 nanoamps (current) with data reduction by Bence and Albee (1968).

The maximum compositional variation estimated by microprobe analyses is shown by the standard deviation. For biotite, SiO_2 (0.6), Al_2O_3 (0.3), FeO (0.7), MgO (0.4), MnO (0.02), TiO_2 (0.1), CaO (0.1),

Na₂O (0.01), K₂O (0.3), F (0.4), and for Cl (0.07). Maximum deviations in amphibole are as follows: SiO₂ (0.3), Al₂O₃ (0.5), FeO (0.3), MgO (0.2), MnO (0.03), TiO₂ (0.1), CaO (0.08), Na₂O (0.1), K₂O (0.05), F (0.4), and Cl (0.03). Plagioclase cores or rims, averaged separately show similar deviations: SiO₂ (0.4), Al₂O₃ (0.4), CaO (0.15), Na₂O (0.3), and K₂O (0.2). Typical variations in magnetite and ilmenite are as follows: for magnetite, FeO (0.50), TiO₂ (0.15), and MnO (0.10); in ilmenite, FeO (0.7), TiO₂ (0.6), and MnO (0.5).

A minimum of ten analyses per grain were made in the essential minerals of each sample trying to detect variations within and between grains. Opaque and accessory phases were analyzed in selected samples.

Twenty alkali feldspar concentrates were homogenized (sanidinized) and analyzed by X-ray powder diffraction techniques (Wright, 1968) to estimate their structural state and composition.

Whole Rock Composition

Ninety samples were cleaned, crushed and split for major and trace element analysis. Fused glass beads were made following the technique of Norrish and Hutton (1969), modified by Harvey and others (1973). These were analyzed by standard X-ray fluorescence methods for all the major oxides except Na₂O. Splits obtained from the same samples were used to make pressed powder pellets using the matrix correction methods of Reynolds (1963), for analysis of Rb, Sr, Y, Ba, and Zr. Sodium was analyzed in pressed powder pellets. Additional analyses of Y, Ba, Zr were made at the U.S. Geological Survey, Reston, Virginia (R. Johnson, pers. comm. 1981), in pressed powder pellets using an Energy Dispersive

unit (KEVEX). Standards for all major and trace element calibrations were made using the U.S.G.S. (PCC-1, GSP-1, BCR-1, AGV-1, and G-2) powders. The precision of SiO_2 , Al_2O_3 , TiO_2 , Fe_2O_3 , CaO , and K_2O is probably better than 1% of the amount, whereas values of about 3% are characteristic of MgO and Na_2O , and about 0.01% for MnO and P_2O_5 . The standard GSP-1 was used for trace element analyses of Ba, Rb, Sr, and Zr with precisions better than 3%. All calibrations at the V.P.I. & S.U. laboratory were done by M. Loiselle.

Rare-earth element compositions were determined by neutron activation analysis at the Massachusetts Institute of Technology (F. Frey, pers. comm., 1980), and at the U.S. Geological Survey.

Whole-rock and Feldspar Lead

Thirty samples were selected for Pb isotopic work and consisted of twenty-six whole rocks and alkali feldspar from the granites and mafic xenoliths, and four from the country rocks intruded by the Bottle Lake Complex. All samples weighed at least 10 kg and these were crushed and cleaned by standard hand magnet, heavy liquid, and hand-picking methods. Samples were dissolved in HF and HNO_3 acid in teflon bombs. They were picked up in a solution of HBr + HCl and eluted through a bromide resin column. Lead was recovered by stripping with 6-N HCl while U was obtained by washing the columns in 7N HNO_3 .

All Pb runs were made on rhenium filaments by dissolving in phosphoric acid and loading with one drop of silica-gel solution. A mass spectrometer with a curvature of 35 cm was employed throughout the study. Repeated running of the California Institute of Technology (CIT)

standard and numerous checks on the total chemistry blank were made to monitor the analytical procedure. All samples were normalized to the absolute values of Catanzaro (1967) obtained on the CIT standard. The low level of the Pb blank (less than one nanogram) suggested that no correction was necessary in the reported values.

TABLE 15. Sample distribution, location, and modal composition of the granites in the Bottle Lake Complex

GRANITE OF PASSADUMKEAG RIVER							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
1R	NL-A-25	5687	500170	--	--	--	--
2R	NL-A-203	5738	50017	27.8	29.7	39.9	2.6
6R	NL-B-109	5649	50012	24.4	19.9	50.1	5.6
8R	SP-D-52	5749	50232	18.8	45.0	25.0	11.2
10R	SP-D-26	5096	50198	19.0	41.4	28.8	10.8
12R	SA-B-101	5468	50000	25.4	24.4	45.4	4.8
14R	SP-D-12	5707	50171	27.1	26.5	45.2	1.2
15R	SP-D-25	5700	50214	27.8	25.4	44.4	2.4
18R	SP-D-129	5701	50214	23.4	31.3	40.7	4.6
19R	SP-D-133	5696	50217	19.2	41.2	28.9	10.7
23R	NL-B-110	5682	49992	19.8	29.3	42.1	8.8
27R	SP-C-103	5675	50195	25.8	27.2	38.4	4.6
30R	NL-A-16	5762	50052	28	21.2	48.6	2.2
35R	NL-A-2	5728	50006	21.6	33.2	34.4	10.8
74R	SL-C-115	5835	50212	16.6	23.6	56.0	3.8
76R	SP-D-15	5627	50193	20.5	28.3	44.0	7.2
77R	SP-D-121	5125	50198	21.6	40.6	27.8	9.8
80R	SA-A-112	5584	49960	27.0	24.7	42.7	5.6
88R	SP-C-11	5648	50188	20.8	31.3	41.1	6.8
89R	SP-D-6	5768	50207	15.8	42.6	30.8	10.8

TABLE 15 (continued)

PASSADUMKEAG RIVER (continued)							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
90R	SP-D-22	5687	50217	28.2	31.5	40.9	4.4
3C	NL-B-106	5643	50091	13.2	51.8	23.6	11.4
4C	NL-B-107	5650	50088	17.2	36.1	31.9	14.6
5C	NL-B-108	5638	50013	22.2	29.4	41.4	7.0
9C	WI-D-101	5542	50142	13.2	11.5	31.7	13.6
11C	NL-B-21	5668	50024	26.4	38.2	28.6	8.8
13C	SL-B-113	5785	50241	25.0	29.0	38.4	7.6
16C	SP-D-40	5712	50110	22.6	32.4	36.0	10.0
17C	SP-D-107	5768	50224	19.0	35.8	35.4	9.8
20C	SP-D-141	5744	50129	20.5	38.8	28.9	12.3
21C	WI-D-34	5515	50192	22.2	31.6	36.8	9.4
22C	WI-D-49	5557	50185	22.2	29.8	33.8	14.2
24C	NL-A-9	5715	50060	18.1	36.5	33.3	12.1
25C	WI-D-43	5562	50179	21.1	25.6	40.9	12.4
26C	NL-B-2	5603	50050	13.7	40.9	35.1	10.2
28C	SL-C-116	5827	50218	18.2	38.8	30.6	12.4
29C	SL-C-117	5833	50221	10.4	42.0	38.4	9.2
31C	NL-B-6	5614	50021	17.1	38.2	37	7.7
32C	SA-A-2	5491	50038	20.4	33.6	33.2	13.0
33C	SP-D-5	5725	50198	21.6	20.6	27.8	12.3

TABLE 15 (continued)

PASSADUMKEAG RIVER (continued)							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
	SP-D-30	5750	50141	17.2	42.4	27.6	12.8
36C	NL-A-13	5717	50075	16.1	42.9	27.0	13.9
66C	SP-D-36	5753	50137	17.4	42.4	27.2	12.6
73C	SA-A-1	5496	50038	14.0	37.2	37.8	11.0
75C	SP-C-7	5656	50140	9.6	48.4	20.2	21.8
78C	SL-C-118	5785	50216	23.2	29.0	41.6	6.2
79C	SA-A-11	5519	50069	20.2	34.4	40.2	5.2
81C	WI-D-104	5542	50117	22.2	44.4	24	9.4
82C	WI-D-103	5543	50127	18.6	38.5	33.3	9.1
84C	SP-C-5	5669	50157	16.4	37.4	39.0	7.4
86C	NL-A-103	5724	50104	16	39.1	30.1	14.8
91C	WI-D-54	5538	50201	22.4	29.8	33.6	14.2
105C	SL-B-112	5805	50245	20.2	38.4	31.8	9.6
MAFIC XENOLITHS							
61M	SL-C-30	5810	50184	—	—	—	—
62M	SL-C-31	5810	50184	—	—	—	—
63M	SP-D-50	5748	50233	—	—	—	—
64M	WI-D-101	5542	50142	—	—	—	—
65M	WI-D-49	5557	50185	—	—	—	—

TABLE 15 (continued)

MAFIC XENOLITHS (continued)							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
66M	SP-D-36	5753	50137	—	—	—	—
71M	WI-D-102	5542	50142	—	—	—	—
99M	SL-C-21	5813	50184	—	—	—	—
GRANITE OF WHITNEY COVE							
38R	SL-D-22	5922	50159	27.4	23.2	46.0	34
39R	SL-D-26	5925	50129	24.4	37.4	34.1	4.1
40R	SL-D-57	5939	50123	29.5	29.3	37.7	3.2
41R	SL-B-116	5819	50265	34	28	34.2	3.8
42R	SL-D-63	5933	50219	29.9	29.0	37.3	3.8
43R	SL-D-70	5912	50223	28.2	24	44.4	3.6
45R	WL-B-63	5823	50064	25.1	27.2	43.1	4.6
46R	WL-B-41	5786	50107	30.8	26.1	40.5	2.6
47R	SL-D-12	5937	50176	29.0	29.5	37.5	4.0
54R	SL-C-58	5841	50146	31.0	26.6	38.6	3.8
55R	SL-C-62	5842	50157	28.8	25.5	43.0	2.7
56R	WL-A-20	5913	50017	23.1	30.0	43.7	3.2
57R	WL-B-5	5811	50062	26.7	25.3	42.4	5.6
59R	SL-D-102	5956	50173	29.0	26.0	42.8	2.2
85R	SL-C-130	5846	50166	28.8	30.0	36.2	5.0

TABLE 15 (continued)

WHITNEY COVE (continued)							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
93R	SL-B-117	5827	50260	33.0	25.0	37.0	5.0
94R	SL-B-111	5812	50260	46.0	22.4	27.6	4.0
95R	76-8-8	5931	50115	24.2	34.6	37.0	4.2
96R	76-8-10	5845	50148	25.8	26.4	43.4	4.4
97R	ME-23	5978	50354	17.2	48.8	21.2	2.8
98R	SL-D-4	5887	50233	32.0	26.2	37.2	4.6
104R	SL-D-60	5928	50137	15.8	26.5	46.7	10.6
37C	SL-C-141	5878	50165	21.8	45.2	29.4	3.6
44C	SL-D-108	5892	50155	20.4	49.6	26.4	3.2
49C	SL-C-108	5833	50137	26.4	37.0	32.4	4.2
50C	SL-C-17	5845	50142	23.4	40.2	33.6	2.8
51C	SL-C-39	5878	50113	26.6	37.2	31.2	5.0
52C	SL-C-45	5859	50130	27.0	38.0	24.0	11.0
53C	SL-C-53	5825	50165	26.8	42.4	26.6	4.2
58C	SL-C-18	5852	50146	26.6	23.8	34.8	4.8
60C	SL-C-111	5852	50120	29.0	29.3	36.7	4.6
92C	SL-D-23	5914	50132	15.5	33.2	44.6	6.2

TABLE 15 (continued)

COUNTRY ROCK XENOLITHS							
Sample		UTM Coordinates		Mode			
Lab	Field	x	y	Q	PL	ALK	MAFIC
67CR	SP-D-42	5753	50245	—	—	—	—
68CR	SP-D-17	5744	50238	—	—	—	—
69CR	WI-C-7	5476	50157	—	—	—	—
70CR	WI-D-47	5562	50177	—	—	—	—
COUNTRY ROCK							
100	SL-A-15	5916	50282	—	—	—	—
101	WI-D-32	5585	50219	—	—	—	—
102	SP-D-1	5710	50242	—	—	—	—
103	SA-B-12	5430	49998	—	—	—	—

Chapter 3.

HETEROGENEOUS SOURCES OF LEAD IN GRANITES FROM EAST-CENTRAL MAINE

INTRODUCTION

The variation in the lead isotopic composition of igneous rocks records an integrated history of the development of uranogenic and thorogenic lead. This observation was used to deduce the nature of the source materials, age and mode of origin of granitic plutons in earlier studies (Doe, 1962, 1967; Zartman, 1965, 1969; Oversby, 1975). More recently, the contrasting geochemical behavior of Th and U commonly seen as variations of Th/U ratios, and in $^{238}\text{U}/^{204}\text{Pb}$ ratio of different materials allowed for the recognition of distinct Pb isotopic reservoirs (Doe and Zartman, 1979). The importance of Pb isotopes to serve as fingerprints of different environments depends to a large extent on the comparison of uranogenic and thorogenic Pb.

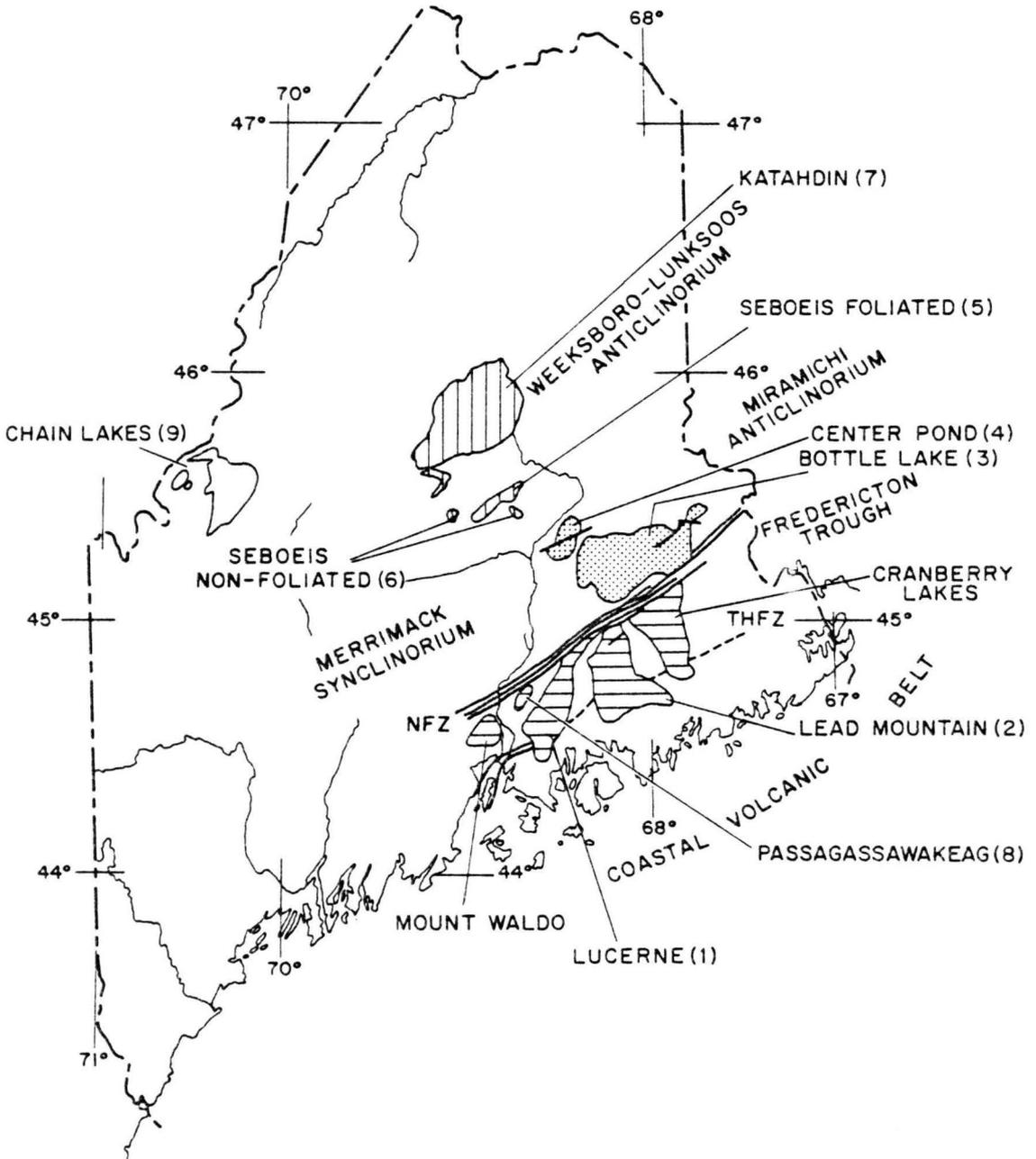
The two objectives of this study were to determine the Pb isotopic composition of the granitic sources on either side of the Norumbega fault system in east-central Maine, and to compare their variation with granites from known tectonic environments.

GEOGRAPHIC SETTING

At least ten granite bodies are represented in a traverse through the Merrimack synclinorium (Fig. 1). They are emplaced in a trend roughly at right angles to its axis and from northwest to southeast include: Katahdin (K), Seboeis (S), Center Pond (CP), Bottle Lake Complex (BLC), Lead Mountain (LM), and Lucerne (L). Some are composite

FIGURE 1.

Map of Maine showing the distribution of plutonic rocks. Light stipple - granite and granodiorite; dark stipple - diorite and gabbro. Unpatterned plutons are those included in this study. 1-Lucerne pluton; 2-Lead Mountain pluton; 3-Bottle Lake complex; 4-Center Pond pluton; 5-Seboeis foliated granitoid; 6-Seboeis non-foliated granites; 7-Katahdin pluton; 8-Passagassawakeag gneiss; 9-Chain Lakes massif; NFZ-Norumbega Fault Zone (modified after Loiselle and Ayuso, 1980).



bodies as exemplified by the Bottle Lake (Whitney Cove and Passadumkeag River), Seboeis, and possibly the Lead Mountain plutons. All are roughly 380 to 410 m.y. old, are associated with the Acadian orogeny in New England, and intrude a Siluro-Devonian (Osberg, 1978) sequence of interbedded silts and shales at low metamorphic grade (greenschist facies).

The Norumbega fault system (NFS) forms the most prominent structural feature in the region and it conveniently divides the plutons into two geographic groups. One of the major traces of the NFS cuts the BLC and plutons to the north from those intruding the southern limb of the synclinorium. This grouping generally corresponds to the boundary of one of the three major geologic and geophysical basements recognized in Maine (Osberg, 1978; Kane and Bromery, 1968; Hodge and others, 1980). Each of these basements has distinct geologic characteristics correlated with changes in gravity signatures. Using the tectonic division of Osberg (1978) all plutons north of the NFS are in the medial zone, while those to the south are in the eastern zone.

The two general groups are also apparent on the basis of petrographic (Ayuso et al., 1980), major and trace element variations (Loiselle and Ayuso, 1980). These two groups tend to show abrupt changes in petrography and geochemistry in a trend across the synclinorium (Table 1). The only petrographic feature that changes smoothly across the traverse is displayed by the increase in grain size from NW to SE. All other petrographic and geochemical characteristics are interrupted by the NFS. On the northern side of the fault, plutons (CP, BLC) emplaced near the core of the synclinorium are amphibole,

TABLE 1. Summary of field relations and characteristic mineralogy of granites from east-central Maine

Specimen no. and unit	Lithology	General features	Mafic and accessory minerals	Source			
KATAHDIN PLUTON							
RH-150	granite	biotite granite of homogeneous mineralogy and chemistry; granophyric; rarely enclosing xenoliths; sharp contacts.	biotite is the major mafic phase; muscovite, garnet and sphene are absent; apatite, zircon, allanite and magnetite present.	Hon, 1980			
RH-29	granite						
RH-41	granite						
SEBOEIS COMPLEX							
SC-066 (Mattamiscontis)	granite	biotite and amphibole granites; heterogeneous mineralogy and chemistry; foliated rocks are mixed with country rock.	biotite > amphibole; muscovite and garnet are absent.	M. Loisel, 1980, pers. communication			
SC-018 (Mattamiscontis)	granite						
SC-032 (Foliated)	granodiorite						
SC-127 (Ebeeme)	granite						
BOTTLE LAKE COMPLEX							
35R (Passadumkeag R.)	granite	biotite and amphibole-rich pluton; heterogeneous in lithology and composition; abundant mafic xenoliths; lit-par-lit contact; pluton is reversely zoned in lithology and composition.	abundant amphibole, biotite and sphene; apatite and allanite common; magnetite > ilmenite.	Ayuso, chapter 2, this study			
34C	quartz monzonite						
36C	quartz monzonite						
10R	granite						
29C	quartz monzonite						
32C	quartz monzonite						
66C	quartz monzonite						
8R	granite						
86C	quartz monzonite						
9C (Feldspar)	quartz monzonite						
9C	quartz monzonite						
65M (Mafic xenolith)	quartz diorite				two families of mafic xenoliths present; quartz diorites are the most abundant and similar in composition to host: wide variation in sizes; especially common in the interior of the Passadumkeag River pluton.	large variation in biotite/amphibole; sphene, apatite and zircon are abundant; magnetite > ilmenite.	Ayuso, chapter 2, this study
9M	quartz diorite						
66M	quartz diorite						
62M	diorite						
63M	quartz diorite						
61M	quartz diorite						
58C (Whitney Cove)	granite	biotite granite of heterogeneous mineralogy; few xenoliths; aplites and pegmatites; lithologically and compositionally reversely zoned.	biotite-rich granite; apatite, zircon, sphene, and allanite abundant; magnetite > ilmenite.	Ayuso, chapter 2, this study			
60C	granite						
37C	granite						
47R	granite						

Table 1 (continued).

Specimen no. and unit	Lithology	General features	Mafic and accessory minerals	Source
94KF (Feldspar)	granite			Ayuso, ch. 2, this study.
95RF (Feldspar)	granite			
57R	granite			
49C	granite			
37C	granite			
CENTER POND PLUTON				
CP-006	granodiorite	biotite and amphibole-rich plutons; heterogeneous in mineralogy and chemis- ty; country rock xenoliths near contact; mafic xenoliths widely disseminated as small and resorbed clots.	abundant amphibole and sphene; musco- vite and garnet absent.	Scambos, 1980.
CP-041	quartz diorite			
CP-066	granite			
LEAD MOUNTAIN PLUTON				
NB-32	granite	petrographically heterogeneous batholith; amphibole and biotite varieties; very coarse-grained.	biotite amphibole; muscovite and garnet absent.	Loiselle and Ayuso, 1980.
LMA-27	granite			
LML-10	granite			
LUCERNE PLUTON				
NT-68	granite	very coarse-grained biotite granite; no xenoliths; compositionally high in silica and alkalies.	biotite-rich pluton; primary sphene, magnetite, garnet, and muscovite absent.	Wones, 1980.
LUE 3	granite			
LUE 1	granite			
LUE 2				
COUNTRY ROCKS				
SA-B-12 (Kellyland Fm)	graywacke	calcareous, subfeldspathic, micaceous rock; Silurian (?). quartz-mica phyllite schist; latest Ordovician to Silurian; contact metamorphosed by BLC.		Larrabee et al. 1965. Osberg, 1968; & Ayuso, ch. 2, this study.
WI-D-32 (Vassalboro Fm)	calcareous turbidites			
SP-D-1 (unnamed)	sulfidic	very rusty and sulfidic rock; highly contorted at contact; shows contact metamorphic effects; Silurian (?).		Larrabee, 1965; & Ayuso, ch. 2, this study.
SL-A-15 (unnamed)	graywacke	siltstones and slates; quartzo-feldspathic rocks; Cambro-Ordovician (?).		Ludman, 1978; & Ayuso, ch. 2, this study.
PAS-2 (Passagassawakeag)	gneiss	quartz-feldspar-biotite augen gneiss; cut by migmatites of Silurian age.		Wones, 1974.
PAS-1 (Passagassawakeag)				

sphene and mafic xenolith-rich, have high color indices, and show compositions that range from diorite to granite. Farther to the NW, the granites are generally restricted to biotite varieties of strictly granitic composition, and are best exemplified by the large and geochemically homogeneous Katahdin pluton (Hon, 1976). Across the NFS, the granites range in mineralogy from biotite-rich rocks as in the case of Lucerne (Wones, 1980) but also include amphibole-bearing plutons (Lead Mountain) which tend to have granitic compositions enriched in alkali elements.

Preliminary Rb-Sr work suggests that plutons north of the NFS are restricted toward lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7080) than at least some of the plutons on the opposite side of the fault (Wones et al., 1981). For example, the initial Sr isotopic composition of the BLC, immediately north of the NFS, is about 0.7055 (Ayuso and Wones, 1980), whereas the Lucerne yields a value of 0.7100 (D. Brookins, personal communication, 1976).

Proterozoic rocks are absent along the traverse, except for a migmatitic terrane (Wones, 1974) exposed to the west of the Lucerne pluton which shows many features common to older basements. Pb-Pb zircon ages (Zartman and Gallego, 1979) suggest migmatite generation during the Silurian (about 421 m.y.). North of the NFS, the closest basement outcrops in the Chain Lakes massif (Boone et al., 1970) where Naylor et al. (1973) obtained a zircon age of about 1.6 m.y. Both terrains are represented by high grade metamorphics with potentially recognizable Pb isotopic variations. Despite the lack of basement outcroppings within the synclinorium in east-central Maine, its input

into newly formed granitic magmas most probably results in retarded, unradiogenic compositions. The use of Pb isotopic compositions to determine the nature and extent of different basements in the western U.S. was highly successful (Zartman, 1974).

EXPERIMENTAL

Forty-six samples were cleaned with a hammer and broken into chips less than 0.5 cm in diameter. Forty samples are from igneous rocks and six are from the country rocks. Four of the forty samples are alkali feldspar splits that were separated, crushed and cleaned by standard hand magnet, heavy liquid, and hand-picking procedures. Six of the whole-rock samples are mafic xenoliths within the BLC (Ayuso, 1979; Ayuso and Wones, 1980; chapter 2, this study).

The four whole-rock metasedimentary samples were obtained from country rocks intruded by the BLC in the core of the synclinorium. Each represents one of the most common lithologies which range from pelites interbedded with calcareous sediments to siltstones (Table 1). Two samples from the melanosome of the Passagassawakeag gneiss were also included as these represent the nearest occurrence of migmatites in the region, although this lithology is confined to the south side of the NFS.

Whole rock samples weighed at least 20 kg. These were split and ground in a tungsten-carbide box. The resulting powders were split into six gram aliquots which were acid washed in dilute hydrochloric acid. Samples were dissolved in HF and HNO₃ acid in teflon bombs. After complete dissolution, all were taken to dryness, dissolved in HBr and

dried again. Lastly, they were dissolved into a solution of HBr + HCl and passed through a bromide resin column. Lead was eluted by stripping with 6-N HCl while U and Th were recovered by washing the columns in 7-N HNO₃ or H₂O. Following the approach of Ludwig and Silver (1977), two euhedral alkali-feldspars were separated from the composite Bottle Lake Complex. Each pluton is represented by its respective core facies. The feldspars are present as megacrysts (2.5 x 3.5 cm) and are characterized by zoned morphologies (Chapter 1, 2, this study). Each zone is punctuated by inclusions of quartz, mafic minerals, and plagioclase. No detectable compositional gradients from core to rim are evident. The lead isotopic variations were monitored by subjecting the alkali feldspar concentrate to HF and HNO₃ attack in teflon beakers, at ½ hour intervals for two consecutive times prior to total dissolution.

All Pb runs were made on single rhenium filaments by dissolving in phosphoric acid and loading with one drop of silica-gel solution. Analysis of lead followed in a mass spectrometer with a curvature of 18 cm. Uranium and thorium were analyzed together by loading U in the center and Th on the side filament. This configuration allowed the analysis of the two species simultaneously because as the U signal decayed the intensity of Th increased.

Throughout this investigation, the analytical procedure was monitored by repeated running of the California Institute of Technology (CIT) standard (Table 2), as well as numerous checks on the total chemistry blank. All samples were normalized to the absolute values of Catanzaro (1967) obtained on the CIT standard. Because of the low level of the Pb blank (less than one nanogram) no correction was necessary.

TABLE 2. Analyses of lead standard

CIT (N = 12)	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$
Average Std.	16.582	15.414	36.104
NBS values ^a	16.625	15.475	36.301

^aCatanzaro, 1967

Calculated $^{238}\text{U}/^{204}\text{Pb}$ ratios using present U abundances and the age of the plutons may be calculated for correction of in situ generation of radiogenic lead (Table 3). However, as a result of the great mobility of U (Rosholt and Bartel, 1969; Rosholt et al., 1973) from tectonic processes such as uplift (Richardson and Adams, 1964; Doe and Delevaux, 1980), constrains the following discussion to emphasize the uncorrected values of the whole-rocks and the enclosed alkali feldspars. Although isotopic analysis of feldspar has many advantages for pointing at the initial composition of the source regions, this phase is often reset and shows evidence for complex changes during growth (Sinha, 1969; Zartman, 1965; Sinha and Tilton, 1973; Doe and Hart, 1963; Ludwig and Silver, 1977). This results in isotopic changes that are difficult to interpret. However, despite the problems introduced by surface mobility of uranium, complicated isotopic histories, and ignorance about the initial Pb isotopic composition (Oversby, 1980) of each pluton, a comparison of the evolutionary patterns of U and Th-derived Pb yields significant constraints on the type and homogeneity of granitic sources in east-central Maine.

RESULTS

Plutonic rocks

Pb isotope analyses (Table 3) of the granitic plutons and country rock are plotted (Fig. 2) with the evolution curves of Doe and Zartman (1979).

TABLE 3. Lead isotopic ratios and concentration of lead and uranium in whole rock and microclines from granite and country rock of east-central Maine.

Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$	Pb ppm	U ppm	Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$	Pb ppm	U ppm
KATHADIN GRANITE						BLC - PRG (con't)					
RH-150	18.765	15.667	38.846			36C	19.149	15.686	39.134		
RH-29	18.722 (18.495)*	15.629 (15.617)	38.749	25.3	1.2	10R	19.065 (18.295)	15.720 (15.678)	39.185	21.2	3.0
RH-41	18.718	15.630	38.617			29C	18.912	15.708	38.866		
SEBOEIS COMPLEX						32C	18.841 (18.403)	15.686 (15.662)	38.951	17.2	1.6
SC-066	18.772 (18.032)	15.656 (15.601)	38.627	29.2	4.5	66C	19.210	15.676	39.041		
SC-018	19.066	15.631	38.723			8R	18.779	15.666	38.563		
SC-032	18.773	15.706	38.693			86C	18.381	15.672	38.367		
SC-127	18.992	15.696	39.086			FS9C	18.271	15.629	38.245		
CENTER POND GRANITE						9C	19.504	15.712	39.901		
CP-006	19.019 (18.403)	15.631 (15.597)	39.024	15.0	1.9	MAFIC XENOLITHS - PASSADUMKEAG RIVER GRANITE					
CP-041	18.856	15.626	38.692			65M	18.596 (18.311)	15.672 (15.656)	38.515	28.5	1.7
CP-066	18.458	15.609	38.714			9M	18.842 (18.289)	15.683 (15.653)	39.108	14.5	1.7
BOTTLE LAKE COMPLEX - PASSADUMKEAG RIVER GRANITE						66M	19.175	15.697	39.003		
35R	19.034 (18.426)	15.654 (15.621)	39.985	14.1	1.8	62M	18.952 (18.335)	15.678 (15.644)	38.957	8.0	1.0
34C	19.160 (18.025)	15.746 (15.686)	38.983	15.3	3.6	63M	19.047 (18.515)	15.696 (15.667)	39.174	19.8	1.8
						61M	18.921	15.703	39.053		

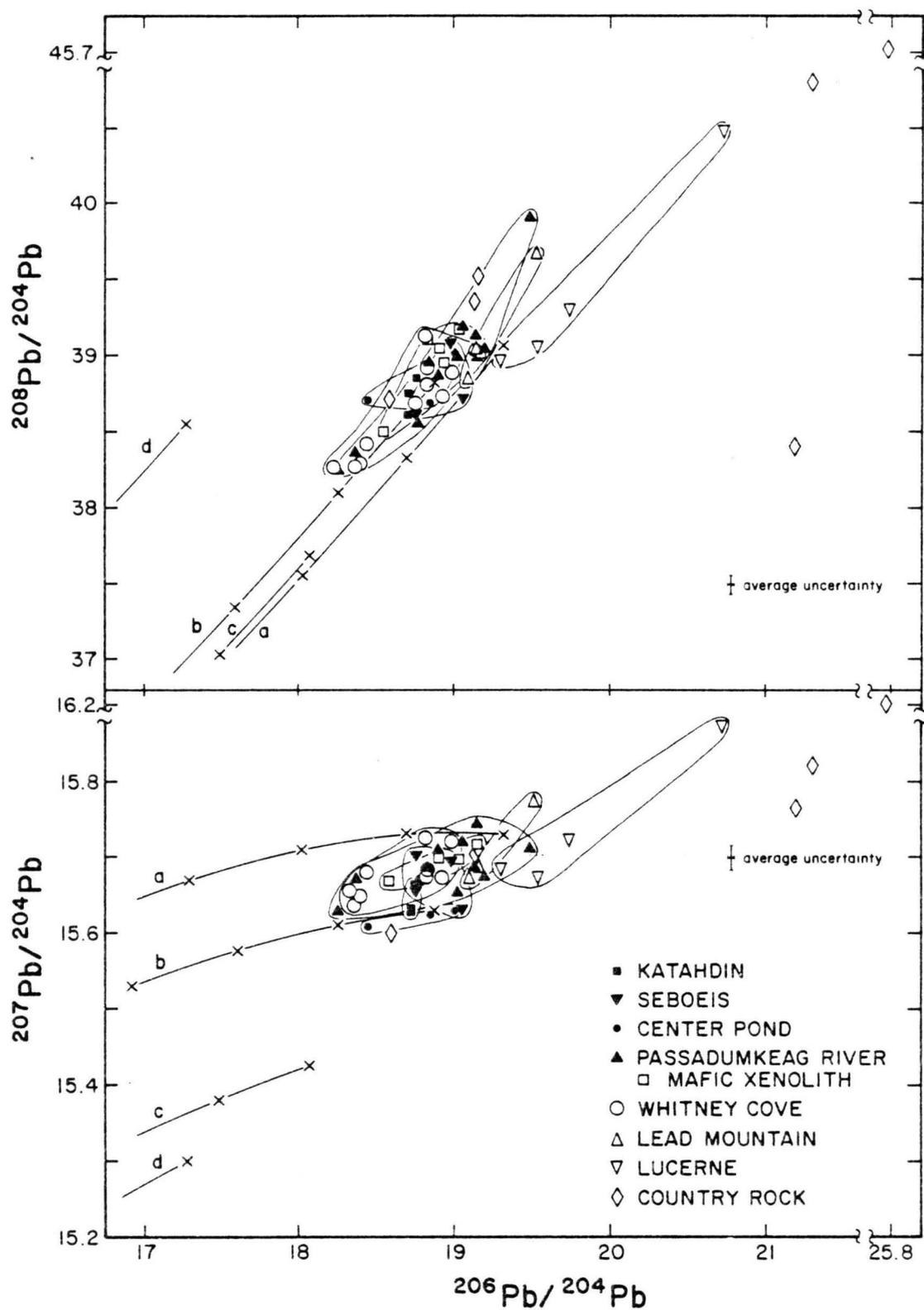
* Corrected values assuming t = 400 m.y.

TABLE 3 (continued)

Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$	Pb ppm	U ppm	Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$	Pb ppm	U ppm
BOTTLE LAKE COMPLEX - WHITNEY COVE GRANITE						COUNTRY ROCK IN THE MERRIMACK SYNCLINORIUM					
58C	18.827	15.726	39.130			SAB12	21.315 (18.372)	15.822 (15.661)	40.799	5.1	2.9
60C	18.842 (18.417)	15.682 (15.659)	38.810	30.1	2.6	SPD1	21.220	15.763	38.417		
FS37C	18.344	15.658	38.277			WID32	18.614	15.603	38.734		
47R	18.897 (18.660)	15.722 (15.709)	38.892	31.0	1.5	SLA15	25.788	16.247	45.705		
FS94R	18.454	15.682	38.423			PAS2	19.182 (18.306)	15.715 (15.667)	39.622	23.1	4.2
FS83R	18.375	15.638	38.269			PAS1	19.145 (18.923)	15.686 (15.674)	29.351	18.3	0.7
57R	18.833 (18.633)	15.687 (15.676)	38.924	22.9	1.0						
49C	18.406	15.648	38.294								
37C	18.938	15.672	38.730								
LEAD MOUNTAIN BATHOLITH											
NB32	19.155	15.686	39.039								
LMA27	19.532	15.771	39.678								
LML10	19.097	15.673	38.849								
LUCERNE PLUTON											
NT68	19.553 (18.107)	15.675 (15.651)	39.058	34.7	3.2						
LUE3	19.306 (18.365)	15.685 (15.680)	38.961	32.3	6.3						
LUE1	19.754	15.726	39.307								
LUE2	20.736	15.872	40.479								

FIGURE 2

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for feldspar and whole-rock from granites of east-central Maine. The isotopic composition of mafic xenoliths in the Bottle Lake Complex, and country rocks from the Merrimack synclinorium are also shown. Curved lines represent the evolution curves of the upper continental crust (a), average orogene (b), oceanic mantle (c), and lower continental crust (d), all taken from Doe and Zartman (1979). All figures show the combined fields defined by plutons south of the NFZ, intruded near the center of the Merrimack synclinorium, and granites near the extreme northern part of the traverse.



Each of these curves represents the most important lead reservoirs considered in this discussion: 1) upper continental crust; 2) orogene; 3) oceanic mantle; and 4) lower continental crust.

The Pb isotopic variation of the plutons in east-central Maine ranges from 18.271 to 20.736 in $^{206}\text{Pb}/^{204}\text{Pb}$, 15.609 to 15.872 in $^{207}\text{Pb}/^{204}\text{Pb}$, and 38.245 to 40.479 in $^{208}\text{Pb}/^{204}\text{Pb}$ (Fig. 2). This range of compositions results in younger ages than the crystallization age, as seen in the position of the 400 m.y. isochron in the $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ plot (Fig. 2). However, such negative ages are more common in the plutons south of the NFS as a result of their radiogenic nature.

Although some of the spread in uranogenic and thorogenic Pb is a result of decay following the crystallization of the plutons, note that age correction tends to reduce the scatter but preserve the trend of the slopes. In this manner, assuming that each pluton represents a small range in $^{238}\text{U}/^{204}\text{Pb}$, the general spread in Pb isotopic composition and distinction among the plutons is nevertheless conserved.

In the plot of $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 2) the general grouping between the plutons on either side of the fault is clearly displayed. Plutons emplaced south of the NFS are typically more radiogenic in $^{206}\text{Pb}/^{204}\text{Pb}$ at a given $^{208}\text{Pb}/^{204}\text{Pb}$. This enrichment results in arrays arranged along slopes distinct from those of granites on the opposite side of the NFS.

The granite of Passadumkeag River is the most heterogeneous pluton as displayed by the regression lines with correlation coefficients (r) of $r_{207/206} = 0.63$, $r_{208/206} = 0.81$) in the traverse (Fig. 2). Its isotopic range encloses a suite of mafic xenoliths ($r_{207/206} = 0.71$,

$r_{208/206} = 0.74$), the Whitney Cove Pluton ($r_{207/206} = 0.71$, $r_{208/206} = 0.90$) and most of the isotopic fields defined by plutons on the north side of the fault. The Center Pond pluton shows a strong correlation in $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ($r = 0.99$) (Fig. 2). With respect to $^{208}\text{Pb}/^{204}\text{Pb}$, the correlation with $^{206}\text{Pb}/^{204}\text{Pb}$ is lower ($r = 0.68$), and suggests geochemical decoupling of Th and U in the source region.

At the extreme northwest extension of the traverse, Kathadin is represented by a small range in isotopic composition (Fig. 2). Minor variations in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ confirm the previously reported petrographic and geochemical homogeneity of this granite (Hon, 1976). In marked contrast to the homogeneity of Katahdin is the variation exhibited by the Seboeis Complex (Fig. 2). Much of the isotopic heterogeneity results from the composite nature of the Complex. Comparison of samples (SEB-018 and SEB-066) belonging to the same pluton (Tables 1, 3) reveals unexpected isotopic variations (much higher $^{206}\text{Pb}/^{204}\text{Pb}$), basically inconsistent with the overall similarity between this pluton and the nearby Katahdin granite. Two other rock types (Table 3) represented in this Complex are either clearly higher in $^{208}\text{Pb}/^{204}\text{Pb}$ (SEB-32), or in both $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ (SEB-127) with respect to Katahdin. In comparison to the plutons emplaced near the core of the synclinorium, the Katahdin and Seboeis plutons are somewhat less diverse in their isotopic compositions.

Plutons emplaced south of the NFS show better correlations in their Pb isotopic ratios, but are displaced toward more radiogenic compositions (Fig. 2). More significantly, the data is arranged along different slopes of $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ compared to $^{206}\text{Pb}/^{204}\text{Pb}$.

However, a word of caution is in order owing to the strong control of the few radiogenic samples on the slopes of each pluton. In addition to the distinctions on either side of the NFS, it is interesting to note the divergence of isotopic compositions indicated by the Lucerne and Lead Mountain pluton. This variation suggests finer scale heterogeneity within the southern block.

Country Rocks

Metasediments from the north side of the NFS are generally higher in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ (Fig. 2, Table 3) and form a wide band partially overlapping the plutons. The possibility of accounting for the petrographic and geochemical features of the plutons north of the NFS and specifically the BLC, by wholesale assimilation of country rocks was not supported in previous petrologic studies (chapter 2, this study). At a given $^{207}\text{Pb}/^{204}\text{Pb}$ value, the country rocks tend to have higher $^{206}\text{Pb}/^{204}\text{Pb}$ ratios than all of the plutons in the traverse, signifying large variations in $^{238}\text{U}/^{204}\text{Pb}$. Although the stratigraphically older sample (SL-A-15) is highest in radiogenic Pb, no coherent trend in the $^{208}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 2) typifies the entire suite of country rocks.

This is in agreement with the suggestion that although some of the Pb isotopic variation in the plutons may result from late-stage reaction with the country rocks, this process is not considered likely to account for the overall isotopic characteristics of the intrusives. Despite the possibility of generating two component mixing lines with respect to $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ between the plutons and the metasediments, equivalent variations are unsupported by $^{208}\text{Pb}/^{204}\text{Pb}$. Thus, there is no

simple set of mixing lines capable of accounting for a variety of Th/U values in the country rocks compared to the small variation in the plutons.

Two analyses of the Passagassawakeag gneiss suggest that such a source of Pb is inadequate to explain the isotopic range present in the plutons south of the NFS. The range in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ is basically similar to that of the mafic xenoliths of the BLC. However, the two groups are clearly distinct in the $^{208}\text{Pb}/^{204}\text{Pb}$ plot, as the gneiss samples are higher in $^{208}\text{Pb}/^{204}\text{Pb}$ at a given value of $^{206}\text{Pb}/^{204}\text{Pb}$. This suggests that although the gneiss has equivalent $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ compositions as the plutons, its $^{208}\text{Pb}/^{204}\text{Pb}$ isotopic range lies at higher values for a given $^{206}\text{Pb}/^{204}\text{Pb}$ and represents higher Th/U ratios.

Alkali Feldspar

Results from stepwise dissolution of alkali feldspar are shown in Table 4. Fig. 3 displays the isotopic variation of Pb in each sample together with the value of the corresponding whole rock (Table 3). In the case of the Passadumkeag River pluton of the BLC, the Pb isotopic composition of the coexisting mafic xenolith (Table 3) is also plotted.

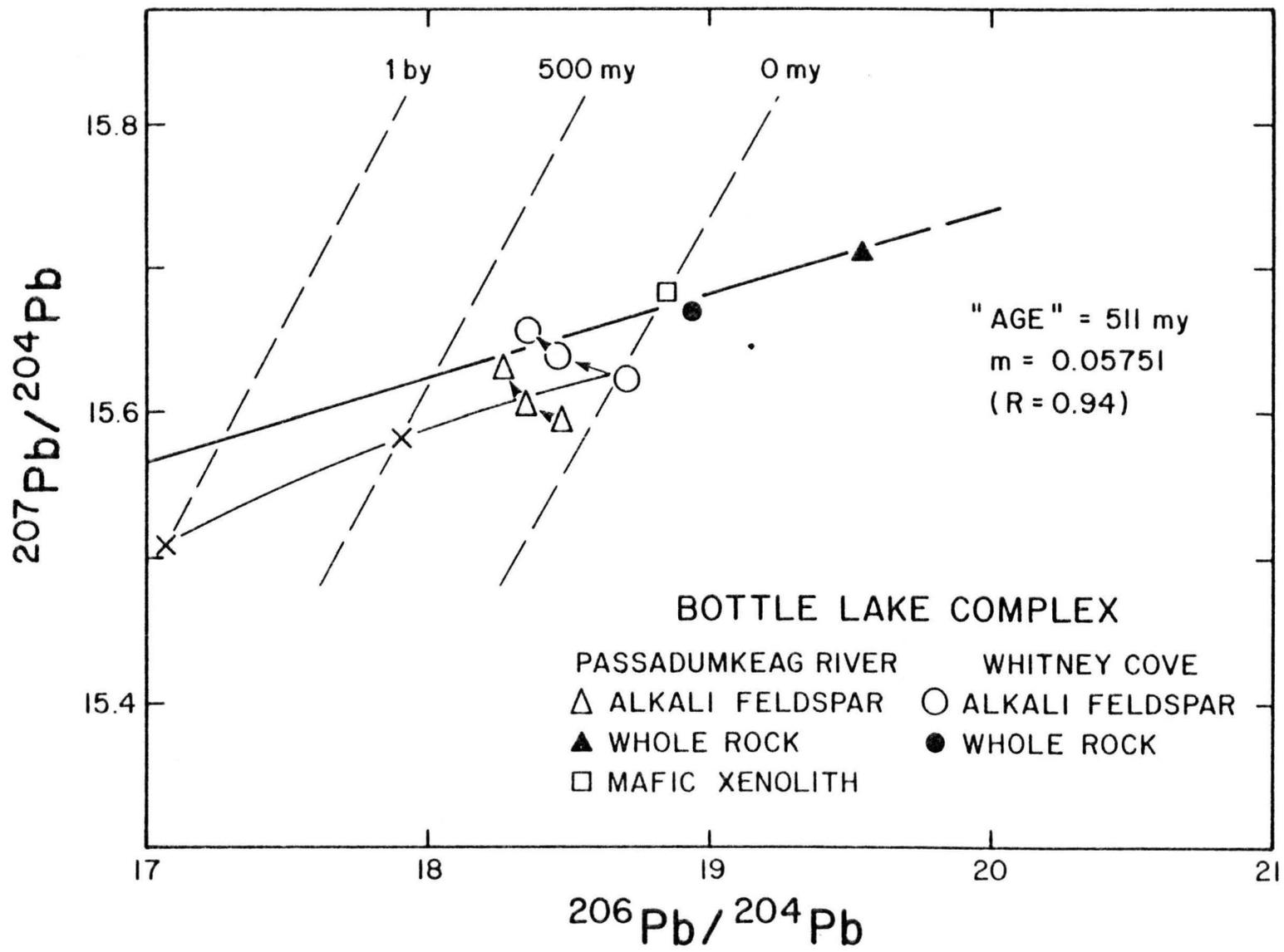
Three successive steps were analyzed in each sample showing that in both plutons the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios decrease consistently in the last dissolution. Although both granitoids exhibit changes in the same direction, the sample from the Whitney Cove pluton tends to show a larger change (Fig. 3). $^{207}\text{Pb}/^{204}\text{Pb}$ shows no variation outside the analytical certainty and this was also evident in the variation of $^{208}\text{Pb}/^{204}\text{Pb}$. Analyses of the stepwise dissolutions suggest an overall

TABLE 4. Lead analyses of alkali feldspar after HF attack and coexisting whole rocks.

Sample	$\frac{206_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{207_{\text{Pb}}}{204_{\text{Pb}}}$	$\frac{208_{\text{Pb}}}{204_{\text{Pb}}}$
FS (37C) first $\frac{1}{2}$ hour	18.698	15.624	38.311
second $\frac{1}{2}$ hour	18.457	15.639	38.307
final dissolution	18.344	15.658	38.277
37C whole rock	18.938	15.672	38.730
FS (9C) first $\frac{1}{2}$ hour	18.477	15.594	38.378
second $\frac{1}{2}$ hour	18.342	15.604	38.213
final dissolution	18.271	15.629	38.245
9C whole rock	19.504	15.712	39.901
9M mafic xenolith	18.842	15.683	39.108

FIGURE 3.

$^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the results of stepwise leaching and total dissolution of feldspar, whole-rock, and mafic xenolith of the plutons in the Bottle Lake Complex. Curved line represents the average orogene of Stacey and Kramers (1975).



change toward isotopic compositions defined by the mixing curve of the whole rocks in the BLC (Fig. 3). Both feldspars display parallel trends consistent with sharing a common geologic history. More importantly, both lie along the line defined by the two whole rocks and coexisting mafic xenolith.

These results suggest the presence of unsupported uraniumogenic Pb within the most leachable fraction of the feldspar. Similar results in Precambrian feldspars (Ludwig and Silver, 1977) emphasize the isotopically complex history recorded by this phase.

Pb ISOTOPIC VARIATION ACROSS THE SYNCLINORIUM

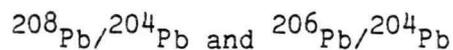
$$^{207}\text{Pb}/^{204}\text{Pb} \text{ and } ^{206}\text{Pb}/^{204}\text{Pb}$$

The $^{207}\text{Pb}/^{204}\text{Pb}$ range of the plutons north of the NFS is surprisingly variable at a given value of $^{206}\text{Pb}/^{204}\text{Pb}$. Despite this variation, however, the data is enclosed by curves characterizing the average orogene and upper crust, and suggest the strong control of miogeosynclinal rocks. In contrast, plutons emplaced across the NFS display more pronounced and regular increases in both $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ which yield arrays along different slopes. These are not constrained by the orogene and upper crust curves but extend to more radiogenic compositions.

Of all the plutons under consideration, only the Center Pond yields a best-fit line that intersects the two-stage evolution curve (Stacey and Kramers, 1975) or the average orogene curve at about 400 m.y. In most cases, however, the resulting ages are geologically unreasonable partly because of the variation in $^{207}\text{Pb}/^{204}\text{Pb}$. Consideration of the best-fit lines in the $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ plot suggests ages

ranging up to 3 b.y. (L.M.). Although no age significance may be attached to these slopes, it is interesting to note that plutons emplaced north of the NFS are generally spread along a line with a slope of 400 m.y. In contrast, plutons from the other side of the NFS show significantly steeper slopes in the $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ plot (Fig. 2).

Calculated slopes for the plutons on the north side of the fault are similar, showing a general increase from NW to SE. In order of increasing slope the gradient is as follows: Center Pond, mafic xenoliths, Passadumkeag River and Whitney Cove. This is interrupted by the NFS, but it continues to steeper slopes in the Lucerne and Lead Mountain plutons. In contrast to the general similarity in the slopes plutons north of the NFS, however, the Lead Mountain and Lucerne plutons define different arrays even though they belong to the same tectonic block.



Study of the Th-derived Pb isotopic composition of the plutons affirms the close association of granites north of the NFS (Fig. 2). The isotopic composition of $^{208}\text{Pb}/^{204}\text{Pb}$ with respect to $^{206}\text{Pb}/^{204}\text{Pb}$ is basically elongated around the average orogene curve and contrasts with the higher $^{206}\text{Pb}/^{204}\text{Pb}$ for equivalent $^{208}\text{Pb}/^{204}\text{Pb}$ found in the granites south of the NFS. An important observation is that neither suite of plutons shows a scatter in $^{208}\text{Pb}/^{204}\text{Pb}$ reminiscent of source rocks with varying Th/U ratios.

A gradual steepening of slopes is evident from Center Pond toward Lead Mountain, although Passadumkeag River, Whitney Cove, and Lucerne have similar values. As expected from the variations in $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios the Seboeis and Katahdin bodies are not well correlated but suggest the steepest slopes in the traverse. However, more importantly, the Lucerne pluton plots below the orogene curve and points at the importance of an old and radiogenic source at low metamorphic grade. Comparison with the Lead Mountain pluton once again shows that despite their geographic association, plutons in the southern block have different isotopic signatures.

AGE OF THE SOURCE

Because of the isotopic range and scatter in $^{207}\text{Pb}/^{204}\text{Pb}$ shown by the plutons, few strict constraints can be placed on the age of the source. None of the studied plutons have single-stage isochrons commensurable to their crystallization ages, although the granites north of the NFS are broadly scattered along the slope corresponding to 400 m.y. on a plot of $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$. However, even after assuming a Pb-Pb age of 400 m.y. for a single pluton, for example Whitney Cove, the age of the source remains geologically unconstrained because the initial and final values of $^{238}\text{U}/^{204}\text{Pb}$ during the evolution of the system are unknown.

This is also evident by comparing data from east-central Maine in the evolution curve of Stacey and Kramers (1975). Essentially all samples lie above the curve, except for the best-fit line representing the Center Pond pluton. A variety of $^{238}\text{U}/^{204}\text{Pb}$ ratios is represented

by the scatter of composition spanning the range from about 9.5 to 10.0, with some of the plutons south of the NFS showing even higher values.

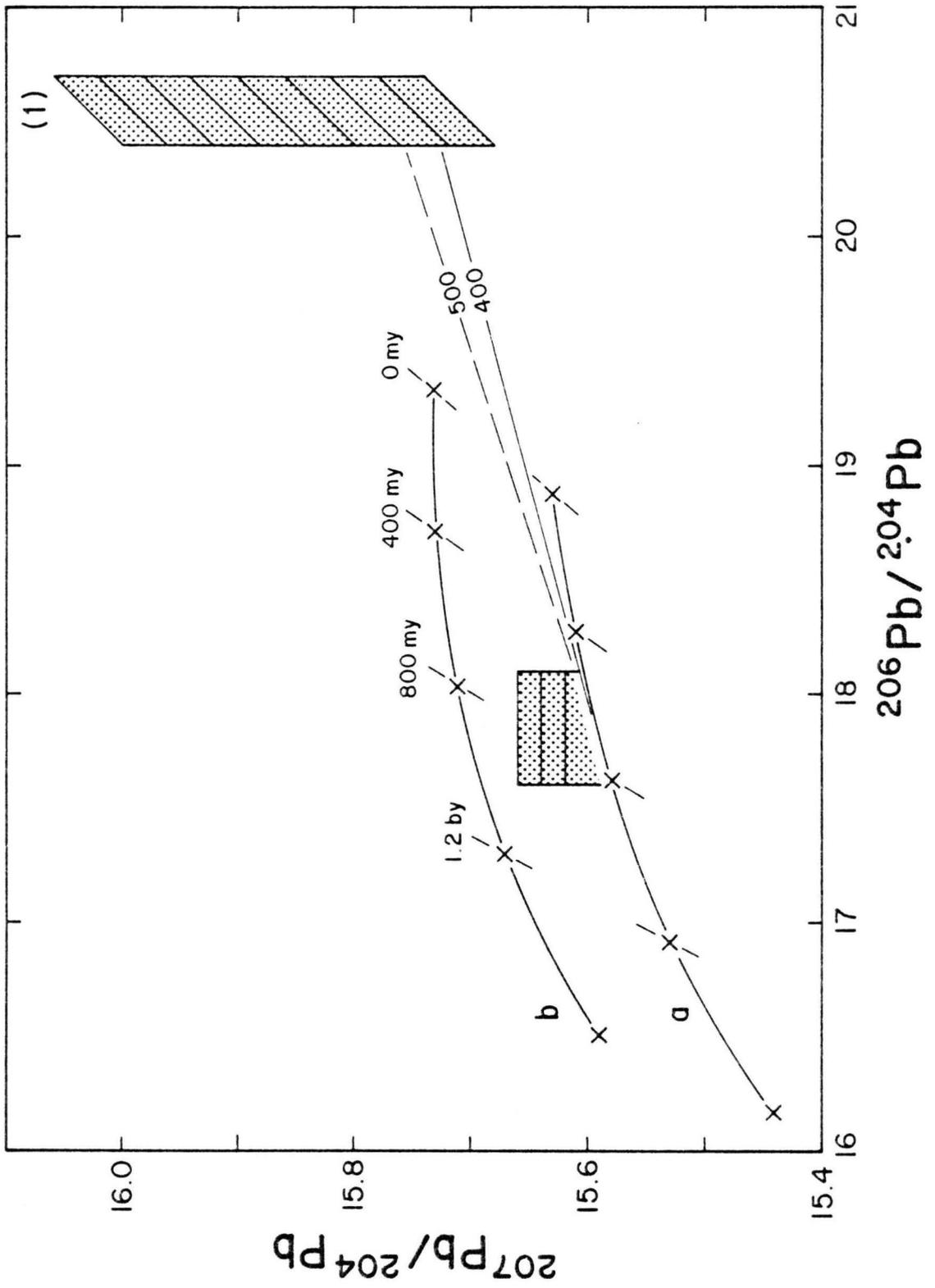
The preferred interpretation for the results from east-central Maine, particularly from plutons on the north side of the NFS, is that they do not yield isochrons because they represent a complex mixture of sources. This follows from consideration of the spread in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios.

Limited data on the alkali feldspars and whole rocks in the BLC show that they are roughly aligned along a best-fit line on a $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ diagram with a slope which corresponds to 511 m.y. (Fig. 3). This age is older than the Pb-Pb zircon age of 404 ± 5 m.y. representing the emplacement of the BLC and cannot be assumed to have direct age significance. A more consistent approach with the genesis of the BLC is to suggest that 511 m.y. is representative of a mixed source, whose average age may be of that magnitude. Older ages (646 m.y.) were suggested for the volcanoclastic Massabesic gneiss (Aleinikoff *et al.*, 1979) in the core of the Merrimack synclinorium in New Hampshire.

The preferred interpretation for the origin and nature of the sources involved in the genesis of the plutons north of the NFS is displayed in Fig. 4, and is especially applicable to the large Bottle Lake Complex in the core of the synclinorium. The source was for the most part similar in Pb composition to that present in the average orogene. At about 400 ± 5 m.y., partial melting of and crystallization of an isotopically variable source was effected and a range of $^{238}\text{U}/^{204}\text{Pb}$ ratios placed in the rocks. The source materials were from

FIGURE 4.

$^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the range in possible composition of the sources of the plutons in east-central Maine. Curved lines are as in Fig. 2, and data in field (1) are from Chow (1965), Hart and Tilton (1966).



the start heterogenous in composition. Despite this heterogeneity, however, generation of felsic magmas from such a source should still yield adequate Pb-Pb ages. Plutons on the north side of the NFS show a large spread in $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ because they represent the integrated effects of melting of the sources, followed by reaction and assimilation. The isotopic composition of the assimilated and mixed material was dominated by radiogenically enriched upper continental debris derived from a Precambrian craton (Grenville). Such debris is isotopically similar to that found in intracratonic basins (Doe and Zartman, 1979) and displays compositions plotting generally in a band characterized by both high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ contents. In this manner, mixing of orogene and upper continental crust in the source region of the plutons resulted in mixing lines that have no direct age significance. The continental affinity of the lead is compatible with a heterogeneous source consisting of volcanoclastic materials and sediments. The input of continental debris is reflected in the position of the data with respect to the orogene curve (Doe and Zartman, 1979). Continental arcs plot in the upper region of the field characteristic of orogenes, while primitive island arcs without an input from upper crustal lead plot in the lower part of the field.

DISCUSSION

Lead isotopic compositions in the traverse suggest the following:

- 1) existence of two general source regions divided by the Norumbega fault; 2) significant spread in $^{207}\text{Pb}/^{204}\text{Pb}$ ratios at a given $^{206}\text{Pb}/^{204}\text{Pb}$ resulting in clustering of the plutons north of the fault;

3) isotopic heterogeneity within individual plutons; 4) absence of a consistent gradient in isotopic ratios along the traverse.

The Norumbega fault system is a major structural surface discontinuity which also divides the upper crust in east-central Maine into two tectonic blocks. Because granite rocks are probes of the types of continental crust, they contain geochemical information about the age, maturity, and composition of the crust on either side of the NFS. Similar slopes on a $^{207}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ imply that plutons on the north side of the NFS, closer to the Grenvillian craton, have initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratios nearly equivalent. This is consistent with a source or sources that show generally the same range in $^{238}\text{U}/^{204}\text{Pb}$. These granites show some spread in slopes in a $^{208}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, suggesting some heterogeneity in Th/U in the source. Although the Passadumkeag River and Whitney Cove plutons are nearly equal in slope, they contrast with the relatively more homogeneous suite of mafic xenoliths.

For plutons on the south side of the fault, the calculated slopes are significantly different from the rest. In fact, the range in slopes implies that each batholith represents sources with different initial $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios that are not confined to the same tectonic block. In comparison to the plutons on the north side of the NFS, lower $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ are evident in the Lucerne and Lead Mountain.

Comparison of the isotopic characteristics of Pb in typical mantle basalts (Tatsumoto, 1969; Church and Tatsumoto, 1975; Tatsumoto, 1978) with the Maine granitoids suggests that the two systems are not directly

related. This is evident because mantle rocks are characteristically lower in $^{238}\text{U}/^{204}\text{Pb}$ ratios and have less radiogenic compositions (Fig. 5). An origin by closed-system fractionation of mantle rocks is unlikely to result in the much higher ratios of the Maine plutons, because negligible isotopic fractionation (Taylor, 1968) has been demonstrated for lighter isotopes in igneous systems. From the study of the petrology of the BLC, it was suggested that the role of mantle material was essentially as a provider of heat for melting continental crust, a heterogeneous section of volcanoclastic and sedimentary material (chapter 2, this study).

As in the case of oceanic mantle, the Pb imprint coming from the lower continental crust is probably also minor (Fig. 5). This follows because the lower crust environment is characterized by retarded radiogenic growth resulting from migration of the heat producing and large ion lithophile elements higher in the crust (Heier, 1973). As a result of this situation, lead isotopic ratios are low and Th/U ratios are high reflecting the faster diffusion of U compared to Th (Tilton, 1979). Many plutonic bodies associated with granulite basements (Fig. 6) tend to display secondary isochrons indicative of the age of the source (Blaxland et al., 1979; Moorbath and Welke, 1969; Sinha and Merz, 1978; Doe and Delevaux, 1973; Doe et al., 1981, in press). This is especially well displayed in the Caledonian plutons of Scotland as they show the strong imprint from the Lewisian basement (Fig. 6). However, the time-correlative plutons from east-central Maine show no such relation with a high rank metamorphic source.

FIGURE 5.

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing different isotopic environments (Doe and Zartman, 1979). The field of Grenville rocks is also shown (Zartman, 1969). Curved lines are as in Fig. 2.

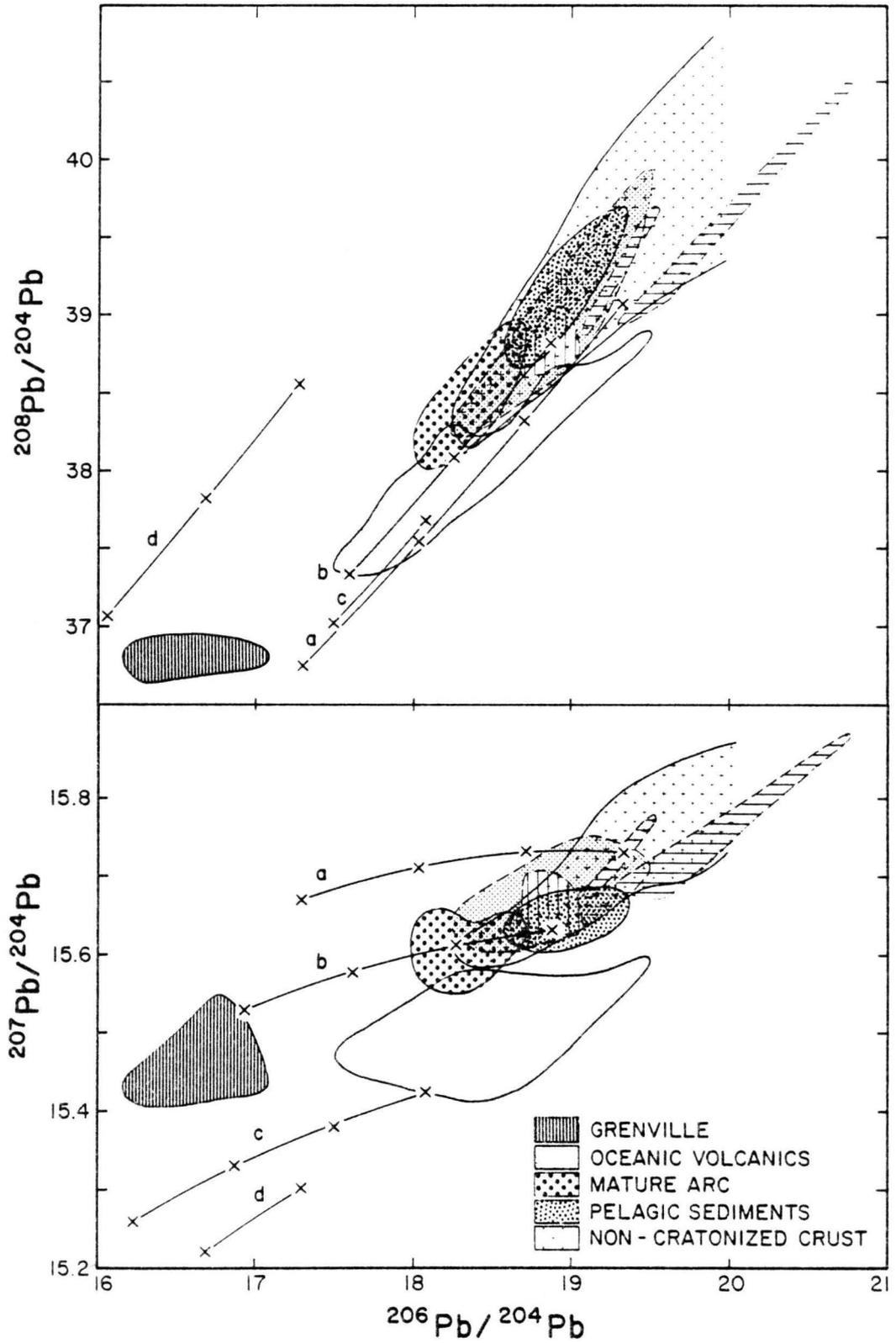
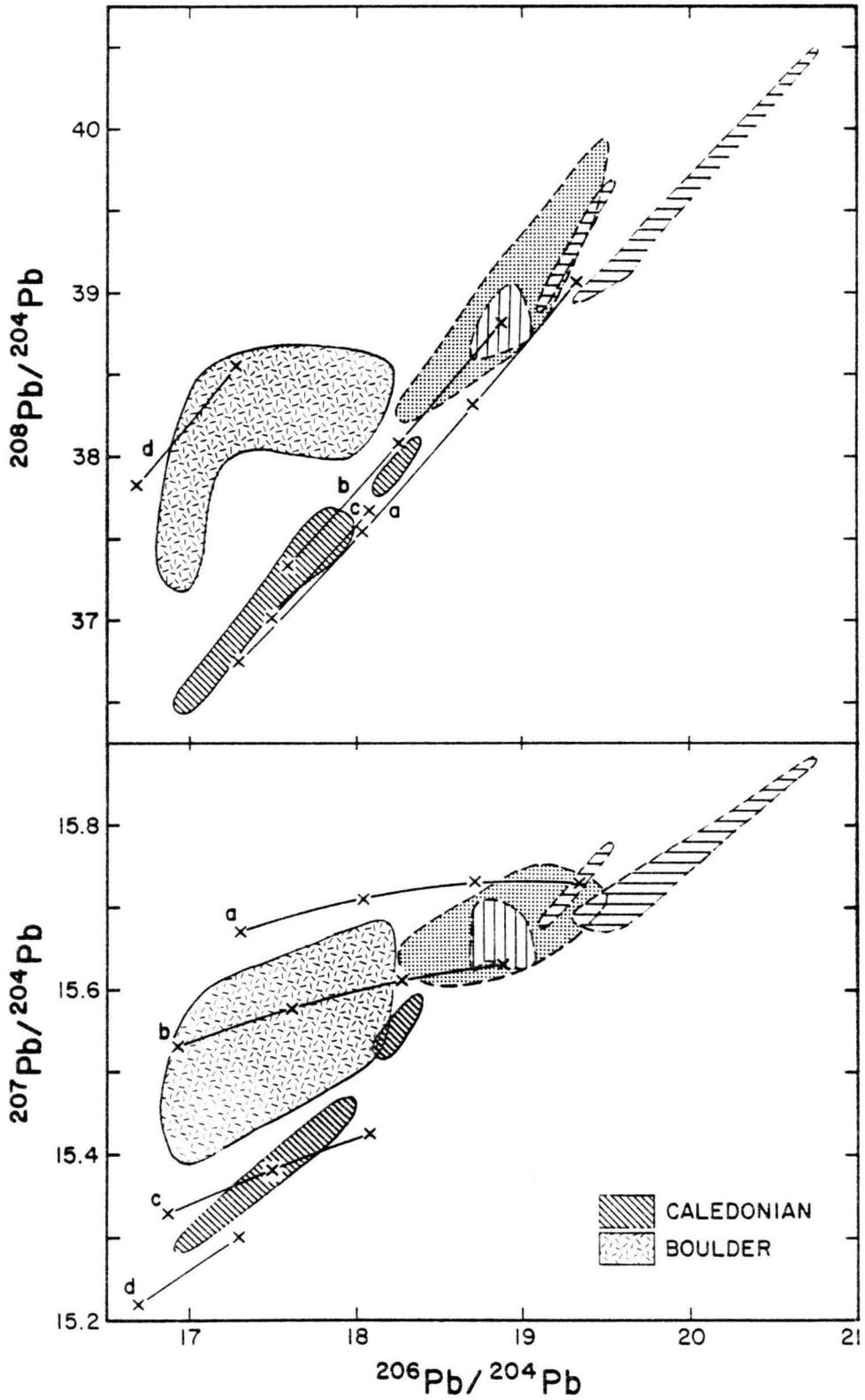


FIGURE 6.

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the isotopic composition of the Scottish Caledonian plutons (Blaxland et al., 1979), Boulder batholith (Doe et al., 1968), and plutons from Maine. Curved lines are as in Fig. 2.



Granitic rocks emplaced north of the NFS have isotopic compositions consistent with a source dominated by the continental environment. This is shown by the spread in the data between the curves of the orogene and upper crust (Fig. 5). The predominance of the continental reservoir is well displayed by their spread in $^{207}\text{Pb}/^{204}\text{Pb}$ and small range in $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$. Mature arcs, non-cratonized crust and pelagic sediments have Pb isotopic variations consistent with that of the plutons. All of these reservoirs are characterized by high $^{238}\text{U}/^{204}\text{Pb}$ environments displaying restricted variation in Th/U ratios. Comparison with plutons to the south of the NFS are in agreement with a Pb reservoir characteristic of erosional products derived from non-cratonized crust.

Recent studies focused on Nd and Sr systematics suggested the importance of continental material, especially like the upper and medium crust in the genesis of granitic plutons (Allegre and Othman, 1980). Pb isotopic variations in east-central Maine are in agreement with such conclusions. Although a laterally heterogeneous source across the synclinorium is evident from the Pb isotopic compositions, finer scale gradients in source composition are absent. This follows despite the zonal or general grouping by Katahdin and Seboeis to the NW, Center Pond and Bottle Lake near the center, and the Lucerne and Lead Mountain batholiths south of the NFS. The trend toward increasing slopes in the $^{208}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ is generally minor but nevertheless indicates the presence of different Th/U values. This is accompanied by a general increase in total Pb from Center Pond in a trend toward Passadumkeag River and Whitney Cove. Other plutons enriched in Pb are Katahdin and

Seboeis. This feature further emphasizes the importance of a reservoir like the upper continental crust. Katahdin and Seboeis plutons are, on the basis of their petrography (Hon, 1976; Ayuso et al., 1980) and composition (Loiselle and Ayuso, 1980) representative of a sedimentary parent, and contrast with the more mafic plutons in the core of the synclinorium.

Compositional changes along the traverse, particularly in plutons emplaced north of the NFS, suggest that the heterogeneous volcanoclastic source present in the core of the synclinorium becomes more homogeneous and dominated by erosional products from the Grenville craton. A progressive change in the character of the lithologies is consistent with the development of a miogeosynclinal sequence east of the craton.

Evidence for petrographic and geochemical heterogeneity within individual plutons in this traverse was documented in the BLC (chapter 2, this study). This diversity is also evident in the Pb isotopic composition of the batholith (Fig. 2) and is in agreement with previous studies showing incomplete isotopic homogenization in other granitic systems (Doe et al., 1968; Oversby, 1975, 1976). The variation in $^{207}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ implies large variations in $^{238}\text{U}/^{204}\text{Pb}$. Similar heterogeneities were documented to persist even in high rank metamorphic rocks (Taylor et al., 1980).

TECTONIC ENVIRONMENT

At least three environments for the generation of granites are commonly cited: 1) within plates in anorogenic areas; 2) at continent-continent collisional regimes; 3) at consuming margins by plate subduction.

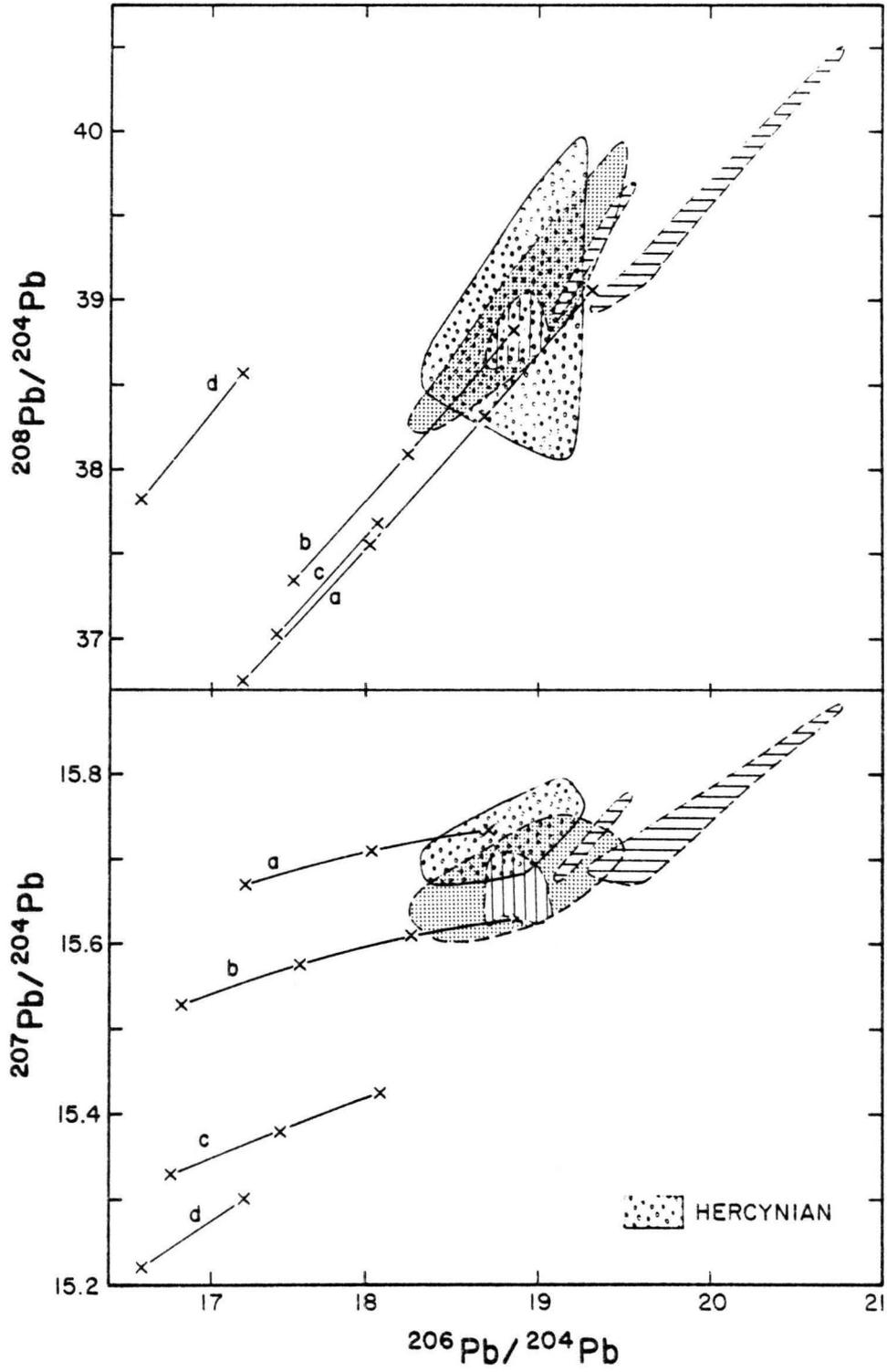
Plutons generated within plates are termed anorogenic and exhibit typical geochemical variations (Barker et al., 1975). Their Pb isotopic composition exhibits a range in values depending on the extent and involvement of the lower and upper continental crust. Among the best studied are plutons in the Boulder batholith (Doe et al., 1968). They represent an example of a batholith with a large input from lower crustal Pb as shown by its relatively unradiogenic nature, and large spread in $^{206}\text{Pb}/^{204}\text{Pb}$ at a given $^{207}\text{Pb}/^{204}\text{Pb}$ ratio (Fig. 6). Plutons from east-central Maine show limited overlap with this field.

A much closer equivalency in Pb composition is shown by granites formed at continent-continent settings exemplified by the Hercynian (Michard-Vitrac et al., 1980) and plutons north of the NSF (Fig. 7). Both show scatter in $^{207}\text{Pb}/^{204}\text{Pb}$ and indicate the importance of continental Pb. This is further reinforced by the higher values of $^{207}\text{Pb}/^{204}\text{Pb}$ in the Hercynian plutons as they completely envelop the evolutionary curve characteristic of the upper crust. Despite their similar range in $^{206}\text{Pb}/^{204}\text{Pb}$, however, Hercynian granites are offset to higher $^{207}\text{Pb}/^{204}\text{Pb}$ ratios representing compositions completely dominated by upper crust Pb, with minimal component from orogene material. On a $^{208}\text{Pb}/^{204}\text{Pb}$ to $^{206}\text{Pb}/^{204}\text{Pb}$ plot, the two groups are also in remarkable agreement, although the Hercynian granites tend to lie in a field somewhat higher in $^{208}\text{Pb}/^{204}\text{Pb}$. This is also in accordance with their continental nature.

Plutons on the south side of the NFS are consistently higher in $^{206}\text{Pb}/^{204}\text{Pb}$ than the Hercynian rocks. Although both plutonic suites display radiogenic compositions, their isotopic signatures are not

FIGURE 7.

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the composition of Hercynian plutons (Michard-Vitrac et al. 1980) and plutons from Maine. Curved lines are as in Fig. 2.



equivalent. Hercynian plutons are enriched in $^{207}\text{Pb}/^{204}\text{Pb}$ at a value of $^{206}\text{Pb}/^{204}\text{Pb}$, whereas the reverse relation is generally evident for plutons south of the NFS. Keeping in mind that $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ originate from parents of contrasting half-lives, the enrichment in $^{206}\text{Pb}/^{204}\text{Pb}$ suggests the predominance of a reservoir of great antiquity. Thus, despite the similarities between the two suites of plutons, the isotopic composition of the source was not entirely equivalent.

Environments representative of complex subduction zones involving orogene and continental material are similar in isotopic composition to the plutons north of the NFS (Figs. 8, 9). These are the sites conducive to the development of large batholith complexes represented by: 1) Sierra Nevada (Doe and Delevaux, 1973; Chen, 1977, 1978); 2) Andes (McNutt et al., 1979); 3) Southern Appalachians (Sinha and Merz, 1978). Closely related to this setting are granites associated with subduction at island arc environments as in Japan (Shimizu, 1964), and probably also represented in the Cascades (Church, 1976).

The value of $^{207}\text{Pb}/^{204}\text{Pb}$ consistently increases in a trend from the Cascades to the Hercynian plutons, suggestive of the gradual decrease in the involvement of oceanic mantle Pb. Rocks formed at complex subduction zones (Sierra Nevada, southern Appalachians, Andes) are intermediate in their $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and these are nearly equivalent to the plutons north of the NFS. However, the importance of the $^{208}\text{Pb}/^{204}\text{Pb}$ variations to provide information about the prevailing Th/U ratios in the source and thus help to distinguish between potential reservoirs is clearly demonstrated. Despite the overlap in $^{206}\text{Pb}/^{204}\text{Pb}$

FIGURE 8.

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the composition of feldspar and whole-rock of granite from Japan (Shimuzu, 1964), volcanics from the Cascades (Church, 1976), and plutons from Maine. Curved lines are as in Fig. 2.

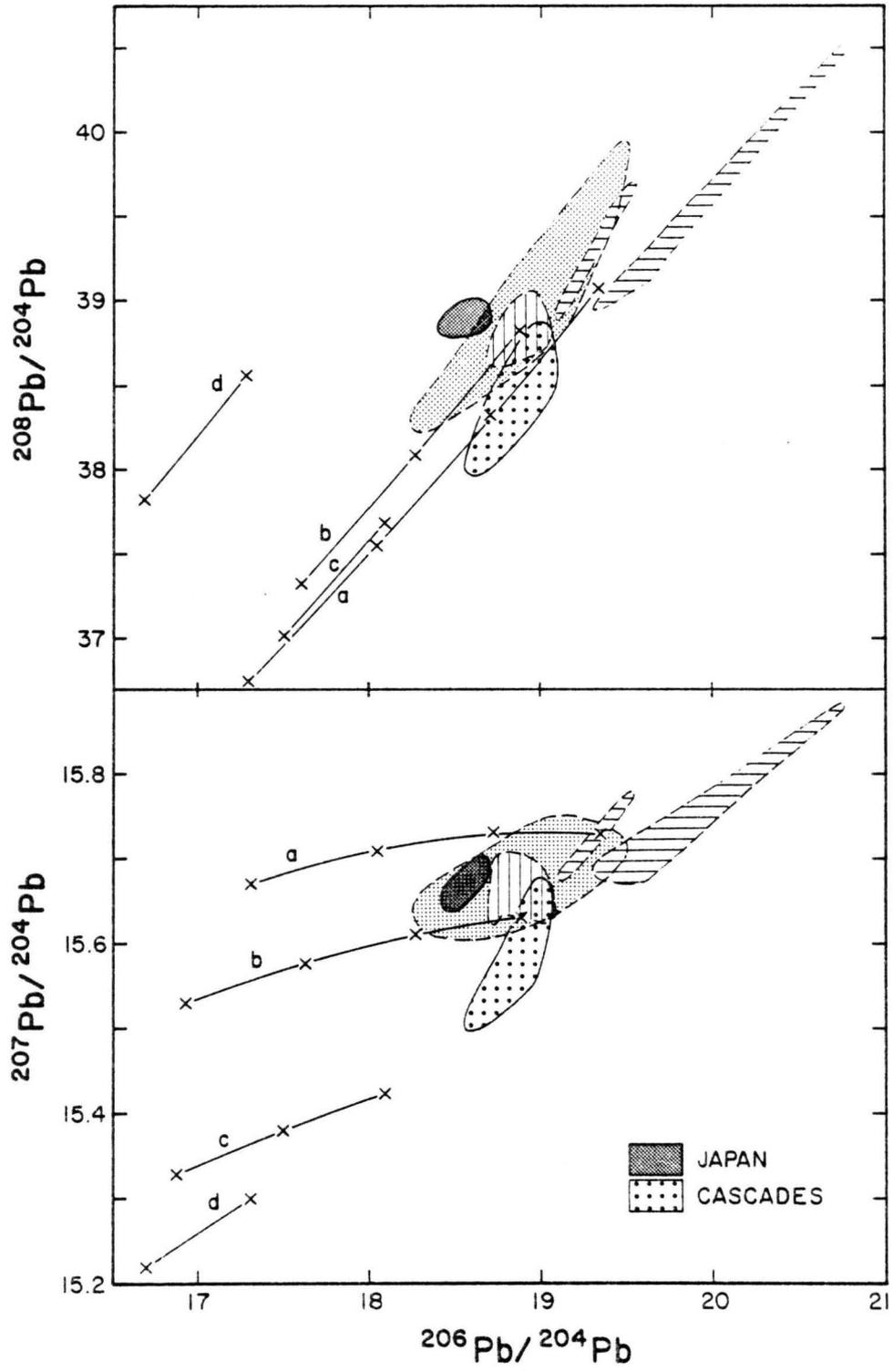
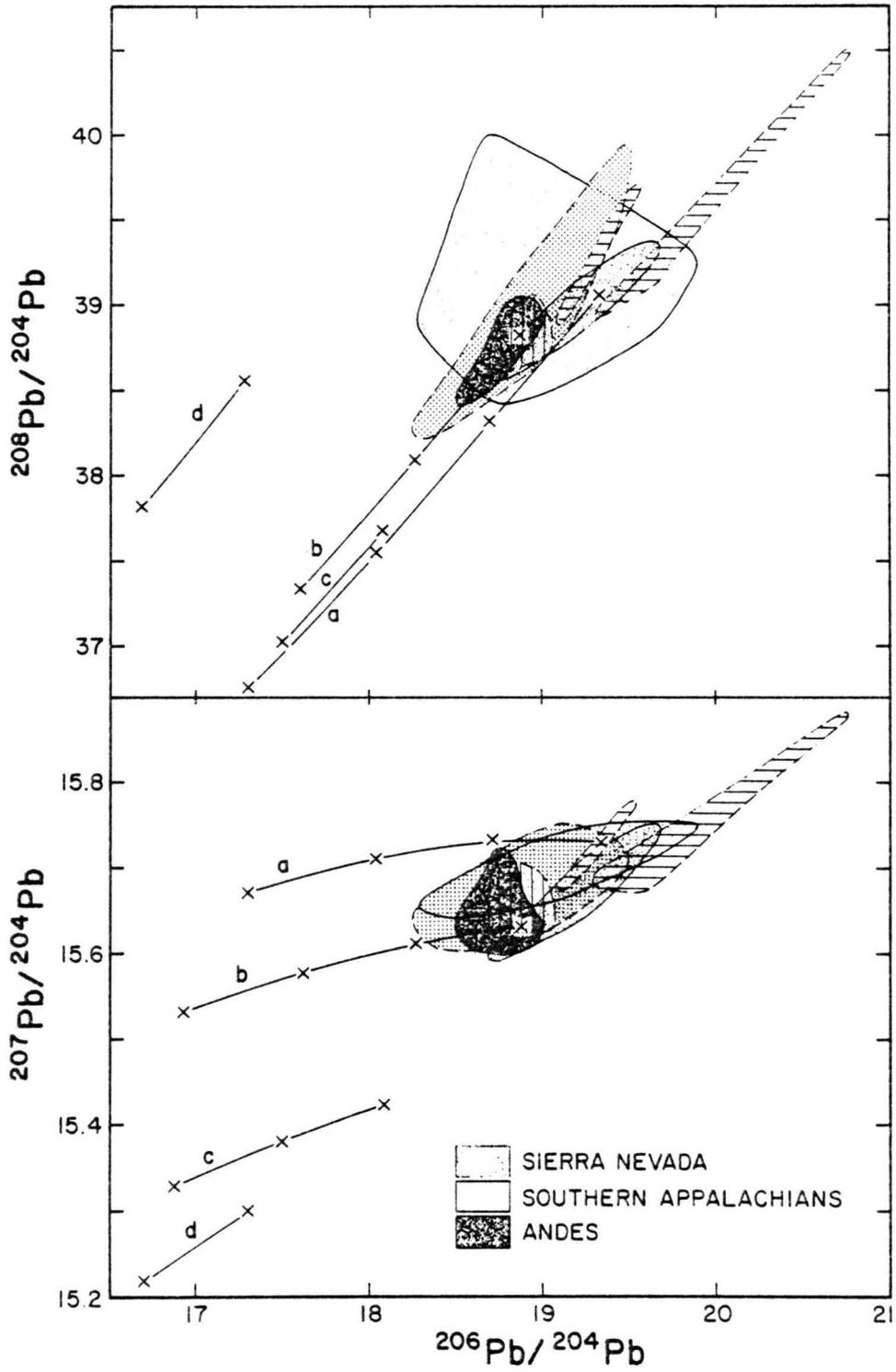


FIGURE 9.

$^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ plot showing the composition of feldspar and whole rock of the Sierra Nevada batholith (Doe and Delevaux, 1972; Chen, 1978), southern Appalachians (Sinha and Merz, 1978), Andes (McNutt, et al., 1979), and Maine granites. Curved lines are as in Fig. 2.



and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios between the Maine plutons and those from the southern Appalachians, the spread in $^{208}\text{Pb}/^{204}\text{Pb}$ in the latter suggests input from high rank metamorphics. This feature, missing in Maine, argues against major input derived from such a Th-rich source.

The conclusion from this comparison is that plutons emplaced north of the NFS represent a Pb reservoir similar to that in operation at complex-subduction (orogene) zones, but that this must be supplemented by a voluminous input from Pb derived from upper continental sources similar to those found in granites formed at continent-continent settings.

A direct dependence of granite generation on plate subduction processes in New England has been opposed by Wones (1980) on the basis of geological comparisons with the Sierra Nevada. Much of the argument centers on the petrological characteristics of the plutons, lack of geochemical gradients as a function of proximity to the Grenville basement, and volumetrically minor presence of andesite volcanics. Similar concerns were expressed after study of granites in New Brunswick (Fyffe *et al.*, 1980) and Newfoundland (Strong, 1980).

If plutonism in New England is not directly a result of plate subduction, alternative explanations include crustal melting by adiabatic decompression following collision, and melting of continental material by basaltic magma through heat transfer (Wones, 1980).

Many studies have demonstrated the existence of voluminous volcanism in New England ranging in age from Precambrian (Rankin, 1976) to Silurian (Aleinkoff, 1977; Hynes, 1976; Moench and Gates, 1976; Osberg, 1978). This suggests that heat transfer from continuous passage

and storage of hot magmas through the continental crust could adequately account for plutonism long after subduction has ceased.

On the basis of Pb isotopic studies the source region north of the NFS resulted from melting of a mixture of volcanoclastic and sedimentary debris which gradually became dominated to the NW by the erosional products from an old craton to the NW. The calc alkaline nature of the plutons tends to decrease from the BLC to Katahdin, and supports a general change in the composition of the source. Lead isotopic data on these plutons suggest that although the parental material show many of the features consistent with destructive margins, they are compatible with melting products of subduction originating in previous orogenic cycles (Ordovician?).

South of the NFS, the plutons probably represent the products of melting of a source wholly dominated by old erosional debris. Their Pb isotopic composition is heterogeneous, and even shows some overlap with plutons on the opposite side of the NFS. It is difficult but nevertheless possible, to relate both suites of plutons across the NFS into a common tectonic setting. This can be done by postulating that the petrographic and geochemical changes across the synclinorium result from different degrees of melting in a basin everywhere floored by similar basement. In this scheme, under ideal circumstances, plutons emplaced along the limits of the synclinorium might be similar, but as a group they are different from those in the core. The Pb isotopic composition of plutons at either end of the traverse (K, S, L, LM) are distinct and show no such similarities. They represent distinct sources of contrasting Pb isotopic makeup. A more plausible model is that

plutons emplaced south of the NFS are derived from a different crust, from a distinct and unspecified tectonic regime, which is coincidentally aligned with plutons emplaced north of the NFS.

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GEOLOGY OF THE BOTTLE LAKE COMPLEX, MAINE

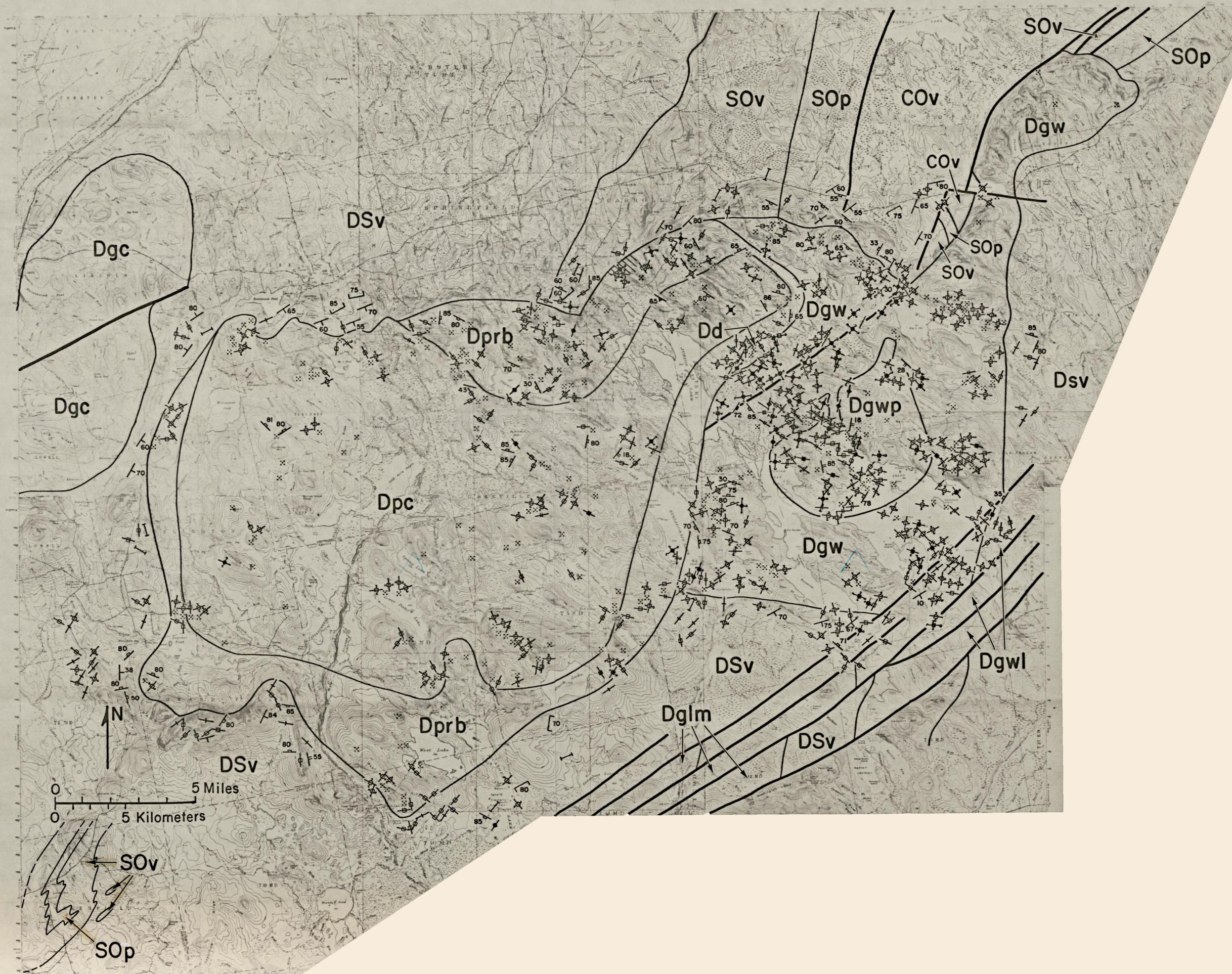
Robert A. Ayuso

(ABSTRACT)

The Bottle Lake Complex is a Paleozoic composite granite emplaced near the core of the Merrimack synclinorium in east-central Maine. The two plutons exposed within the Complex are reversely zoned in their mineralogy, major and trace element compositions. Each intrusive exhibits characteristic features including the abundance of amphibole and mafic xenoliths as in the Passadumkeag River granite, and relative abundance of biotite, aplites, and pegmatites in the granite of Whitney Cove. Both display geochemical variations identifying the respective core facies as the least differentiated zones compared to the rims. On the basis of field relations the relative sequence of intrusion is established between the two intrusives, but geochronologic studies using Pb-Pb zircon ages do not display a clear age difference. The granite of Passadumkeag River is, as judged by the field relations, the youngest pluton in the Complex. This granite is also the most heterogeneous body as expressed by petrography, mineral chemistry, and bulk composition. The numerous mafic xenoliths enclosed by the Passadumkeag River pluton display textural, mineralogical, and geochemical variations distinct from those found in the host granitoid rocks.

The source of the Bottle Lake Complex was heterogeneous in composition as suggested by the petrology of the granites and xenoliths, and by the wide range in $^{238}\text{U}/^{204}\text{Pb}$ of the batholith. Fractional crystallization accounts for most of the variation within each pluton,

although other processes such as mixing of liquids must also be postulated. In the case of the Whitney Cove pluton, mixing occurred prior to the major stage of fractionation. The granite of Passadumkeag River, however, records the mixing of a different batch of liquid during fractionation. Comparison of the geologic relations in the granites of east-central Maine, emplaced across the Merrimack synclinorium indicates that a major discontinuity in the sources of granitic liquid exists on either side of the Norumbega fault system. The Bottle Lake Complex is a distinctive batholith representative of the plutons emplaced in the core of the synclinorium. Together with the nearby Center Pond granite they form a distinct subgroup in comparison to the rest of the plutons on the northside of the Norumbega fault. The lead isotopic compositional variation across the synclinorium is unlike the documented changes present in complex subduction systems such as the Sierra Nevada. This is in agreement with previous geologic studies which suggested an absence of features characteristic of destructive tectonic margins in this area of New England. Granite generation across the synclinorium occurred in a short time interval probably by melting volcanioclastic materials on the north side of the fault, and by melting cratonic detritus on the opposite side.



LEGEND

PLUTONIC ROCKS - Bottle Lake Complex

Granite of Passadumkeag River

- Dpc** Coarse-grained biotite-hornblende bearing facies--generally quartz monzonitic composition, high color index, euhedral amphibole prisms, and abundant mafic inclusions
- Dprb** Coarse-grained biotite-hornblende granitic to quartz-monzonitic facies--commonly heterogeneous in texture; quartz forms large mosaic textures, generally poorer in mafic minerals than rocks in the interior

Amphibolite

- Dd** Diabase (?) intruded in cataclastic zone

Granite of Whitney Cove

- Dgwp** Medium- to coarse-grained, biotite bearing facies--homogeneous in composition, typically porphyritic, and low color index
- Dgw** Coarse-grained biotite facies granite--equidimensional texture, low color index, biotite in pseudo-hexagonal books

PLUTONIC ROCKS - Other Granitic Rocks

- Dgc** Granite of Center Pond--medium-grained, granitic rock ranging from diorite to biotite granite; contains abundant hornblende
- Dglm** Undifferentiated granitic rocks, usually coarse-grained, biotite-hornblende bearing rocks
- Dwl** Medium-grained granite found only within Norumbega fault zone, lower mafic-mineral content than Bottle Lake Complex

METAMORPHIC ROCKS

- DSv** Vassalboro Fm (?)--calcareous siltstones and pelites showing prominent mineralogic zonation from contact metamorphic effects imposed by the Bottle Lake Complex
- SOv** Undifferentiated Siluro-Ordovician (?), volcanic rocks, rusty pelitic beds; includes the Ordovician (?) Cemetery Hill Fm. (Olson, 1972)
- SOp** Undifferentiated Siluro-Ordovician (?), pelitic siltstones containing graded beds; includes the Ordovician (?) Greenfield Fm. (Olson, 1972)
- COu** Graywakes, siltstones, slates are the main lithologies of Cambro-Ordovician (?) age

Geology by R. A. Ayuso and assistants (1977, 1978, 1979); based on fieldwork by D. Larrabee and assistants (1965), R. K. Olson (1972), A. Ludman (1978a, b), D. R. Wones (1979), and T. Scambos (1980).

- 15  Inclined bedding
-  Vertical bedding
- 15  Inclined cleavage
-  Vertical cleavage
- 15  Inclined joint
-  Vertical joint
-  Joint, variable strike and dip
- ∴ Massive rock, no foliation
- 15  Inclined cataclastic surface
-  Vertical cataclastic surface
-  Cataclastic surface, variable strike and dip
- 15  Inclined foliation
-  Vertical foliation
-  Foliation, variable strike and dip
- 15  Inclined leucocratic dike
-  Vertical leucocratic dike
-  Leucocratic dike, variable strike and dip
-  Abundant leucocratic dike
-  Fault
-  Contact
- 15  Plunge of antiform
- 15  Plunge of synform