Geology of Selected Quadrangles In Massachusetts

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STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

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CONTENTS

[The letters in parentheses preceding the titles designate separately published chapters]

Bedrock Geology of the Salem Quadrangle and Vicinity Massachusetts

By PRIESTLEY TOULMIN 3d

GEOLOGY OF SELECTED QUADRANGLES IN MASSACHUSETTS

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CONTENTS

Descriptions of rock units—Continued

Middle(?) Paleozoic rocks, etc.—Continued

ILLUSTRATIONS

[Plate in pocket]

TABLES

GEOLOGY OF SELECTED QUADRANGLES IN MASSACHUSETTS

BEDROCK GEOLOGY OF THE SALEM QUADRANGLE AND VICINITY, MASSACHUSETTS

By PRIESTLEY TOULMIN 3d

ABSTRACT

The Salem quadrangle, about 15 miles northeast of Boston, Mass., is underlain by metamorphic and igneous rocks and is best known geologically for its "alkalic" igneous rocks.

The oldest rocks in the area are the gneisses and plagioclase amphibolites of the Marlboro(?) Formation, possibly Precambrian in age. These rocks are folded into a southwest-plunging overturned syncline whose axial plane strikes northeast and dips about 60° northwest. The Marlboro(?) Formation is overlain unconformably by the Newbury Formation, which consists of altered volcanic and sedimentary rocks and contains fossils of Silurian or Devonian age. The Newbury Formation is intruded by granodiorites collectively designated the younger subalkaline intrusive series, which may be related to the volcanic rocks of the Newbury Formation. The Salem Gabbro-Diorite and Newburyport(?) Quartz Diorite, grouped as the older subalkaline intrusive series, are believed to be intermediate in age between the Marlboro(?) Formation and the Newbury Formation.

The "alkalic" intrusive series consists of six rock units, which were intruded more or less simultaneously. These rocks, the youngest major bedrock units in the area, are massive and fresh, in contrast to the older rocks. The rocks of the "alkalic" series occur in two major intrusive bodies: the Peabody stock, consisting almost entirely of granite, and the Cape Ann pluton, consisting of granite, syenite, and several minor rock types. Feldspathoidal rocks are not abundant and occur only as dikes; they seem to be the youngest rocks in the areas in which they are found. The most abundant rock of the Cape Ann pluton is granite, syenite and other rocks being concentrated around its margins; only the southwestern margin of the pluton is included in the Salem quadrangle.

The feldspars of the "alkalic" series are microcline-microperthite; none of the analyzed specimens contains more than about 3½ weight percent $CaAl_2Si_2O_8$. The ratio of Ab ($NaAlSi_3O_8$) to Or ($KAlSi_3O_8$) varies widely and systematically: Phenocrysts of the locally developed porphyritic border facies of the granite contain 56 to 61 weight percent Or, feldspar of the main bodies of granite contain 44 to 52 weight percent Or, and feldspars of the syenite contain 24 to 43 weight percent Or. Compositions were determined by X-ray diffraction methods and by chemical analyses of selected samples.

Chemical analyses of amphiboles from both granite and syenite show that the amphiboles are essentially ferrohornblende, but arfvedsonite ($NaNa_2Fe^{+3}_2 Fe^{+2}_3Fe^{+3}Si_7O_{22}(OH)_2$) is an important component in the amphibole of the syenite.

INTRODUCTION

LOCATION AND ACCESSIBILITY

The area described in this report includes the Salem 7½-minute quadrangle, Mass., and that part of Salem Neck lying in the Marblehead North 7½-minute quadrangle, Mass. (fig. 1). The area is about 15 miles northeast of Boston and is traversed by U.S. Route 1 and Massachusetts Route 128, both major, limited access, divided multilane highways. It is densely populated and is served by many roads and streets.

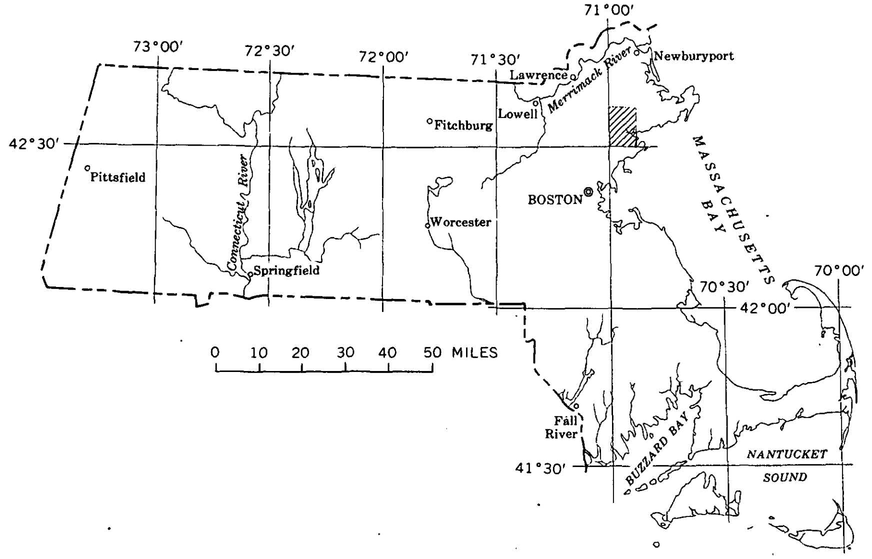

FIGURE 1.—Index map showing location of Salem quadrangle.

PREVIOUS WORK

Many geologists have studied different aspects of the area, but most of them have been interested primarily in the "alkalic" igneous rocks. The works of Clapp (1910; 1921), Washington 1898–99), and Sears (1905) are the most detailed studies available. Warren and McKinstry (1924) studied the "alkalic" rocks of the Cape Ann area but did not describe the area of the present report. No attempt will be made here to summarize all previous geologic investigations in the area; references to earlier studies may be found in the publications cited.

METHODS OF STUDY

Detailed geologic mapping was done on a topographic base provided by the Salem and Marblehead North 7½-minute quadrangles published by the U.S. Geological Survey in 1951 at the scale of 1:31,680. The geology was recompiled on the subsequently improved and enlarged base on which it is presented (pl. 1). Because of the abundance of cultural features, location by inspection was feasible in most of the area, but where this method was not adequate, pace-and-compass traverses and resection by Brunton compass were employed.

Laboratory investigations included examination of thin sections and mineral powders by conventional petrographic methods and detailed X-ray diffraction studies of the feldspars of the "alkalic" rocks. Chemical analyses were made of certain minerals of the "alkalic" rocks.

PURPOSE AND SCOPE

This report is concerned both with the general bedrock geology of the Salem quadrangle and with the petrology of the "alkalic" rocks for which the Salem area is renowned. The northwestern part of the Salem quadrangle is underlain by metamorphic rocks which on previous geologic maps of the area are assigned to the Salem Gabbro-Diorite (for example, Clapp, 1921, pls. I, II, where, however, vaguely defined areas within the Salem Gabbro-Diorite are shown by a special pattern representing "Salem Gabbro-Diorite with amphibolite schist"). An important goal of the present study has been to separate the metamorphic rocks from the truly igneous Salem Gabbro-Diorite and to determine their structural and stratigraphic relationships to the other rocks of the area.

The "alkalic" igneous rocks of the Salem area have been studied in the light of significant advances in mineralogic and petrographic techniques and petrologic theory that have been made since Clapp's detailed study (1921) of the "alkalic" rocks of Essex County. Much of the evidence bearing on the petrology of the "alkalic" rocks is based on the author's study of areas adjacent to the Salem quadrangle. Details of this work are in an unpublished doctoral thesis at Harvard University[1]; some of the most important results have been published elsewhere (Toulmin, 1960).

ACKNOWLEDGMENTS

Most of the work on which this report is based was done under a cooperative program of the Massachusetts Department of Public Works and the U.S. Geological Survey. Much of the work on

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[1] Toulmin, Priestley 3d, 1958, Bedrock geology of the Salem area, Massachusetts: Ph.D. thesis, Harvard Univ., Cambridge, Mass., 167 p.

adjacent parts of the Marblehead North quadrangle was done while the writer was a pre-Doctoral Fellow of the National Science Foundation. The Department of Mineralogy and Petrology, Harvard University, financed chemical analyses of amphiboles and feldspars. The Peabody Museum, Salem, through the courtesy of Miss Dorothy E. Snyder, Curator of Natural History, gave access to Sears' collection of Essex County rocks. Credit for specific analyses and paleontologic determinations is given in the appropriate sections of the text.

The advice and guidance of Professors J. B. Thompson, Jr., and M.P. Billings, of Harvard University, are deeply appreciated. Drs. E-an Zen and R. F. Schmalz offered stimulating discussions of many of the problems that arose during the study. For enlightening discussions of nearby areas, the author is indebted to R. O. Castle and R. F. Novotny. M. S. Toulmin gave invaluable assistance in the laboratory.

DESCRIPTIONS OF ROCK UNITS

PRECAMBRIAN(?) ROCKS

MARLBORO(?) FORMATION

DISTRIBUTION AND NAME

Exposures of gneiss, schist, and amphibolite form a belt 1 to 1½ miles wide that extends from the Peabody-Danvers town line west of U.S. Route 1 (the Newburyport Turnpike in this area) northeastward about 4 miles through the town of Danvers to the Wenham town line northeast of Putnamville. The extent of these rocks under the surficial deposits to the northwest and southeast is largely conjectural, but their eastward extent in the vicinity of Putnamville is limited by the exposures of Cherry Hill Granite east of Frost Fish Brook. These rocks are tentatively assigned to the Marlboro Formation because of their general lithologic similarity to, and structural continuity with, rocks so mapped by R. O. Castle (written communication, 1961) in the Reading quadrangle. An area of similar rocks in the northwestern corner of the Salem quadrangle is assigned to the Marlboro(?) Formation on the basis of lithologic similarity to the rocks of the main belt of outcrop.

SUBDIVISION

The rocks of the main belt of the Marlboro(?) Formation in the Salem quadrangle are subdivided in this report into four map units, which are, in ascending order of structural position, unit A, unit B, a band of amphibolites, and a band of chloritic schists. Units A and B underlie most of the area of the Marlboro(?) Formation in the Salem quadrangle. Unit A is composed almost exclusively of massive and foliated plagioclase amphibolites; unit B is distinguished from it by the presence of beds of augen gneiss interbedded with the plagioclase amphibolite. The contact between the two members is taken arbitrarily at the easternmost and presumably lowest bed of gneiss found.

Representative estimated modes of various lithologic types found in the Marlboro (?) Formation are given in table 1.

UNIT A

Unit A consists of plagioclase amphibolite. The rock is medium grained and rather dark, owing to the high proportion of mafic minerals. Hornblende, plagioclase, and locally biotite and quartz may be recognized in hand specimen. Foliated and unfoliated varieties of plagioclase amphibolite exist; the foliation results from parallel alinement of hornblende crystals and in some specimens is parallel to a layered structure consisting of thin discontinuous bands having different proporations of plagioclase and amphibole. No differences in mineralogical composition were noted between the foliated and unfoliated varieties.

TABLE 1.—*Representative estimated modes of rocks of the Marlboro (?) Formation*

Mineral	Groundmass of augen gneiss [1]	Plagioclase amphibolite							Amphibolite	
		SG431	SG432	SG438	SG482	SG484	SG498	SG541	SG250	SG491
Quartz	10	20	10	5	1	--------	8	1	--------	10
Plagioclase	35	50	50	55	39	45	72	55	15	8
Microcline	12	3	--------	--------	--------	--------	--------	--------	--------	--------
Augite	10	--------	--------	--------	Tr.	2	--------	15	--------	--------
Hornblende	--------	15	32	29½	55	45	15	15	80	80
Biotite	30	10	8	10	3	--------	3	10	--------	--------
Chlorite	1	--------	--------	--------	--------	3	--------	--------	5	--------
Epidote	Tr.	1	Tr.	--------	--------	--------	Tr.	--------	--------	--------
Apatite	Tr.	--------	Tr.	Tr.	½	Tr.	Tr.	1	Tr.	--------
Zircon	Tr.	--------	--------	--------	--------	--------	--------	--------	--------	--------
Opaque	2	--------	Tr.	½	1½	5	2	3	Tr.	2
Sphene	--------	1	--------	--------	--------	--------	--------	--------	--------	--------

[1] Average composition of five specimens.

SG431. Plagioclase amphibolite at farmhouse 1,000 ft east of East Street, Middleton, on eastward extension of Peabody Street.
SG432. Strongly foliated plagioclase amphibolite, south end of hill 600 ft east of Thunder Bridge, Middleton.
SG438. Plagioclase amphibolite, East Street (Endicott Road) at Boxford-Middleton town line.
SG482. Plagioclase amphibolite, abandoned quarry north of Wenham Street, Danvers, 500 ft southwest of Wenham town line.
SG484. Plagioclase amphibolite, about 1,500 ft west of bench mark 84 at intersection of Routes 1 and 114, Danvers.
SG498. Plagioclase amphibolite, hill east of Norris Brook, southwest of Goodale Cemetery, Danvers.
SG541. Plagioclase amphibolite, intersection of Routes 1 and 114, Danvers.
SG250. Laminated amphibolite, outcrop in Sons of Jacob Cemetery 500 ft west of Goodale Cemetery, Danvers.
SG491. Amphibolite, in woods 150 ft east of Goodale Cemetery, Danvers.

In thin section, the plagioclase is seen to be generally rather highly altered to sericite and clay minerals; saussurite was not observed. ("Sericite" is used here to designate very fine-grained micaceous minerals with positive elongation and rather high birefringence. The few specimens that have been checked by X-ray diffraction techniques have proved to be micas having a basal spacing of 10 angstrom units.) Much of the fresh plagioclase is twinned polysynthetically and has extinction angles that indicate a composition ranging from andesine to sodic labradorite. The twinned plagioclase is subhedral to anhedral, and many grains show continuously and normally zoned extinction. Some of the plagioclase of a few sections is clear and untwinned; this material presumably represents completely recrystallized feldspar.

Common hornblende makes up from 20 to 50 percent of the rock. It occurs most commonly as individual crystals, generally of irregular outline, from 0.1 to 5 mm in diameter, but also forms aggregates of 0.3-mm crystals very similar in appearance to the bulk of the feldspar-poor amphibolite described below. The depth of color varies considerably from specimen to specimen, but most slides show Z, slightly bluish-green; Y, yellowish-green; and X, light tan. Augite forms irregular cores in some of the hornblende crystals and constitutes as much as 15 percent of some rock specimens. Biotite, pleochroic in reddish brown, occurs in shreds and flakes as much as a few tenths of a millimeter across. Quartz occurs in a few specimens in irregular anhedral grains but is absent or very rare in most slides. The most characteristic accessory mineral is apatite, which makes up 3 to 4 percent of some specimens. Zircon and sphene occur locally; magnetite is ubiquitous and generally associated with hornblende. Epidote was seen in a few slides, associated with hornblende. Chlorite is associated with hornblende in several specimens.

The composition of the plagioclase amphibolite is compatible with either of two possible protoliths: impure dolomite, and andesite or diorite. The proportion of clastic material and the magnesium content of a thick unit of impure carbonate rock might be expected to vary, so that beds or zones of calcareous shale or of more calcitic limestone would occur in the stratigraphic sequence. The metamorphosed equivalents of such beds would readily evident as calc-silicate rocks or aluminous schists, but such rocks have not been observed in association with the plagioclase amphibolite. The foliation of the plagioclase amphibolite composing units A cannot be shown to be relict bedding or mimetic after bedding, but similar foliation in plagioclase amphibolites in unit B is parallel to bedding where both features are seen together. This resemblance, as well as the transitional nature of the contact between unit A and the bedded unit B, suggests a supracrustal protolith for the plagioclase amphibolite. It seems most reasonable to assume that the parent rock was volcanic, perhaps in part pyroclastic, and roughly andesitic in composition.

UNIT B

Unit B underlies a larger area in the Salem quadrangle than any other part of the Marlboro(?) Formation. Unit B is distinguished from unit A by the presence of beds of augen gneiss interlayered with the dominant plagioclase amphibolite. Exposure is extremely poor over most of the area underlain by unit B, and no reliable estimate of the proportions of its two lithologies can be made.

The plagioclase amphibolite is identical to that of unit A, and need not be described further.

The augen gneiss is composed essentially of microcline, plagioclase, and biotite, and accessory amounts of quartz, hornblende, epidote, pyroxene, chlorite, and magnetite (table 1). The rock is characterized by feldspar megacrysts, most of which are microcline. Perhaps as many as one-fifth of the megacrysts are plagioclase. The megacrysts are ellipsoidal, mostly about 1 cm long and 3 to 5 mm across; in most outcrops the long dimensions of the megacrysts are parallel to one another, to the schistosity of the biotite-rich matrix in which they occur, and to the bedding.

Some of the augen show a distinct zonal structure; the generally rather thin rims are different in color and degree of alteration or weathering from the main body of the crystal. None of the thin sections studied happened to show this feature, but X-ray diffraction patterns of the core and rim of a single megacryst indicate that the core is microcline and the rim is plagioclase having a composition about An_{30}. Figure 2 shows a typical specimen of augen gneiss containing zoned megacrysts.

The distinctly bedded structure of the augen gneiss indicates a sedimentary or pyroclastic origin. The writer favors a pyroclastic origin because of the relatively small amount of quartz and the association with plagioclase amphibolite, which is believed to be of volcanic origin; the local high ratios of potassium to sodium, shown by abundant microcline and mica, may represent admixtures of shaly material. Highly aluminous rocks, however, have not been found in unit B.

AMPHIBOLITE

Dark-green, schistose amphibolite is exposed in the vicinity of the Goodale and Sons of Jacob Cemeteries in Danvers. The typical rock is very fine grained and shows a fine lamination, few individual laminae being more than ½ mm thick. Common green hornblende ($Z \wedge c = 18°$; pleochroism: Z, bluish green; Y, green; X, tan) predomi-

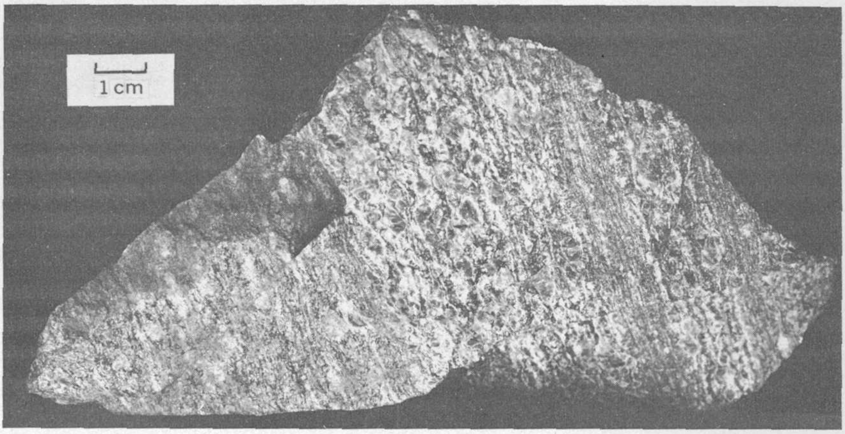

FIGURE 2.—Specimen of augen gneiss of unit *B* of Marlboro(?) Formation, from outcrop at intersection of Routes U.S. 1 and State 114, Danvers. Note even compositional banding shown by layers of different proportions of feldspar megacrysts. These layers are of remarkably uniform thickness. A few of the megacrysts are zoned, having microcline cores (dark in photograph) and plagioclase rims (light in photograph).

nates over untwinned calcic plagioclase, but the proportions of the two minerals vary widely from lamina to lamina. The hornblende forms euhedral and subhedral crystals elongated in the plane of the lamination; most of the crystals are about 0.05 mm long, but a few are as long as 0.7 mm. The plagioclase occurs in very small (about 0.02 mm), equant anhedra. Colorless to very light green chlorite is intergrown with hornblende in small irregular patches and rounded knots as much as 1 mm in diameter.

A slightly coarser grained, equally strongly foliated, spotted variety of amphibolite contains lenticular aggregates 2 to 3 mm thick and 1 to 2 cm long that are composed exclusively of hornblende in euhedral and subhedral crystals 0.1 to 0.5 mm in size. These aggregates of hornblende crystals are separated from one another by a granular mosaic of the same hornblende, untwinned plagioclase, and possibly some quartz—all of which range from a few hundredths of a millimeter to a rare maximum of 0.1 mm. A few of the plagioclase grains show fine albite twinning, and the extinction angles of 32° normal to (010) indicate a composition of An_{60}.

Closely associated with the amphibolite, and included with it on plate 1, is an evenly and thinly bedded, very fine-grained (average, 0.05 mm) quartzo-feldspathic rock. Chlorite is rather abundant in this rock, which also contains some tiny pleochroic shreds that may be amphibole. This rock is interpreted as a slightly metamorphosed siltstone or very fine grained sandstone. About 1,750 feet N. 80° W. from the intersection of Buxton Lane and Andover Street, Danvers, exposures of pebbly sandstone and conglomerate are associated with the siltstone and amphibolite on a knoll of about 80 feet elevation. It is possible, however, that the conglomerate exposed is not in place.

The association of the amphibolite with clastic sedimentary rocks indicates an origin near or at the surface of the earth. Although the metamorphism of a shaly magnesian limestone or dolomite might produce the mineral assemblage of the amphibolite, the writer thinks it more likely that the amphibolite is a metamorphosed pyroclastic rock of basaltic or andesitic composition. Neither lime-silicates nor high-alumina silicates have been seen in the amphibolite unit, even locally; their absence requires an unusually constant ratio of carbonate to argillaceous material, if the original rock were an impure carbonate rock. The preservation of fine lamination in the amphibolite suggests that inhomogeneities of bulk composition have persisted over large distances, so that one might expect at least a few clay-rich or carbonate-rich beds to be represented by aluminum silicates or lime-silicate minerals (or carbonates). The overall compositional homogeneity of the amphibolite is more in keeping with a volcanic protolith, or parent rock, and the fine, even lamination suggests deposition of pyroclastic material, perhaps in water.

CHLORITE SCHIST

Along the hill east of Norris Brook are a few exposures of a chlorite-bearing rock at least some of which seems to be a metamorphosed breccia, perhaps pyroclastic. Angular fragments as much as several millimeters across are enclosed in a schistose matrix of light-green chlorite. Most of the fragments are of a fine-grained mosaic of quartz and untwinned plagioclase; at least one fragment is composed of tiny (about 0.03 mm) feldspar granules in a dominant, dark-green chlorite matrix.

UNDIFFERENTIATED MARLBORO(?) FORMATION

The area mapped as undifferentiated Marlboro(?) Formation in the northwest corner of the Salem quadrangle consists mainly of amphibolitic rocks. Medium- to fine-grained quartz- and biotite-bearing plagioclase amphibolites predominate. They are composed essentially of andesine and hornblende, and both massive and schistose varieties are common. A few outcrops show well-developed gneissic structure, in which bands of fine grained (1–2 mm) quartzo-feldspathic granulite alternate with fine-grained schistose amphibolite.

AGE AND CORRELATION

Most of the rocks here assigned to the Marlboro(?) Formation were included by LaForge (*in* Emerson, 1917) in the Salem Gabbro-Diorite, but they are lithologically more similar to other rocks referred by him to the Marlboro(?) Formation, of probable Algonkian age. The rocks of the main belt are continuous with rocks mapped as Marlboro Formation in the Reading and Wilmington quadrangles by R. O. Castle (written communication, 1961).

The rocks assigned to the Marlboro(?) Formation in the Salem quadrangle are shown on plate 1 as Precambrian(?) in age; they are the most highly deformed and metamorphosed rocks in the quadrangle and are probably older than any of the rocks with which they are in contact. The Marlboro(?) Formation is believed to be intruded by the Salem Gabbro-Diorite and Newburyport(?) Quartz Diorite and to be unconformably overlain by the Newbury Formation. A minimum pre-Late Silurian age is thus indicated for the Marlboro(?) Formation in this area.

PRECAMBRIAN(?) OR LOWER PALEZOIC(?) ROCKS (OLDER SUBALKALINE INTRUSIVE SERIES)

In this report, the rocks designated the subalkaline group by Clapp (1921) are further divided into two subgroups according to their apparent ages relative to the Upper(?) Silurian or Lower(?) Devonian Newbury Formation. For convenience, these subgroups are designated the older and younger subalkaline series. The older subalkaline series consists of the Salem Gabbro-Diorite and the Newburyport Quartz Diorite.

SALEM GABBRO-DIORITE

NAME

The name Salem Gabbro-Diorite was first applied to the gabbroic and dioritic intrusive rocks of Salem, Massachusetts, by C. H. Clapp (1910). The name is retained here because the map unit includes both gabbros and diorites, as well as much rock that is too badly altered for precise determination. Probably more of the unit is diorite than is gabbro, and the "olivine gabbro phase" of Clapp in particular is very rare, and may be more closely related to the "alkalic" series than to the Salem Gabbro-Diorite.

DISTRIBUTION

The Salem Gabbro-Diorite crops out abundantly in the southeastern and central parts of the Salem quadrangle. It is particularly well exposed in the hilly area south of the city of Salem and along the South Salem and Marblehead shores. A tongue of Salem Gabbro-Diorite extends northeastward into the adjacent Marblehead North quadrangle in the vicinity of Wenham. Several outcrops of hornblende diorite about 1.5 miles north of Beverly Airport are believed to belong to the Salem Gabbro-Diorite.

DESCRIPTION

The rocks of the Salem Gabbro-Diorite are heterogeneous texturally and compositionally. Representative estimated modes are given in table 2. The rock of the type area, between Salem and Lynn, is dominantly a hornblende-augite diorite or gabbro varying from fine grained to moderately coarse grained. It is highly and complexly jointed, and is cut by many small shear zones and minor faults. A foliated structure is present only very rarely; it is a small-scale, local feature associated with zones of shearing. The rock is greyish green on unweathered surfaces; the weathered rock is characteristically dark brown.

Basalt and diabase dikes cut the Salem Gabbro-Diorite in great abundance. Pegmatite dikes and pods, composed of pink feldspar, quartz, epidote, and more rarely calcite, are common and are probably related to the intrusion of the gabbro-diorite. Many other dikes of granite, micropegmatite, quartz porphyry, and similar rocks are clearly related to the "alkalic" series, as may be some of the diabase dikes.

Plagioclase constitutes 50 percent or more of the typical rock; nearly all the plagioclase is very highly altered to an aggregate of sericite, clay minerals, and calcite. The feldspar varies considerably in composition, but it is rarely more calcic than An_{50} and is commonly more sodic than An_{40}, especially where large amounts of sericite and clay are present. The calcic cores of zoned plagioclase crystals are more thoroughly converted to sericite and clay than the more sodic rims.

Hornblende is the principal dark mineral in the typical rock, of which it constitutes as much as 20 percent. The hornblende is pleochroic with X, light tan; Y, deep dirty green; and Z, dark brownish green. The apparent extinction angle $Z' \wedge c$ ranges from 18° to almost 30°; 2V is large (as much as 70°) and negative.

Augite constitutes a few percent of most specimens but is absent from a few sections. It generally occurs as ragged, presumably residual cores in hornblende crystals. Augite is a major constituent of a few specimens, making up as much as 20 percent of the rock; in such rocks hornblende forms discontinuous rims around the augite crystals. Most augite grains are colorless or very pale green in thin section, but a few are faintly pleochroic in light pink. Inclusions of magnetite (or ilmenite) and rutile(?) are common; the rutile(?) occurs as clusters of long, thin, parallel rods. Biotite occurs in most specimens of Salem Gabbro-Diorite, but rarely amounts to more than a few percent of the rock. It is typically dark brown except in a few sections where it has been bleached by alteration, which also resulted in the formation of thin layers of leucoxene (and sphene?) along the cleavage.

Minor amounts of quartz occur in a few sections as irregular grains as much as 2 mm in greatest dimension. Potassic feldspar without visible twinning is rather rare but constitutes about 10 percent of one or two of the sections examined, in which it is slightly perthitic. Chlorite is intergrown with biotite in a few sections and occurs as pseudomorphs after biotite in several specimens. Remarkably long, thin apatite needles are characteristic of the rock; magnetite and pyrite are other common accessories. Thin veinlets of calcite, locally associated with prehnite, cut many specimens.

AGE AND CONTACT RELATIONS

The Salem Gabbro-Diorite is intruded by many dikes of the "alkalic" series, and therefore is older than that series. Its contact with the Marlboro(?) Formation seems to transect the structure of the Marlboro(?). Although metamorphism apparently extended across the area now occupied by the Salem (see p. A69), this rock unit has not undergone the intense regional metamorphism that has affected the rocks of the Marlboro(?) Formation. It is therefore concluded that the Salem Gabbro-Diorite is younger than, and probably intrusive into, the Marlboro(?) Formation. It may be of Early Paleozoic age.

The origin of the Salem Gabbro-Diorite generally has been thought to be connected with that of the rocks mapped as Newburyport(?) Quartz Diorite in the Boston area (LaForge, 1932, p. 27–28). Direct evidence for or against this assertion is not available in the Salem area, but the general degree of alteration and the structural relations of the two units are compatible with approximately simultaneous origin.

NEWBURYPORT(?) QUARTZ DIORITE

DISTRIBUTION AND NAME

Quartz diorites cropping out along the western boundary of the Salem quadrangle south of Howe are here provisionally assigned to the Newburyport Quartz Diorite on the basis of lithologic similarity to rocks so mapped in the Boston area by LaForge (1932).

LITHOLOGIC DESCRIPTION

The rock is a medium-grained (3 mm) quartz diorite composed of quartz, altered plagioclase, and chloritized hornblende. In hand specimen it presents a mottled green appearance. In thin section the quartz grains are seen to be mosaic aggregates of equant anhedra 0.3 to 0.5 mm in diameter, showing undulatory and patch extinction. Almost no fresh plagioclase remains in the rock, but stubby subhedral pseudomorphs, 0.5 to 3 mm across, consisting of an aggregate of sericite and epidote, are abundant. The epidote occurs in granules 0.02 to 0.05 mm in diameter and apparently varies somewhat in iron content, for many of the grains are colorless and show the anomalous blue interference colors of clinozoisite, whereas others are pleochroic and show higher interference colors. The epidote of some saussurite aggregates is zonally arranged in such a manner as to suggest reversed or even oscillatory zoning in the original plagioclase crystal. A little microcline, slightly microperthitic, occurs in anhedral masses interstitial to the plagioclase and ferromagnesian minerals. It is notably less altered than the plagioclase.

Hornblende crystals as much as 3 mm long are more or less euhedral, except where they are intergrown with chlorite and epidote. The unaltered hornblende is pleochroic in light green and tan, and $Z\Lambda c=15°$. The epidote associated with hornblende occurs in larger grains (as much as about one-half millimeter) and is much more strongly pleochroic and birefringent than that in the saussurite.

It is estimated that the rock was originally composed of about 30 percent quartz, 45 percent plagioclase, 5 percent microcline, and 20 percent hornblende. Alteration has produced about 5 percent epidote, 10 percent chlorite, and 30 percent sericite at the expense of plagioclase and hornblende. The foregoing estimates of modal composition are shown in table 2.

AGE AND CORRELATION

Authorities differ as to the age of the Newburyport(?) Quartz Diorite. Billings (1956, p. 105–106) concludes, on the basis of its supposed consanguinity with the Dedham(?) Granodiorite of Essex County and the proven Precambrian age of the Dedham Granodiorite in North Attleboro, Mass. (Dowse, 1950), that the Newburyport is probably Precambrian. Emerson (1917, p. 172–181) assigns a Devonian(?) age to the "Dedham granodiorite and related rocks", in which group he includes the Dedham, the Newburyport(?), and the Salem Gabbro-Diorite. Cecil J. Schneer (unpublished data) found that field relations in the Ipswich quadrangle indicate that the Newbury volcanics (Newbury Formation of this report) overlie Newburyport(?) Quartz Diorite unconformably. LaForge (1932, p. 28–30, 69–70) also concluded that the volcanic rocks of the Newbury basin were deposited upon an eroded surface of Newburyport Quartz Diorite and related rocks. R. Novotny (oral communication, 1957) concludes from relationships in southeastern New Hampshire that quartz diorites continuous with those at Newburyport, Mass., intrude the Kittery Quartzite of supposed Silurian age. The contact between the quartz diorite and the Newbury Formation cannot be located well enough in the Salem quadrangle to permit any conclusion as to the relative ages of the two units; the contact is drawn to agree with Schneer's chronology because his are the only observations specifically on the relationship between the Newbury Formation and the Newburyport(?) Quartz Diorite.

SILURIAN OR DEVONIAN ROCKS

Datable rocks of Silurian or Devonian age have only limited exposure in the Salem quadrangle, but are of geologic importance because they contain an ostracod fauna of the same age as the brachiopod fauna found in the Newbury Formation, about 10 miles to the northeast.

NEWBURY FORMATION

NAME

The name Newbury Formation as used herein is an extension of the name Newbury Volcanic Complex, applied by LaForge (*in* Emerson, 1917, p. 161–164) to the rocks of the Parker River area, south of Newburyport, Mass.

DISTRIBUTION AND GENERAL LITHOLOGIC CHARACTER

The rocks assigned to the Newbury Formation in the Salem quadrangle crop out in a northeast-trending band about 0.3 mile wide in the northwest part of the quadrangle. They consist mainly of metavolcanic rocks and fine-grained clastic rocks, but they also include at least one thin bed of fossiliferous limestone.

DESCRIPTION

Greenstone and fine-grained clastic sedimentary rocks crop out along Old Copper Mine Road and Rowley Bridge Road in Topsfield. The greenstone consists of altered plagioclase phenocrysts in a highly altered groundmass of chlorite, carbonate, feldspar, and epidote. The original composition of the plagioclase phenocrysts, which are now replaced largely by epidote and carbonate, cannot be determined in the sections examined, but it was probably as calcic as andesine or labradorite. The rock is therefore an altered basalt or andesite.

The clastic rocks are interbedded very fine-grained sandstone and siltstone. The overall color of the rock is bluish to greenish gray, the coarser beds commonly showing tan or buff shades. Individual sandstone beds are composed of 0.1- to 0.3-mm quartz grains in a very fine grained chloritic, feldspathic matrix. The interbedded siltstone contains a higher proportion of matrix material than the sandstone, and its phenoclasts are rarely as much as 0.1 mm in diameter.

Metamorphosed mafic volcanic rocks, some strikingly porphyritic, crop out on the north-northeast-trending ridge in the bend in Ipswich River 0.4 mile west of Middleton Colony in Middleton. Stubby white phenocrysts of saussuritized plagioclase 1 to 2 mm long, and less abundant quartz phenocrysts of the same size, are set in a groundmass of plagioclase, epidote, and chlorite. The epidote of the groundmass is appreciably deeper in color and more highly birefringement than that in the altered plagioclase phenocrysts, and similar green epidote forms a few pseudomorphs of 0.1-mm augite crystals. The plagioclase phenocrysts now have the composition of sodic oligoclase, but presumably they were originally much more calcic. The quartz phenocrysts, like those of most volcanic rocks, are rounded and appear corroded. The rock was probably originally a quartz-bearing andesite or basalt. Its estimated modal composition is shown in table 2. These rocks are assigned to the Newbury Formation on the bases of lithologic similarity and apparent structural continuity with the rocks of the Newbury Formation exposed 1½ to 2 miles to the northeast. Unfortunately, there are no outcrops between the two areas.

The intense alteration of the rocks exposed at the old Endecott copper mine, southwest of the intersection of Hill Street and Rowley Bridge Road in Topsfield, makes their positive identification difficult, but both volcanic and clastic rocks of the Newbury Formation are probably present. Hematite is the most conspicuous alteration product. Fine-grained hematite is also abundant in sandstone and siltstone of the Newbury Formation along the new U.S. Route 1, about 1,000 feet N. 80° W. of the intersection of Hill Street and Rowley Bridge Road. The hematite alteration and presumed mineralization may be related to the nearby Topsfield Granodiorite.

LIMESTONE AND FOSSILS

A 6-inch-thick bed of blue-gray, finely crystalline, fossiliferous limestone occurs in Topsfield on the east side of the little hill northwest of Old Copper Mine Road 1,900 feet north of Nichols Brook. A sketch map of the fossil locality is given in figure 3.

The limestone contains one or two thin beds of grayish-green silicate-rich material, possibly of pyroclastic origin. The silicate-rich beds pinch and swell abruptly, the thickness changing from a centimeter to a couple of millimeters in a lateral distance of about a centimeter. These beds are composed of tremolite and plagioclase, and also contain minor quartz and calcite. The limestone itself contains minor amounts of tremolite and lacks dolomite. Both the limestone and the silicate-rich beds contain pyrite. These mineral assemblages indicate that metamorphism of the limestone has advanced to a stage at which dolomite and quartz are unstable relative to calcite and tremo-

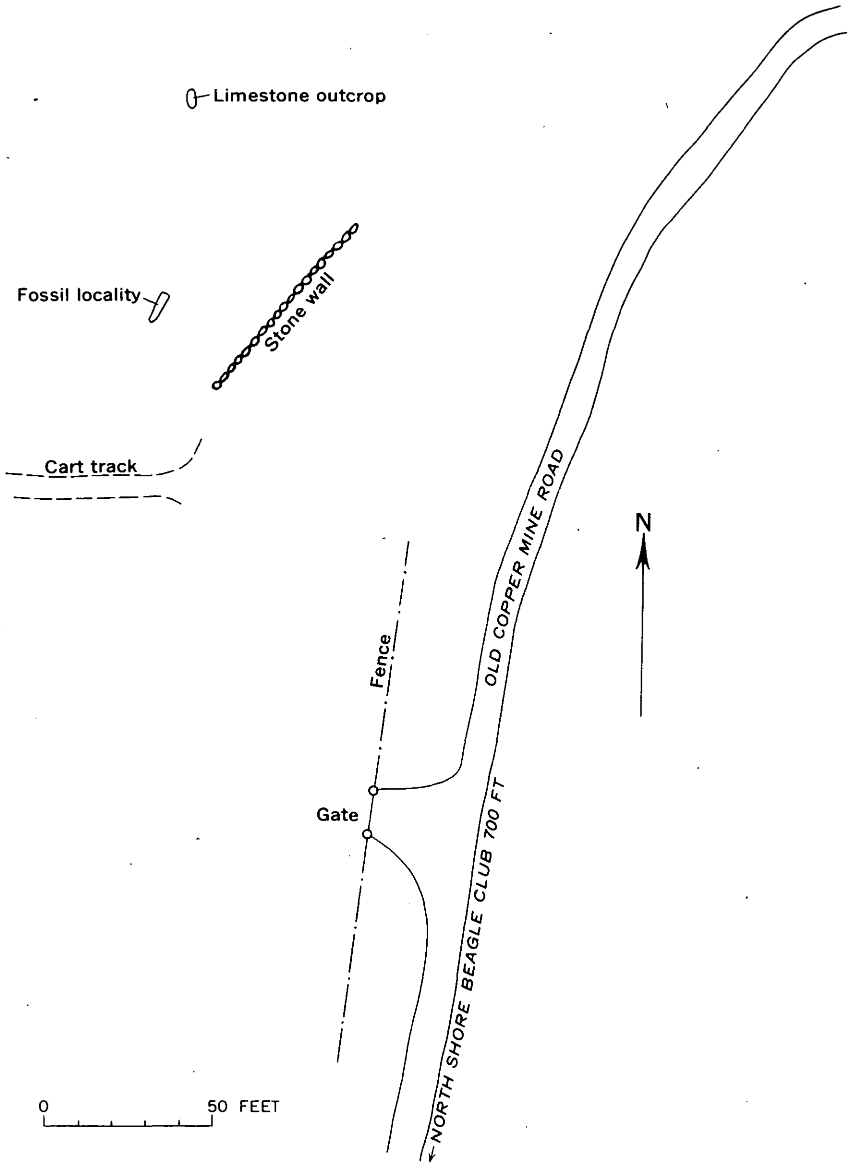

FIGURE 3.—Sketch map showing location of fossil locality in Newbury Formation in Topsfield. General area is 1,800 feet north of Nichols Brook on Old Copper Mine Road. Pace-and-compass traverse, September 1958.

lite. This reaction occurs, of course, at a relatively low grade of metamorphism, roughly equivalent to the epidote-amphibolite facies, as is indicated by the mineralogy of the associated greenstones.

Foerste (1920) reported the discovery (in 1894) of fossils in a "relatively soft quartzite or sandstone" north of Nichols Brook in Topsfield. The fossils were identified by R. S. Bassler of the U.S. National Museum as *Leperditia* sp., of the *L. alta* group; this determination indicates a Cayugan age. Foerste was unable to recover the locality to add to his collection and work out the geological relationships. The locality has been found by a party consisting of M. P. Billings, A. J. Boucot, J. B. Thompson, H. B. Whittington, and the author, and a collection has been made of its fossils. Some of the specimens were submitted to J. M. Berdan of the U.S. Geological Survey, who states (written communication, Jan. 27, 1958):

> The collection contains leperditiids and other smaller ostracodes which are too poorly preserved to be identified. The leperditiids are not well preserved, but two or three specimens show traces of the eye tubercle, chevron-shaped muscle scar and round adductor muscle scar. * * * The range of leperditiids having both a chevron-shaped scar and an adductor scar is Upper Ordovician to Middle Devonian, but in the known Upper Ordovician species the chevron-shaped scar is weakly developed, and would not leave as marked a trace as is present in these specimens. The age of this collection, therefore, may be considered to be Silurian or Devonian, probably Upper Silurian or Lower Devonian, based on the distribution of leperditiids in the Appalachian region.

AGE AND CORRELATION

The age indicated by these fossils is thus the same as that implied by the fossils in the Newbury Volcanic Complex at Rowley, Mass. (Emerson, 1917, p. 163–164). The rocks of the Newbury Formation in the Salem quadrangle cannot be traced continuously into the rocks mapped by Emerson (1917) as Newbury Volcanic Complex, because the two areas are separated by the Topsfield Granodiorite, but the similarities in overall lithology and geological age warrant correlation of the two rock units; the age of the Newbury Formation is considered to be Late (?) Silurian or Early (?) Devonian.

CONTACT RELATIONS

The Newbury Formation is the only paleontologically dated formation in the Salem quadrangle, and its age relations with the rocks with which it is in contact are therefore of considerable interest. Unfortunately, these relationships are not clear-cut, owing to the sparsity of outcrops. The Topsfield Granodiorite transects the structure of the Newbury Formation and separates the body of Newbury Formation in the Salem quadrangle from the main area of the formation in Newbury. For this reason and because of alteration and mineralization in the Newbury Formation near its contact with the Topsfield, the granodiorite is considered to be younger than, and intrusive into, the Newbury Formation. The great difference in degree of metamorphism between the Newbury and Marlboro(?) Formations is consistent with a much greater age for the Marlboro(?) than for the Newbury. Evidence for the age relations between the Newbury Formation and the Newburyport(?) Quartz Diorite is lacking in the Salem quadrangle, but the volcanics of the Newbury Formation overlie the Newburyport(?) Quartz Diorite unconformably in the Ipswich quadrangle, according to C. J. Schneer (unpublished data). The age relations between the Newbury and the undifferentiated diorite and gabbro are not known; the contact between the two units is probably a fault.

MIDDLE(?) PALEOZOIC ROCKS (YOUNGER SUBALKALINE INTRUSIVE SERIES)

UNDIFFERENTIATED DIORITE AND GABBRO

DISTRIBUTION AND NAME

Mafic igneous rocks exposed in the northwest corner of the Salem quadrangle are shown on the geologic map as undifferentiated diorite and gabbro. These rocks are continuous with rocks mapped by R. O. Castle (written communication, 1961) in the Reading and South Groveland quadrangles as an intrusive complex whose type locality is at Sharpners Pond, North Andover. The rocks are lithologically similar to other rocks in eastern Massachusetts that have been mapped under the name Salem Gabbro-Diorite. Inasmuch as these rocks are clearly distinguishable from the gabbro and diorite of the Salem area (see below), the present writer prefers not to apply the name "Salem" to them.

LITHOLOGIC DESCRIPTION

The rocks comprising this unit are somewhat diverse; coarse-grained (3 to 5 mm) quartz-bearing hornblende diorite and hornblende-biotite diorite are the dominant rock types. The diorite consists of andesine, hornblende, and a variable but small amount of biotite. Hornblende gabbro, composed essentially of hornblende and labradorite, is exposed locally in the hilly area northwest of Thunder Bridge. The rocks are all fresh and massive; no foliation was seen in them.

The undifferentiated diorite and gabbro differ from Salem Gabbro-Diorite in several respects. The undifferentiated diorite and gabbro are fresher and less deformed than the Salem Gabbro-Diorite. Augite, which is common in Salem Gabbro-Diorite, was not seen in the undifferentiated diorite and gabbro in the Salem quadrangle. The undifferentiated diorite and gabbro do not seem to be intruded by the many trap dikes that cut nearly every sizable outcrop of Salem Gabbro-Diorite. The two rock units are easily distinguished in the field, and the available evidence neither proves nor disproves their correlation. In the absence of strong evidence for correlation, the undifferentiated diorite and gabbro cannot be included in the Salem Gabbro-Diorite.

AGE RELATIONS

The diorite and gabbro intrude the plagioclase amphibolite and gneiss assigned to the undifferentiated Marlboro(?) Formation, and their freshness and massive structure indicate that they are probably younger than the principal regional metamorphism. Dikes of medium-grained granodiorite cut diorites of the series on the hill north of Howe. The age of the diorites relative to the Newbury Formation is not known, and their contact is thought to be a fault. Because of their relative freshness, the diorite and gabbro are here tentatively assigned to the younger subalkaline intrusive series, of which, however, they are the oldest member.

MEDIUM-GRAINED GRANODIORITE

DISTRIBUTION

A medium-grained granodiorite crops out in a northeast-trending belt about half a mile wide on the northwest side of the band of outcrop of Newbury Formation in the northwest part of the Salem quadrangle (pl. 1). This unit is identical to and continuous with a unit to be described by R. O. Castle, U.S. Geological Survey, and to be named by him for its type locality at Middleton Pond in the Reading quadrangle (R. O. Castle, written communication, 1958). Similar rocks are associated with Topsfield Granodiorite at the Topsfield school and in a railroad cut east of the Topsfield Fairgrounds, both in the adjacent Georgetown quadrangle.

DESCRIPTION

Megascopically, the medium-grained granodiorite is a fine- (½ to 1 mm) to medium-grained (2 to 3 mm) light-pink to orange rock composed largely of quartz and feldspar; tiny grains of biotite and hornblende are peppered through the rock.

The microscope reveals two feldspars in the rock; subhedral to anhedral grains of calcic oligoclase are from ½ to 2 mm in greatest dimension and are distinctly more altered than the associated microcline, which is more irregular in shape and as much as 2 mm in diameter. The larger microcline grains are slightly microperthitic. Quartz occurs as irregular composite grains showing undulatory extinction and contains many small fluid inclusions. The composite quartz grains are typically about a millimeter in diameter.

Among the ferromagnesian minerals, biotite predominates over hornblende. The biotite occurs in grains as much as 0.1 mm in greatest dimension and is generally somewhat chloritized. Muscovite and opaque iron oxides in grains rarely as large as 0.1 mm are associated with it. Common green hornblende occurs in slightly smaller, irregular, equant grains. Apatite is a minor accessory mineral.

The ferromagnesian and accessory minerals comprise less than 10 percent of a typical specimen of the medium-grained granodiorite. Of the remainder, quartz constitutes about a third, and plagioclase slightly exceeds microcline in amount. Representative estimated modes are included in table 2.

AGE, CORRELATION, AND CONTACT RELATIONS

The contact between the medium-grained granodiorite and rocks of the Newbury Formation is nowhere exposed, and the age relations between these two units must be inferred indirectly. Dikes of the granodiorite cut rocks of the Marlboro(?) Formation on Wolcott Island and near Curtiss Cemetery in Boxford, and cut diorite of the undifferentiated diorite and gabbro on the hill north of Howe. The granodiorite is therefore younger than these rocks.

A dike of medium-grained granodiorite that cuts diorite of the undifferentiated series in a roadcut on Endicott Road, Boxford (the continuation of East Street, Middleton), a few hundred feet north of the northern limit of the Salem quadrangle, contains milky quartz grains of rounded outline that resemble the quartz grains of the Topsfield Granodiorite, though the quartz grains in the granodiorite dike are smaller than those in the Topsfield. A coarse-grained, almost pegmatitic, patch in the pink granite exposed east of Ipswich River at the end of the trail south of Gould Hill contains rounded quartz grains of about the same size as those of the Topsfield Granodiorite. As mentioned previously, typical medium-grained granodiorite is associated, apparently as a local textural variant, with Topsfield Granodiorite at several localities in the Georgetown quadrangle. These facts, together with the similarity in mineral composition of the two rocks, suggest that the rocks are closely related in origin and time of emplacement. Because the Topsfield is younger than the Newbury Formation, the medium-grained granodiorite is also considered to be younger than the Newbury Formation.

TOPSFIELD GRANDIORITE

NAME AND DISTRIBUTION

The name Topsfield Granodiorite is here proposed for a distinctive porphyritic granodiorite that crops out in a northeast-trending belt about half a mile wide and 2 miles long in the northwest part of the Salem quadrangle. The band widens to the northeast in the Georgetown quadrangle, where excellent exposures in the village of

Topsfield are the basis for the name. To the southwest the rocks disappear under a band of drumlins and do not reappear.

DESCRIPTION

The rock at the type locality is pink or orange, coarse-grained granodiorite characterized by the presence of many ellipsoidal grains of quartz (fig. 4). The quartz is milky on weathered surfaces but rather glassy where freshly broken. The rocks of most outcrops are sensibly unfoliated, although in some outcrops (as in Topsfield Village, in the Georgetown quadrangle) a distinct foliation results from parallel orientation of the ellipsoids.

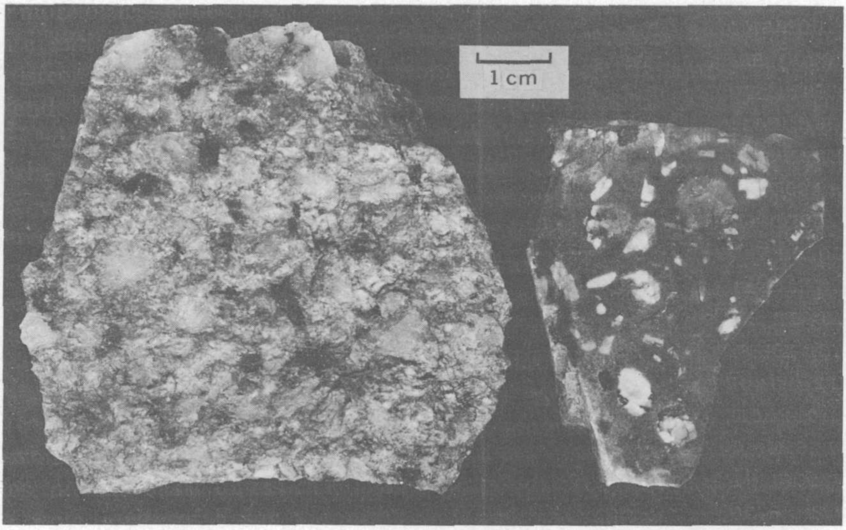

FIGURE 4.—Specimens of typical Topsfield Granodiorite (left) and of finer grained porphyritic facies (right). The specimens were collected at the localities described in table 2. Note characteristic oval phenocrysts of quartz (gray to milky) in both rock types.

Under the microscope, the rock is seen to consist of quartz, plagioclase, microcline, and chloritized hornblende and biotite. Quartz grains as large as 1 cm in greatest dimension show generally oval cross sections though in detail their boundaries are extremely irregular and sinuous. Tiny liquid(?) inclusions are abundant and are distributed in straight lines. Subhedra of microcline, generally microperthitic, a few tenths of a millimeter across, are commonly included within the quartz. Some of the quartz grains are aggregates of several individual crystals, each crystal being separated from the others by thin, discontinuous selvages of microcline. Subhedral to euhedral crystals of plagioclase as large as 1 by 3 mm in size make up about 30 percent of the rock. The plagioclase, which has approximately the composition of oligoclase, is uniformly rather strongly sericitized, and most grains contain many small granules of epidote, most of which are less than 0.01 mm in diameter. Microcline, commonly somewhat microperthitic, occurs chiefly in anhedral grains rarely more than 1 to 2 mm in diameter and is notably fresher than the plagioclase. Each of the minerals quartz, microcline, and plagioclase, constitutes about 30 percent of the rock.

The ferromagnesian minerals of the rock, which originally included both hornblende and biotite, have been largely converted to chlorite, some of which shows strong abnormal purple interference colors. Some epidote in masses as large as 0.1 mm in diameter generally is associated with chlorite pseudomorphs after hornblende; a little biotite is still present in the rock, but the former existence of hornblende is deduced from the presence of well-formed chlorite pseudomorphs. The relative amounts of the two minerals in the original rock cannot be stated with certainty; hornblende seems to have predominated, and the two minerals together comprised about 10 percent of the rock. An estimated mode of the typical rock is given in table 2.

Just east of Old Copper Mine Road, about 500 feet north of its crossing of Nichols Brook, typical Topsfield Granodiorite is cut by a porphyritic dike having practically the same composition as the granodiorite (fig. 4, table 2). The groundmass is a mosaic of quartz, alkali feldspar, and plagioclase in the approximate ratios 2:2:1 (estimated from X-ray diffraction data), together with small amounts of sericite, chlorite, and epidote. The grain size ranges from about 0.05 mm to about 0.2 mm. Patches of micrographic quartz-alkali feldspar intergrowth as much as 1 mm in greatest dimension are rare. The phenocrysts, which make up 15 to 20 percent of the rock, consist of quartz and plagioclase in approximately equal amounts and minor amounts of chloritized ferromagnesian minerals. The quartz phenocrysts are about 1 cm in diameter and show generally euhedral outlines, although in detail the margins are irregular and appear embayed. The quartz phenocrysts contain many irregular equant and elongate inclusions of groundmass material, most of which are from ½ to 1 mm in size. Highly altered plagioclase phenocrysts are euhedral to subhedral crystals as much as 7 mm long. The principal alteration products of the plagioclase are sericite and epidote. The nature of the original ferromagnesian phenocrysts is not known, the primary mineral or minerals having been entirely converted to chlorite.

TABLE 2.—*Representative estimated modes of rocks of the subalkaline intrusive series and volcanic rocks of the Newbury Formation*

Mineral	Salem Gabbro-Diorite				Newburyport(?) Quartz Diorite		Newbury Formation		Topsfield Granodiorite			Medium-grained granodiorite	
					SG549		SG476		SG444				
	SG5	SG64	SG72	SG128	Present composition	Inferred original composition	Phenocrysts	Groundmass	Phenocrysts	Groundmass	SG449	SG543	SG544
Quartz		3	Tr.		30	30	5	6	10	30	45	35	31
Plagioclase	75	54	60	50	5	45	35	42	10	15	20	30	36
Microcline					5	5				30	30	25	26
Augite	10		5	15									
Hornblende	2	30	20	18	5	20							2
Biotite	5	10	2									2	5
Muscovite												5	<1
Chlorite	3		10	15	10			3	3	½	5	2	Tr.
Epidote					5			8		½			
Clinozoisite					10								
Carbonate				1									
Sericite					30								
Apatite	Tr.	½	1	1									Tr.
Opaque	5	2½	1	Tr.				1		½		1	Tr.
Sphene								Tr.		½			
							40	60	23	77			
Total	100	100	100	100	100	100	100		100		100	100	100

SG5. Salem Gabbro-Diorite, grounds of Salem High School, Salem.
SG64. Salem Gabbro-Diorite, hill of elevation 110 ft, 2,600 ft S. 47° E. of triangulation station on Folly Hill, Danvers and Beverly.
SG72. Salem Gabbro-Diorite, Curtis Hill, Peabody (northeast corner of the intersection of Central and Tremont Streets).
SG128. Salem Gabbro-Diorite, Lynn Sand and Stone Co. quarry, Swampscott (Lynn quadrangle), Mass.
SG549. Newburyport(?) Quartz Diorite, hill 750 ft north of Route 114 at boundary between Salem and Reading quadrangles.
SG476. Porphyritic greenstone, Newbury Formation, south end of ridge in bend of Ipswich River 2,000 ft west of Middleton Colony, Middleton.
SG444. Porphyritic dike rock of Topsfield Granodiorite, hill of elevation 138 ft, 1,150 ft east of point where Old Copper Mine Road crosses Nichols Brook (outcrop is in town of Topsfield).
SG449. Topsfield Granodiorite, west side of new Route 1 on south side of first hill north of Nichols Brook, Topsfield. About 500 ft north-northeast of outcrop of SG444.
SG543. Medium-grained granodiorite, top of hill on boundary between Reading and Salem quadrangles, 1,500 ft N. 42° W. of bench mark 49 at point where Route 62 crosses Ipswich River east of Howe, Middleton.
SG544. Medium-grained granodiorite, outcrop by Ipswich River at end of trail over hill south of Gould Hill, Middleton.

AGE AND CONTACT RELATIONS

The Topsfield Granodiorite is thought to be younger than the Newbury Formation for reasons discussed in the section on that formation and in the section on structural geology. It may be of middle(?) Paleozoic age.

UPPER(?) PALEOZOIC ROCKS ("ALKALIC" INTRUSIVE SERIES)

GENERAL STATEMENT

The intrusive rocks of Essex County fall naturally into two broad groups, to which Clapp (1910, 1921) gave the names "alkaline" and "subalkaline". The "subalkaline" rocks are in general more calcic, have a higher ratio of alumina to alkalies, a higher ratio of magnesia to iron, and are more altered and deformed than the "alkaline" rocks. The term "'alkalic' series" is used here for the rocks designated "alkaline" by Clapp because many of the rocks in the series contain peralkaline minerals. The term "alkalic" is used between quotation marks, however, because chemical analyses of the rocks do not support a peralkaline character for the series as a whole. Shand (1951, p. 229) defines a peralkaline rock as one in which the molar ratio of combined alkalies (Na_2O+K_2O) to alumina exceeds unity; a rock in which alumina exceeds alkalies plus lime is called peraluminous. For purposes of this discussion, the term "calcalkaline" refers to rocks intermediate between peralkaline and peraluminous. The molar ratios $(Na_2O+K_2O)/Al_2O_3$ and $(Na_2O+K_2O+CaO)/Al_2O_3$ have been calculated from published analyses of 26 specimens of rocks of the "alkalic" series in Essex County, and are shown in table 3. Six are peralkaline, 8 are peraluminous, and the remaining 12 are calcalkaline.[2]

Rocks of the "alkalic" series intrude all the other rocks with which they are in contact, except for the Triassic(?) diabase dikes. Age relationships cannot be demonstrated between the "alkalic" group and the Newburyport(?) Quartz Diorite, Newbury formation, Topsfield Granodiorite, and undifferentiated diorite and gabbro in the Salem quadrangle, but these rocks are all presumed to be older than the "alkalic" series.

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[2] At least some of these analyses are suspect, however, for they cannot be reconciled with the mineralogical composition of the analyzed rocks. For example, the analysis of a ditroitic nepheline syenite from "Great Haste Ledge" (Washington, 1898–99, p. 801–804) indicates a rather strongly peraluminous character ($CaO+Na_2O+K_2O/Al_2O_3=0.814$), which is incompatible with the reported mineral assemblage (aegirite, fresh alkali feldspar, nepheline, and altered sodalite). The writer has examined a specimen of this rock from Sear's collection at the Peabody Museum of Natural History, Salem, Mass., and has found by X-ray diffraction that the alteration product of the sodalite is cancrinite. Since none of the minerals can be peraluminous, the analysis must be incorrect.

TABLE 3.—*Molar ratios for analyzed rocks of the "alkalic" series in Essex County and of the granites at Quincy, Mass.*

Analysis [1]	$(Na_2O+K_2O)/Al_2O_3$	$(CaO+Na_2O+K_2O)/Al_2O_3$
1	0.975	1.028
2	1.018	1.087
3	1.023	1.048
4	1.000	1.018
5	.910	.925
6	.915	.955
7	.919	.986
8	1.010	1.160
9	.983	1.062
10	.788	1.000
11	.736	.939
12	.832	1.098
13	.793	.960
15	.934	1.050
16	.931	1.055
17	.960	1.060
18	.934	1.034
19	0.778	0.814
20	.940	1.000
21	1.063	1.099
22	1.042	1.392
23	1.097	1.190
32	.930	1.054
33	.913	1.027
34	.731	.776
35	.790	.914
36–38	1.035	1.070
39	1.016	1.128
40	1.008	1.123
41	.832	1.239
42	.931	1.338
43	.908	.924
45	1.050	1.160

[1] Analyses 1–23 are numbered in the order in which they appear on the insert in Clapp (1921), where the original references will be found. Analyses 32–35 are given by Warren and McKinstry (1924) and are identified below by their numbers (Roman numerals). Analyses 36–45 are given by Warren (1913) and are identified below by his numbers.

1. Hornblende granite, Rockport.
2. Aplite, border of dike, Bass Rocks, Cape Ann.
3. Aplite, center of same dike.
4. Paisanite, Magnolia.
5. Keratophyre (bostonite), Marblehead Neck.
6. Keratophyre (bostonite), Marblehead Neck.
7. Quartz syenite, inclusion in granite No. 1 above.
8. Peabody Granite, South Lynnfield.
9. Quartz keratophyre, West Lynn.
10. Quartz syenite porphyry, Squam Light, Cape Ann.
11. Nordmarkite, Wolf Hill, North Gloucester.
12. Akerite, Prospect Street, Gloucester.
13. Rhyolite, Marblehead Neck.
15. Hedrumitic pulaskite, Salem Neck.
16. Sölvsbergite, Coney Island, Salem Harbor.
17. Pulaskite, Salem Neck.
18. Syenite porphyry, sölvsbergite, Coney Island, Salem Harbor.
19. Ditroite, Great Haste Island, Salem Harbor (Incorrectly labelled 'foyaite' in Clapp).
20. Foyaite, Salem Neck.
21. Analcite tinguaite, Pickard Point, Manchester.
22. Umptekite, Beverly.
23. Glaucophane sölvsbergite, Andrews Point, Cape Ann.
32. Hornblende granite, Babson Farm, Cape Ann. W–McK I.
33. Nordmarkitic hornblende granite, Cape Ann. W–McK IV.
34. Fine granite, Andrews Point, Cape Ann. W–Mck VIII.
35. Quartz-syenite phase of fine granite, Andrews Point, Cape Ann. W–McK IX.
36–38. Average of three specimens of Quincy Granite (CHW 1, 2, 3). Average given by Warren (1913) as his analysis No. 4.
39. Fine granite, south of Ruggles Creek, Quincy. CHW 10.
40. Granite porphyry, Rattlesnake Hill, Blue Hills. CHW 13.
41. Dark rhombenporphyry, Rattlesnake Hill, Blue Hills. CHW 15. Numbered '13' on p. 271, but correctly numbered on p. 282.
42. Rhombenporphyry xenolith in granite, Pine Hill area. CHW 16.
43. Aporhyolite, Wampatuck Hill, Blue Hills. CHW 18.
45. Slightly porphyritic phase of Quincy Granite, Rattlesnake Hill, Blue Hills. CHW 15.

The map units included in the "alkalic" series are: Peabody, Cape Ann, and Cherry Hill Granites, Wenham Monzonite, Beverly Syenite, and porphyritic microgranite.

AGE AND CORRELATION OF THE GRANITES

The granites of the "alkalic" group have generally been mapped under the name Quincy Granite because of their probable correlation with the granites at Quincy, Mass. The Quincy Granite, though itself only slightly peralkaline, is apparently more consistently peralkaline than the granites of Essex County. Warren's (1913) analyses of granites, "fine-granite," and granite porphyry from the Quincy area show all these rocks to be slightly peralkaline; alkali-alumina ratios range from 1.070 to 1.128 (table 3). Furthermore, riebeckite is much more abundant in the Quincy Granite than in the granites of Essex County.

The petrographic similarities between the granites of Essex County and the Quincy Granite are much more striking than their differences, and the general correlation of the two groups seems justified. On the other hand, their differences are sufficient to distinguish them, and the two areas of outcrop are 20 miles apart. For these reasons, the name Quincy Granite is not applied to the granites of Essex County in this report. The names Peabody Granite and Cape Ann Granite were originally proposed by Clapp (1910, p. 8–9); for many years the Peabody and the Cape Ann have been mapped under the name Quincy Granite, but as the two units are petrographically distinguishable and occur in separate intrusive bodies, the names Peabody and Cape Ann are here revived.

The granites of Essex County and the granites in Quincy have generally been considered equivalent to the White Mountain Plutonic-Volcanic Series of New Hampshire (Billings, 1956, p. 105; Greenwood, 1951, p. 1173). Age determinations have been made on these rocks in recent years (Webber and others, 1956; Tilton and others, 1957; Lyons and others, 1957; Quinn and others, 1957; Aldrich and others, 1958; Jaffe and others, 1959; Hurley and others, 1960), and suggest strongly that the "alkalic" rocks of Essex County and in Quincy are significantly older than many of the rocks that have been assigned to the White Mountain Series in New Hampshire and Vermont. The U.S. Geological Survey regards the White Mountain Series as Permian in age.

Because of difficulties in some of the analytical procedures, the reliability of the absolute age figures is difficult to assess. On the basis of presently available data (June 1960), the Quincy and Essex County rocks seem to be $260–270 \times 10^6$ years old, whereas many of the White Mountain Series rocks of New Hampshire and Vermont seem to be about 185×10^6 years old. The analytical problems of the lead-alpha method, on which most of the determinations of interest here are based, are discussed by Rose and Stern (1960). Age problems of the "alkalic" rocks of New England are discussed in a brief note by Toulmin (1961).

At present, it seems clear that correlation of the "alkalic" rocks of New England cannot safely be based on lithologic similarity, and retention of local names such as Quincy, Peabody, and Cape Ann is therefore justified.

FELDSPARS

NOMENCLATURE

The principal feldspar in rocks of the "alkalic" series is a microperthitic intergrowth of microcline and sodic plagioclase. The plagioclase of these intergrowths typically forms discontinuous, anastomosing, lenticular veinlets crudely parallel to one another throughout a given microperthite crystal. Each of the two phases of a single microperthite crystal has a constant crystallographic orientation throughout the crystal. Either phase of the perthitic intergrowth may be referred to as "perthitic"; thus "perthitic plagioclase" refers to the plagioclase phase of the perthitic intergrowth.

Adjacent microperthite crystals may be in direct contact with each other or may be separated by finer-grained granular aggregates of feldspar with or without quartz. The material of such aggregates is referred to as "interperthitic."

Some rocks contain independent crystals of plagioclase comparable in size to the microperthite crystals; this plagioclase is referred to as "extraperthitic." The term "antiperthitic" is applied to an intergrowth in which the plagioclase phase exceeds in amount the microcline phase.

Perthitic (and antiperthitic) intergrowths are interpreted as resulting from unmixing of an originally homogeneous feldspar; thus what is now a perthitic intergrowth crystallized from the magma as a single feldspar phase. Interperthitic aggregates may result either from crystallization of the last remnants of trapped interstitial liquid or from migration to grain boundaries of feldspathic material at about the time of unmixing of the original feldspar to form perthite. The latter mechanism is not applicable to quartz-rich interperthitic aggregates. Extraperthitic plagioclase individuals presumably crystallized directly from the magma, and their presence in the same rock with microperthite implies simultaneous crystallization of two feldspar phases from the magma. Subsequent unmixing may, of course, give these extraperthitic plagioclase crystals an antiperthitic structure.

The abbreviations "Or", "Ab", and "An" are used to designate, respectively, the formulae "$KAlSi_3O_8$", "$NaAlSi_3O_8$", and "$CaAl_2Si_2O_8$"; it is important to bear in mind that these symbols refer to components, not phases, in the phase-rule sense.

DETERMINATION OF COMPOSITION

Compositions of plagioclase feldspars were determined by standard optical methods and by the X-ray diffraction method outlined by Goodyear and Duffin (1954, 1955) and by J. V. Smith (1956). The objections to this X-ray method raised by J. R. Smith and Yoder

(1956) apparently do not apply to the "alkalic" rocks of Essex County, for compositions determined from indices of refraction agree closely with those obtained from X-ray diffraction data.

Determining compositions of alkali feldspars is complicated by the facts that the bulk composition of the perthitic intergrowth (which is the composition of the original magmatic feldspar) is desired and that the determinative methods are not as well developed as for the plagioclases. The method adopted in the present study was to measure the angular separation, for CuKα radiation, of the quartz $(10\bar{1}0)$ X-ray diffraction maximum and the $(20\bar{1})$ diffraction maximum of the feldspar after homogenization (not sanidinization) by dry heating to 900°–920° C for 24–96 hours in unsealed platinum envelopes. The quartz was calibrated against the thoria measured by Frondel (1955) and Skinner (1957). Its $2\theta(10\bar{1}0$ for CuKα radiation is 20.89_2°. The composition was then found from a linear least-squares regression equation derived from data obtained by O. F. Tuttle and W. S. MacKenzie on synthetic high sanidine (F. Chayes, written communication; the data are plotted in fig. 4 of Tuttle and Bowen (1958), but numerical values are not given). The chief sources of error in applying this equation to the data from the natural feldspars of the present study are: (1) the different thermal states of the homogenized natural feldspars and the synthetic feldspars, and (2) the presence of the An component in the natural feldspars. The latter error is certainly minor, for the data of J. V. Smith (1956, table III, p. 52) indicate that 5½ weight percent An in an alkali feldspar should produce an overestimation of 1 weight percent Or. Of 13 analyses for CaO made on feldspars of the "alkalic" series in connection with the present study, the highest An content found was only 3½ weight percent An. In general, An affects the $(20\bar{1})$ spacing in the same way that Ab does. The error arising from different thermal states is a more serious one, and the data of Coombs (1954) and J. V. Smith (1956) indicate that the error will be an underestimation of Or content. The error is known to be negligible for compositions more Or-rich than Or$_{65}$[3] and apparently amounts to about 6 weight percent Or at pure Ab. Most of the chemical analyses of feldspars made in connection with the present study were of sodic feldspars and serve as checks on the X-ray compositions.

Samples of feldspar were obtained from the hand specimens with an electric scribing tool; if the rock was sufficiently coarse-grained, each sample was confined to a single crystal. In certain instances, a number of individual crystals from a single hand specimen were

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[3] Stewart, D. B., 1956, Rapakivi granite of the Deer Isle region, Maine: Ph.D. Thesis, Harvard Univ., Cambridge, Mass., table 18.

determined; with very few exceptions the compositions agree with one another quite closely, confirming the interpretation of the microperthite as an exsolution intergrowth from an initially homogeneous feldspar, rather than the result of metasomatism.

It is an important fact that the bulk compositions of microperthite crystals in a single hand specimen (or, for that matter, in a single rock type) do not show a large scatter (table 4). For example, three crystals from a specimen of Peabody Granite gave compositions of 49.5±1.2, 50.4±0.2, and 49.7±0.3 percent Or. Two crystals from another hand specimen collected 2.0 miles away gave 48.9±0.3 and 50.7±0.7 percent Or (uncertainties are expressed as precision standard deviations and do not represent the probable accuracy of the compositions). If the microperthite were the result of "albitization" of a preexisting potassium feldspar, that is, if the perthitic structure had formed by introduction of sodium and removal of potassium after the feldspar had crystallized, the compositions of the albite and microcline members of the perthitic intergrowth should be identical throughout a single specimen, but their proportions in any given crystal would be indeterminate. The bulk compositions of different microperthite crystals should therefore vary erratically; the fact that they do not is very strong evidence for exsolution as the origin of the perthites.

PEABODY GRANITE

DISTRIBUTION

The Peabody Granite forms a stock of roughly elliptical ground plan having an area of approximately 15 square miles, of which slightly more than half lies in the southwestern part of the Salem quadrangle. Adjacent parts of the stock have been mapped by R. O. Castle (written communication, 1961) in the Reading quadrangle and by K. G. Bell[4] in the Lynn and Boston North quadrangles.

DESCRIPTION

The granite is a uniform, massive, medium- to coarse-grained rock composed essentially of microperthite, quartz and iron-rich amphibole. It is gray to green on fresh surfaces and characteristically weathers to a light cream or tan. The hornblende weathers more readily than the other minerals, and knobby weathered surfaces commonly result. Xenoliths of thoroughly altered fine-grained dark rocks are locally abundant in the granite; most of them retain a generally angular outline, though their characteristically gradational contacts with the surrounding granite suggest that considerable reaction between

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[4] Bell, K. G., 1948, Geology of the Boston metropolitan area: Ph. D. thesis, Massachusetts Inst. of Technology, Cambridge, Mass.

TABLE 4.—*Partial chemical analyses of feldspars*

[Analysts: Paul J. Byler, Booth, Garrett, and Blair, Philadelphia, Pa; Jun Ito, Department of Mineralogy and Petrography, Harvard University, Cambridge, Mass.]

Specimen	Sample	Weight percent						Analyst
		K_2O[1]	Na_2O[1]	CaO[1]	Or	Ab	An	
SG225	Bulk mineral concentrate	6.02	6.39	0.03	39.63	60.20	0.17	Byler
SG259A	do	5.09	7.78	.38	30.72	67.36	1.92	Do.
SG271	do	6.04	6.77	.48	37.43	60.07	2.50	Do.
SG280	do	5.59	6.71	.60	35.60	61.19	3.21	Do.
SG285	do	5.60	6.71	.26	36.31	62.28	1.42	Do.
SG308	do	4.62	8.18	.60	27.45	69.56	3.00	Do.
SG354	do	4.86	8.16	.03	29.33	70.51	.15	Do.
SG400	do	6.60	5.20	.03	46.91	52.91	.18	Do.
	Single crystal [2]	7.0	6.5	-------	43.0	57.0	-------	Ito
	do [2]	6.2	8.7	-------	43.2	56.8	-------	Do.
	do [2]	6.7	6.0	-------	43.8	56.2	-------	Do.
SG514	Bulk mineral concentrate	4.11	8.40	.70	24.58	71.91	3.51	Byler
SG506	do [3]	4.4	6.4	.3	32.0	66.3	1.7	Ito
	do [3]	4.4	6.2	.5	32.2	64.7	3.0	Do.
	do [4]	5.3	7.7	.5	31.7	65.7	2.4	Do.
SG398	Single crystal [2]	7.0	5.2	-------	48.6	51.4	-------	Do.
	do [2]	7.5	5.9	-------	46.5	53.5	-------	Do.
SG290	do [2]	5.6	5.2	-------	42.9	57.1	-------	Do.
	do [2]	6.5	5.3	-------	46.2	53.8	-------	Do.
SG347	do [2]	5.4	5.3	-------	41.6	58.4	-------	Do.
	do [2]	6.5	5.4	-------	45.7	54.3	-------	Do.
SCQ	Bulk mineral concentrate [5]	8.08	5.59	.45	49.08	48.63	2.29	Do.

[1] Because of the presence of inert diluents (mostly quartz), not all the analyses total 100 percent feldspar.
[2] Analysis made on small sample, error reported as less than 0.1 percent.
[3] Each of these samples contained 14.0 weight percent quartz, added as an internal standard for X-ray diffraction study.
[4] This sample contained no added quartz; the analysis sums to 98.7 weight percent feldspar.
[5] Also determined: Fe_2O_3, 0.45; Al_2O_3, 18.78.

SG225. Beverly Syenite. Woodbury Point, Beverly. Marblehead North quadrangle.
SG259A. Trachytic syenite. Dike in road cut on north side of Route 127, Beverly, about 100 yards east of driveway to Tupper Hall, Endicott Junior College. Marblehead North quadrangle.
SG271. Beverly Syenite. Coney Island, Salem Harbor.
SG280. Beverly Syenite. Excavation at Salem Power Plant, Salem Neck.
SG285. Beverly Syenite. Shore of Allen Head, Pride's Crossing. Marblehead North quadrangle.
SG308. Trachytic Syenite. Dike on west shore of Cat Cove, Salem Neck.
SG354. Beverly Syenite. Point south of Chubb Creek, West Manchester. Marblehead North quadrangle.
SG400. Peabody Granite. Hill north of bench mark 72, west of Cedar Grove Cemetery, South Peabody.
SG514. Beverly Syenite. Shore of point northeast of West Beach, Beverly Farms. Marblehead North quadrangle.
SG506. Trachytic syenite. Dike 1 ft thick cutting Salem Gabbro-Diorite, Palmer Point, South Salem.
SG398. Peabody Granite. Hill 400 ft west of bench mark 161, Lynnfield Street, Lynn.
SG290. Cape Ann Granite. Endicott Junior College, Beverly. Marblehead North quadrangle.
SG347. Porphyritic microgranite. Dike on shore west of Black Cove, West Manchester. Marblehead North quadrangle.
SCQ. Peabody Granite. Quarry north of Route 128, Peabody, about 3,500 ft southwest of Salem Country Club.

xenolith and granitic magma has taken place. Most of the xenoliths could not be positively identified, but many presumably represent blocks of Salem Gabbro-Diorite and plagioclase amphibolite of the Marlboro(?) Formation. A few xenoliths in the granite have sharp borders and are relatively little altered; these in general seem to be diabasic.

In addition to the essential minerals microperthite, quartz, and ferrohornblende, the microscope reveals accessory amounts of pyroxene, zircon, magnetite, ilmenite, biotite, sphene, allanite(?), riebeckitic amphibole, sulfides, and in some specimens a little extraperthitic plagioclase.

Results of modal analyses by point count are given in table 5. Standard deviation precision error of the major mineral percentages is probably about 2 percent for the average of the two analyses of sample PQ; the IC number is 32.2 for this rock, and the measured area was approximately 625 mm^2. ("IC number" is defined by Chayes (1956, p. 72) as the number of major-mineral identity changes in a 40-mm linear traverse of the rock.) The corresponding error for a single thin section is about 3½ percent. This error estimate is only approximate, however, because Chayes developed the relationship between error and IC for rocks having somewhat different proportions of major minerals.

TABLE 5.—*Modal analyses of Peabody Granite*

[All figures are volume percent]

Mineral(s)	1a	1b	1c	2	3	4	5
Quartz	25.2	31.1	28.2	27.3	29.8	24.5	21.7
Feldspar	66.8	57.5	62.1	66.3	64.5	70.9	69.1
Ferrohornblende	5.8	9.6	7.7	3.7	4.1		
Light-colored amphibole					1.3		
All amphibole						4.1	
Pyroxene				1.4			
Biotite	.3	.3	.3	.3	Tr.		
Riebeckite(?)				.2			
All ferromagnesian and accessory minerals							9.1
Opaque	1.6	1.3	1.4	.2	.1		
All accessories						.23	
Nonopaque accessories	.3	.3	.3	.6	.2		
Total	100.0	100.1	100.0	100.0	100.0	99.73	99.9

1. Specimen PQ, from quarry on north side of Route 128, Peabody, on hill 232, about 4,000 ft southeast of Forest Street. 1a and 1b are point counts of two different thin sections; 1c is their average. Measurement areas, about 625 mm^2. IC, 32.2. Points counted: 1,000 each.
2. Specimen SG398, from hill south of Lynnfield Street, Lynn, about 500 ft WNW of BM 161 (Salem quadrangle). Points counted: 1,129.
3. Specimen SG400, from hill just north of Spring Pond, Peabody, about 400 ft N. of BM X72. Points counted: 1,237.
4. Average of 8 Rosiwal analyses of "representative rocks of the Peabody stock." Pearce, J. S., and Robinson, B. A., thesis, Massachusetts Inst. of Technology, 1909, quoted by Clapp (1921, p. 79). Feldspar given as 57.7 percent microperthite, 13.2 percent albite.
5. From same quarry as specimen PQ (1 above). Designated "Quincy granite" by Tuttle and Bowen (1958, p. 81).

The microperthite crystals are generally subhedral, and range from ½ to 1½ cm in length. Plagioclase lamellae are abundantly distributed throughout the generally untwinned host. Some thin sections show a concentration of plagioclase in the marginal parts of the perthite crystals. Interperthitic plagioclase is minor in amount, and occurs as thin selvages between adjacent microperthite crystals. The selvages are complex intergrowths of plagioclase of two optical orientations, one parallel to the plagioclase of each of the two adjacent microperthite grains. A few randomly oriented extraperthitic plagioclase crystals may be seen in some specimens. The bulk composition of microperthites from the Peabody Granite, as determined by chemical analysis and by X-ray diffraction methods on thermally homogenized samples, ranges from 47 to 52 weight percent Or. The plagioclase phase is albite, rarely sodic oligoclase. The CaO content of the bulk feldspar was determined in two analyses; the results are equivalent to 0.15 and 2.29 weight percent $CaAl_2Si_2O_8$. Compositional data on the feldspars are set out in table 6.

The principal amphibole of the Peabody Granite is very strongly pleochroic: Z is nearly opaque in thin section; Y is deep green; and X is yellowish green. It occurs in 1- to 5-mm subhedra, commonly enclosing poikilitically small crystals of zircon, apatite, allanite(?) and opaque minerals. Minerals such as allanite and zircon, which contain radioactive elements, are surrounded by dark haloes in the ferrohornblende.

TABLE 6.—*Compositional data on feldspars of Peabody Granite*

Specimen	$\Delta 2\theta$ (degrees)	Weight percent			
		Or		Ab	An
		X-ray diffraction	Chemical analysis [1]	Chemical analysis [1]	Chemical analysis [1]
SG292	0.624	47.2			
SG398	.590	50.4	47.5		
SG400	.590	50.2	43.3		
			46.91	52.91	0.18
SCQ	.569	51.9	49.08	48.63	2.29

1. See table 4.

SG292. Abandoned quarry on hill, 1,000 ft east-northeast of Bartholomew Pond, Peabody.
SG398. Hill 400 ft west of bench mark 161 south of Lynnfield Street, Lynn. Average of 14 pairs of $\Delta 2\theta$ determinations.
SG400. North side of hill 300 ft north of bench mark 72, north of Spring Pond, Peabody. Average of 15 pairs of $\Delta 2\theta$ determinations.
SCQ. Quarry on north side of Route 128, 4,000 ft southeast of Forest Street, Peabody.

The chemical composition of the amphibole, as determined by Mr. Jun Ito, Department of Mineralogy and Petrology, Harvard University, is given in table 7, together with certain of its physical properties. The formula corresponds to an iron-rich hornblende with about 10 percent of the arfvedsonite component in solid solution (0.19 Na in the eight-fold position). The concentrate submitted for analysis contained almost 5 percent impurities, whose amounts were determined by point count. The analysis was corrected for these impurities, as shown in the table.

The optical orientation of the ferrohornblende is shown in figure 5, which also illustrates a seldom-realized relationship of true and apparent extinction angles in monoclinic minerals, namely, that even when the plane of the optic axes is (010) the apparent angle between a vibration direction and the *c*-axis, as seen on faces in the [001] zone, may exceed the true angle between the corresponding bisectrix

TABLE 7.—*Chemical composition and physical properties of amphibole from Peabody Granite*

[Chemical analysis by J. Ito. Amphibole from specimen PQ, collected in quarry on north side of Massachusetts Route 128, Peabody, 400 ft southwest of Forest Street]

Chemical analysis

Oxide	Original analysis	Analysis corrected for impurities (see modal analysis)	Metal atoms per 24 oxygen atoms	Metal atoms grouped into structural positions
SiO_2	40.06	39.01	6.730	8.000
Al_2O_3	7.34	6.91	1.270	
			.138	5.191
Fe_2O_3	5.45	5.45	.704	
FeO	28.40	26.34	3.800	
MgO	1.83	1.80	.466	
TiO_2	1.89	.63	.083	
MnO	.92	.92	.135	2.000
CaO	9.04	9.04	1.667	
Na_2O	2.71	2.71	.198	
			.713	.920
K_2O	1.18	.94	.207	
H_2O+	1.09	1.00	1.160	1.160
H_2O-	.52			
F	$<.1$			
ZrO_2	None			
V_2O_5	Tr.			
Total	100.43	94.75		

Modal analysis of analyzed material

Mineral	Volume percent	Density	Weight percent	Assumed composition
Amphibole	95.3	[1] 3.385	94.82	
Biotite [2]	2.7	3.22	2.55	$KFe_{2.53}Mg_{0.14}Al_{1.67}Si_{2.67}O_{10}(OH)_2$
Ilmenite	1.7	4.79	2.39	$FeTiO_3$
Quartz	.3	2.65	.23	SiO_2

Optical properties of amphibole

Direction	n[3]	Color	Orientation
X	1.709±0.002	Tan	
Y		Deep green	$=b$.
Z	1.715±0.002	Dark brownish green	$\wedge c=7^\circ$, greater for red than for blue light. On (110) cleavage fragments, $Z'\wedge c=12^\circ$.

$2V_x=40^\circ\pm1^\circ$

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[1] Measured on Berman balance.

[2] $nY=nZ=1.673\pm0.002$; density and composition from Winchell and Winchell (1951, fig. 257), assuming Al :Si=5:8.

[3] Measured on (110) cleavage fragments in sodium light.

and the *c*-axis, measured in the optic plane (Daly, 1899a, 1899b). Thus the maximum extinction angle $Z'\wedge c$ seen in grains whose *c*-axes lie in the plane of a thin section. for example, is not the same as the true angle $Z\wedge c$, but exceeds it (in the case of the ferrohornblende from the Peabody Granite) by 4°. The amphibole cleavage angle is such that cleavage fragments of amphiboles having the optical orientation of the ferrohornblendes of the "alkalic" series show approximately their maximum apparent extinction angles on cleavage

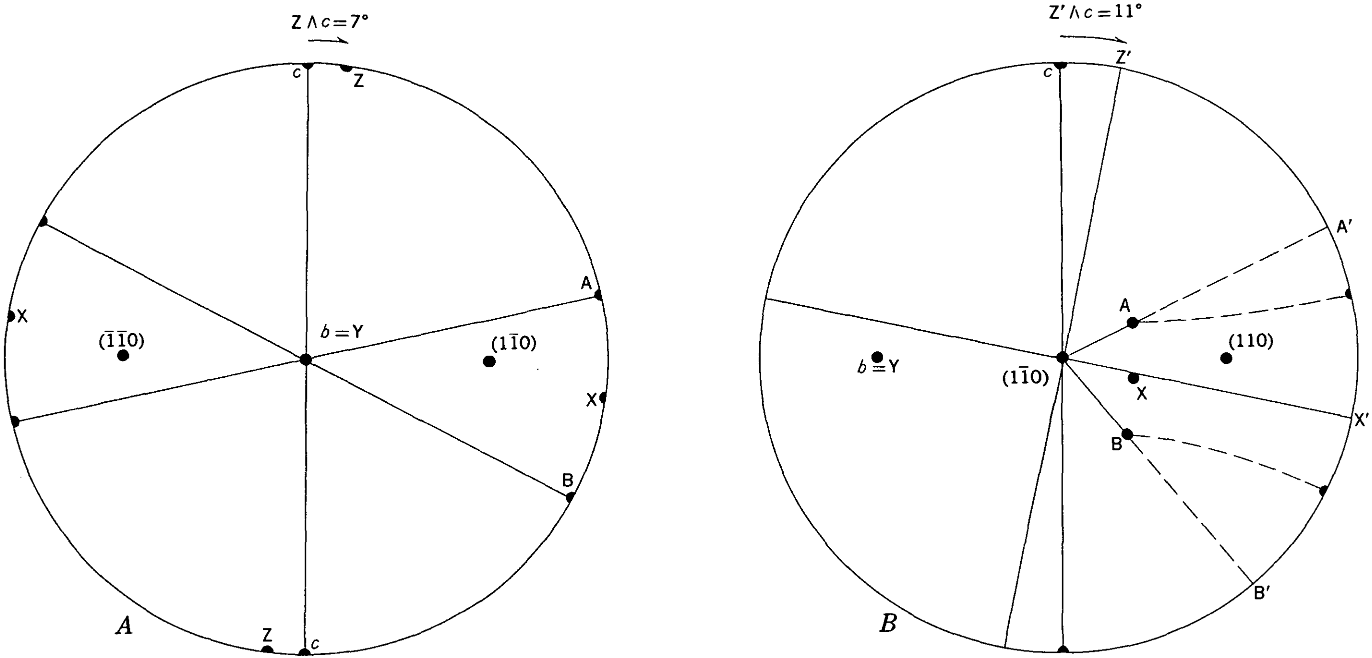

FIGURE 5.—Stereograms illustrating optical orientation of ferrohornblende from Peabody Granite. Both plotted on upper hemisphere. Stereogram (*A*) shows the elements of the indicatrix (X, Y, Z, and optic axes A and B) with the optic plane (010) horizontal. Stereogram (*B*) shows the same elements rotated 62½° about the *c*-axis to bring a cleavage face horizontal; this is the position in which the mineral is usually observed in immersion mounts. *AA′* and *BB′* are the extensions of the vertical planes through the optic axes. By the law of Biot and Fresnel, the extinction directions are given by the bisectors of the angles between these planes, X′ and Z′. Note that the extinction angle is greater on a cleavage fragment than when the crystal is oriented with the optic plane horizontal.

fragments. Measurements of such angles in immersion mounts are therefore particularly poor estimators of the true angle $Z\Lambda c$. At least some of the high values of $Z\Lambda c$ reported in the literature for iron-rich hornblendes probably arise from this error.

Much of the ferrohornblende is very fresh, but some grains show considerable alteration to fine-grained biotite, hydrous iron oxides, and unidentified fine-grained material, possibly in part chloritic.

Some specimens of Peabody Granite contain small amounts of a nearly colorless amphibole in addition to the ferrohornblende. The light-colored amphibole is slightly pleochroic in thin section: X, very light yellow, almost colorless; Y, light green; Z, light grass-green with a slight bluish tinge. 2V is very large, probably negative, and dispersion was not observed; $Z\Lambda c$ is about 23°. The birefringence is rather high, and second-order interference colors are observed in thin section. This amphibole occurs typically in clusters of 0.1-mm stubby prisms associated with shreds of biotite and minor amounts of ferrohornblende and apatite. Its optical properties resemble those of certain amphiboles in plagioclase amphibolites and diorites of the Marlboro(?) Formation more closely than they resemble those of any primary amphiboles of the "alkalic" series; it is possible that the clusters of amphibole are remnants of disaggregated xenoliths of country rocks intruded by the Peabody Granite. In Wenham Monzonite a rather similar amphibole, which is probably cummingtonite, forms sharp-bordered rounded cores of ferrohornblende crystals; the texture suggests magmatic corrosion of the light-colored amphibole and precipitation of ferrohornblende around it (fig. 7).

Pyroxene occurs in several specimens of Peabody Granite, but is always subordinate to amphibole. It ordinarily is rimmed by and irregularly intergrown with ferrohornblende, and forms small, irregular residual(?) grains in the centers of some ferrohornblende crystals. The pyroxene is green and shows a very weak pleochroism, Z' being a little lighter and yellower green than X'. The extinction angle, $X\Lambda c$, is approximately 35°. The optical properties suggest an iron-rich augite containing a smaller amount of the aegirite component than the pyroxenes of the syenites of this area. This relationship is entirely in accord with the higher arfvedsonite content in the syenitic amphibole than in the granitic amphibole.

Tiny needles of pleochroic blue amphibole, presumed to be riebeckitic (though optical criteria for the distinction between riebeckite and arfvedsonite are virtually nonexistent), form sheaves and sprays near the margins of pyroxene grains; they are particularly abundant at contacts of pyroxene with quartz, where the riebeckite(?) needles project into the quartz.

Biotite never exceeds a fraction of a percent, and occurs in small grains associated with ferrohornblende and opaque material. The commonest accessory minerals are zircon and apatite, and some specimens show sphene as well. Dark red-brown allanite occurs rarely, and a few specimens contain small amounts of a number of red, orange, and brown minerals that have not been positively identified. All these minerals have very high refractive indices and are strongly colored, and none of them is present in sufficient amount to permit easy separation for X-ray or optical determination. The optical properties observed in thin section suggest the possible presence of pyrochlore ($\mathrm{NaCa(Cb,Ta)_2O_6F}$) and lamprophyllite ($\mathrm{Na_3(Sr,Ca,Fe,Mn)Ti_3Si_3O_{12}(O_2OH)}$?). Astrophyllite ($\mathrm{(K,Na)_2(Fe,Mn)_4(Ti,Zr)(OH,F)_2(Si_2O_7)}$?), which has been observed in the Beverly Syenite and Cape Ann Granite, was not seen in the Peabody Granite.

No chemical analysis of the Peabody Granite was made in connection with the present study. Point-count modal analyses were made of two thin sections of the specimen which provided the analyzed amphibole, however, and the chemical composition of the rock was calculated from the average of the two modal analyses. The composition of the amphibole is known from the analysis (table 7), that of the biotite is estimated from its optical properties (table 7), and that of the feldspar is given by an analysis made by Mr. Jun Ito in connection with tests of the X-ray determinative procedure for alkali feldspars (table 5). The results are shown in table 8, which includes an analysis of Peabody Granite from South Lynnfield given by Clapp (1921, p. 78) and a more recent analysis of a specimen from the same quarry as specimen PQ, given by Tuttle and Bowen (1958, p. 81). Tuttle and Bowen refer to their rock as "Quincy granite"; the locality was ascertained from Dr. Felix Chayes (oral communication), who collected the specimen. The agreement among the three analyses is satisfactory and corroborates the petrographic inference that the Peabody Granite is uniform in composition.

CAPE ANN GRANITE

NAME, DISTRIBUTION, AND GENERAL LITHOLOGY

The name Cape Ann Granite is used in this report for a map unit comprising the granites exposed on the island of Cape Ann, Mass., and thence westward and southwestward into the towns of Ipswich, Danvers, and Beverly, Mass. Only the southwestern fringe of this granite body extends into the Salem quadrangle. The rocks mapped in this unit are characteristically medium- to coarse-grained granites of variable composition. Local areas are underlain by rocks poor enough in quartz to be called quartz syenites, but continuous areas sufficiently large to be shown on the map, and having mappable contacts with the surrounding rocks, have not been found.

TABLE 8.—*Chemical composition of Peabody Granite*

	1	2	3
SiO_2	71.19	71.90	72.26
Al_2O_3	12.21	12.98	13.18
Fe_2O_3	1.94	.81	.24
FeO	3.71	2.85	2.77
MgO	.19	.02	.20
MnO	.10	.08	.10
CaO	1.19	1.04	1.10
Na_2O	3.67	4.19	3.99
K_2O	5.08	5.60	5.01
H_2O+	.11	.20	.20
ZrO_2	.34	.12	n.d.
TiO_2	.33	.34	.36
Total	100.06	100.13	[1] 99.60

[1] Includes 0.07, P_2O_5; 0.04, CO_2; 0.08, H_2O-.

1. From quarry on State Route 128, Peabody, calculated from point-count modes and chemical and optical analyses of individual minerals, as described in text.
2. Old quarry, South Lynnfield. M. F. Connor, analyst (Clapp, 1921, p. 78).
3. From same quarry as (1). Referred to as "Quincy granite" by Tuttle and Bowen (1958, p. 81).

Cape Ann Granite underlies a strip one-half to three-quarters of a mile wide along the eastern border of the Salem quadrangle from Beverly Harbor north to the northern boundary of the quadrangle. It is interrupted in North Beverly by a tongue of Salem Gabbro-Diorite that extends northeastward into the adjacent Marblehead North quadrangle.

DESCRIPTION

The overall color of the Cape Ann Granite is gray to green. Quartz, feldspar, hornblende, and more rarely pyroxene and biotite can be distinguished in hand specimen. The Cape Ann Granite is locally porphyritic, but the porphyritic texture is not always visible in hand specimen. Alkali feldspar forms the phenocrysts of the megascopically porphyritic varieties.

In thin section, the Cape Ann Granite shows both textural and compositional variation. Estimated modes are given in table 9. The typical rock is composed dominantly of microperthite, which forms large crystals of somewhat irregular rectangular outline. The proportion of the two phases of the perthitic intergrowth varies from grain to grain, and some of the intergrowths have the appearance of antiperthite. This apparent variability may be in large part the result of different orientations of the perthite crystals relative to the thin section; the effect could also be produced by zoned microperthite crystals cut at different distances from their centers by the plane of the thin section. An example of zoning is very clearly shown by a thin section of a specimen from the south side of the hill northwest of Beverly Hospital (fig. 6); a continuous band of fine antiperthite separates a core of "normal" microperthite from a rim of the same material, each of the two phases of the intergrowth maintaining a constant crystallographic orientation throughout the whole crystal. X-ray diffraction determinations indicate that the bulk composition of microperthite of the specimens of Cape Ann Granite studied is identical, within the limits of accuracy of the method, to that in the Peabody Granite. Data are given in table 10, and include specimens collected outside the Salem quadrangle.

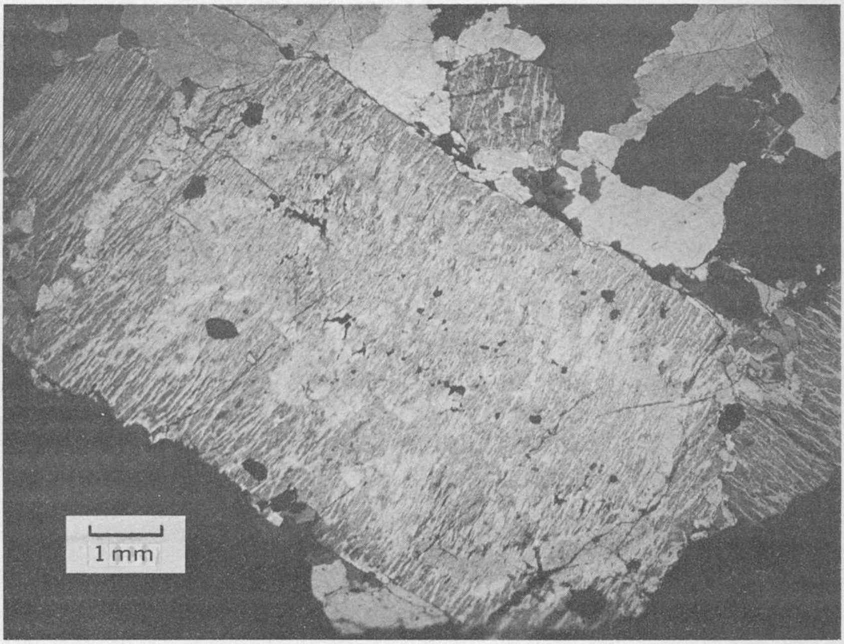

FIGURE 6.—Photomicrograph of zoned microperthite crystal in Cape Ann Granite. Crossed nicols. In the photograph, the plagioclase member of the perthitic intergrowth is lighter colored than the microcline. An irregular plagioclase-rich zone is about half a millimeter wide and is best developed along the upper edge and right-hand end of the crystal as seen in the photograph; it is parallel to the outline of the crystal and a little less than a millimeter from its margin. It is interpreted as a zone of originally more sodic composition than the inner and outer parts of the crystal. The specimen was collected on the southwest side of the hill northwest of Beverly Hospital.

Interperthitic plagioclase occurs most commonly as thin strings of fine-grained (0.1–0.3 mm) granular material separating adjacent microperthite crystals; such material is not so commonly crystallographically continuous with perthite plagioclase in the Cape Ann as in the Peabody Granite. A few specimens contain larger extraperthitic crystals of plagioclase, but these are rare in all the rocks studied.

Quartz makes up as much as half of some specimens of Cape Ann Granite and perhaps less than 10 percent of others, which, as noted, might better be termed quartz syenites. In most specimens, quartz grains are about the same size as microperthite grains but are ordinarily composed of a mosaic intergrowth of several more or less equant anhedral individual crystals about a millimeter in diameter. The quartz of some specimens is irregular in form and is molded around the more nearly euhedral feldspars. Strongly undulose extinction is rare even in sections showing stringerlike zones of microbreccia.

The most abundant ferromagnesian mineral of the Cape Ann Granite is a ferrohornblende that appears to be identical to that of the Peabody Granite. Its occurrence and habit are also almost the same as those of the Peabody mineral, the most notable differences being the more irregular form of the crystals and the greater amount of poikilitically included euhedral zircon crystals in the amphibole of the Cape Ann Granite.

TABLE 9.—*Estimated modes of Cape Ann Granite*

Specimen	Quartz	Microperthite	Ferrohornblende	Pyroxene
SG290	30	65	<1	4
SG385	8	85	6	1
SG390	40	55	1	4
SG392	30	60	10	-------------

SG290. Endicott Junior College campus, Beverly (Marblehead North quadrangle).
SG385. Hill north of Hale Street, Beverly Farms, about 1,500 ft north of intersection with West Street. Petrographically quartz syenite (Marblehead North quadrangle).
SG390. Railroad cut about 1,500 ft east of intersection of Cross Lane and Boston and Maine tracks, Beverly (Marblehead North quadrangle).
SG392. About 1,000 ft east of SG390.

TABLE 10.—*Compositional data on feldspars of Cape Ann Granite*

Specimen	$\Delta 2\theta$ (degrees)	Orthoclase (weight percent)	
		Determined by X-ray	Chemical analysis[1]
SG290	0.657	44.2	42.9
SG290	.638	45.9	46.2
SG386	.593	50.1	-------------

[1] See table 4.

SG290. Endicott Junior College campus, Beverly (Marblehead North quadrangle.)
SG386. Southwest slope of hill about 1,500 ft northwest of Beverly Hospital, Beverly.

A green pyroxene, probably a slightly aegiritic ferroaugite, occurs in several of the specimens of Cape Ann Granite studied. The depth of color, birefringence, pleochroism, and extinction angle $X \wedge c$ differ considerably from specimen to specimen; these variations suggest related variations in the proportions of the aegirite component. The mineral occurs in irregular grains that range in size from granules a few hundredths of a millimeter in diameter to ragged crystals a few millimeters across.

Associated with the most aegiritic pyroxene observed is a small amount of sodic amphibole, probably riebeckite. It occurs in sprays of tiny needles radiating out from the pyroxene and as irregular bands and patches large as 0.1 mm within the pyroxene grains. The mineral is characterized by its low birefringence and extinction angle, strong pleochroism, and deep-blue color for the ray vibrating parallel to the length of the needles. The optical character of this ray is masked by the higher interference colors of the quartz and feldspar into which the needles project.

Irregular aggregates of fibrous or lamellar, orange-yellow, nearly isotropic material, almost certainly pseudomorphic after fayalite, occur in several of the thin sections examined. The material has much lower birefringence than either "iddingsite" or bowlingite, and corresponds to the material described by Warren and McKinstry (1924, p. 327–328) as an alteration product of fayalite in the Cape Ann Granite at Cape Ann; it rims and veins fresh fayalite in one specimen of Cape Ann Granite examined in the present study. The olivine has a negative optic axial angle of about 55°, which corresponds to that of very nearly pure fayalite.

In many specimens, accessory amounts of biotite occur in small shreds both independent of other ferromagnesian minerals and associated with the more abundant ferromagnesian minerals.

Varieties of the Cape Ann Granite that are obviously porphyritic are not abundant in the area here described, but some thin sections reveal a porphyritic texture in rocks that megascopically seem equigranular. In these rocks, what appears in hand specimen to be interstitial quartz is actually a fine-grained mosaic of slightly perthitic untwinned alkali feldspar, twinned and untwinned oligoclase, and perhaps a little quartz. The phenocrysts, which make up about two-thirds of the rock, are microperthite crystals about a centimeter long, smaller ferrohornblende crystals (3 to 5 mm long), commonly with inclusions of magnetite(?) and zircon, and abundant 3- to 5-mm aggregates of 0.1- to 0.3-mm anhedra of quartz. Quartz thus constitutes a considerably larger proportion of the phenocrysts than of the groundmass in these varieties of Cape Ann Granite. The crystallization mechanism producing a quartz-poor groundmass is somewhat obscure, but may involve a cooling rate more conducive to crystallization of quartz on the existing quartz phenocrysts than to nucleation at additional points, while the feldspars formed new nuclei more readily.

CHERRY HILL GRANITE

NAME AND DISTRIBUTION

The name Cherry Hill Granite is here proposed for a pink-weathering alaskitic granite exposed in scattered outcrops near Cherry Hill, along Burley Street, and at Beverly Airport, all in Danvers.

DESCRIPTION

The rock is composed essentially of milky quartz and pink-weathering alkali feldspar in grains roughly a centimeter across. A little magnetite may be discerned in hand specimen.

The feldspar is microperthitic microcline; the relative amounts of the two phases in the perthitic intergrowth indicate that the bulk composition of the feldspar is probably near the middle of the alkali feldspar series. In addition to the quartz and feldspar, which make up all but about 1 percent of the rock, microscopic examination reveals magnetite rimmed by hydrous iron oxides, and accessory crystals of zircon.

CORRELATION AND CONTACT RELATIONS

The mineralogical composition of the rock clearly indicates its relationship to the alkaline rocks. Its coarseness of grain and lack of mafic constituents serve to distinguish it lithologically from the typical granites of the Peabody and Cape Ann plutons, and its occurrence as a single body warrants a separate name for this rock.

The Cherry Hill Granite is at least slightly younger than the Wenham Monzonite, for dikes of the granite intrude the monzonite just south of the Beverly Airport. Its age relations to the other members of the alkalic group are not known.

PORPHYRITIC MICROGRANITE

DISTRIBUTION AND OCCURRENCE

In the Salem quadrangle, porphyritic microgranite occurs as dikes that cut Salem Gabbro-Diorite in the hilly area south of the towns of Salem and Peabody and as xenoliths in Cape Ann Granite on the hill northwest of Beverly Hospital in Beverly, near the contact with Salem Gabbro-Diorite. A large area of porphyritic microgranite occurs in Beverly (Marblehead North quadrangle), and dikes similar to those in the Salem quadrangle cut Cape Ann Granite and Beverly Syenite along the Beverly shore.

DESCRIPTION

The porphyritic microgranite is a gray to cream-colored rock characterized by euhedral or subhedral phenocrysts of alkali feldspar 5 mm to 1 cm in diameter set in a groundmass of rather finely granular quartz, feldspar, and ferromagnesian minerals. Rare varieties have a few phenocrysts of quartz or hornblende. The proportion of phenocrysts to groundmass varies widely; there seems to be a continuous series from equigranular micrograbnites to rocks containing feldspar phenocrysts so abundant that the rocks are difficult to distinguish from massive Beverly syenite, or, where quartz and hornblende are also phenocrysts, from massive granite.

The feldspar of the phenocrysts is microperthite similar in most respects to that of the granite and syenite. Phenocrysts from the large area of porphyritic microgranite near Beverly (in the Marblehead North quadrangle) are more potassic than even the feldspars of the granites; those from the dikes along the shore seem to be intermediate between feldspars of the granites and those of the syenite. A phenocryst of a xenolith in Cape Ann Granite has a composition close to that of the feldspar of the enclosing granite (47.3 and 50.1 weight percent Or, respectively).

The ferromagnesian minerals of the porphyritic microgranite include pyroxene, amphibole, and biotite. Ferrohornblende is the only ferromagnesian mineral that forms phenocrysts, and these have been noted in only a few localities. The hornblende more commonly occurs in the groundmass as ragged grains a few tenths of a millimeter across. Brown biotite shreds are a common minor constituent of the groundmass and are characteristically associated with magnetite. Pyroxene is confined to the groundmass and generally occurs in small granules or subhedra. The pyroxene of the large area of porphyritic microgranite in Beverly is a colorless to light green augite, but some of the dikes along the shore contain aegirine-augite.

WENHAM MONZONITE

NAME AND DISTRIBUTION

The name Wenham Monzonite is proposed for a medium-grained quartz-poor rock of the "alkalic" series exposed in scattered outcrops south of Wenham Swamp in the towns of Wenham and Beverly.

DESCRIPTION

The rock is composed primarily of cream-weathering feldspar, and contains about 10 percent dark minerals; dark-green to black hornblende in crystals 2 to 5 mm long is more abundant than biotite, which occurs in lustrous black flakes about 3 mm in diameter. Small amounts of quartz are visible with a hand lens.

Microscopic examination reveals two feldspars in approximately equal proportions, although they are not readily distinguishable in hand specimen. Oligoclase (nX' on cleavage fragments 1.538 ± 0.002, corresponding to An_{19}) and microcline occur in subhedral to anhedral crystals approximately 3 mm in diameter. The oligoclase has a slightly greater tendency toward euhedral form than does the microcline, and some grains show a weak, continuous normal compositional zoning. Much of the microcline is microperthitic, but perthite lamellae are rare near the margins of microcline grains adjacent to plagioclase crystals.

The average bulk composition of the microperthite, determined by X-ray diffraction methods on thermally homogenized material, is approximately 75 weight percent Or. The proportions of the two phases in the perthitic intergrowth appear to vary from grain to grain. Some of the apparent compositional variation of the microperthite doubtless results from accidents of distribution of perthitic lamellae with respect to the plane of the thin section; any real variation may be explained by (1) incomplete exsolution or (2) failure of the crystals and liquid to maintain equilibrium during crystallization.

Ferrohornblende is the most abundant dark mineral in the rock, and occurs in 2- to 5-mm ragged individuals associated in clusters with biotite, sulfides, ziron, apatite, and a colorless clinoamphibole. The ferrohornblende has a rather small negative optic angle (estimated at about 40°) and is strongly pleochroic: X, tan; Y, yellowish olive-green; and Z, very dark green; $Z'\Lambda c$=about 25°. Highly birefringent, colorless amphibole is associated with the ferrohornblende both as apparently independent grains and as sharp-bordered cores of ferrohornblende crystals (fig. 7) The amphibole cleavage is continuous across the sharp boundary between the two amphiboles, and the cores of some grains are rounded and even cuspate in outline; the texture suggests resorption of earlier colorless amphibole followed by crystallization of ferrohornblende in crystallographic continuity with it. The colorless amphibole is monoclinic ($Z'\Lambda c=12°–14°$) and has a rather high negative optic angle. Its approximate indices of refraction are $nX=1.665\pm0.004$, $nY=1.677\pm0.004$, $nZ=1.695\pm0.004$. These properties are consistent with a member of the cummingtonite series containing about 70 percent of the grunerite component. Its occurrence and composition are very different, however, from the grunerite previously reported from Cape Ann Granite at Rockport by Bowen and Schairer (1935) and by Warren and McKinstry (1924, and Warren (1903), under the name "ferroanthophyllite"). The colorless amphibole of the Wenham Monzonite, like that already described from the Peabody Granite, is interpreted as xenocrystic material, probably acquired from the nearby plagioclase amphibolites of unit A of the Malboro(?) Formation.

Biotite occurs independently of the amphiboles as well as in association with them. Accessory minerals include zicron, apatite, magnetite, and pyrite. Quartz occurs in small (0.1–0.5 mm) anhedra interstitial to the other minerals.

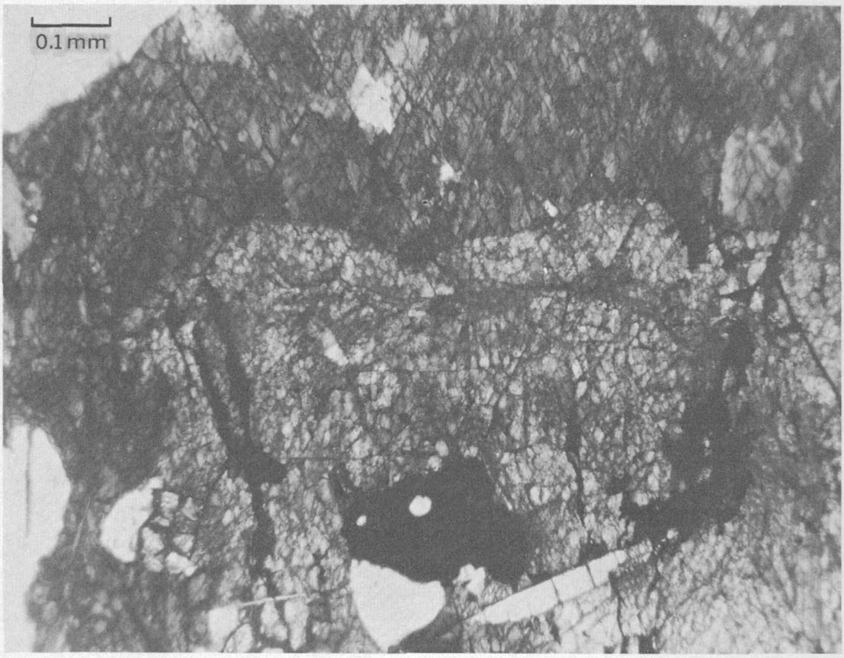

FIGURE 7.—Photomicrograph showing textural relations of amphiboles in Wenham Monzonite (specimen SG460, table 11). Ferrohornblende crystal has sharp-bordered core of "colorless" amphibole (light in photograph) whose outline is partly irregular and partly cuspate. Unpolarized light.

Point counts of one thin section from each of two specimens of Wenham Monzonite from different outcrops in Wenham Swamp gave the results presented in table 11.

TABLE 11.—*Point count modal analyses of Wenham Monzonite*

[Volume percent]

Mineral	1	2	Mineral	1	2
Microperthite	44.1	41.2	Quartz	1.8	3.8
Plagioclase (An_{19})	35.3	39.6	Opaque	1.2	.9
Myrmekite	4.1	2.5	Apatite	.2	.5
Ferrohornblende	8.9	8.3	Zircon	.4	.1
Colorless amphibole	1.5	1.1	Muscovite	.1	.0
Biotite	2.4	1.9	Sphene	.0	.1

1. Specimen SG459, from isolated outcrop in southern part of Wenham Swamp about 1,000 ft south of 70-ft hill on canal. Total number of points counted, 1,468; measurement area, 650 mm^2.
2. Specimen SG460, from outcrop by houses about 2,500 feet west-northwest of Muddy Pond, in Wenham Swamp. Total number of points counted, 1,277; measurement area, 600 mm^2.

BEVERLY SYENITE

NAME, DISTRIBUTION, AND GENERAL LITHOLOGY

The Beverly Syenite is exposed on Salem Neck and as a discontinuous strip along the shore from Beverly to Manchester in the Marblehead North quadrangle. In addition, dikes of the syenite cut Salem Gabbro-Diorite in South Salem, and a syenite dike apparently intrudes rocks of the Marlboro(?) Formation in Danvers. The rocks constituting the unit are dominantly coarse grained, massive, cream-colored syenite of variable grain size and composition. The coarse-grained massive syenite is cut by fine-grained trachytic dikes of practically the same composition, as well as by more mafic and more siliceous rocks. A few feldspathoidal rocks are present, chiefly in dikes cutting the other varieties.

MASSIVE SYENITE

The massive syenite is the rock described by Clapp (1921) under the designations "pulaskite" and "umptekite." He distinguished the two types by the dominant ferromagnesian mineral, which is aegirine-augite in pulaskite and amphibole in umptekite. The distinction is not a useful one for mapping, for both minerals are present in much of the rock and are not easily distinguished in hand specimen, especially when the two are intergrown. It is also doubtful whether much petrologic significance can be attached to the distinction, in view of the continuously varying proportions of the mafic minerals. Clapp (1921, p. 89) regards the umptekite as a "hybrid between pulaskite and gabbro-diorite" and supports his argument by comparing chemical analyses of pulaskites with an analysis of umptekite from Beverly by Wright (1900). Wright's analysis shows considerably higher MgO and CaO than is normal for any of the rocks of the "alkalic" series, as would be expected from Clapp's hypothesis. It would appear, however, that there are "umptekites and umptekites," for Wright's chemical analysis contains far too much magnesia (1.30 percent) to correspond to a rock in which the principal ferromagnesian mineral is as magnesia-poor as his own analyzed amphibole (0.17 percent) or the amphibole analyzed for the present study (0.68 percent), which also came from an amphibole syenite on the Beverly shore. The ferromagnesian minerals of some of the syenites may have been derived by assimilation from CaO-rich country rocks, but there is no direct correspondence between such assimilation and syenites in which the principal ferromagnesian mineral is amphibole.

The typical syenite is a medium- to coarse-grained rock composed largely of alkali feldspars. Ferromagnesian minerals, which rarely make up more than 10 percent of the rock, include arfvedsonitic ferrohornblende, lepidomelane, and augite containing a variable amount of the aegirite component. Apatite. zircon, sphene, magnetite, and sulfides are the chief accessory minerals. Allanite is rare, and astrophyllite was seen in one section. Estimated modes are given in table 12.

TABLE 12.—*Estimated modes of massive Beverly Syenite*

Specimen	Microperthite	Biotite	Pyroxene	Ferrohornblende	Opaque	Apatite
SG271	97	1	0.5	1	Tr.	Tr.
SG280	95	2		2	Tr.	Tr.
SG532a	85	4.5	7.5	1.5	1.5	
SG532b	77	4.5	8.5	7	2	1

SG271. Coney Island, Salem Harbor (Marblehead North quadrangle).
SG280. Excavation at Salem Power Plant, Salem Neck.
SG532. Allen Head, Pride's Crossing (Marblehead North quadrangle). Specimens a and b were collected within 25 ft of each other and were not separated by any contact.

The feldspar is microperthite or antiperthite and occurs in subhedra a few millimeters to a few centimeters long. (It will be convenient in the following discussion to refer to all two-phase feldspar intergrowths as "microperthite" regardless of which phase is more abundant.) The bulk composition of the microperthite varies much more from specimen to specimen in the syenite than in the granites. Compositional data are given in table 13. More extensive sampling of the massive syenite along the Beverly and Manchester shores in the Marblehead North quadrangle has shown a rather wide range of feldspar compositions. The limits of variation observed by X-ray diffraction and chemical analysis are 24½ and 43 weight percent Or; the most potassic syenite feldspar thus has about the same composition as the most sodic granite feldspar. The microperthite grains are rarely separated by interperthitic feldspar other than thin concentrations of plagioclase crystallographically continuous with perthitic plagioclase. The feldspars are generally quite fresh, though a little fine argillaceous material is scattered through the potassic phase of most intergrowths. Carbonate is very rare but does occur in veinlets cutting through microperthite; epidote was not observed. Grains of muscovite as large as several tenths of a millimeter across occur in microperthite of several slides and are believed to be of secondary origin.

The microscopic appearance of the amphibole of the Beverly Syenite is relatively uniform throughout the unit, doubtless in part because physical properties are rather insensitive to compositional variation in sodic hornblendes very rich in iron. The amphibole is very strongly pleochroic, varying from olive green (X) through very deep green (Y) to extremely dark greenish-brown, virtually opaque in thin

TABLE 13.—*Compositional data for feldspars of massive Beverly Syenite*

Specimen	$\Delta 2\theta$ (degrees)	Weight percent			
		Or		Ab	An
		X-ray diffraction	Chemical analysis [1]	Chemical analysis [1]	Chemical analysis [1]
SG271	0.748	35.5	37.43	60.07	2.50
SG280	.787	31.9	35.60	61.19	3.21
SG355a	.824	28.5			
SG355b	.763	34.4			

[1] See table 4.

SG271. Coney Island, Salem Harbor, Marblehead North quadrangle.
SG280. Excavation at Salem Power Plant, Salem Neck.
SG355. Southwest tip of point south of Chubb Creek, West Manchester (Marblehead North quadrangle) 1,400 ft south of bench mark 11; a, euhedral feldspar included within ferrohornblende; b, subhedral feldspar outside ferrohornblende. See figures 8 and 9.

section (Z). Because of the deep color and strong dispersion of the bisectrices, the precise orientation of the indicatrix could not be determined on the universal stage. The mineral has a low negative optic angle ($2V_x$ as low as 20° in some cases) and a rather large apparent extinction angle, $Z'\wedge c$ (20° to 21°). It occurs in irregular crystals as large as 5 mm in diameter, usually associated with other ferromagnesian minerals and opaque oxides. In a few rocks amphibole forms discontinuous rims on pyroxene grains. It commonly is poikilitic toward accessory minerals, and in some specimens includes feldspar as well. The amphibole of one specimen of biotite- and pyroxene-free syenite from the Marblehead North quadrangle poikilitically encloses euhedral crystals of feldspar and is surrounded by coarser anhedra of similar feldspar (figs. 8, 9).

The amphibole was separated, cleaned of its feldspar inclusions, and analyzed by Mr. Jun Ito. A point count of the concentrate submitted for analysis showed it to be pure amphibole. The analysis and some of the physical properties of the amphibole are given in table 14, together with similar data for an amphibole from the Beverly Syenite analyzed by Wright (1900). The formula calculated from the present analysis corresponds to a ferrohornblende having about 25 percent of the arfvedsonite component $(NaNa_2Fe_2^{+3}Fe_3^{+2}Fe^{+3}Si_7O_{22}(OH)_2)$ in solid solution (0.48 Na in the eight fold position). Wright's analysis corresponds to approximately 30 to 35 percent arfvedsonite in ferrohornblende (0.66 Na in eight-fold position).

The euhedral feldspar crystals included in the ferrohornblende contain 28.5 weight percent Or, whereas the irregular feldspar crystals outside the ferrohornblende contain 34.4 weight percent Or. The included feldspars must have been protected by the hornblende from reaction with the melt during the later states of crystallization, and

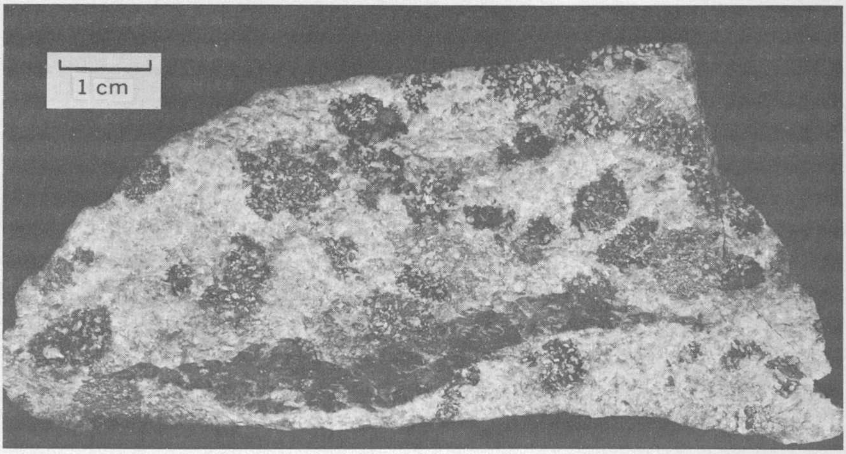

FIGURE 8.—Specimen of Beverly Syenite showing large single crystals of ferrohornblende (black) enclosing small crystals of microperthite. The specimen was collected on the southwest tip of the point south of Chubb Creek, West Manchester, 1,400 feet south of bench mark 11 (Marblehead North quadrangle).

FIGURE 9.—Photomicrograph of a thin section of the specimen shown in figure 8, showing euhedral microperthite crystals enclosed by ferrohornblende (large dark area enclosed by dashed line in right-central part of photograph) and larger, irregular microperthite crystals outside the ferrohornblende (in the rest of the photograph). Partially crossed nicols.

this rock thus provides the information that its feldspars became richer in Or as crystallization proceeded.

Golden-brown, very strongly pleochroic biotite occurs as scattered shreds and rarer crystals as much as 1 to 2 mm across. Its refractive indices are high, approaching those of pure annite (Winchell and Winchell, 1951, p. 374).

TABLE 14.—*Composition and properties of amphiboles from the massive Beverly Syenite*

	Amphibole analyzed in present study (J. Ito, analyst)			Amphibole analyzed by Wright (1900)		
	Composition					
	Weight percent oxides	Metal atoms per 24 oxygen atoms	Structural grouping of metal atoms	Weight percent oxides	Metal atoms per 24 oxygen atoms	Structural grouping of metal atoms
SiO_2	38.77	6.336	8.000	35.42	5.82	
Al_2O_3	8.92	1.664 .054		8.89	1.71	8.00
Fe_2O_3	7.67	.942		9.73	.47 .73	
TiO_2	2.62	.322		1.34	.17	
FeO	24.72	3.377	5.000	24.48	3.35	
MnO	.68	.094		1.17	.15	5.00
MgO	.68	.166		.17	.04	
CaO	8.96	.045 1.523	2.000	6.93	.56 1.34	2.00
Na_2O	3.36	.477 .587		5.13	.66 .30	
K_2O	1.67	.347	.934	3.23	.68	.98
H_2O+	1.44	1.570	1.570	3.15	3.46	3.46(!)
H_2O-	.15					
Total	99.64			99.64		
Density—3.45₁ g per cc (23.5°C)				Sp gr—3.44		
	Optical properties					
Direction	*n*	Color	Orientation	*n*	Color	Orientation
X	[1] 1.708	Light olive drab to tan.		1.673	Greenish yellow.	
Y		Deep green	=*b*	1.695	Olive-green	=*b*
Z	[1] 1.721	Very dark brownish green.	$\wedge c=10°$	1.696	Blue-green	[2] $\wedge c=8°$
2Vx	20°±5°			Approx. 36°, from 2E=63°22′		

[1] Measured on cleavage fragments in sodium light.

[2] Calculated from Wright's reported apparent extinction angle on cleavage fragments and 2V. Wright's reported value for the true extinction angle is inconsistent with the other optical constants he reports.

The pyroxene of the Beverly Syenite varies both in amount and in character. Estimated volumetric amounts of pyroxene range from trace amounts to 9 percent. Depth of color, pleochroism, extinction angle, and optic axial angle are variable, even within a single thin section, but zoned pyroxene crystals are rare. Where zoning is present, the outer part of the crystal is more deeply colored and pleochroic than the center and has a lower extinction angle $X\wedge c$. The optical properties are those of augite containing a variable amount of the aegirite component in solid solution. The extinction angle $X\wedge c$ ranges 50° to 10°, and 2V ranges from high and positive to high and negative. In all cases where pleochroism has been observed, the fast ray is darker than the slow ray and is grass green in contrast to the yellower green of the slow ray. A few slides show rims of ferrohornblende around pyroxene, but the reverse relationship of pyroexene rimming amphibole, common in the Quincy Granite (Warren, 1913, p. 216), has not been observed.

The ferromagnesian minerals of the syenite tend to occur in clusters of several grains. Most or all of the ferromagnesian minerals are represented in most of the clusters, and the accessory minerals also are concentrated in the clusters.

TRACHYTIC SYENITE

The rocks designated "trachytic syenite" in this report include those described by Capp (1921) under the name "sölvsbergite" and probably include many of the rocks called "hedrumitic pulaskite" by him and by Washington (1898–99). The rock is a cream to gray, fine-grained syenite with a pronounced trachytic or fluidal texture, and occurs in dikes from a few inches to several yards thick. The dikes cut the massive syenite along the Beverly shore and cut massive syenite and Salem Gabbro-Diorite on Salem Neck and in South Salem. Estimated modes are given in table 15.

Microperthite makes up 70 to 90 percent of the trachytic syenite and typically occurs in thin tablets alined more or less parallel to one another and to the dike walls, where these were seen. Perthitic lamellae are elongate normal to the long dimension of the tablet as seen in this section; the space between major plagioclase lamellae is generally laced by much thinner, anastomosing stringers of plagioclase, crystallographically continuous with the major lamellae and linking them together. Grain size is somewhat variable, but the typical rock is composed dominantly of tablets about 2 by 1 by 0.1 mm in size. Many of the dikes are sparingly porphyritic, and microperthite phenocrysts may be as large as ½ to 1 cm. Compositions of feldspars from the trachytic syenite are given in table 16.

Pyroxene, biotite, and hornblende are the ferromagnesian minerals of the trachytic syenite. Two of these ordinarily predominate greatly over the third, and in many specimens only two are present. Pyroxene and hornblende are very rarely found in significant quantity in the same rock. Biotite is the most widespread of the three, and is typically a very strongly pleochroic variety, nearly opaque to light vibrating parallel to the basal cleavage and orange-yellow or orange-brown

TABLE 15.—*Estimated modes of trachytic syenite*

Specimen	Microperthite	Plagioclase	Biotite	Pyroxene	Ferrohornblende	Opaque
SG259A	85		7		8	
SG388	85		7	7		
SG518	85		5	10		
SG452[1]		93		5		1

[1] Also contains 0.5 percent nepheline and 0.5 percent sodalite.

SG259A. North of Hale Street, Beverly, about 1,400 ft southeast of intersection with Boyle Street (Marblehead North quadrangle).
SG388. Northwest shore of Salem Neck, just west of cove east of hospital.
SG518. Winter Island, 290 ft north-northeast of lighthouse, on shore.
SG452. Outcrop at intersection of Newburyport Turnpike and North Street, Danvers.

TABLE 16.—*Compositional data on feldspars of trachytic syenite*

Specimen	$\Delta 2\theta$ (degrees)	Weight percent			
		Or		Ab	An
		X-ray diffraction	Chemical analysis[1]	Chemical analysis[1]	Chemical analysis[1]
SG259A	0.865	24.8	30.72	67.36	1.92
SG506	.813	29.7	32.0		
SG308	.807	30.1	27.45	69.56	3.00

[1] See table 4.

SG259A. North of Hale Street, Beverly, about 1,400 ft southeast of intersection with Boyle Street (Marblehead North quadrangle).
SG506. Palmer Point, South Salem; 1-ft dike cutting gabbro-diorite.
SG308. West shore of Cat Cove, Salem Neck.

in light vibrating normal thereto. The pyroxenes differ among themselves in their properties in much the same way as the pyroxenes of the massive syenite, but more commonly show the deep-green fast ray, strong pleochroism, low extinction angle $X \wedge c$, and negative optic sign characteristic of aegirite-rich pyroxene. The hornblende of the trachytic syenite seems to be little different from the arfvedsonitic ferrohornblende of the massive syenite, though in some slides it is very much darker than any other amphibole seen in any of the "alkalic" rocks.

In a few specimens of trachytic syenite the amphibole occurs in an exaggerated form of the poikilitic texture described in the massive Beverly Syenite. These specimens consist largely of parallel tablets of microperthite, among which are scattered small shreds of biotite, associated in one slide with small crystals of aegirine-augite and, in another slide, with magnetite. The amphibole, a dark-green hornblende, is found only in rounded areas a few millimeters across, where it is interstitial to the microperthite; each of these areas is surrounded by a zone a few millimeters wide in which very little or no ferromagnesian material is present. All the amphibole in each such rounded area has the same crystallographic orientation and presumably is physically continuous in the third dimension. In a few instances, the hornblende is continuous in the plane of the section, and so encloses the feldspar poikilitically. The enclosing material in one specimen is magnetite accompanied locally by very fine grained biotite; these minerals form patches which are interpreted as pseudomorphic after hornblende. In another specimen, the hornblende is locally replaced by an aggregate of fine-grained biotite.

The patches of poikilitic (or interstitial) amphibole are interpreted as representing the crystallization of amphibole at rather widely scattered nuclei in a liquid in which many feldspar crystals were floating. The biotite, aegirine-augite, and magnetite of the trachytic syenite probably began to crystallize after the hornblende, for they are absent from zones around the amphibole, where the ferromagnesian material had been abstracted from the liquid. Had the biotite, pyroxene, and magnetite crystallized earlier than the amphibole, partially resorbed crystals of them should exist in the zones around the amphibole, but such partially resorbed crystals are not present. Further evidence is afforded by the partial conversion of the amphibole to magnetite and biotite, which suggests a reaction relationship between hornblende and the other ferromagnesian minerals.

The accessory minerals are those typical of the "alkalic" series: zircon, apatite, sphene, magnetite. The amount of sphene is particularly variable. Zircon is definitely less abundant than in the granites. None of the rare accessories allanite, astrophyllite, or aenigmatite, was seen. A few specimens contain nepheline or sodalite, but in very minor amounts.

NEPHELINE-SODALITE SYENITE

The nepheline-sodalite syenites were divided by Clapp (1921) into foyaite and ditroite, according to whether they were fine grained and trachytic, or coarse grained and massive. Only the fine-grained nepheline-sodalite syenite has been found in the field by the writer, but two specimens of the coarse-grained variety from the collection of J. H. Sears, late curator of geology and mineralogy at the Peabody Museum of Natural History, in Salem, have been examined.

The fine-grained nepheline-sodalite syenite is a fresh, blue-gray rock with a trachytic texture; it occurs in dikes from 1 to 5 yards thick that cut the other syenites and the Salem Gabbro-Diorite. These dikes are especially abundant along the shore of Winter Island and Cat Cove on Salem Neck, and have also been found on Great Misery Island.

Gray tablets of feldspar, gray to pinkish feldspathoid having a greasy luster, and black, shiny biotite and amphibole can be recognized in hand specimens of the typical rock. Both nepheline and sodalite are present but can be distinguished only in thin section or by the use of long-wave ultraviolet light, in which the sodalite fluoresces a brilliant orange, as does the sodalite that occurs as an essential mineral in the feldspathoidal rocks at Red Hill, N.H. (Quinn, 1935, 1937). The rock is distinctly porphyritic; it contains phenocrysts of microperthite as much as 5 mm in diameter in a groundmass of dominant tabular feldspar, feldspathoids, and ferromagnesian minerals.

Trachytic texture is not so strong as in many of the trachytic syenites, though both phenocrysts and groundmass feldspars are tabular in habit. The phenocrysts are microperthite, almost identical with that of the trachytic syenite, with plagioclase lamellae more or less normal to the long dimension of the crystals and anastomosing minor plagioclase veinlets between the major lamellae. The feldspars of the groundmass are complexly and irregularly intergrown; some crystals are clearly perthitic individuals but in much of the groundmass the potassium-rich and sodium-rich feldspars are so irregularly intergrown that individual grains cannot be distinguished. Nepheline forms stubby prismatic crystals ½ to 1 mm long and about two-thirds as wide. Sodalite is anhedral and interstitial to the other minerals. The sodalite, and to a lesser extent the nepheline, has altered to cancrinite. Both feldspathoids are distributed fairly evenly throughout the rock.

Hornblende is the major ferromagnesian mineral of the rock and occurs in euhedral to subhedral crystals many of which are about 2 mm long and 0.3 mm thick. The hornblende is similar to that of the other syenites, but is perhaps a little darker parallel to X. Y is deep, almost grass green, and Z is very dark olive green. The extinction angle $Z \wedge c$ is large, probably about 25°, but cannot be determined precisely because of the strong dispersion of the bisectrices; 2V is low and negative, and the birefringence is low.

Aegirine-augite occurs in small granules, commonly scattered poikilitically within amphibole crystals. The mineral is not very abundant in any of the fine-grained nepheline-sodalite syenite specimens, and its optical properties are very difficult to determine because of the small size of the grains. Its depth of color suggests that the mineral may be more aegirite-rich than the pyroxene of the other syenites. In some specimens the amphibole tends toward the poikilitic texture described in the trachytic syenites.

Yellow-brown biotite is a minor constituent of one or two specimens. Accessories vary widely in amount from specimen to specimen; they include apatite, zircon, and sphene, as well as magnetite. The results of a point-count modal analysis and estimated modes are given in table 17.

TABLE 17.—*Estimated and measured modes of nepheline-sodalite syenite in volume percent*

Mineral	SG296	SG302		SG516
		Estimated	Point count	
Microperthite	80	70	72.2	73
Plagioclase	3	1		
Nepheline	5	8	10.2	10
Sodalite	1	9	5.5	5
Amphibole	8	10	10.2	8
Pyroxene	------	1	0.3	1
Biotite	2	------	------	Tr.
Opaque	1	<1	0.8	3
Apatite	<1	Tr.	Tr.	Tr.
Cancrinite	<1	<1	0.7	------
Sphene	------	Tr.	Tr.	------
Zircon	------	Tr.	0.1	------

SG296. Cat Cove, Salem Neck. Dike on west shore.
SG302. Cat Cove, Salem Neck. Dike on southwest point.
SG516. Winter Island, dike on shore 380 ft due north of lighthouse.

The coarse-grained nepheline-sodalite syenite was not found in the present study, but examination of two specimens collected by Sears reveals certain interesting differences between the coarse- and fine-grained nepheline-sodalite syenites. One of the specimens, from "Great Haste Ledge" (presumably Great Haste Island), is composed of microperthite, plagioclase, nepheline, sodalite, and their alteration products, and exceedingly minor amounts of biotite and zircon. It is crudely banded, alternate bands differing in grain size and mineralogical composition. Coarse-grained bands contain microperthite crystals 1 to 2 cm long and irregular grains of dark gray sodalite about the same size; this sodalite, which constitutes 20 percent of the coarse bands, fluoresces brilliant orange. A little blue sodalite is present in irregular small grains but does not fluoresce. Brownish nepheline is somewhat less abundant than sodalite. The finer grained bands are composed dominantly of albite and nepheline crystals a millimeter or less in size, and a smaller amount of interstitial microperthite and sodalite. The sodalite of the finer bands does not fluoresce and appears to be the blue variety.

The other specimen is from Coney Island (in Salem Harbor) and contains the same leucocratic minerals as the one just described, together with aegirite and magnetite. This specimen possesses a much more pronounced banded structure than the other, and the bands differ sharply in texture and mineralogical composition. The bands seem fairly regular in hand specimen, but a large thin section (5 by 7 cm) shows considerable irregularity of form and distribution. The aegirite occurs in small (0.1 mm) subhedral crystals and (in another band) as slightly poikilitic crystals several millimeters across. It is strongly pleochroic, with X deep dark grass green; Y, grass green; Z, yellowish green; $2V = -75°$, corresponding to an aegirite content of about 70 to 75 percent (Winchell and Winchell, 1951, fig. 306, p. 415). Magnetite occurs as subhedral crystals as much as 1 cm in diameter. Fluorescent sodalite is confined to one of the bands, in which it occurs as isolated grains several millimeters to a centimeter across. Textural variation is extreme, adjacent bands being composed of feldspars 0.1 mm and 10 mm in length.

Nepheline from coarse-grained nepheline-sodalite syenite was separated and its composition determined by the X-ray diffraction method of Smith and Sahama (1954). (This method uses curves of diffraction-angle separation plotted against composition; the curves were derived from data on synthetic phases in the binary system $NaAlSiO_4$-$KAlSiO_4$ and so do not reflect the possible effects of Ca and Si in excess of the above formulae. On the other hand, Smith and Sahama (1954, p. 442) plot 24 analyzed natural nephelines on their determinative chart, and these points cluster fairly closely around the lines representing the synthetic phases. Inspection of their figure indicates that their method may underestimate the molar percentage of $KAlSiO_4$ but probably by less than 5 percent.) The resulting composition is $K/(K+Na+Ca)=0.143\pm0.005$, as shown by the following data from specimen 509, Sears' Collection of Essex County rocks, Peabody Museum of Natural History, Salem, Mass., collected from Coney Island, Salem Harbor (chart made on a linear-recording diffraction spectrometer, using nickel-filtered copper radiation, scanning rate ¼° per min, chart speed 30 inches per hr, collimation 1° divergence and scatter slits, 0.003-inch receiving slit, annealed quartz internal standard):

*hk*l*	2θ ($CuK\alpha$)	$K/(K+Na+Ca)$
21*0	27.26_9	0.138
20*2	29.69_2	.149

Fluorescent sodalite nearly identical to that in the nepheline-sodalite syenite of the Salem area occurs in similar rocks at Red Hill, N.H., and Quinn's description (1935; 1937, p. 386) of the Red Hill material applies very well to the Salem material. The intense orange fluorescence of the material is suggestive of the variety hackmanite, although even the freshest specimens are gray rather than the reddish-violet color typical of hackmanite. Haüynite also fluoresces orange. Both hackmanite and haüynite contain sulfur and have somewhat higher refractive indices than pure sodalite; haüynite has a distinctly greater cell edge than sodalite (9.10 A as opposed to 8.87 A for sodalite, according to Winchell and Winchell, 1951, p. 349–350). Quinn (1937, p. 386) reports $n=1.483\pm0.002$ for fluorescent sodalite from Red Hill; this value indicates essentially pure sodalite. The unit-cell edge of fluorescent sodalite from a coarse-grained nepheline sodalite syenite (one of Sears' specimens, from Great Haste Ledge) was determined to be 8.880±0.005 A, almost exactly that of pure sodalite.

Blue sodalite, which does not fluoresce, is also present in Sears' specimens. The X-ray diffraction pattern of this material is not measurably different from that of the fluorescent sodalite.

CONTACT ZONE ON SALEM NECK

The area shown on the geologic map as "contact zone of Beverly Syenite" is underlain both by syenite and by gabbro-diorite, but the characteristic rock of the zone is a dark mafic porphyry that is commonly mixed with syenite in a very distinctive structure in which the porphyry forms ellipsoidal masses separated from one another by thin selvages of syenite. The rounded masses of porphyry range from about 10 cm to 1 m or so in diameter but are of fairly uniform size in any one outcrop. Most of the syenite is confined to the spaces between the ellipsoidal masses or porphyry, but a few irregular stringers with vague borders penetrate the porphyry blocks.

The porphyry is apparently in part the rock described by Clapp (1921, p. 97–98) and Washington (1899, p. 285–287) as camptonite; its groundmass is predominantly green hornblende, and it contains lesser amounts of brown biotite, small laths of plagioclase, and irregular grains and skeletal crystals of magnetite. Local accumulations of granular, colorless augite are surrounded by coronas of biotite, which separate the pyroxene from hornblende and feldspar. Phenocrysts make up less than 10 percent of the rock, and are euhedral crystals of labradorite 1 to 3 mm long. Many of the phenocrysts have rounded cores of much more sodic composition, probably sodic oligoclase or albite; the boundary between core and rim is sharp and is marked by a difference in relief, a sharp Becke line, a great difference in optical orientation, and some difference in degree of alteration.

The syenite stringers between the elliptical masses of porphyry are composed essentially of microperthite or antiperthite, aegirine-augite, and minor ferrohornblende and magnetite. The thin stringers that penetrate the porphyry masses are nearly identical, except that minerals of the porphyry are scattered about through the syenitic material. A few partially resorbed labradorite crystals are surrounded by albite rims, but other than this there is surprisingly little textural evidence of reaction between the included minerals and the syenite. Some of the stringers carry euhedral crystals of sphene, small granules of which are present in the adjoining mafic porphyry but absent from thin sections of the same ovoid a few centimeters farther away from the stringer; the sphene may have been produced by recrystallization of the opaque material or of the ferromagnesian silicates of the mafic porphyry, but there is no indedependent textural support for such an origin.

The perfection of the ellipsodial structure varies considerably, but in some outcrops it is strikingly exhibited. In one exposure, about 200 feet south of Memorial Drive, 700 feet S. 60° W. of the triangulation station at Fort Lee, the structure is very well shown (figs. 10 and 11), the long axes of the ellipsoids being alined in the form of a transverse section of a symmetrical syncline. Vertical tension fractures in the axial region may have resulted from tensional stress due to stretching of the lower layers. Some of the ellipsoids in this outcrop have blunt, rounded projections that extend into the spaces between other ellipsoids; this relationship suggests that the ellipsoids accumulated before they had acquired a high rigidity.

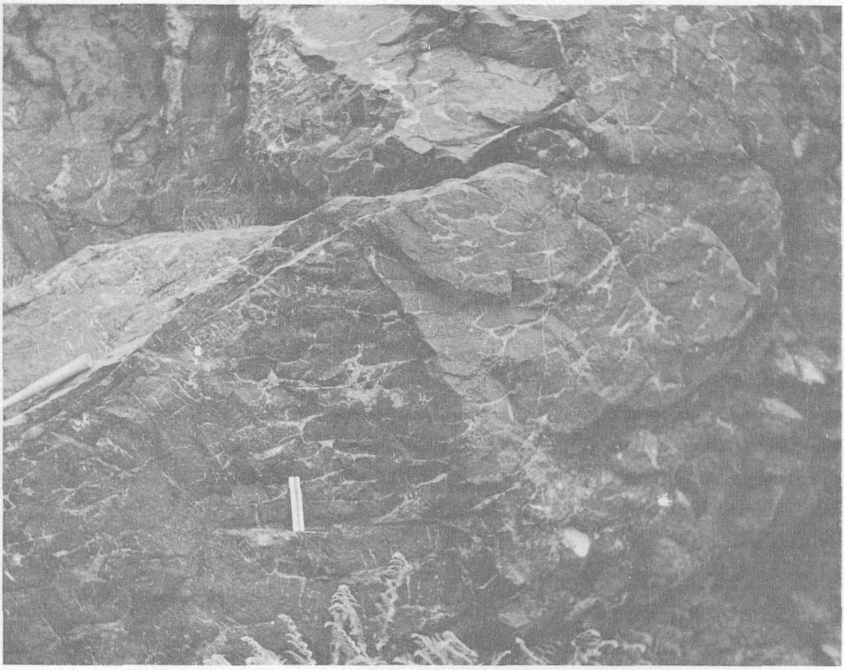

FIGURE 10.—Outcrop in contact zone of Beverly Syenite on Salem Neck, showing ellipsoidal structure referred to in the text. The mafic porphyry ellipsoids are separated by syenite. The area shown in the photograph is the axial region of what appears to be a symmetrical syncline having a wavelength of about 150 feet; the vertical seams of syenite penetrating the porphyry ellipsoids are confined to this region and may represent tensional fractures produced by bending individual ellipsoids. The ruler is about 6 inches long.

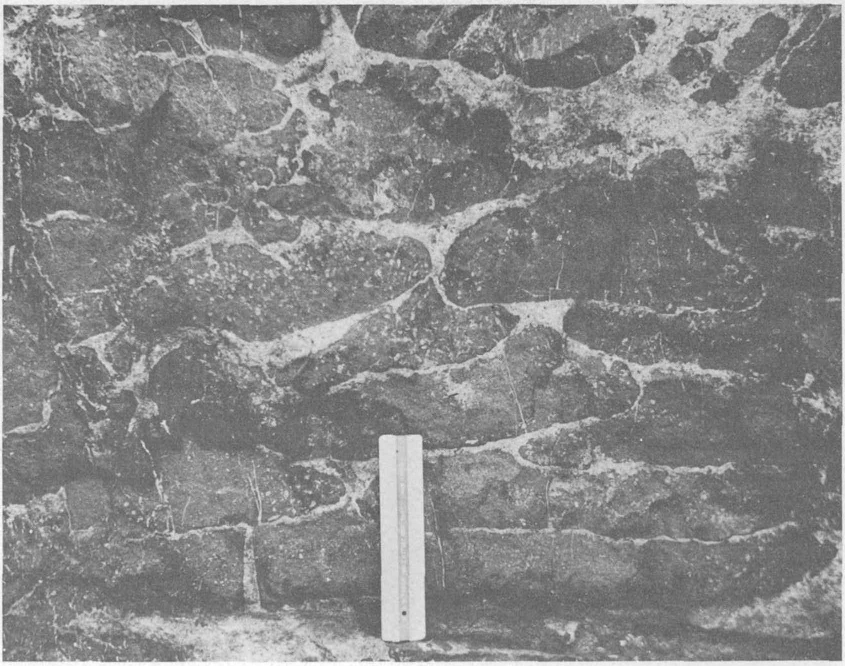

FIGURE 11.—Closer view of the ellipsoids shown in figure 10; the forms suggest deformation by the overlying ellipsoids.

The gabbro-diorite of the contact zone varies from a fresh to a highly altered rock. This rock is well exposed at Cat Cove on Salem Neck and on Great Haste and Coney Islands in Salem Harbor; it is the rock described by Washington (1899, p. 56) as the "hyperitic variety of essexite." Prior to alteration, much of the gabbro-diorite on Salem Neck was probably identical with this rock. The fresh variety is rather coarse grained and is composed of labradorite (50 percent), augite (20 percent), hornblende (5 percent), biotite (15 percent), olivine (4 percent), magnetite (5 percent, perhaps including some exsolved ilmenite), and accessory amounts of apatite and serpentine. The larger crystals of biotite (as much as 7 mm long) poikilitically enclose perfectly euhedral hexagonal prisms of apatite, some of which are as large as 1 by 0.2 mm. Olivine is nearly always rimmed by serpentine or hornblende, and is altered to serpentine along fractures. A few grains have crude concentric rims of serpentine, hornblende, and biotite, in that order, from core to margin.

Two masses of coarse-grained mafic rocks apparently surrounded by syenite crop out on the shore at Salem Willows. One consists of fresh augite, hornblende, and minor biotite, and highly altered plagioclase containing 8±2 weight percent An, as determined by X-ray diffraction methods. Although the pyroxene itself apparently had no tendency to break down, the assemblage pyroxene plus magnetite appears not to have been stable, for these two minerals are everywhere separated by a thin zone of hornblende. The other mass is composed of ragged, poikilitic hornblende and biotite, a few residual patches of augite, and abundant fresh plagioclase (18 weight percent An by X-ray; 21 weight percent An by refractive indices on cleavage fragments).

The nepheline-sodalite syenite dikes occur only in and near the contact zone, where many other porphyritic dikes of exceedingly variable texture and composition are found. These dikes consist of the rock described by Clapp (1921, p. 123–126) as hybrid rocks between syenite and gabbro-diorite or diabase. Clapp's description agrees in most respects with the writer's observations, which therefore need not be recorded here in detail. It should be pointed out, however, that most of the rocks of this type can be demonstrated to occur in dikes intrusive into gabbro-diorite or syenite; they therefore probably represent the crystallization products of highly contaminated syenite magma, rather than of contact metamorphism in the usual sense of that term. The writer agrees with Clapp's conclusion that these rocks are the "essexites" of Sears and Rosenbusch and that they are not part of the normal differentiation sequence of the "alkalic" series in Essex County. The descriptions of Sears (1891), Washington (1898–99, p. 53–57), Rosenbusch (1907, p. 292, 398–399), and Clapp (1921, p. 121–126) indicate that two different rocks from Salem Neck have been included in descriptions of the type "essexite." One of these, to which Washington (1898–99, p. 56) refers as a "hyperitic variety," is the olivine gabbro just described; Washington notes the absence of nepheline and rarity of alkali feldspar in this rock. The other rock type is that referred to above and described by Clapp (1921, p. 123–124) as "hybrid rock" and (in part) as "contact-metamorphosed olivine diabase." Neither rock is a satisfactory type specimen for essexite, as that rock is usually defined.

Tilley (1958) has referred to the vermicular intergrowth of nepheline and plagioclase originally described by Sears (1891, p. 32) and Rosenbusch (1907, pp. 292, 398–399) in "essexite" from Salem Neck. Clapp (1921, p. 124, pls. XVII and XVIII) described what is apparently the same material as "microperthite," but Shand (1946, p. 401) confirmed the original identifications of nepheline. As indicated in the preceding paragraph, the writer has examined specimens that fit Clapp's description very well. At least some of the intergrowths in this rock are composed of a single phase, for the components of the intergrowth can be distinguished only with crossed nicols; the material of this type of intergrowth is untwinned, has a large optic angle, and has indices of refraction slightly less than the mounting medium of the thin section. This material is certainly albitic plagioclase; why it should form a vermicular intergrowth with itself is not clear, but the intergrowth is obviously not an equilibrium texture. Other similar intergrowths in the same thin section show preferential alteration of one of the textural elements, and in none of these could useful interference figures be obtained; it is possible that they are nepheline-plagioclase intergrowths similar to those described by Sears, Rosenbusch, and Shand, but the plagioclase of the present writer's specimens is albite-oligoclase rather than the labradorite of Sears and Rosenbusch.

TRAP DIKES

Dikes of fine-grained mafic rocks, most of them altered diabase or basalt, cut most of the other rock types of the Salem area, with the exception of the Peabody Granite, in which only a single diabase dike has been found. (See p. A65.)

Most of the diabases have been highly altered, and their feldspars are nearly indeterminable. Hornblende is the dominant ferromagnesian mineral, but residual grains of augite are common. Apatite is the most abundant accessory mineral, though sphene is quite abundant in some specimens.

Olivine diabase is rare; the best example found by the writer is a dike on Coney Island, in Salem Harbor. Strongly porphyritic diabase, containing labradorite phenocrysts as much as several centimeters long, occurs in a few dikes in the area; the rock is very similar to the labradorite porphyry at Pigeon Cove and along the north shore of Cape Ann (Warren and McKinstry, 1924, p. 320–321), but no rocks as coarse grained as those exposed on Cape Ann have been found in the Salem area.

PEGMATITES AND APLITES

Dikes of aplite and pegmatite-aplite cut granite, syenite, and older rocks in many localities along the Beverly-Manchester shore and inland. A few such dikes cut granite of the Peabody stock. The aplites have typical aplitic texture and are poor in dark minerals; quartz, microcline, albitic plagioclase, and occasionally microperthite are the principal minerals. Several of the aplite dikes are coarser grained at their margins than in their interiors, a feature described by Washington (1898–99, p. 105–108). Both continuous and discontinuous coarsening have been observed, and the borders of a few dikes are pegmatite, generally in sharp contact with the aplite. Grain-size variation within the aplite is characteristically erratic.

Pegmatites of syenitic and granitic composition are fairly abundant and are well exposed along much of the Beverly-Manchester shore.

The granitic pegmatites are rather less abundant than the syenitic and occur mostly as tabular dikes in granite and syenite. At the little quarry north of Central Cemetery in Beverly, irregular pods and patches of granite pegmatite occupy the spaces between parts of disrupted trap dikes in porphyritic microgranite.

Syenite pegmatite occurs as even, sharply bordered dikes cutting syenite, as stringers cutting through syenite and broken mafic dikes, and as irregular masses between parts of disrupted dikes in syenite, as shown in figure 12. The last mentioned type of pegmatite clearly is no older than the intrusion of the trap dike into the syenite and presumably originated by recrystallization and perhaps partial fusion of the syenite.

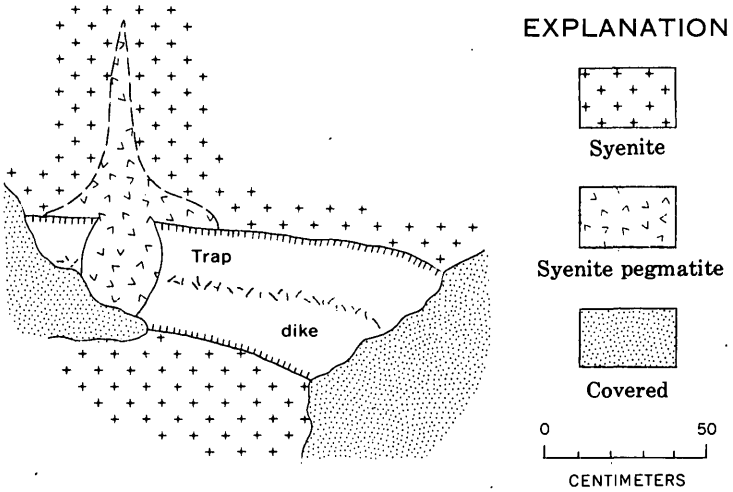

FIGURE 12.—Sketch of outcrop on east shore of Mackerel Cove, Beverly, showing syenite pegmatite in massive Beverly Syenite. The trap dike is chilled against massive syenite but not against pegmatite. The pegmatite is believed to have formed by recrystallization and possibly partial fusion of the massive syenite, presumably at the time of intrusion of the trap dike.

"LAMPROPHYRE" DIKES

The "lamprophyre" dike rocks of the Salem area have been well described by Washington (1898–99, p. 284–287), MacKenzie[5], and Clapp (1921), the last of whom also summarized many of MacKenzie's descriptions. As pointed out by Washington, these rocks lack mafic phenocrysts and therefore are not typical lamprophyres.

The most abundant type is a porphyritic rock containing highly altered plagioclase phenocrysts in a groundmass of hornblende, biotite, and plagioclase. Magnetite, sphene, and apatite are especially

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[5] MacKenzie, J. D., 1911, The dikes of West Manchester, Essex County, Massachusetts: Manuscript thesis, Massachusetts Inst. Technology.

abundant accessories. Estimated modes of representative specimens are given in table 18. The mineralogical composition of some of these rocks is similar to that which would be expected from a more or less normal basaltic magma crystallizing under conditions of high activity of H_2O.

TABLE 18.—*Estimated modes of "lamprophyres"*

	SG289	SG524
Phenocrysts		
Plagioclase	10	----------
Groundmass		
Plagioclase	16	29
Hornblende	60	----------
Biotite	12	39
Aegirine-augite	----------	29
Sphene	.5	----------
Apatite	.5	3
Opaque	1	----------

SG289. East shore of Plum Cove, Pride's Crossing (Marblehead North quadrangle). Dike 20 cm thick cutting syenite.

SG524. Allen Head, Pride's Crossing (Marblehead North quadrangle). Xenolith in trap dike.

The objection has been raised that basaltic magma does not contain enough K_2O to produce the amounts of biotite in these rocks. Analyzed lepidomelane from Rockport (Clarke, 1886) contains 8.46 percent K_2O, and diabase from Rockport contains 1.11 percent K_2O (Washington, 1898–99, p. 481). The diabase could therefore yield a maximum of 13 percent of the lepidomelane. Granting that the analyses are old, that the mica is from a pegmatite, and that not all the potassium of the rock would be in biotite, the conclusion still seems justified that some of the "lamprophyres" are similar to "wet" diabase.

The porphyritic rock described in the contact zone of Beverly Syenite on Salem Neck seems to be petrographically identical to at least some of the rocks called "camptonite" by Washington (1898–99, p. 284–287) and Clapp (1921, p. 97–98).

PETROLOGY OF THE "ALKALIC" SERIES

The detailed petrology of the granites and syenites of the "alkalic" series has been considered in other papers (Toulmin, 1960).[6] Because much of the relevant evidence comes from areas outside the Salem quadrangle, only a summary of the conclusions reached will be presented here.

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[6] See also Toulmin, 1958, Bedrock geology of the Salem area, Massachusetts: Ph.D. thesis, Harvard Univ., Cambridge, Mass., 167 p.

The microperthites of the Peabody and Cape Ann Granites have bulk compositions of 44 to 52 weight percent Or; the phenocrysts of the porphyritic microgranite of the large area in Beverly, regarded as a porphyritic border facies of the Cape Ann pluton, have compositions of 56 to 61 weight percent Or. The petrographic evidence thus indicates that the feldspars crystallizing from the granitic magma were progressively richer in Ab as crystallization proceeded. This is precisely the crystallization trend that would be predicted from the composition of the granite and phase-equilibrium data in the system Ab-Or-Q-H_2O (Tuttle and Bowen, 1958.) The microperthites of the Beverly Syenite are more sodic, containing 24 to 43 weight percent Or, and there is strong evidence that the feldspar of at least some of the syenite changed toward a more potassic composition as crystallization proceeded. These compositional data and various observations on the mode of association of the granite and syenite and the contact between them are best explained by the hypothesis that the syenite consists of feldspar crystals formed when the granitic magma was devolatilized, presumably by volcanic activity. Volcanic rocks on Marblehead Neck and several islands in Salem Harbor are thought to be extrusive equivalents of the granitic rocks (Clapp, 1921) and are nearest that part of the Cape Ann pluton whose margin is syenitic.

W. B. Joyner[7] has shown that a large positive gravity anomaly exists under Salem and Beverly Harbors and the shore of Massachusetts Bay in Beverly. The shape and magnitude of this anomaly require that the granite and syenite at the surface be underlain at rather shallow depth by denser rocks, and indicate that the contact between the surface rocks and the denser rocks dips northward in this area at about 20° to 40°. If this contact is assumed to be a local shelf on the floor of the pluton, the marginal strip of syenite along the Beverly shore may reasonably be regarded as a gravitational accumulation of the shower of sodic feldspar crystals that would result from devolatilization of the granitic magma. The generally continuous nature of the contact between granite and syenite on the Beverly shore reflects the return to the undisturbed course of crystallization of the granitic magma. (See pp. A72–A73.)

Field evidence supports the interpretation that the Peabody Granite is somewhat younger than at least some of the rocks of the Cape Ann pluton (see pp. A72–A73). The homogeneity of the rock indicates that the Peabody Granite crystallized under very uniform conditions. No

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[7] Joyner, W. B., 1958, Gravity in New Hampshire and adjoining areas: Ph.D. thesis, Harvard Univ., Cambridge, Mass., 126 p. See especially figure 24.

evidence of volcanic activity associated with the emplacement of the Peabody stock has been preserved in the granite, although of course if the contact dipped steeply in an area of volcanism no accumulation of sodic feldspar crystals, such as that which constitutes the Beverly Syenite, could have formed.

Tuttle and Bowen (1958, p. 83–84, 92) found that the amphibole of the Peabody Granite (referred to by them as "Quincy granite") was unstable relative to biotite at the steam pressures of their experiments, and they suggested that biotite was the primary ferromagnesian mineral of the granite. The petrographic evidence is not compatible with this suggestion; it is possible that ferrohornblende was stabilized relative to biotite by a lower chemical potential of H_2O than that obtaining in their experiments. Such a lower chemical potential could result either from a lower volatile content in the magma than the saturation value at the pressures they used or from the effect of other fugitive components in the magma.

The lack of fresh specimens of the Cherry Hill Granite prevents accurate description of its composition and origin. The Wenham Monzonite is the only rock of the "alkalic" series in this area that contains large amounts of two feldspars, and the crystallization of two feldspars from its magma clearly reflects its more calcic composition. The relationship of the Wenham Monzonite to the Beverly Syenite and the more abundant granites is not entirely clear; the monzonite may represent an earlier stage in a differentiation series that produced the granitic magma, or it may reflect contamination of a calcium-poor magma by the more calcic country rocks. The textural relations between the two amphiboles of the Wenham Monzonite are suggestive of assimilation, as mentioned on page A43, but strong evidence of such assimilation is wanting.

The field relations of mafic dikes and their wallrocks of porphyritic microgranite and syenite (pp. A73–A75) indicate strongly that magmas of very different compositions must have been available for intrusion at very nearly the same time. Unless the two magmas represent a pair of immiscible liquids, they must have been intruded from physically separate reservoirs. Although Holgate (1954) has recently revived the suggestion that such immiscible pairs may be important in petrogenesis, it seems unlikely that basaltic and granitic melts constitute such a pair (Roedder, 1951; 1953; 1956; oral communication). It is therefore concluded that mafic and felsic magmas existed more or less contemporaneously in separate reservoirs under the Salem area at the time of intrusion of the "alkalic" series. The origin of these contrasted magmas is open to conjecture.

The diversity of rocks in the contact zone of the Beverly Syenite on Salem Neck is almost certainly due to processes of contamination and assimilation. For reasons not yet clearly understood, these processes operated much more vigorously at the contact between syenite and gabbro-diorite than at the contact between granite and gabbro-diorite. The restriction of nepheline-sodalite syenite to this contact zone and its occurrence in late dikes suggest that undersaturated magma was derived by differentiation of contaminated syenitic magma, but the detailed process involved has not been deciphered.

The present study of a small part of the "alkalic" series does not justify a lengthy discussion of the origin of the granitic magma regarded as the source of the leucocratic rocks of that series. If, as the author believes, the "alkalic" series of Essex County is to be correlated with the White Mountain Plutonic-Volcanic Series of New Hampshire, the problem is that of the differentiation mechanism of that magma series, well outside the scope of the present report (Chapman and Williams, 1935). The petrologic importance of the Salem quadrangle (together with the adjacent Marblehead North quadrangle) lies in the example it furnishes of an unusual differentiation mechanism operating after emplacement at a shallow level of the crust to produce a variety of rocks, including syenite, from a magma of granitic composition (Toulmin, 1960).

TRIASSIC(?) OR OLDER ROCKS

DIABASE

Dikes of diabase and basalt cut most of the other rock types of the Salem area, as noted on p. A60. Many of these dikes are clearly closely related to rocks of the "alkalic" series, for they were intruded during the same general period of magmatic activity (see pp. A73–A75). It is likely, however, that some of the diabase dikes, especially those that are notably less altered than their country rocks, may be much younger than the "alkalic" series. In New England, basaltic and diabasic dikes younger than any other bedrock units in their vicinity are traditionally regarded as of Triassic age, in the absence of evidence to the contrary. Such an age assignment is as reasonable in the Salem quadrangle as at other localities far from demonstrable Triassic igneous activity.

The largest Triassic(?) dike in the Salem quadrangle, and the only one shown on the geologic map (pl. 1), is the only diabase dike known to intrude Peabody Granite. It is exposed in the low hills northwest of Pierces Pond, Peabody; it is about 100 meters wide and trends about N. 30° W. Its central part is medium-grained diabase, composed of labradorite (about 75 per cent), augite (about 35 per cent), magnetite (about 5 per cent) and chlorite (about 3 per cent). The chilled margin of the dike is porphyritic, having plagioclase and rare augite phenocrysts in a fine-grained matrix characterized by flow-aligned feldspar laths. The rock is fresher than most of the diabase dikes along the shore.

STRUCTURAL GEOLOGY

GENERAL STATEMENT

The structural interpretation tentatively presented here is that the Precambrian(?) metamorphic rocks are folded into a syncline that plunges southwest, probably steeply, and is overturned to the northwest. These rocks are intruded by rocks of the older subalkaline intrusive series, and both are overlain unconformably by the sediments and volcanic rocks of the Newbury Formation. The rocks of the Newbury Formation, in turn, are tilted to moderately steep northwest dips and intruded by rocks of the younger subalkaline intrusive series. The youngest rocks in the area, with the possible exception of some of the diabase dikes, are the intrusive rocks of the "alkalic" group.

PRECAMBRIAN(?) METAMORPHIC ROCKS

The planar structures of the Marlboro(?) Formation characteristically strike northeast and dip rather steeply to the northwest. The structure mapped is generally a foliation (in the sense of Billings, 1954, p. 286–287, fig. 231) resulting from parallel alinement of tabular mineral grains, especially grains of feldspar. In the augen gneiss, regular and even bands of different proportions of feldspar megacrysts commonly parallel the foliation; these bands are interpreted as reflecting differences in original composition of the rock, and hence represent bedding. In all outcrops where both features are present, the foliation and bedding are parallel.

Inspection of the geologic map (pl. 1) shows that the attitudes of foliation in the plagioclase amphibolites of the Marlboro(?) Formation in the hilly area between Beverly Airport and Putnamville Reservoir change continuously from a north-northeast strike at the south to a north-northwest strike at the north. The boundary between units A and B of the formation also seems to curve slightly from a north-northeast trend southeast of St. John's School to a north or north-northwest trend near Putnamville Reservoir. Foliation in the undifferentiated Marlboro(?) Formation in the northwest corner of the Salem quadrangle strikes east or east-northeast, and this trend suggests possible original continuity with the rocks of the Putnamville area. In the vicinity of the Sons of Jacob Cemetery in Danvers, a zone of distinctive amphibolite seems to be thrown into a rather tight fold, which closes to the northeast. The trace of the axial plane of this fold, extended to the northeast, passes between the areas of Marlboro(?) outcrop near Putnamville and in the northwest corner of the quadrangle; this plane could therefore be the axial plane of the fold suggested by the foliation attitudes of the plagioclase amphibolites of unit A and gneisses of the undifferentiated Marlboro(?). The fold seems to plunge southwestward, implying the geometry of a syncline overturned to the southeast. Because of uncertainties in correlation of individual parts of the Marlboro(?) Formation between the Salem quadrangle and the type area, however, it cannot be stated definitely whether the fold is truly synclinal or anticlinal.

Minor structures observed in the rocks of the Marlboro(?) Formation have been of little service in deciphering the major structure. Most of the small folds in the augen gneiss are associated with local pinching-out of layers of plagioclase amphibolite. The brittle plagioclase amphibolite layers have apparently broken and separated, the space between the two parts being filled by inflowing augen gneiss, which must have behaved plastically. An excellent example of this feature is exposed on the top of a roadcut in the intersection of Routes U.S. 1 (Newburyport Turnpike) and Massachusetts 114 (Andover Street), in Danvers, where a 5-foot layer of plagioclase amphibolite ends in a bluntly rounded nose beyond which the augen gneiss contains many fragments of the amphibolite (fig. 13). The foliation of the augen gneiss adjacent to the amphibolite is parallel to the layer of amphibolite except at the discordant nose, where a foliation-free ag-

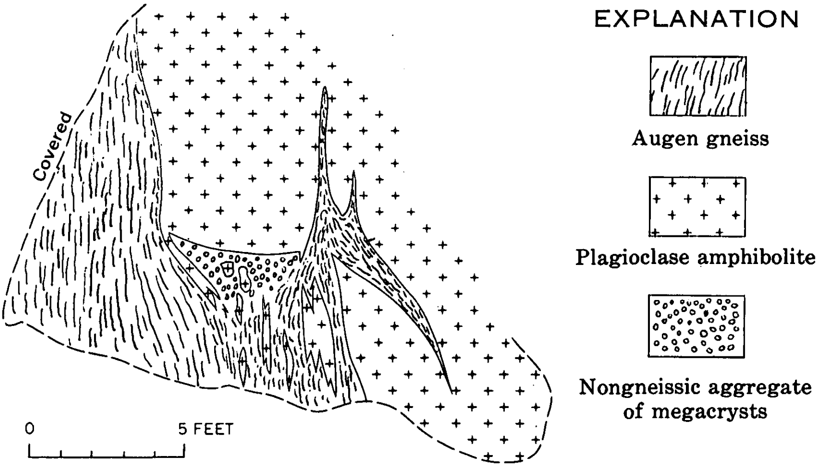

FIGURE 13.—Sketch of outcrop in unit B of Marlboro(?) Formation at intersection of Routes U.S. 1 and State 114, Danvers. Plagioclase amphibolite has fractured, and augen gneiss has flowed into the fractures. Note nonfoliated aggregate of feldspar megacrysts in strain shadow at blunt end of plagioclase amphibolite layer.

gregation of feldspar augen forms a wedge-shaped strain shadow next to the amphibolite. The foliated gneiss wraps around the amphibolite nose in a gentle curve outside the strain shadow. Such a structure indicates plastic or liquidlike behavior of the augen gneiss, yet its evenly bedded character in this same outcrop (fig. 14) cannot be

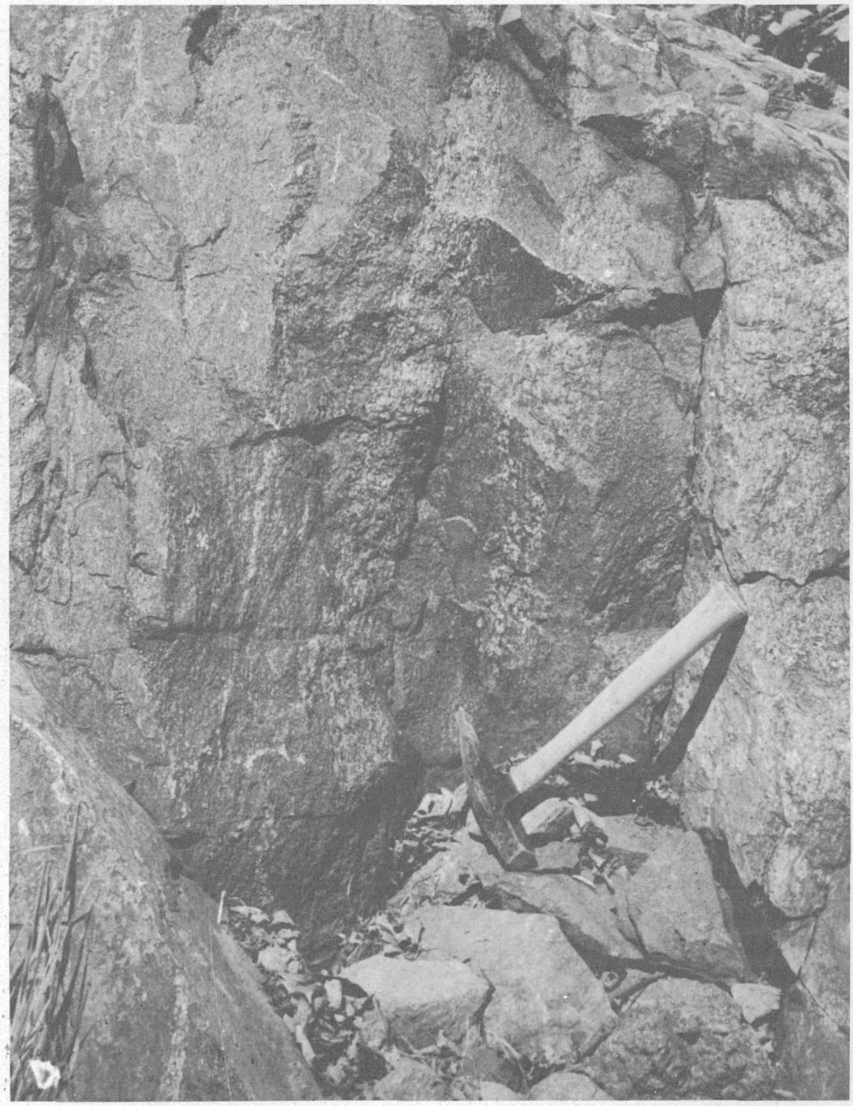

FIGURE 14.—Augen gneiss of unit B of Marlboro(?) Formation, from outcrop at intersection of Routes U.S. 1 and State 114, Danvers. Evenly banded compositional variation is interpreted as a reflection of original bedding and is parallel to foliation.

reconciled with any great degree of melting. The structure is most reasonably explained in terms of solid flow and recrystallization in the presence of strong stress gradients at a sharp flexure in the boundary of the tough plagioclase amphibolite.

A somewhat larger fold in unit B is well exposed in the interchange at Dayton Street on Route 1 in Danvers. It also appears to be controlled by the abrupt breaking-off of a bed of plagioclase amphibolite.

It should be pointed out that the writer has seen no exposure showing both segments of the broken amphibolite layer. The blunt endings of amphibolite layers, deformation of the gneiss, and small fragments of amphibolite in the gneiss (fig. 13) leave little doubt, however, as to the process involved.

A few drag folds observed in rocks of the main belt of outcrop of the Marlboro(?) Formation are consistent with a position on the southeast limb of a syncline plunging steeply southwest.

OLDER SUBALKALINE INTRUSIVES

Virtually every outcrop of Salem Gabbro-Diorite is cut by diversely oriented joints in such profusion that no attempt was made to record their attitudes. Small shear zones are common, as are dikes and irregular pods of pegmatite. The rocks are also cut by many basaltic and diabasic dikes, most of which are apparently as altered as the gabbro-diorite and are cut by all the joints that cut their wall rocks. These dikes probably formed during the same general period of magmatic activity as the gabbro-diorite. Other diabase dikes are fresher, somewhat less jointed, and probably related to later periods of magmatic activity. The existence of diabase dikes much younger than the Salem Gabbro-Diorite is demonstrated by the dikes that cut granite and syenite of the "alkalic" series.

The location of the contact between Salem Gabbro-Diorite and Marlboro(?) Formation is uncertain because of poor outcrop, but it seems to transect the foliation and the contact between units A and B of the Marlboro(?) Formation. A small area of Marlboro(?) type gneiss, along with various highly schistose rocks, occurs in syenite along the Beverly shore east of Woodbury Point (Marblehead North quadrangle); thus the regional metamorphism that produced the strongly foliated structure of the Marlboro(?) Formation seems to have extended over the area now occupied by Salem Gabbro-Diorite. Since the Salem Gabbro-Diorite lacks a general foliation, it probably is younger than this regional metamorphism. The evidence available does not indicate whether the contact between the Salem Gabbro-Diorite and the Marlboro(?) Formation is a fault or an intrusive contact, but on the hypothesis that the gabbro-diorite is the younger rock, it is simpler to assume that the contact is intrusive.

The Newburyport(?) Quartz Diorite of the Salem quadrangle, like the Salem Gabbro-Diorite, is a massive rock apparently younger than the principal regional metamorphism. It is somewhat less jointed than the gabbro-diorite, but even more thoroughly altered. Very little can be deduced about its contact relations from exposures in the Salem quadrangle. Its age and correlation have been discussed in the description of the rock.

It should perhaps be emphasized that the older and younger subalkaline intrusive series are separated only on somewhat indirect evidence; it cannot be demonstrated that the Salem Gabbro-Diorite, Newburyport(?) Quartz Diorite, Topsfield Granodiorite, and the medium-grained granodiorite are not all part of a single igneous sequence. The Newburyport(?) Quartz Diorite of the Salem quadrangle differs in certain respects from the rock said by Schneer (unpublished data) to underlie the Newbury Volcanic Complex in the Ipswich quadrangle, and if the two rocks are not the same, there is no evidence concerning the relative ages of the Newburyport(?) Quartz Diorite and the Newbury Formation in the Salem area. The alteration of the Newburyport(?) is similar to that of nearby volcanic rocks of the Newbury Formation and seems more severe than that of the Topsfield Granodiorite and the medium-grained granodiorite, although it is admittedly difficult to distinguish the effects of different original compositions from those of different physical conditions during alteration.

Alteration products of the supposedly roughly contemporaneous Salem Gabbro-Diorite and Newburyport(?) Quartz Diorite differ principally by the presence of carbonate in the Salem and of epidote in the Newburyport(?). This may represent either a difference in the physical parameters, temperature and pressure, or a difference in some chemical parameter such as chemical potential of carbon dioxide during alteration.

NEWBURY FORMATION

At the few places where data could be obtained, the bedding of the sediments in the Newbury Formation strikes northeast and dips 40°–75° NW. The adjoining formation northwest of the area where these attitudes were measured is the medium-grained granodiorite which is believed to be intrusive into the Newbury Formation. In the vicinity of Howe, where the undifferentiated diorite and gabbro is in contact with the Newbury Formation to the northwest, the Newbury Formation occupies a much narrower band and is represented only by altered porphyritic andesites whose attitude cannot be determined.

The narrowing of the Newbury Formation may express either the closing of a northeast-plunging syncline or truncation of the Newbury Formation by a fault or intrusive contact against the undifferentiated diorite and gabbro. Because the rocks in the outcrops south of Howe are highly crushed and sheared, and because the west limb of the supposed syncline is nowhere exposed, the writer prefers to hypothesize a fault between the Newbury Formation and the undifferentiated diorite and gabbro. It is not known whether this fault displaces the contact of the medium-grained granodiorite or is truncated by the granite.

YOUNGER SUBALKALINE INTRUSIVES

The forms of the intrusive bodies of Topsfield Granodiorite and medium-grained granodiorite are difficult to determine with certainty. The elongate area underlain by Topsfield Granodiorite in the Salem quadrangle suggests the outcrop pattern of a large, more-or-less concordant tabular body. Reconnaissance mapping in the southern part of the Georgetown quadrangle indicates, however, that near the village of Topsfield the Topsfield Granodiorite widens into an equant body about 2 miles in diameter, whose contact cuts across the structure of the Newbury Formation and the medium-grained granodiorite. Mafic volcanic rocks of the Newbury Formation are exposed along the Newburyport Turnpike (Massachusetts Route 17) as far south as a point about 2 miles northeast of Topsfield; these rocks are presumably continuous with those of the type area at Newbury and the fossil locality at Glen Mills (Emerson, 1917, p. 163). They are alined exactly with the band of Newbury Formation in the Salem quadrangle. Topsfield Granodiorite thus forms a cross-cutting intrusive body separating the two areas of Newbury Formation and must be at least somewhat younger than the Newbury Formation. The contact relations also suggest that the Topsfield Granodiorite is slightly younger than the medium-grained granodiorite, although the previously noted commingling of the two rock types in a few outcrops suggests that the difference in age is probably small. The rounded quartz phenocrysts of the Topsfield Granodiorite are characteristic of subvolcanic intrusive rocks that have crystallized at relatively shallow depths. The close spatial association of the younger subalkaline intrusive rocks with the Newbury Formation suggests that the Topsfield Granodiorite may be an intrusive related to the volcanic rocks that are abundant in the Newbury Formation. The medium-grained granodiorite seems to form a fairly regular tabular intrusive in the Salem quadrangle, but in the Reading quadrangle it has a less regular form, according to mapping by R. O. Castle (written communication, 1961). The two rock types are probably best regarded as forming somewhat irregular, partly concordant intrusives that were emplaced during a single epoch of igneous activity and that may constitute a single complex intrusive body. It is possible that the volcanic rocks of the Newbury Formation are related to the same period of igneous activity.

"ALKALIC" SERIES

The rocks of the "alkalic" series are massive, undeformed, and generally fresh. They occur in discordant intrusive bodies and are apparently the youngest major rock units in the area.

The large area of Peabody Granite in the southwest part of the Salem quadrangle is interpreted as a stock because of its regular, smooth outline and internal homogeneity. Widely spaced joints, many of which are continuous over distances of several hundred feet, cut the granite. The joints in the area south of Lynnfield Street, Peabody, may be divided into two sets, one of which strikes between N. 30° W. and N. 20° E. and dips westward at angles between 65° and 90°. A more poorly defined set of joints strikes east and dips steeply. The Peabody Granite is cut by relatively few dikes, nearly all of which are cognate aplites and pegmatites. A single diabase dike cutting Peabody Granite has been found.

Because of the rather low topographic relief of the area and lack of exposure of the actual contact of the stock, the dip of the contact cannot be determined. The granite near the margin of the stock is texturally and structurally identical to that of the interior. Xenoliths are apparently no more numerous near the margin, nor is flow structure present there. Many granite dikes cut Salem Gabbro-Diorite near the contact, but the gabbro-diorite does not appear to be more highly deformed there than elsewhere. These features are consistent with emplacement by stoping, and the lack of abundant xenoliths near the margin of the stock suggests that cauldron subsidence rather than piecemeal stoping may have been involved (Billings, 1954, p. 322). The outline of the stock is faintly cuspate (convex outward), but its internal homogeneity does not suggest the coalescence of separate intrusions. The stock may have been emplaced by a mechanism similar to that proposed by Greenwood (1951, p. 1165–1166, 1175–1176), in which large blocks of country rocks on the sides and shoulders of a rising magma body become detached by arcuate tension fractures and fall away into the magma.

The Cape Ann pluton is a larger and much more complex intrusive than the Peabody stock. It extends eastward from the Salem quadrangle about 18 miles to Rockport, Mass., and an unknown distance farther under the Atlantic Ocean. The main body of the pluton is granite of variable composition, and syenitic rocks are concentrated near the margins of the mass. Both mafic and felsic dikes are abundant in the plutonic rocks but seem to be absent from some areas of uniform granite, which therefore resemble Peabody Granite. In the Salem area the outline of the Cape Ann pluton is more irregular than that of the Peabody stock and is complicated by the satellitic bodies of Wenham Monzonite and Cherry Hill Granite. The northeast-trending tongue of Salem Gabbro-Diorite projecting into Cape Ann Granite between Wenham and North Beverly probably does not extend more than a mile or two into the Marblehead North quadrangle, but reconnaissance of the area along its projection did not reveal enough outcrops to define closely the northeast limit of the tongue. The granites on opposite sides of the tongue are indistinguishable, and many granitic dikes cut the gabbro-diorite of the tongue.

The lithologic complexity and irregular outline of the Cape Ann pluton strongly suggest that it is a composite intrusion emplaced in several stages. One of the latest stages may have corresponded to the emplacement of the Peabody stock. Structural data relating to the dip of the contract of the Cape Ann pluton are wanting; the contact itself is not exposed in the area studied, nor are exposures elsewhere reported in the literature. The irregularity of its trace in the Wenham-North Beverly area may suggest a rather low dip, the tongue of gabbro-diorite representing a minor irregularity on the contact; it is probably better regarded as a steeply dipping septum of country rock not engulfed by the magma. Geophysical and petrologic arguments have been presented (p. A63) to show that the Cape Ann pluton along the Beverly shore has a shallow floor dipping north at a low angle. If the dip steepens northward from the shore, as the geophysical data suggest, the shore area may be a flat lip on a generally steep walled pluton.

The simple outline of the body of Cherry Hill Granite suggests a crosscutting body with steeply dipping walls. Data on the form of the Wenham Monzonite body are wanting.

Certain observations in the little quarry north of Central Cemetery in Beverly (Marblehead North quadrangle) have an important bearing on the nature of the intrusive process. The principal rock of the quarry is a porphyritic microgranite whose microperthite phenocrysts are about 1 cm in greatest dimension and make up about two-thirds or three-fourths of the rock; the groundmass is a very fine grained intergrowth of quartz and feldspar. A porphyritic andesite dike 8 to 10 inches thick is exposed for a distance of more than 50 feet along a joint surface. The andesite is chilled at its even, regular walls. Near the middle of its exposed length, the dike is broken and displaced in such a manner as to suggest that its two parts have been pulled apart (fig. 15). The surfaces along which the dike broke are planar and parallel to each other and transect the chilled borders of the dike; they do not continue into the porphyritic microgranite, however, and the porphyritic microgranite between the two segments of the dike is indistinguishable from that along the walls of the dike. The dike and the surfaces along which it broke intersect the surface of the exposure at a high angle; the apparent displacement of the two segments normal to the breaking surfaces is real and is not an illusory effect of the intersection of irregular surfaces.

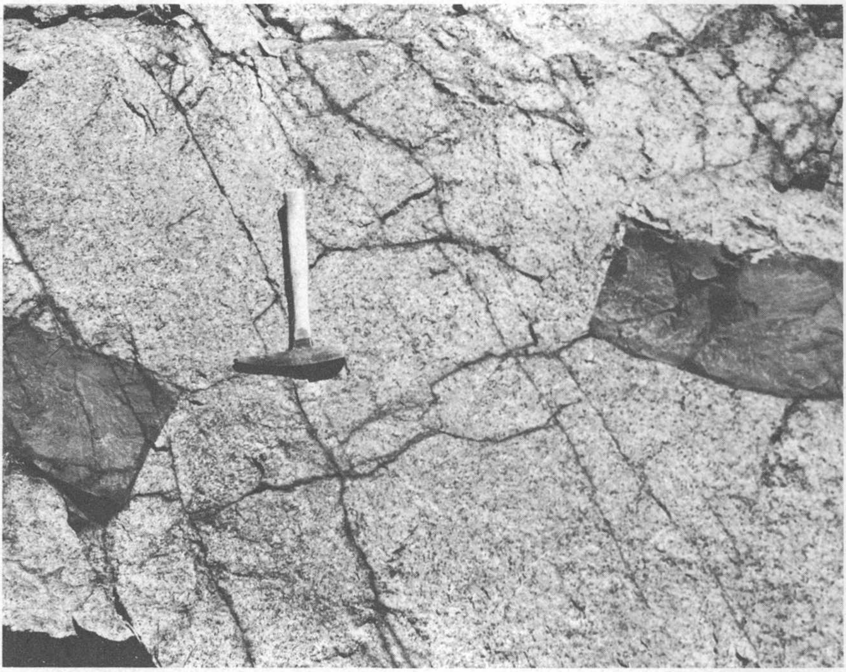

FIGURE 15.—Broken trap dike in phenocryst-rich porphyritic micrograndte at quarry in Beverly. Chilled borders of dike (poorly shown in photograph, but discernible in right-hand fragment) are truncated by surface along which dike broke. The dike is continuous for more than 50 feet both to the right and to the left.

The most reasonable explanation of the facts seems to be: The porphyritic microgranite was emplaced as an aggregate of alkali feldspar crystals in a liquid matrix and cooled rapidly enough to prevent crystallization of the matrix, so that a vitrophyre resulted. Such a rock, though not completely crystalline, would have sufficient rigidity to behave as a solid toward short-term stresses. Apparently a fracture formed and andesitic magma entered it. The temperature of the vitrophyre was far enough below the andesite liquidus to lower the temperature rapidly, and a fine-grained zone of andesite crystallized as a chilled border of the dike. Even after this chilled zone and the rest of the dike had crystallized, however, the glassy matrix of the vitrophyre near the dike may have been warm enough to behave as a viscous liquid to somewhat longer term stresses. Thus, in response to some minor tectonic stress, the crystalline dike fractured, the two segments drifted apart, and the wallrocks flowed together. Subsequently the matrix of the wallrocks has crystallized to an aggregate principally of quartz, feldspar, and hornblende, and the phenocrysts have unmixed to microcline microperthite. (Unmixing may, of course, have occurred at any stage of the process but apparently was not connected with the dike intrusion, for the degree of unmixing is not spatially related to the dike.) Although, in the particular example described, this process seems to have occurred by the simple softening and mechanical flowage of the glassy matrix as a whole, several similarly disrupted dikes in the same quarry and elsewhere show concentrations of quartzofeldspathic pegmatite in the space between the parts of the dike; these concentrations presumably formed by the selective movement of low-fusing constituents into this space.

The relations just described imply that the andesitic and granitic magmas were intruded within a very short period of time, for it is unlikely that the andesitic magma could have supplied enough heat to soften the vitrophyre matrix had the vitrophyre not been at a temperature near its softening range to begin with. Such a high temperature further implies that a chronologic sequence of the alkalic rock types based primarily on small-scale crosscutting relationships need not reflect the differentiation sequence by which the rocks are supposed to be related, for different kinds of magma clearly must have been available for intrusion at almost the same time.

Granite and syenite are the major lithologic types of the Cape Ann pluton, and their contact relations are thus of considerable interest. Clapp (1921, p. 93) states that the two rocks are gradational along the West Manchester shore, syenite passing into granite by a continuous increase in quartz. His descriptions of the gradational contacts along the West Manchester shore agree with the writer's observations, in that the syenite becomes increasingly quartz-rich nearer the granite. The actual contact, however, is everywhere quite sharp, though it is marked only by an abrupt increase in the proportion of quartz (from perhaps 5 percent to 30 or 35 percent) in an otherwise continuous aggregate of feldspar crystals. Long stretches of the contact are not exposed, and it is so irregular that no general attitude could be determined. The lack of structural demarcation of the contact does not accord with an intrusion of magma into a solid rock; it suggests rather a change in the number of crystalline phases separating from a single magma.

ECONOMIC GEOLOGY

The principal mineral products of the Salem quadrangle have been dimension stone and crushed stone. The granite of the Peabody stock was formerly quarried for dimension stone, but no quarries are now active. The principal quarries are described by Dale (1908; 1911).

The Salem Gabbro-Diorite is quarried in the Lynn quadrangle for crushed stone, and mafic rocks of the Marlboro(?) Formation are being quarried for the same purpose in the Reading quadrangle. These rock units extend into the Salem quadrangle, but no bedrock quarries are now in operation within the quadrangle.

The first attempt to mine copper in the English colonies in North America was made in 1648 in the northwestern part of the Salem quadrangle on land then belonging to Governor John Endecott. No production seems to have been achieved at that time, but a single shipload of ore is reputed to have been produced from the mine in Revolutionary times. An unsuccessful attempt to reopen the mine was made in 1839. The mine shaft, now almost completely caved, is in much-altered rocks of the Newbury Formation near their contact with the Topsfield Granodiorite, about 300 feet west-southwest of the intersection of Rowley Bridge Road and Hill Street, Topsfield. Dow (1940) devotes a chapter to the history of the mines.

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