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GEOLOGICAL SURVEY

SEARCH FOR RADIOACTIVE INTRUSIVE ROCKS IN NEW JERSEY, NEW YORK, AND NEW ENGLAND*

By

Robert R. Coats

April 1956

Trace Elements Investigations Report 392

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*This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

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SEARCH FOR RADIOACTIVE INTRUSIVE ROCKS IN NEW JERSEY, NEW YORK, AND NEW ENGLAND

By Robert R. Coats

ABSTRACT

Intrusive igneous rocks in eight areas in New Jersey, New York, and the New England states were investigated for radioactivity during August and September 1951. The purpose of the investigation was to find intrusive bodies having uranium contents of possibly economic significance, and to determine the geological causes for the variation in the content of radioactive elements within igneous rock bodies. None of the samples collected proved to have more than 0.008 percent equivalent uranium, or more than 0.003 percent uranium. In one igneous rock body, the radioactivity was found to increase significantly in the contact zone. Evidence from the petrographic work done for this report does not disagree with earlier findings that, in general, the most radioactive constituents are zircon, allanite, and sphene; in a few rocks, small grains of an unidentified opaque mineral, possibly thorianite, appeared to be highly radioactive. Significant differences were found in the radioactivity of similar and closely related igneous rocks from one area to another. In general, the more alkalic and siliceous igneous rocks have the highest radioactivity.

INTRODUCTION

Reason for study

A field examination of certain intrusive rocks of New Jersey, New York, and the New England states was made during August and September 1951 on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. The purpose of the study was threefold:(1) to find intrusive bodies that contain sufficient uranium for large-scale mining, (2) to learn as much as possible about the geologic factors controlling the distribution of radioactive elements within certain bodies of igneous rock and (3) to select areas where further study might be worthwhile. The discovery of certain granites, relatively rich in uranium, in Nigeria (Beer, K. E., 1952) and the fact that many of the intrusive rocks of New England bear many points of resemblance to the rocks of Nigeria, (Billings and Keevil, 1946) lead to the inception of this study. After the field work for this project was finished, Greenwood (1951) pointed out additional similarities between the intrusive rocks of New England and those of Nigeria.

Basis of choice of subject areas

Billings and Keevil, (1946, p. 801-810) showed that the rocks of the White Mountain Magma series, characterized chemically by alkalic composition, were more radioactive than the rocks of three other magma series in New Hampshire. They described many areas in New Hampshire, and some in Vermont and Maine, that are underlain by rocks of the White Mountain Magma series. In other areas, rocks which may be related

to the White Mountain Magma series were found by a literature search. The New Hampshire areas were not examined, as they were the subject of investigation by another geologist. The areas examined are indicated on figure 1.

Methods of study

Field methods

Radioactivity was measured in the field with a Geiger counter or scintillation counter. At the beginning of the season two Geiger counters were used almost exclusively with a 2 x 20 inch Gamma probe. Later in the season, a scintillation counter was used for most of the rest of the work. Calibration of the counters was attempted by taking readings over rocks, presumably of fairly constant radioactivity, which had been previously sampled and analyzed; the samples analyzed seldom came from the places where the counters were read. The higher counting rate which may be read for a given level of radiation flux density and the stability of meter readings resulting from the constant use of the 10-second averaging circuit seemed to make the scintillation meter preferable to the Geiger counters; however, near the end of the season it was found that the readings of the scintillation counter would drift slowly downward, by as much as fifty percent, over a period of several hours and, on occasion, the counter would also give wildly erratic high readings. The drift could be prevented by avoiding continuous operation, but no cause or remedy for the erratic high readings was found.

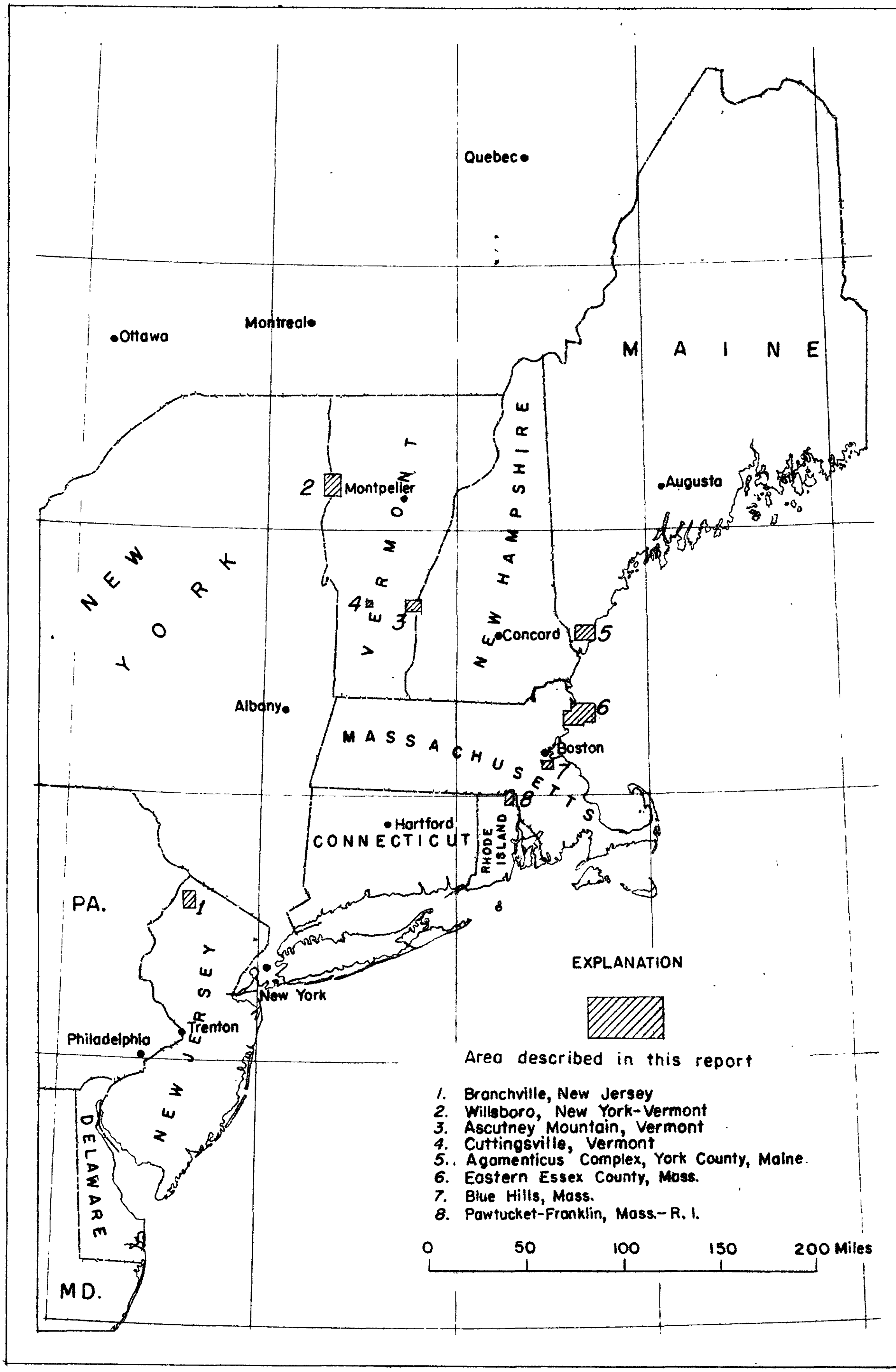


FIGURE 1—. INDEX MAP OF PART OF NEW YORK, NEW JERSEY, AND NEW ENGLAND, SHOWING LOCATION OF AREAS DESCRIBED IN THIS REPORT.

Laboratory methods

About a hundred samples were taken in the course of the work, and were analyzed in the Geological Survey laboratories under the direction of J. C. Rabbitt. Determinations of equivalent uranium were made with a beta-gamma counter, using powdered samples, by B. A. McCall; uranium was determined fluorimetrically by Mary Delavaux. In the tables that accompany each section, showing results of the analyses, the figures for uranium and equivalent uranium that are underlined represent the laboratory determinations. The figures not underlined are estimations, made by using a curve constructed by plotting laboratory determinations against field counter readings. No elaborate statistical study of these was made, but there seems to have been some variation in the accuracy of the field counting methods from time to time.

Thin sections were prepared and studied of all samples that were collected for analysis. It was not feasible to include studies of nuclear stripping emulsions or mineral separations, which would be required to identify conclusively the more obscure radioactive minerals and measure accurately the relative contributions of the several minerals to the radioactivity of the rocks.

Districts investigated

The following areas were investigated and are reported on in some detail: Branchville, New Jersey; Ascutney Mountain, Vermont; Willsboro, Vermont-New York; Cuttingsville, Vermont; Mt. Agamenticus, Maine; eastern Essex County, Mass.; Blue Hills-Brockton, Mass.; Pawtucket-Franklin, Rhode Island-Mass. (fig. 1).

Brief examination was made of a number of other areas, but they are not reported here, either because the radioactivity was relatively low, or because the relationships of the several rock types were not readily deciphered. Such areas include Dannemora, New York; Mt. Monadnock, Vt.; Litchfield, Maine; Tyngsboro, Mass.; North Jay, Maine; East Greenwich and Crompton, Rhode Island; and Pleasant Mt., Maine.

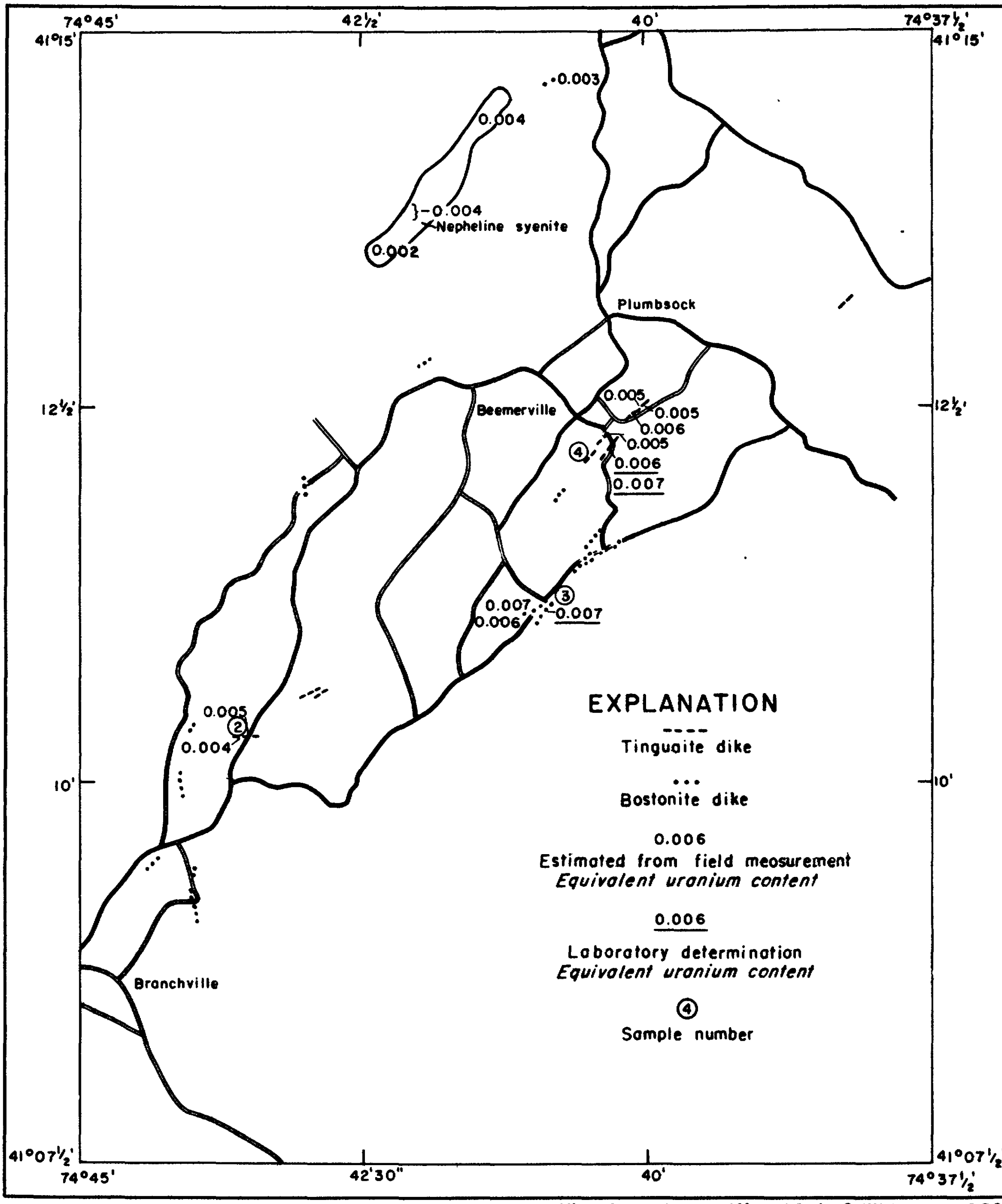
RESULTS OF INVESTIGATION BY DISTRICTS

Branchville, Sussex County, N. J.

Igneous geology

In the Branchville quadrangle there is a northeastward-trending zone of moderately radioactive tinguaite and bostonite intrusives. The dike rocks in this zone comprise a group of relatively short and thin intrusive bodies, striking generally northeastward, parallel to the trend of the Ordovician Martinsburg shale, which they intrude. They range in width from a few feet to 150 feet and in length from 150 feet to 2,400 feet. Because of the small number of outcrops the exact relationship of the intrusives to the enclosing rocks can rarely be determined. Wilkerson (1952, p. 121) thought most of them to be sills but recognized occasional discordances. These intrusives were described by Wolff (1908, p. 11); they have been studied more recently by Parker (1948) and Wilkerson (1952), and by Charles Milton (oral communication).

The better known and larger intrusive body of nepheline syenite near Beemerville and the intrusive bodies described by Wolff (1908) as "basic breccia" (fig. 2) are not described here because of their lower content of radioactive material as is indicated by the results of field examination reported in table 1.



Radioactivity measurements by R. R. Coats

Geology modified from J. E. Wolff, 1908; A. S. Wilkerson, 1952; and Charles Milton, 1950

FIGURE 2-DISTRIBUTION AND MEASURED RADIOACTIVITY OF SOME INTRUSIVE ROCKS IN THE BRANCHVILLE, NEW JERSEY, QUADRANGLE

0 2000 Feet

½ mile mile

Table 1.--Radioactivity and uranium content of some igneous rocks from the Branchville quadrangle, N. J., (See fig. 2.)

Station	Equivalent uranium (Percent x 10^{-3})		Uranium (Percent x 10^{-3})	Rock type	Sample No.
	Measured	Estimated			
4		4		Tinguaite	
Near 4		5		Tinguaite	
4	6		2	Tinguaite	(51C2)
Near 5		7		Bostonite	
5		6		Bostonite	
6	7		2	Bostonite	(51C3)
7	6				
7	7		1	Tinguaite	(51C4)
Near 7		5			
8		5		Bostonite	
9		6		Bostonite	
Near 9		5		Bostonite	
Near 10		4		Nepheline syenite	
10		2		Nepheline syenite	
12		4		Nepheline syenite	
13		3		Basic breccia	

Petrography

The dike rocks fall into two groups, tinguaite and bostonite. The close relationship between the two is shown by the field association and by resemblances in mineral composition and in the characters of the constituent minerals; the principal differences are in the proportions of the several minerals present. The most extensive work on the petrography of these rocks has been done by Wilkerson (1952, p. 121-125), from whom most of the following descriptions are abstracted.

Tinguaite.--Tinguaite is medium gray to dark gray, locally greenish. It is commonly altered. The texture is aphanitic to porphyritic; megascopic phenocrysts are feldspar, nepheline, and biotite and may range in amount from 5 to 50 percent of the rock. Microscopic phenocrysts are orthoclase, microperthite, nepheline, biotite, and aegirine-augite. Feldspar and nepheline are present in approximately equal amounts and considerably exceed in quantity the biotite or pyroxene. Few feldspar phenocrysts exceed a size of 10 mm; they have inclusions of all the principal minerals, especially of nepheline. Much of the feldspar is replaced by clay and a colorless mica; locally it is replaced by calcite or epidote; locally sodalite replaces portions of the orthoclase.

Phenocrysts of nepheline are as much as 6 mm in maximum dimension. Sphene and soda-pyroxene are common inclusions. Much of the nepheline has been altered to a colorless mica and calcite, locally to sodalite.

Biotite is as much as 1.5 mm in maximum dimension; it may make up as much as 10 percent of the phenocrysts. Inclusions of sphene and apatite are common. It is pleochroic from light yellow to reddish brown. Commonly, the biotite is altered to chlorite, rutile, epidote, and calcite.

Aegirine-augite makes up as much as 10 percent of the phenocrysts and reaches a maximum dimension of 3 mm.

The groundmass is an aggregate of nepheline, orthoclase, microperthite, biotite or soda-pyroxene, sphene, apatite, magnetite, and zircon. Nepheline and feldspar are present in about equal proportions and together make up about 90 percent of the total. Biotite or soda pyroxene may make up 15 percent; garnet locally as much as 10 percent (Milton and Davidson, 1950, p. 502).

Locally, nepheline and orthoclase are altered to cancrinite and melilite. Apatite and sphene locally attain millimeter size. Milton and Davidson also found allanite.

Bostonite.-- The bostonite is medium to dark gray, locally greenish gray. It is aphanitic and usually porphyritic. Feldspar phenocrysts reach sizes of as much as 8 mm. The texture of the groundmass is commonly trachytic; in equigranular varieties the grain is somewhat coarser, but the texture is similar to that of the groundmass in the porphyritic phases. The phenocrysts are orthoclase and microperthite, the groundmass chiefly orthoclase or microperthite, locally with a little plagioclase, aegirine, and biotite. A small amount of sphene, magnetite, apatite and zircon are also present.

Distribution of radioactivity

No clues to the source of the reported radioactivity were found in the petrographic work. One of the more highly radioactive dikes is the tinguaite from locality no. 4, which is close to the place where allanite was collected by Milton and Davidson (1950, p. 505-506). They report that A. T. Myers found 0.X percent Th in the allanite spectrographically. Allanite, however, is too rare a constituent to account for all the radioactivity.

The equivalent uranium content of samples of the igneous rocks near Branchville is about the same as the equivalent uranium contents reported by Phair (1952, p. 11) for syenitic bostonite porphyry and monzonite porphyry in the Central City district of Colorado but is substantially below the values reported by him for the quartz-bearing bostonites of that area.

The uranium content is also comparable to that of the monzonite and syenitic bostonite in the Central City district, and likewise falls far below the uranium content of the highly radioactive quartz bostonite dikes. It may be significant that fluorite, which is common in the bostonites of the Central City district and is present in many quartz-bearing radioactive intrusives, has not been recorded from the bostonites and tinguaites of the Branchville quadrangle. It is tempting to speculate upon a possible connection between the fluorine content and the uranium-thorium ratio, but insufficient data are at hand to support any generalizations.

Willsboro, Essex County, New York and Chittenden County, Vermont

Igneous geology

On both sides of Lake Champlain, the Paleozoic rocks are cut by dikes and other minor intrusives of igneous rocks representing a number of petrographic types. Those that were studied in the course of this investigation were the rocks of syenitic or quartz syenitic composition. These rocks were described in considerable detail by Kemp and Marsters (1893). The occurrences on the New York side of the lake have been described more recently by Hudson and Cushing (Hudson, 1931) and by Buddington, (Buddington, and Whitcomb, 1941, p. 78-86). In the lowland area of Lake Champlain, underlain by Paleozoic rocks, the outcrops are in general poor, except along the lake shore and a few stream valleys. Few of the intrusives could be traced any distance inland from the shore cliffs. The distribution of intrusives is shown in fig. 3.

Most of the intrusives are narrow felsic dikes ranging from 2 to 40 feet in width. The Cannon's Point intrusive, on the west side of the lake, is apparently a sill or laccolithic sheet, of no great thickness, that happens to lie nearly parallel to the present surface. At Barber Hill, just south of Charlotte in Vermont, is a stock, approximately a quarter of a mile in diameter, of hornblende-biotite syenite, which appears to be closely related to the felsic dikes.

The exact age of the intrusions has not been determined. Kemp and Marsters noted that the youngest rocks they cut are the Utica shale (Canajoharie), and considered them post-Ordovician. Hudson and Cushing considered the bostonite Taconic in age, (Hudson, 1931, p. 96-97). No new evidence regarding the age of dike rocks was found during this study.

Petrography

Kemp and Marsters (1893, p. 18) lump all the light-colored dike rocks as bostonite, while recognizing that they might be referred to as trachyte. They note the phenocrysts of orthoclase, rarely of quartz, in a groundmass having a trachytic structure and consisting chiefly of orthoclase or anorthoclase prisms, and interstitial quartz. A carbonate mineral and limonite are common secondary products. Buddington classified the rocks as trachyte porphyry (bostonite), rhyolite porphyry, and keratophyre. The rhyolite porphyry differs from the trachyte porphyry in having quartz phenocrysts; the keratophyre in consisting chiefly of plagioclase, and secondary minerals replacing amphibole and biotite (?). Buddington also noted (sparse) zircons and a few magnetite grains in the trachyte porphyry from Cannon Point.

Little can be added to the existing descriptions of the bostonite or quartz-bostonite dikes, but a study of the Barber Hill intrusive is instructive, because it suggests the nature of the minerals in which some of the radioactive elements must be concentrated. The rock of Barber Hill is a porphyry, in which the phenocrysts make up perhaps nine-tenths of the total. The phenocrysts average 3 to 7 mm in size, and the groundmass, which has an aplitic texture, consists of grains from 0.03 to 0.07 mm in size. The essential phenocryst minerals are microperthite, albite-oligoclase, and quartz; the accessory minerals are brown biotite, pale greenish hornblende, allanite, sphene, zircon, apatite, and magnetite. Zircon and apatite are relatively rare; the other accessory minerals are present in roughly equal proportions. Thus the proportion of allanite and sphene to the ferromagnesian minerals is unusually high in the syenite. Pleochroic haloes in the biotite were 0.012 mm wide around allanite, and 0.045 mm wide around an unknown black opaque inclusion. Pleochroic haloes were also seen around grains of zircon.

Results of the reconnaissance for radioactivity of the igneous rocks in the Willsboro quadrangle are given in table 2.

Table 2.--Reconnaissance radioactivity measurements on post-Ordovician syenite porphyry bodies, Willsboro quadrangle, New York - Vermont

Station	Equivalent Uranium per cent ($X 10^{-3}$)_/	Rock type
	3	Fine phase of Barber Hill syenite
	4	Southwest side Barber Hill syenite (51C18)
29	4	Bostonite (51C19)
30		Bostonite (51C20)
	4	Same dike
31	3	Breccia-filled bostonite (51C21)
32	3	Bostonite
	5	Bostonite (51C22)
33	1	Camptonite
33	3	Bostonite
37	4	Bostonite (51C26)
38	4, 4	Bostonite (51C27)
38b	5	Cannon Point bostonite (51C28)

_/ Underlined values are laboratory determinations of equivalent uranium, others are estimates from field measurements.

Field measurements were made with 20" probe, using intermediate scale.

Ascutney Mountain, Windsor County, Vermont

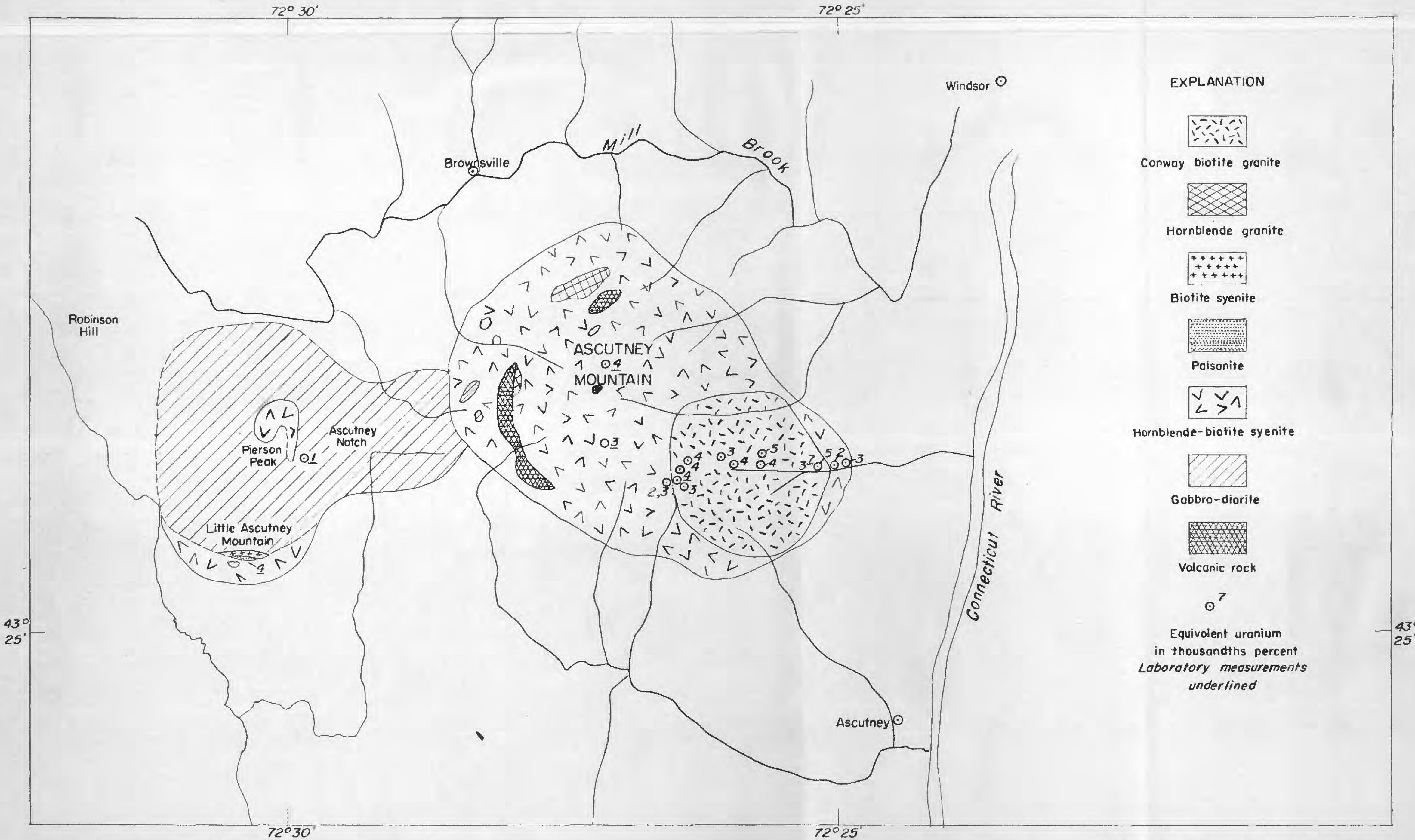
Introduction

Ascutney Mountain in Windsor County, Vt., is the highest point of a moderately radioactive plutonic complex, approximately 2 by 5 miles at the surface. The mountain rises steeply from the western edge of the terraced lowland of the Connecticut River to a height of more than 3,000 feet. It was made famous by the early studies of Daly (1903), who described the rocks in great detail and attributed the placement of the composite pluton to magmatic stoping. The area was later remapped by R. W. Chapman and C. A. Chapman (1940, p. 191-212), who attributed the emplacement to cauldron subsidence. In this report the Chapman map has been used (fig. 4). The petrographic work of Daly, which has not been superseded by any later work, will be referred to extensively; it has been supplemented by the work of the author.

Igneous geology

The number of separate members mapped in this complex depends on the degree to which it is desired to distinguish between rock masses that are similar to one another but not precisely identical. Chapman and Chapman (1940, p. 200) recognized 8 separate phases but mapped some of these with the same symbol. The rocks are listed below in the order of intrusion, the youngest on top; an asterisk marks the phases of uncertain age.

Conway granite stock
Hornblende granite stock
Biotite syenite dike*
Paisanite dike*
Main syenite stock
Syenite stock of Pierson Peak
Syenite dike of Little Ascutney Mountain
Gabbro diorite stock



Planimetry from Claremont and Ludlow quadrangles, Vermont.

Geology by R. W. and C. A. Chapman, 1940.
Radioactivity measurements by R. R. Coats

FIGURE 4—. RECONNAISSANCE MEASUREMENT OF RADIOACTIVITY OF ASCUTNEY MOUNTAIN PLUTON
WINDSOR COUNTY, VERMONT.

0 1 2 3Miles

Three of these rock bodies listed above are considered to be the major members of the intrusive complex; they are the gabbro-diorite stock, the main syenite stock, and the Conway granite stock. These three bodies have been most studied and will be considered in the greatest detail.

Petrography

Gabbro-diorite:--The gabbro-diorite is a rock body that is non-uniform in composition; the range in composition is shown by the relative proportion of the different constituents and by the composition of the minerals. Of the essential minerals, the feldspar is strongly zoned, ranging in composition from basic labradorite to oligoclase; the diopsidic augite is variably and extensively altered to hornblende. Biotite is also an essential constituent. Ilmenite, apatite, pyrite and sphene are constant accessories; zircon and quartz are found in the more dioritic phases. The radioactivity, which attains only a low level, may possibly be due to the allanite found in some phases.

Main syenite stock.--The syenite stock is composed of several differing phases of a coarsely granular gray rock, which quickly changes to a dull green on exposure to air. The principal minerals are microperthite or microcline-microperthite, quartz, plagioclase ranging from oligoclase to albite, hornblende and biotite. The principal accessories are magnetite, apatite, zircon, allanite. Locally, monazite is present. Fluorite was seen in one section. Both allanite and zircon are radioactive, as is shown by the pleochroic haloes about individual grains embedded in biotite and hornblende. In some places the syenite is sufficiently rich in quartz

to be termed a granite. Traverses in the field do not suggest that the radioactivity in the syenite is significantly less than that in the main portion of the Conway granite stock; this relationship is unlike that found by Billings and Keevil (1946) for other occurrences belonging, like the Ascutney Mountain pluton, to the White Mountain magma series.

Conway biotite granite.-- The essential minerals of the Conway biotite granite are microperthite, orthoclase, or microcline, quartz, oligoclase, and biotite. The principal accessories are sphene magnetite, zircon, allanite, and apatite. In addition, dense pleochroic haloes were observed about an unidentified opaque accessory mineral. As was noted by Daly, (1903, p. 84) there is an endomorphic contact zone, averaging about 20 feet wide, surrounding the granite stock, within which the granite is more porphyritic in appearance, and the quartz appears as phenocrysts. Miarolitic cavities are common, and a small amount of muscovite was found in one specimen. Some pleochroic haloes were observed around sphene, in the contact zone, but the color is not particularly intense. Unidentified opaque alteration products were found about sphene.

Relationship of radioactivity to rock type

Though the equivalent uranium content of the Conway granite proper is not greatly in excess of that observed in the syenite, it is considerably in excess of that found in the gabbro-diorite (table 3). The highest radioactivity found in the area during the field reconnaissance was that detected in the endomorphic contact zone of the Conway biotite granite. The readings obtained in the field examination were disproportionately higher than the laboratory determinations. That no uranium was

Table 3.--Reconnaissance measurement of radioactivity at Ascutney Mountain, Vermont

Station	Field Reading	Equivalent Uranium percent (X 10^{-3})[1]	(Instrument NICC 2610A, 20" probe) Rock type
14	8.7	3	Nordmarkite (syenite)
Nr. 14	6.7	2	Nordmarkite (syenite)
Nr. 14	10.8	5	Contact phase, Conway granite
Nr. 14	15.7	7	30' from contact, in Conway
Nr. 14	9.3	<u>3</u>	50' from contact, normal Conway (51C8
15	9.5	4	Conway granite
16	11.1	5	Conway granite
17	9.4	4	Conway granite
Nr. 17	8.5	3	Conway granite, pinkish gray
18	10.4	4	Conway granite, with coarse quartz
19	10.2	4	Conway granite, with coarse quartz
20	8.6	3	Conway granite
21	17.3	<u>4</u>	Conway granite, at the contact with Syenite
	11.5	4	
	8.5	3	
Nr. 21	7.7	3	Syenite, near contact with Conway granite
22	10.5	<u>4</u>	Syenite (51C5)
23	6.2	<u>3</u>	Coarse hornblende-biotite syenite (51C6)
	7.5	<u>4</u>	Syenite (Little Ascutney Mt.) (51C43)
	4.1	<u>1</u>	Gabbro diorite (51C44)
45	5.5	1	Gabbro diorite
	5.5	<u>3</u>	Windsorite (granite aplite)

[1] Underlined values are those determined in laboratory. Uranium, in all cases where determined chemically, was less than 0.001 percent.

found chemically in any of the specimens analyzed indicates, in all probability, that much of the radioactivity is derived from thorium, most of which is probably in allanite, zircon, and at least locally, sphene. The pleochroic haloes found about the sphene are not well developed; possibly they are connected with the alteration of the sphene.

Enrichment of hyperfusible constituents in the endomorphic zone of the Conway granite is shown by the presence of muscovite, suggestive of conditions similar to those involved in the production of greisen, by the pegmatitic texture, and by the miarolitic cavities. This enrichment may also account for the increased radioactivity in the endomorphic zone. If further work is done on the Ascutney Mountain intrusives, special attention should be given to the several phases of the Conway granite. Both eastern and western contacts of the Conway are well exposed on the road to the summit of the mountain.

Cuttingsville, Rutland County, Vermont

Introduction

The composite pluton of Cuttingsville, Rutland County, Vt., is another of the small intrusive masses of alkaline affinity that are spread across New England from the Monteregian Hills of Quebec to East Greenwich, R. I. The work of Billings and Keevil (1946) has shown that rocks of this (White Mountain) magma series include the most radioactive known in the New England area; it therefore seemed desirable to investigate the Cuttingsville pluton, for which no radiometry was available, in order to determine, if possible, the relationship between radioactivity and rock type in this well-differentiated mass.

The Cuttingsville pluton has been mapped and the principal rock types described in considerable detail by J. W. Eggleston (1918). The writer had the benefit of Mr. Eggleston's map in the field, and it is here reproduced, somewhat simplified (fig. 5).

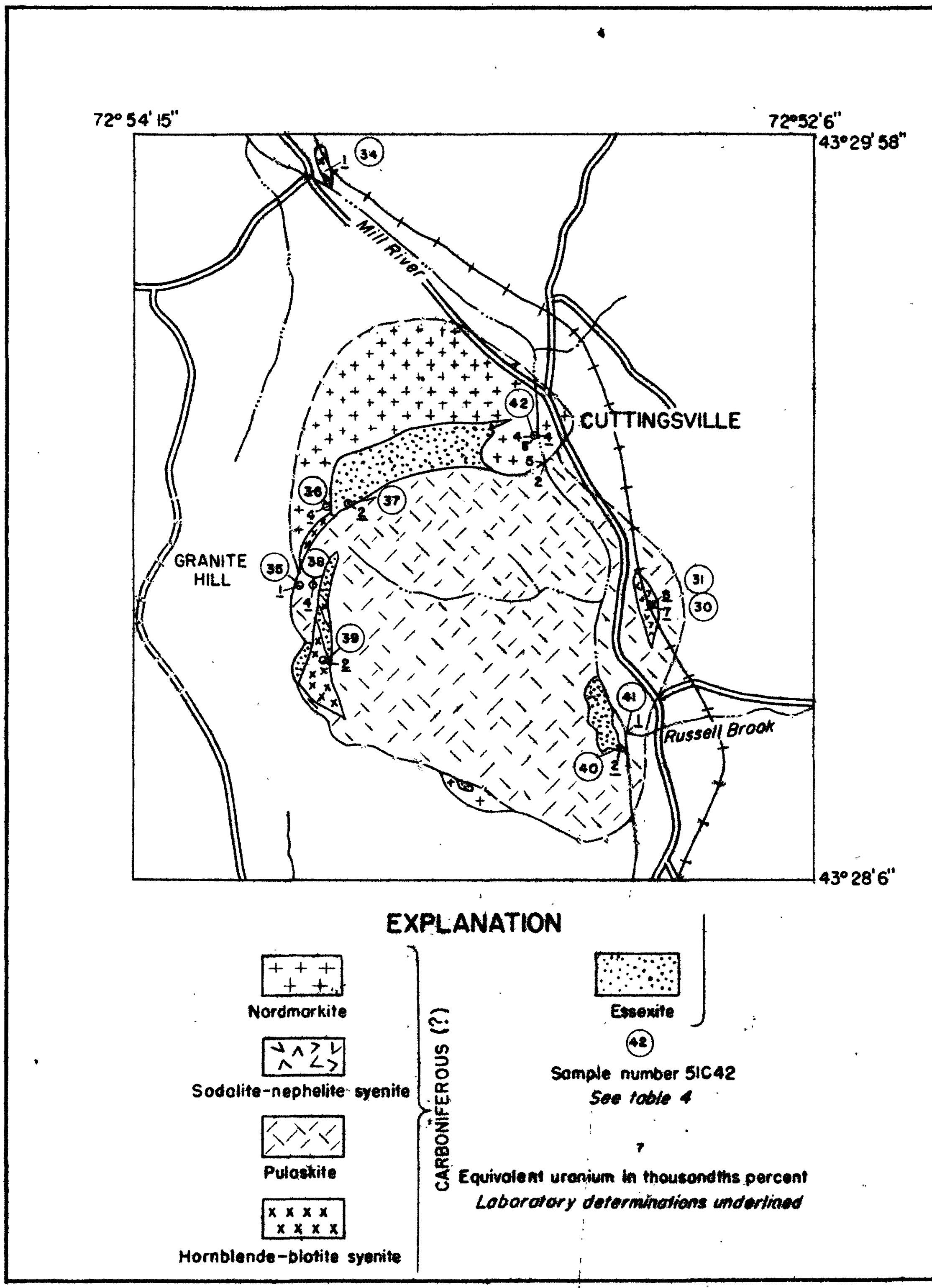
Petrography

Eggleston (1918) suggested that the order of intrusion of the several rock bodies at Cuttingsville is from basic toward acidic, that is essexite, hornblende-biotite syenite, pulaskite, sodalite-nephelite syenite, and nordmarkite.

Essexite.--Essexite is a black to gray, medium to coarse-grained gabbroid rock. About sixty percent of the rock is plagioclase, ranging from An_{70} to An_{30}, about 5 to 10 percent orthoclase, and the rest hornblende, pyroxene, and biotite, in nearly equal amounts. Accessory minerals include olivine in large grains, magnetite, sphene, apatite, pyrite, and possibly pyrrhotite.

Hornblende-biotite syenite.--This syenite is a moderately coarse-grained, very light gray rock, with feldspar, amphibole, and mica. Eighty to ninety percent of the rock is feldspar, partly oligoclase-albite, and partly microperthite (orthoclase, according to Eggleston 1918). The other essential minerals include hornblende, occasionally with a core of augite and brown biotite. Magnetite, sphene, and apatite are the commoner accessories (Eggleston also records zircon and pyrite).

Pulaskite.--Pulaskite is a generally coarse-grained, allotrimorphic-granular rock, consisting almost entirely of microperthite. Near the molybdenite prospect on the western edge of the intrusive, it contains, beside



Planimetry enlarged from Wallingford quadrangle, U. S. Geological Survey

Geology modified from J. W. Eggleston, 1918
Radioactivity measurements by R.R. Coats

FIGURE 5.-RECONNAISANCE MEASUREMENT OF RADIOACTIVITY OF THE CUTTINGSVILLE, VERMONT, PLUTON

0 1000 2000 3000 4000 Feet

pyrite and molybdenite which fill cavities and replace feldspar, a trace of chloritized biotite and of zircon. A few hundred feet east, on the inner slope of the hill, the coarse-grained syenite has small amounts of sphene, zircon, (up to 0.5 mm) magnetite, brown biotite, apatite, and diopsidic augite, grading to aegirine augite.

Sodalite-nephelite syenite.--Sodalite-nephelite syenite forms a relatively small lenticular body, as mapped by Eggleston, exposed along the railroad grade near the southeastern margin of the stock. It is a moderately coarse-grained aggregate of light-gray feldspar, with interstitial black pyroxene and brownish nepheline. Considerable pyrite is disseminated through some phases of the rock. The section the author examined is about 90 percent microperthite; Eggleston reports as much as half the feldspar being albite. Other constituents are sodalite and cancrinite, which replace nepheline; also aegirine-augite and biotite, with small amounts of zircon, magnetite, and calcite, which appears to be primary. Another section of a pyrite-rich phase showed replacement of the nepheline by a zeolite with sphene as an additional accessory. Also observed was a single grain of a yellow, highly refringent, isotropic mineral (beckelite). A prismatic grain of an opaque mineral is radioactive and has produced an intense pleochroic halo in biotite. The opaque mineral is surrounded by a bright orange, fine-grained alteration product.

Nordmarkite.--Nordmarkite (quartz syenite) is found in two principal areas, one on the northern margin of the pluton, extending into the town of Cuttingsville, and the other on the southern margin of the pluton. The fresh rock is bluish gray to grayish green, changing in a short time to olive green. Seventy-five percent or more of the rock is feldspar, mostly

microperthite. The interstices between the larger feldspar grains are occupied by the other minerals, chiefly augite, grading to aegirine-augite; partly serpentinized olivine and magnetite have also been observed. Eggleston reports also zircon, apatite, and possible allanite.

In addition to the major members of the complex, Eggleston maps or mentions a number of types of dike rocks: essexite porphyry, nephelite syenite, syenite porphyry, zircon-rich pulaskite porphyry, aplite, tinguaite, and camptonite. The bostonite, (51C41) is apparently the same rock as the tinguaite described in Eggleston.

Distribution of radioactivity by rock type

Although the relationship normally observed in the White Mountain magma series, that of increasing radioactivity toward the granite end of the series (Billings and Keevil, 1946, p. 809), is also traceable here; though crudely, some exceptional relationships may also be seen. The least radioactive rock from this complex is the bostonite, collected from a dike in the bed of Mill River near the mouth of Russell Brook. This rock has an equivalent uranium content of only 0.001 percent (Sample 51C41, table 4)--a result quite unexpected in the light of the field reading, and entirely variant with the expectable behavior of bostonites in most igneous areas. The next highest in equivalent uranium content are the essexite, a comparatively silica-poor rock, and the hornblende-biotite syenite. The pulaskite and nordmarkite are slightly more radioactive. Nordmarkite and nordmarkite porphyry contain 0.001 percent uranium. Sodalite syenite, and the pyritized phase thereof have the highest/equivalent uranium and uranium content of any of the rocks of the complex. Samples (51C30 and 31, table 4)

Table 4.--Reconnaissance measurement of radioactivity of the Cuttingsville pluton Rutland County, Vermont

Station	Field Reading	Equivalent Uranium, percent ($X10^{-3}$)[1]	Uranium percent ($X10^{-3}$)	Rock type
	13.1	7	2,3	Sodalite syenite (51C30)
	16	8	2	Pyritized sodalite syenite (51C31)
	9.3	4	1	Nordmarkite porphyry
	10.6	5	1	Fresh nordmarkite
41	5	5	-	Essexite porphyry (51C32)
	6.5	2	-	Nordmarkite (51C33)
42	5.1	1	-	Hornblende-biotite syenite (51C34)
	5-7.5	4	-	Molybdenite bearing pulaskite (51C35)
43	9.5	4	-	Nordmarkite (51C36)
44	5.8	2	-	Essexite (51C37)
	5.5	4	-	Pulaskite (51C38)
	6.8	2	-	Hornblende-biotite syenite (51C39)
	4.5	2	-	Essexite (51X40)
	9.1	1	-	Bostonite (51C41)
	11.5	4	-	Nordmarkite porphyry (51C42)

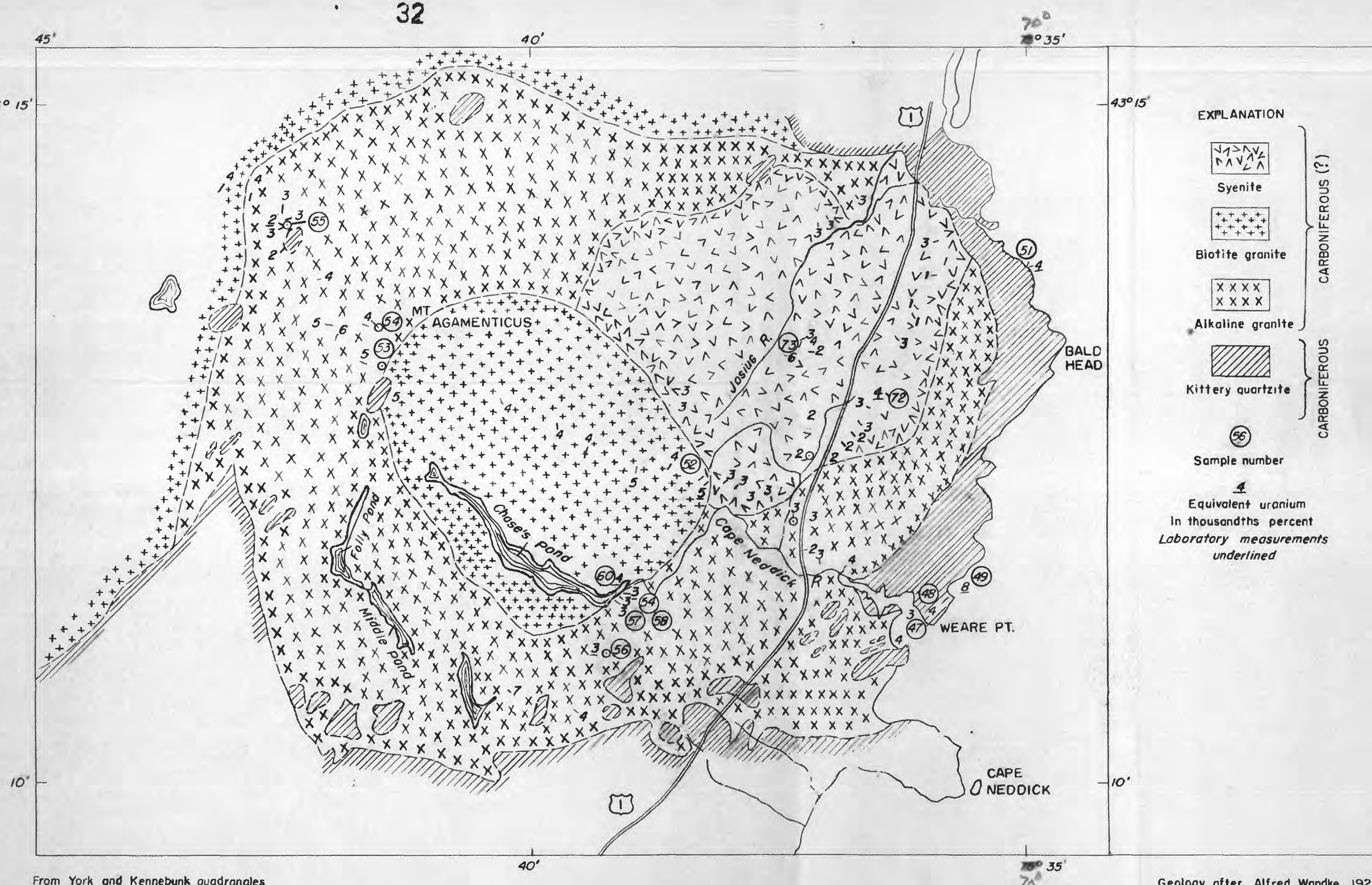
[1] Underlined values are laboratory determinations of equivalent uranium; others are estimated from field measurements.

of these rocks were collected from the lens-shaped body exposed in the railroad cut near the southeast margin of the stock. To find that the silica-poor and alkali-rich rocks contained the most uranium was quite unexpected, in the light of Billings' and Keevil's work on the White Mountain magma series. Possibly, the explanation may be sought in the evidence of replacement of the earlier minerals by cancrinite, sodalite, and zeolites. The presence of pyrite might suggest a hydrothermal introduction of radioactive elements, but pyritized phases are not uncommon elsewhere in the intrusive; none have been found showing any radioactivity in excess of that found in the unpyritized equivalent. The pyrite- and molybdenite-bearing pulaskite from the western margin of the stock shows no higher radioactivity than the pulaskite that lacks any sulfide minerals.

Mount Agamenticus, York County, Maine

Introduction

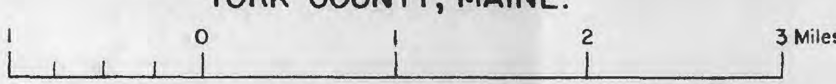
Just west of Bald Head, a prominent landmark on the coast of York County, Maine, is a plutonic complex exposed in a subcircular area about 5 miles in diameter. Under the name "Agamenticus complex", derived from the prominent peak underlain by several members of the complex, it has been described by Wandke (1922, p. 152-153). The three principal rock types making up the complex are, in order of succession (according to Wandke): biotite granite, alkaline granite, and syenite. Wandke also suggests that a small stock of quartz diorite (not shown on the map (fig. 6)) is later than the biotite granite. The biotite granite, as mapped by Wandke, includes a stock-like central area, and a much larger area outside



From York and Kennebunk quadrangles
U. S. Geological Survey

Geology after Alfred Wandke, 1922.
Radioactivity measurements by R. R. Coats

FIGURE 6—. RECONNAISSANCE MEASUREMENT OF RADIOACTIVITY OF THE ROCKS OF THE AGAMENTICUS COMPLEX, YORK COUNTY, MAINE.



the margin of the alkaline granite complex that includes the smaller stock. It seems possible that biotite granite of two different ages is present here, and that only the central mass is part of the complex. This discussion will be limited principally to the complex made up of alkaline granite, syenite, and the central stock of biotite granite. A few minor dikes that show by their mineralogy a relationship to the alkaline intrusives will also be included in the discussion.

Petrography

Biotite granite.--The biotite granite of the central stock is a relatively fine-grained, even-grained rock, consisting of orthoclase, quartz, zoned oligoclase-albite, brown biotite, and rare brown hornblende. Accessories include allanite, apatite, and zircon. Both allanite and zircon show diminished birefringence, suggestive of partial alteration or metamictization. Pleochroic haloes are present about zircon grains included in biotite.

Alkaline granite.--Characteristically the alkaline granite is medium to coarse grained with a texture controlled chiefly by the rough tablets of microperthite, or orthoclase with microperthitic border zones. The ferromagnesian minerals include aegirine-augite in deep green prisms, replaced by hastingsite and arfvedsonite and brown biotite; zircon, apatite, and magnetite are accessory minerals. Inclusions of zircon in hastingsite produce pleochroic haloes and a system of radial cracks. Locally moderate amounts of fayalite, generally partly altered to serpentine, and of a euhedral, brown prismatic mineral which appears to be aenigmatite, are

fairly common. The aenigmatite amounts to about 15 percent by volume in some small veinlets cutting the granite in Young Hill, about a mile south of the east end of Chase's Pond.

Syenite.--The syenite is typically a greenish rock, variable in grain size, consisting essentially of microcline-microperthite, quartz, aegirine-augite, and hastingsite-arfvedsonite, irregularly intergrown. Wandke reports fayalite, riebeckite, allanite and zircon. Locally a more quartz-rich phase has brown biotite and greenish-yellow hornblende, suggesting the biotite granite of the central stock. The latter, however, seems to have perthite instead of microcline-perthite as the chief feldspar.

Dike rocks.--Three kinds of dikes that appear genetically related to the alkaline rocks of the Agamenticus complex have been found, mostly in the stretch of cliffs that extends for about a mile northeast of Cape Neddick Harbor. The alkaline dikes are far less numerous than those of diabase, presumably related to the gabbro of Cape Neddick.

One type of dike is exemplified by a medium-gray aphanitic paisanite dike, with sparse 3 mm phenocrysts of aegirine-augite, each surrounded by a bleached zone. Microscopically, the aegirine-augite appears to be partly replaced by riebeckite, and the fine-grained groundmass of the dike is a xenomorphic aggregate of riebeckite, quartz, orthoclase, and oligoclase-albite.

Another paisanite dike, exposed on the sea cliffs about a mile northeast of Weare Point, is only 3 feet wide, medium dark gray, and contains a few feldspar phenocrysts up to 2 mm in size. It is, microscopically, a xenomorphic granular aggregate of quartz, orthoclase, albite (An_5), aegirine, and deep brown biotite.

Relation of radioactivity to rock type

The overall impression given by the distribution on the map of the figures representing outcrop estimations of radioactivity as well as laboratory determinations suggests that the radioactivity increases with rock type in the following order: (1) syenite, (2) alkali granite, and (3) biotite granite. This is the same order found by Billings and Keevil (1946, p. 809) for rocks of the White Mountain magma series in New Hampshire. Numerous anomalous readings, however, complicate the general picture. The petrographic evidence, which is based on the distribution of pleochroic haloes, about radioactive mineral inclusions in the ferromagnesian minerals, suggests that some at least, of the radioactivity is from allanite and zircon, and possibly certain unidentified opaque minerals. Work in other areas (Picciotto, 1950, p. 180) has shown that as much as 20 percent of the alpha activity of granites can be concentrated in fractures and secondary rock-making minerals. The highest radioactivity observed in any of the rocks of the Agamenticus area was found in the 3 foot dike of aphanitic paisanite with aplitic texture, described above. No obviously radioactive minerals were found in thin section. This rock (Sample 51C49, table 5) was the only one found in the area in which a measurable amount of uranium (0.002 percent) was found by chemical analysis. In the work of Billings and Keevil (1946) on the radioactivity of the White Mountain magma series, a paisanite dike proved to be one of the most highly radioactive rocks.

Table 5.--Reconnaissance measurements of radioactivity on rocks of the Agamenticus Complex, York County, Maine

Part I

Syenite

Station Number	Field Reading (Scintillometer)	Equivalent uranium (Percent x 10^{-3})	Uranium Percent (x 10^{-3})	Rock type (sample no.)
52	50	1		
53	55	2		
54	50	1		
55	90	4.5	<1	Quartz syenite (51C72)
56	80	3		Hornblende syenite
57	85	3		Nordmarkite
58	70	2		Coarse hornblende syenite
59	75	3		Coarse hornblende syenite
60	80	3		Coarse hornblende syenite
61	75	3		Medium-grained hornblende syenite
62	72	3		Do.
63	77	3		Do.
64	85	3		Do.
65	95	4		Do.
66	82	3		Porphyritic fine-grained hornblende syenite
67	80	3		Medium-grained hornblende syenite
68	55	2		Do.
68	90	3		Schliere in preceding, mafic-rich
69	75			Medium-grained hornblende syenite
69	115	6	<1	Biotite hornblende syenite (51C73)
70	70	3		Medium-grained hornblende syenite
71	52	2		Do.
72	50	2		Do.
74	85	3		Porphyritic fine-grained quartz syenit
75	80	3		Trachytoid nordmarkite

Table 5.--Reconnaissance measurements of radioactivity on rocks of the Agamenticus Complex, York County, Maine--Continued

Syenite--Continued

Station Number	Field Reading Scintil-lometer	Equivalent uranium, Percent (x 10^{-3}	Rock type (sample no.)
76	65	2	Green nordmarkite
77	65	2	Medium-grained hornblende syenite
78	80	3	Coarse hornblende-quartz syenite
97	75	3	Coarse hornblende syenite
98	80	3	Coarse hornblende syenite
99	65-70	3	Hornblende granite
100	80-90	3	Hornblende quartz syenite
101	80-100	4	Hornblende-quartz syenite

Part 2, Biotite granite

Station number	Field Reading (Scintil-lometer)	Equivalent uranium, percent (x 10^3)	Uranium percent (x 10^3)	Rock type (Sample No.)
79	100-115	5	<1	Hornblende biotite granite (51C52)
107	150-220	4	<1	Porphyritic biotite granite (51C60)

Table 5.--Reconnaissance measurements of radioactivity on rocks of the Agamenticus Complex, York County, Maine--Continued

Part 3, Alkaline granite

Station Number	Field Reading (Scintil-lometer)	Equivalent uranium percent (x 10^{-3})	Rock type (Specimen Number)
86	110	5	(51C53) Alkali granite
	110	4	(51C54) Alkali granite
87	130-140	6	Alkali granite
88	115-125	5	Alkali granite
89	98	4	Alkali granite
91	90	3	Alkali granite
	150	2	(51C55) Alkali granite
92	80	3	Alkali granite
93	100	4	Alkali granite
94	80	3	Alkali granite
95	75	4	Alkali granite
102	110	4	Alkali granite
102	80	5	Alkali granite 30' from sedimentary contact
103	105-115	4	Alkali granite
104	90	3	(51C56) Aenigmatite (?)-rich segregation in alkali granite
105	170	3	(51C57) Alkali granite
105		3	(51C58) Alkaline granite with pegmatitic veins
106	150	3	(51C59) Alkaline granite

Table 5.--Reconnaissance measurements of radioactivity on rocks of the Agamenticus Complex, York County, Maine--Continued

Part 4, Dikes

Station Number	Field reading (Scintillometer)	Equivalent uranium percent (x 10^{-3})_/	Uranium percent (x 10^{-3})_/	Rock type (Specimen No.)
46	65	2		Granite porphyry
47	110	4		Alkali granite porphyry (51C47)
48	110	4		Alkali granite porphyry
50	130	8	2	Paisanite (51C49)
51	210	4		Biotite aplite (51C51)

_/ Underlined values of equivalent uranium and uranium represent laboratory determinations; other values are estimates, derived from field readings on the counter by comparison with the laboratory determinations on samples from certain places where field readings were taken.

Eastern Essex County, Massachusetts

Essex County is the northeasternmost county in Massachusetts, and the igneous rocks that form most of the bedrock have long been famous for their chemical and mineralogical peculiarities. The most recent map of these rocks is by Clapp (1921). Earlier petrographic work on the area includes that by Washington (1898-1899), and more recently, that by Warren and McKinstry (1924). The area included in this report is only a small part of Essex County and is part of the four 7 1/2-minute quadrangles, Rockport, Gloucester, Marblehead North, and Ipswich.

Igneous geology

All the rocks studied and most of those in the area mapped are intrusives of middle Carboniferous age, and hence are approximately equivalent in age to the rocks of the White Mountain magma series of New Hampshire. Four types of granular intrusive rocks are indicated on fig. 7. These are the Beverly syenite, nordmarkite or quartz syenite, Quincy granite, and Squam granite. In addition, there is a multiplicity of satellitic dikes, most of which are believed to be related to the Quincy granite and the Beverly syenite. These fall into three general classes; lamprophyric dikes, alkaline porphyries, and silica-rich types, including quartz porphyry and paisanite. The lamprophyric dikes include comptonite, vogesite, kersantite, and minette. The alkaline porphryies include solvsbergite and tinguaite. There are also numerous diabase dikes, in part older and in part younger than the alkaline plutonics. A few of these diabase dikes are related to the plutonic rocks.

Petrography

The mineral compositions of the principal types of plutonic rocks are given in the following table (table 6).

Table 6.--Mineral composition of principal plutonic rock types of eastern Essex County, Mass.

	Beverly Syenite	Nordmarkite	Quincy Granite	Squam
K-feldspar	Microperthite	Microperthite	Microperthite	Orthoclase and Microcline
plagioclase	Albite	Albite	Albite	Albite
Quartz		Quartz	Quartz	Quartz
Amphibole	Katophorite	Hornblende	Katophorite	Hornblende
Pyroxene	Aegirite (Diopside)	Hedenbergite Diopside		
Mica	Biotite Lepidomelane			Biotite
Accessories	Magnetite Sphene	Magnetite Zircon (Fluorite) (Apatite)	(Fayalite) Zircon Magnetite Allanite Apatite Fluorite	

(Mineral names in parenthesis are the minor and occasional constituents)

The mineral composition of most of those dike rocks that are believed to be related to the alkaline intrusives is given in table 7. The alkaline porphyries and the quartz-rich rocks are combined in a single table, as felsic dikes (Clapp, 1921, p. 33)

Table 7.--Mineral composition of the principal alkaline dike rocks of eastern Essex County, Mass.

Mafic dikes

	Camptonite	Vogesite	Kersantite	Minette
K-feldspar				Orthoclase
Plagioclase	Andesine-labradorite	Oligoclase	Oligoclase	Oligoclase-albite
Amphibole	Barkevikite	Barkevikite		Hornblende
Pyroxene	Diopside	Augite-diopside	Augite	
Mica	Biotite		Biotite	Biotite
Accessories	Magnetite Sphene	Magnetite Apatite	?	Magnetite Apatite

Felsic dikes

	Quartz-porphyry	Paisanite	Sölvsbergite	Tinguaite
K-feldspar	Microperthite	Microperthite	Microperthite	Anorthoclase
Plagioclase	Albite		Albite-oligoclase	
Feldspathoid				Analcite Nepheline
Quartz	Quartz	Quartz		
Amphibole		Glaucophane-riebeckite	Hornblende	
Pyroxene			Aegirite (Diopside)	Aegirite
Mica			Biotite	Biotite
Accessories	Magnetite Glaucophane Riebeckite Sphene			

Relation of radioactivity to rock type

Samples were assayed only for equivalent uranium; their uranium content is inferred to be less than 0.001 percent. (See table 8.) The radioactivity is probably due essentially to members of the thorium series. The pegmatitic minerals reported from Cape Ann (Warren and McKinstry, 1924, p. 351) include thorite, fergusonite, cyrtolite, and gadolinite.

There is little petrographic evidence of the distribution of the radioactivity, which is not surprising, considering the low level of radioactivity found. Some sections of Quincy granite contain allanite, which has produced visible pleochroic haloes in the ferromagnesian minerals. Contrary to expectation, zircon and sphene show no evidence of being radioactive.

The lowest level of radioactivity was found in the diabase dikes, which is the normally expectable result. The radioactivity of Beverly syenite and nordmarkite is, in general, about 0.002 to 0.003 percent equivalent uranium. The Quincy granite, in general, has a slightly higher radioactivity, and the minor felsic dikes seem to be yet higher, but the number sampled is too small for a valid conclusion, in view of the small differences found between representatives of the several types. Keevil (1942, p. 19) made no direct measurements on the accessories but assumed that most of the radioactive elements are concentrated in allanite and zircon, and that these minerals had a higher thorium-uranium ratio than the amphibole and biotite, which carried most of the rest of the radioactive elements. Keevil also suggested that the evidence did not forbid the idea that the Essex County intrusives might be Devonian, rather than Carboniferous.

Table 8.--Radioactivity measurements on igneous rocks from eastern Essex County, Mass.

Station	Field Reading	Equivalent Uranium Percent/ $(x10^{-3})$	Rock type (Sample No.)
125	65-70	3	Quincy granite
126	75-100	3-4	Quincy granite
126	100	3	Quincy granite, pegmatitic phase (51C84)
127	75-95	3	Quincy granite
128	75-90	3	Quincy granite
129	75	3	Porphyritic Quincy granite
130	55	2	Coarse Quincy granite
131	65-50	2	Nordmarkitic Quincy granite
132	55-75	2	Do.
133	60	2	Quincy granite
134	55-70	2	Do.
135	42	1	Nordmarkite
136	55-70	2	Do.
137	50-55	2	Quartzose Quincy granite
138	70	2	Quincy granite
138	20	2	Sölvsbergite
	65-80	4	Quincy granite (51C84)
139	50	2	Beverly syenite
140	50	2	Do.
141	55	2	Granite
142	50-55	2	Squam granite
143	50-75	3	Squam granite
144	75	4	Quincy granite

/ Underlined values are laboratory determinations of equivalent uranium; others are estimated from field measurements.

Table 8.--Radioactivity measurements on igneous rocks from eastern Essex County, Mass.--Continued

Station	Field Reading	Equivalent Uranium Percent ($x10^{-3}$)	Rock type (Sample No.)
145	80	4	Paisanite (51C75)
146	65	3	Coarse Quincy granite
146	80-90	4	Fine Quincy granite
147	70	2	Diabase (51C78)
148	55	1	Diabase (51C79)
149	95	4	Tinguaite (51C80)
150	70	3	Sölvsbergite (51C80a)
151	35	1	Diabase (51C81)
151	50	3	Beverly syenite (51C82)
N. of 151		2	Camptonite (51C83b)
N. of 151		3	Beverly syenite (51C83a)
152	75	2	Quartz porphyry (51C86)
152	95	3	Quartz porphyry (51C87)
153	45	2	Quincy granite
154	40-45	2	Quincy granite
155	40-45	3	Beverly syenite (51C89)
156	50	3	Quincy granite
157	45-50	3	Quincy granite
158	30	2	Beverly syenite

Blue Hills-Brockton, Norfolk County, Massachusetts

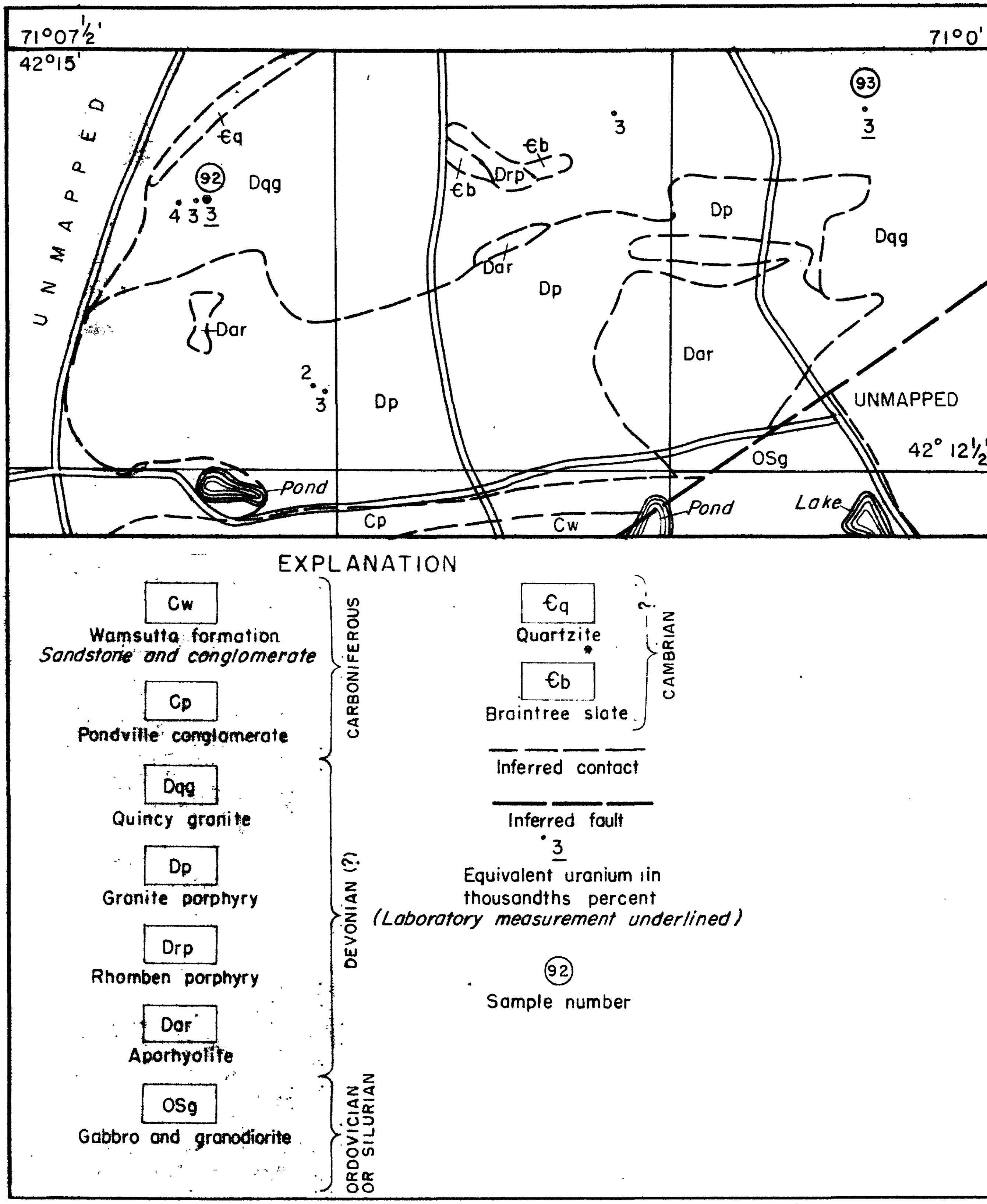
Igneous geology

In the Blue Hills quadrangle and in the Brockton quadrangle, adjacent to it on the south, two of the principal types of igneous rock are the Dedham granodiorite and the Quincy granite. Each of these rock types has a suite of satellitic rock types accompanying it.

The Dedham-granodiorite is a pinkish, medium-grained rock composed of plagioclase, microcline, biotite, and quartz, with accessory titanite, magnetite, and apatite (Chute, 1950). In the Brockton quadrangle there are both a porphyritic phase, and a light gray phase, that is found in an alteration zone, marginal to a later intrusive of riebeckite granite. In the Brockton quadrangle, a few dikes of albite granite, considered a phase of the Dedham, were also found by Chute. The Dedham granodiorite was considered by Chute (1950) to be early Paleozoic.

The Quincy granite is a rock well-known, both commercially and geologically, having been quarried for many years in the vicinity of Quincy, Mass., and intensively studied by many geologists (Warren, 1913).

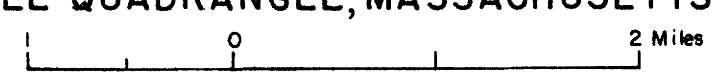
Numerous natural and artificial exposures of the Quincy granite may be seen in an area about 10 miles long from east to west and 3 miles in maximum width, most of which lies within the Blue Hills quadrangle (Chute, 1940, p. 12). The areal distribution of bedrock types in a portion of the Blue Hills quadrangle is shown in figure 8, taken from Chute. The presence of a heavy surficial cover of glacial material obscures the bedrock in much of the area of the two quadrangles.



Radioactivity measurements by R. R. Coats

Geology by N. E. Chute, 1940

FIGURE 8-RECONNAISSANCE MEASUREMENT OF RADIOACTIVITY OF THE IGNEOUS ROCKS OF PART OF THE BLUE HILL QUADRANGLE, MASSACHUSETTS



The Quincy granite is but one of the numerous intrusives of alkali-rich granitic rocks which are widely distributed in New England. For many of these a Devonian or early Carboniferous age is well-supported (La Forge, 1932, p. 35).

Typical Quincy granite is a bluish gray rock, moderate to coarse-grained, that contains feldspar, quartz and black amphibole. It grades into and intrudes, a granite porphyry which is interpreted by Chute as a marginal facies of the Quincy. It also cuts two related types of volcanic rock, described as rhombenporphyry and aporhyolite, which were not examined in the field and will not be discussed.

A small dike, termed rhyolite by Chute (1950) cuts Dedham granodiorite in the approximate center of the Brockton quadrangle. This dike Chute correlated with the Mattapan volcanic rocks (Devonian or Carboniferous). The rock is lilac-gray in color, and sparsely porphyritic, with dihexahedra of quartz and prisms of anorthoclase in a graphophyric groundmass of quartz, albite, and orthoclase. Secondary magnetite, epidote, and hydromica are also present. The age relations do not preclude, and the alkaline character of the feldspar suggests, correlation of this dike with the intrusive stock of aegirite-albite granite, which is correlated with the Quincy granite, and which crops out a few miles to the west, on the western edge of the Brockton quadrangle.

Measured radioactivity of intrusive rocks

Dedham granodiorite.--The Dedham granodiorite and the rocks associated with it were examined only in the Brockton quadrangle. Field determinations made with a scintillation counter indicate a very low level of radioactivity in the Dedham and associated rock types, including the albite granite dike mapped by Chute in the Brockton quadrangle. (See table 9.)

Quincy granite.-- The average level of radioactivity in the Quincy granite is about twice that of the Dedham, generally ranging from 0.003 to 0.004 percent equivalent uranium. Higher values seem characteristic of the small stock in the Brockton and adjacent Mansfield quadrangles than of the Quincy granite in the Blue Hills quadrangle. No reason for the difference could be detected on petrographic examination of sections from the two localities, but the Quincy granite from the Blue Hills quadrangle shows more alteration of a type that has resulted in the conversion of the ferromagnesian minerals to iron oxide than does the riebeckite granite in the Brockton quadrangle.

The highest value of the radioactivity determined for any of these rocks was that found in the small rhyolite porphyry dike, mentioned above, that occurs near the center of the Brockton quadrangle, which has by laboratory determination, an equivalent uranium content of 0.006 and a uranium content of 0.001. The relatively high radioactivity and the presence of anorthoclase suggest that the rock may be related to the Quincy granite.

No petrographic evidence of the source of radioactivity in the Quincy granite was found. One specimen (51C96)_/ from the Norwood quadrangle, to the west of the Blue Hills quadrangle, has an equivalent uranium content of 0.004 percent. This rock has an accessory minerals allanite, zircon, and sphene, all of which have produced pleochroic haloes in adjacent chlorite. The correlation of this rock with the Quincy, because of the difference of mineralogy, is however, somewhat doubtful.

_/ Not on table 9

[redacted]

Table 9.--Radioactivity measurements on igneous rocks from the Blue Hills, Brockton, Norwood, and Mansfield quadrangles, Mass.

Station	Field Reading	Equivalent Uranium Percent 1/ (x 10^{-3})	Uranium Percent (x 10^{-3})	Rock type (Sample No.)
		Blue Hills Quadrangle		
180	180-140(?)	(?)		Quincy granite
181	145-155	3		Quincy granite
182	140	<u>3</u>		Quincy granite (51C92)
183	120-95	2		Granite porphyry
184	95	3		Granite porphyry
185	90	3		Granite
186	85	<u>3</u>		Quincy granite (51C93)
		Brockton Quadrangle		
187 2/	125	6	1	Rhyolite porphyry (51C94)
187	50	2		Dedham granite
188	45	2		Fine-grained granite (phase of Dedha
189	95	<u>4</u>		Riebeckite-aegirite-albite granite (51C95a)

1/ Underlined values are laboratory determinations of equivalent uranium; others are estimates from field measurements.

2/ Coordinates on Massachusetts (Mainland) 10,000 foot grid for points in Brockton, Mansfield, and Norwood quadrangles are:

Pt.	N.	E.
187	389 200	715 420
188	396 700	708 200
189	394 350	702 750
190	408 900	700 130
191	413 400	685 100
192	416 000	682 400

Table 9.--Radioactivity measurements on igneous rocks from the Blue Hills, Brockton, Norwood, and Mansfield quadrangles, Mass.--Continued

Station	Field Reading	Equivalent Uranium Percent (x 10^{-3})	Uranium Percent (x 10^{-3})	Rock type (Sample No.)
		Mansfield Quadrangle		
190	60	3		Quartz-poor riebeckite granite
		Norwood Quadrangle		
191	25	1		Aegirite syenite
192	85	4		Aplitic phase of Quincy (?) granite

Pawtucket-Franklin, Providence County, Rhode Island--Norfolk Norfolk County, Massachusetts

Igneous geology

Two small stocks of riebeckite granite and a number of dikes and irregular intrusive masses of related granite porphyry crop out in the northern part of the Pawtucket quadrangle and the southern part of the adjacent Franklin quadrangle. These rocks have been described in some detail by Warren and Powers (1914, pp. 463-470) and mapped in part by Quinn, Ray and Seymour (1949). Roughly half of the area of riebeckite-granite is included in the Pawtucket quadrangle. This granite was regarded by Warren and Powers as middle Pennsylvanian in age.

Little can be added to the description of the granite given by Warren and Powers. In many places, as they point out, the granite has a pronounced gneissoid structure, but the lack of strain in the constituent minerals, which might be expected to be quite susceptible to deforming stress, indicates that the gneissoid texture is primary.

The principal minerals are quartz, microcline-microperthite, riebeckite, sphene, brown biotite, lavender fluorite, and calcite. Warren and Powers do not record calcite or biotite, but do report astrophyllite, zircon, aegirite, and ilmenite. Powers and Warren also found fluorite of deep-purple color.

The granite porphyry occurs in small dikes and marginal phases, or apophyses of the granite. The phenocrysts are quartz, and microperthite, the groundmass microperthite, quartz, magnetite, fluorite, and calcite, with biotite and garnet(?). In some specimens, remnants of riebeckite and aegirite are found.

Measured radioactivity of intrusive rocks

The alkaline granite and porphyry of the Pawtucket-Franklin area are among the most radioactive granitic rocks found in New England during this investigation. The high radioactivity seems to be quite uniformly distributed in the portions of the stock examined; fewer stations were examined on the granite porphyry (table 10). That the radioactivity is mostly present as thorium is suggested by the difference between equivalent uranium and uranium. Using the value (0.28) calculated by Phair (1952, p. 34) for the ratio between the activities of old uranium and old thorium, the thorium content of 51C97 should be about 0.0216 percent or about 11 times the uranium content. As the area has not been completely explored radiometrically, and the radioactivity appears higher than that in most igneous rocks, this area appears to be a relatively favorable place in which to explore the distribution of uranium and thorium in a small granitic intrusive.

Table 10.--Radioactivity measurements on certain granitic rocks in the Pawtucket-Franklin area, Rhode Island-Massachusetts.

Station Number	Field Count 1/	Equivalent Uranium Percent (x 10^{-3}) 2/	Uranium Percent (x 10^{-3}) 2/	Rock type (Sample No.)
194	190	8	2	Riebeckite Granite (51C97)
195	210	9	2	Do.
196	150	6	1	Do.
197	200	8	2	Do.
198	170	7	1	Do.
199	180	8	2	Do.
200	165	7	1	Do.
201	175	7	1	Do.
202	160	6	1	Do.
203	185	7	1	Do.
204	170	7	1	Do.
205	170	7	1	Do.
206	195	8	2	Do.
207	175	7	1	Do.
208	155	6	1	Do, with quartz vein
209	190	8	2	Do.
210	200	8	2	Do, porphyry
211	150	7	1	Do, porphyry (51C99)

1/ Scintillation counter

2/ Underlined values are laboratory determinations of equivalent uranium; others are estimated from field measurements.

SUMMARY

Nine areas of plutonic and hypabyssal intrusive rocks in New Jersey, New York, and the New England states were examined radiometrically in the field, and samples of the principal rock types were assayed for equivalent uranium and uranium.

The rocks examined are characterized by richness in soda; both highly silicic and subsilicic varieties are present. The rocks are, in part, correlated with intrusives belonging to the White Mountain magma series of New Hampshire; it is possible that all may be correlative in age with that series.

The maximum radioactivity found was about 0.008 percent equivalent uranium. Only a small proportion of the rocks sampled had more than 0.001 percent uranium. The highest amount found in any of the rocks was 0.003 percent.

Variation of radioactivity with rock type

The highest radioactivity was found in riebeckite granite, in sodalite syenite, in certain phases of the Conway biotite granite from Ascutney Mountain, in certain bostonite dikes from the Branchville quadrangle, New Jersey, and a paisanite dike from York County, Maine. In other areas and outcrops, however, similar rock types had much lower radioactivity; though in general the radioactivity seems to increase toward the more silicic end of the differentiation series, no consistent difference could be traced between biotite granite, and riebeckite and aegirine granites. Small dikes of highly sodic and silicic rocks, such as paisanite, seem to be more consistently high than most types, but relatively few were

sampled. Granitic rocks are generally somewhat more radioactive than syenites, and these, in turn, are more radioactive than the less felsic rocks, such as gabbros and essexites.

Uranium-thorium ratio

The uranium-thorium ratio seems to be generally low, and most of the rocks that are most radioactive are inferred to be thorium-rich. No uranium was found in the rocks of some areas by the methods used, but the amount of uranium is generally so low that it is impossible to calculate a valid thorium-uranium ratio for most areas. No uranium was found in the rocks of Willsboro, New York-Vermont; Ascutney Mountain, Vermont; Essex County, Massachusetts. In the Mt. Agamenticus area and the Blue Hills-Brockton area uranium was found in but a single small dike in each area. In the Cuttingsville stock, uranium was found in two samples out of thirteen; in the Branchville, N. J., area, in three out of three; in the stock of the Pawtucket-Franklin area, in both of the analyzed samples.

Variation in radioactivity within a single rock body

Only two examples of variation of radioactivity within a single rock body were found. One of these was the Conway biotite granite stock of Mt. Ascutney, in which the pegmatitic contact zone of the granite appears to be notably more radioactive than the rest of the stock. Notable textural differences were apparent here, in the field. The other example was a small aplitic dike, apparently related to the Agamenticus complex of York County, Maine, in which differences of as much as 25 percent could be found between the wall zone and the central part of the dike. This

difference could not be correlated with any visible change in the texture or composition, but it has not been investigated by a study of serial rock sections.

Relative frequency of occurrence of radioactivity in various accessory minerals

Earlier work had shown that much of the content of uranium and thorium is found in the accessory minerals of an igneous rock; such evidence as was available from this study tends to confirm this conclusion. The only criterion of radioactivity available, however, was the development of pleochroic haloes; it is evident that minerals which did not happen to occur as inclusions in other minerals that are capable of developing such haloes would appear to be non-radioactive. Nevertheless, the petrographic criteria indicated that some of the radioactivity in most of the rocks was concentrated in the common accessory minerals, such as zircon, allanite, and sphene.

In some rocks, pleochroic haloes were observed about opaque inclusions, black in reflected light, and not otherwise identified. Such rocks included those of Barber Hill in the Willsboro quadrangle, the Conway granite of Ascutney Mountain, the sodalite syenite of Cuttingsville and the alkaline granite of Mt. Agamenticus. The observed properties of the mineral do not contradict the supposition that this mineral may be thorianite; further work would be required to substantiate this interesting hypothesis.

Areas most favorable for further work

In view of the variation in average radioactivity from one area of the White Mountain magma series to another, it is evident that relatively low results in one such area should not be regarded as unduly discouraging to further work in another area. The area that seems to be consistently high in radioactivity and in uranium content is the Pawtucket-Franklin area, of Rhode Island and Massachusetts. Only the part of this area within the Pawtucket quadrangle was examined in the course of this work; the part of the larger stock, and the smaller stock, that crop out in the Franklin quadrangle deserve further examination.

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