BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 797-828, 8 PLS., 2 FIGS. SEPTEMBER 1946

PETROGRAPHY AND RADIOACTIVITY OF FOUR PALEOZOIC MAGMA SERIES IN NEW HAMPSHIRE

BY M. P. BILLINGS AND N. B. KEEVIL

PUBLISHED BY THE SOCIETY
SEPTEMBER, 1946

Made in United States of America

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 57, PP. 797-828, 8 FIGS. SEPTEMBER 1946

PETROGRAPHY AND RADIOACTIVITY OF FOUR PALEOZOIC MAGMA SERIES IN NEW HAMPSHIRE

BY M. P. BILLINGS AND N. B. KEEVIL

CONTENTS

ILLUSTRATIONS

ABSTRACT

The Ordovician (?), Silurian, and Devonian strata of New Hampshire are intruded by igneous rocks belonging to four magma series, the oldest of which is late Ordovician (?), the youngest of which is Mississippian (?). Each magma series consists of rocks ranging from gabbro, diorite, or quartz diorite to granite.

Although individual specimens from a rock type within a single magma series commonly show considerable range in radioactivity, the average values show a progressive increase in radioactivity toward the granitic end of the series, which is three to four times as radioactive as the gabbro-diorite end of the series. The reason for this increase toward the granitic end of the series is not always clear, but in the White Mountain magma series this appears to be due to an increase in the amount of allanite and probably zircon. This magma series is twice as radioactive as the other magma series and considerably more radioactive than similar rocks elsewhere in North America. It is suggested that the parental basaltic magma from which the White Mountain magma series was differentiated was more radioactive than the primary magmas from which the older magma series were derived.

INTRODUCTION

GENERAL STATEMENT

This investigation of the radioactivity of the intrusive rocks of New Hampshire is one phase of a larger project concerned with a similar study of the plutonic rocks of North America. New Hampshire is an unusually fertile area for special study because of the presence of four magma series, the oldest of which is late Ordovician (?), the youngest of which is Mississippian (?); each series contains a fairly complete sequence ranging from gabbro or diorite to granite. Thus, a rare opportunity is available to compare and contrast the radioactivity of four magma series, each with its own distinctive mineralogy, texture, structure, and mechanics of intrusion.

The methods of studying the radioactivity of rocks have been described elsewhere (Keevil and Grasham, 1943). It will suffice here to say that the results are expressed in terms of the number of alpha particles emitted per milligram of rock per hour. From this may be calculated, by multiplying by 2.25 (Keevil, 1943), the radiogenic heat in calories produced per gram of rock per million years.

MAGMA SERIES OF NEW HAMSPHIRE

A magma series may be defined as a group of comagmatic igneous rocks, evolved during a relatively short part of geologic time. Both intrusive and extrusive phases may be represented. The magma series of New Hampshire have been intruded into metasedimentary and metavolcanic rocks of Ordovician (?), Silurian, and

Devonian age (Fig. 1). The metamorphism of these rocks is low grade along the Connecticut River, but increases to middle grade 5 to 8 miles to the southeast, and still farther southeast is high grade (Billings, 1937, p. 470–472, 539–544).

Four magma series have been recognized in western and central New Hampshire (Billings, 1934). The distribution of these magma series is shown in Figure 1. The Highlandcroft magma series, of late Orodvician (?) age, is confined to three relatively small areas near the Connecticut River. The Oliverian magma series, which is middle Devonian (?), lies some 12 miles southeast of the Connecticut River. The late Devonian (?) New Hampshire magma series, syntectonic with the Acadian revolution, is extensively developed throughout the State. The Mississippian (?) White Mountain magma series occupies a north-south belt, extending from the northern limit of the map (Fig. 1) to the Lake Winnipesaukee region.

Although the characteristics of these magma series are well known to geologists conducting research in New Hampshire, and details are given in numerous areal reports, no comprehensive summary has yet appeared. Data for the White Mountain magma series have been assembled by R. W. Chapman and Williams (1935), and their conclusions on its evolution have been substantiated by more recent studies. Moreover, Quinn (1944) has compared and contrasted the New Hampshire and White Mountain magma series in the Winnipesaukee region. However, inasmuch as a general summary of the characteristics of the various magma series has not been published, it is desirable to present brief descriptions of each series in the present paper. In preparing this material, it was necessary to rely on existing data; new studies to rectify possible errors and deficiencies were impossible.

SOURCE OF SPECIMENS

The radioactivity of 135 specimens of intrusive rocks from New Hampshire was determined. The detailed data will be presented soon in Keevil's paper covering all of North America, and it is unnecessary to repeat them here. Many of the specimens came from the petrographic collections in the Mineralogical Museum at Harvard University, and they will be so designated under "Donor" in the tables to be published in the latter paper. Most of the other specimens came from collections still retained in Billing's office at Harvard University, and in the tables will be designated "M. P. Billings" in the column headed "Donor"; one specimen, 3221-NH-122, was donated by E. B. Sandell.

The areal distribution of the specimens is shown in Figure 2. A more uniform distribution over the State was impossible for several reasons. Many areas have not been studied, and consequently collections have not been made. Moreover, because several geologists were away from home during the war, specimens from several excellent collections were not available; this is notably true of the Mt. Cube, Mt. Chocorua, Claremont, and Newport quadrangles, and the northern half of the Mt. Washington quadrangle. A total of 13 specimens came from the Bellows Falls, Monadnock, Milford, and Concord quadrangles, which are beyond the limits of the area covered by Figure 1.

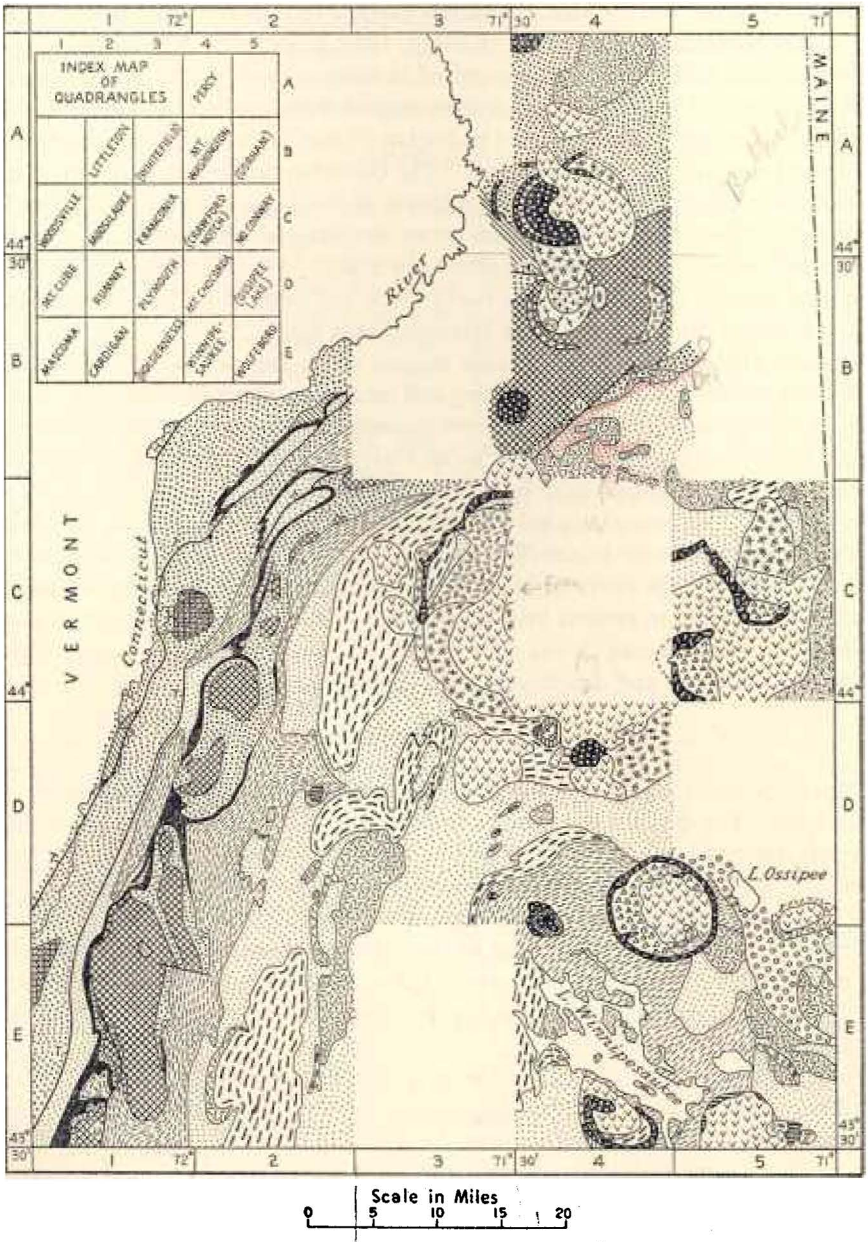
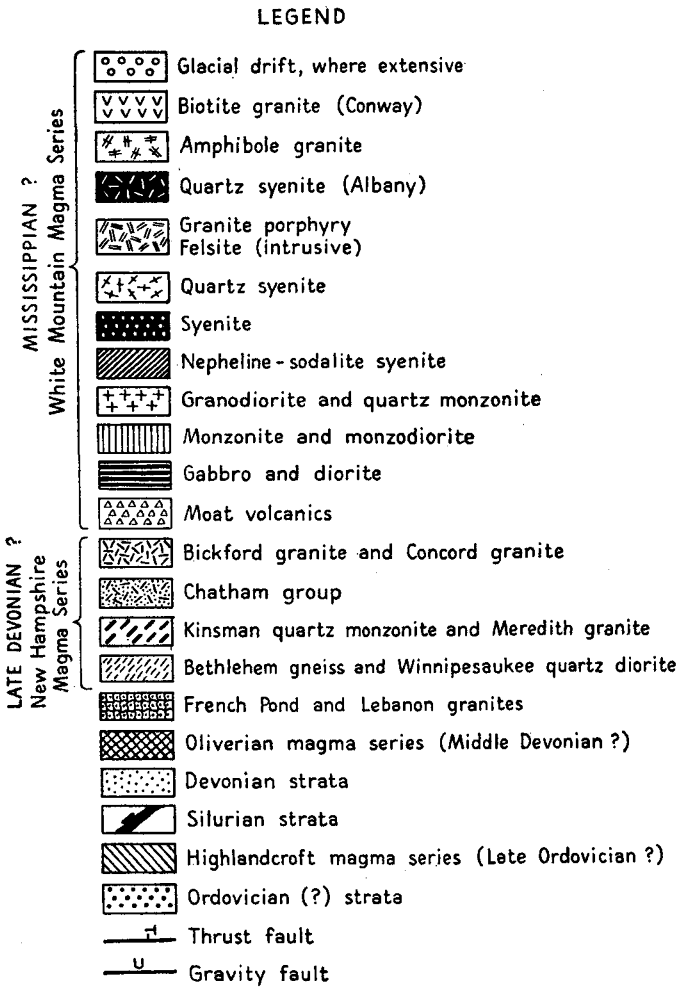


FIGURE —*Geological map of central New Hampshire*



WHITE MOUNTAIN MAGMA SERIES

GENERAL STATEMENT

As shown in Figure 1, the Mississippian (?) White Mountain magma series occupies a north-south belt extending from the northern end of the map to south of Lake Winnipesaukee. There are also small bodies at the following localities shown in Figure 2: Pleasant Mtn., Maine; Pawtuckaway Mtns., New Hampshire; Mt. Ascutney, Vermont; and Monadnock Mtn., northeastern Vermont.

PETROGRAPHY

The White Mountain magma series consists of extrusive phases, known as the Moat volcanics, and intrusive phases, including both plutonic and dike rocks. This series is alkalic, in contrast to the three older subalkalic magma series. The plutonic rocks

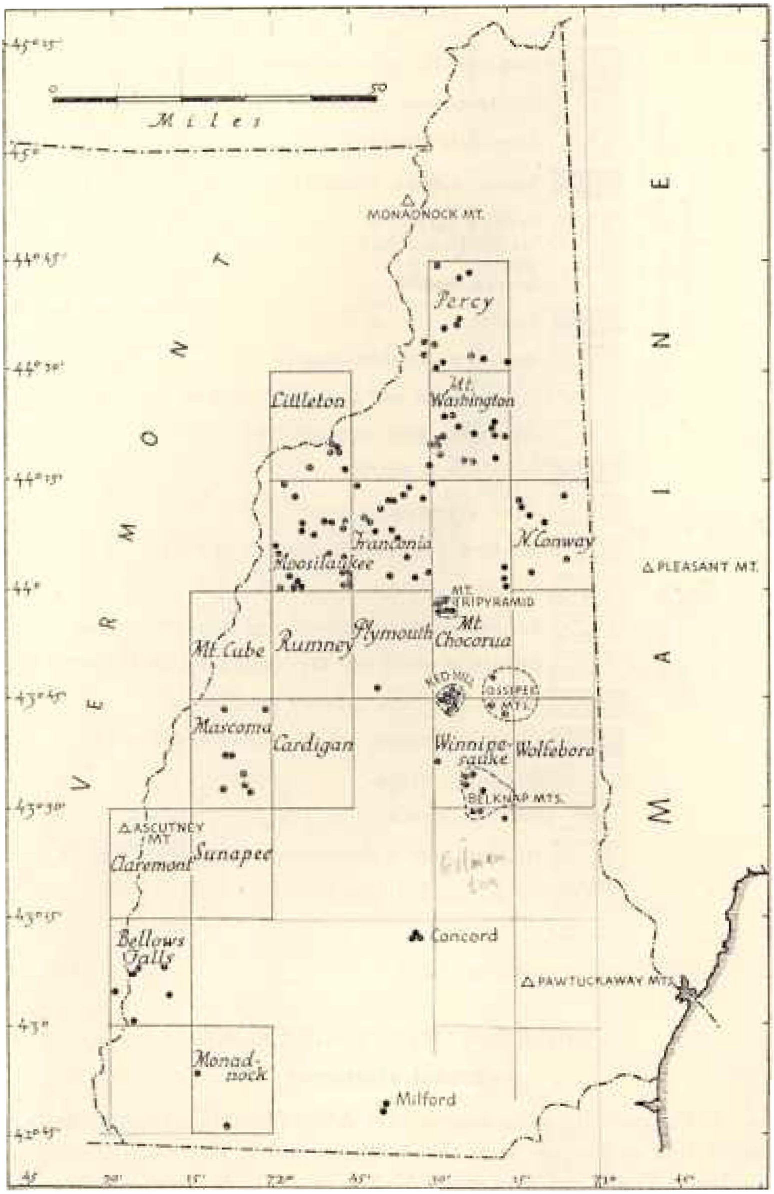


FIGURE 2.—*Index map giving location of specimens*

Map of New Hampshire and adjacent areas. Each dot represents one specimen. Quadrangles, mountains, and unicipalities referred to in text are indicated.

are almost invariably massive, foliation and banding being limited to some of the gabbro and diorite. The rock bodies are typically (Fig. 1) ring-dikes and stocks (Billings, 1945).

The rocks have been classified as follows: gabbro, norite (hypersthene diorite),

diorite, quartz diorite, monzodiorite, granodiorite, monzonite, quartz monzonite, syenite, nepheline-sodalite syenite, analcime syenite (Pleasant Mountain, Maine), quartz syenite, granite porphyry, amphibole granite, riebeckite granite, hastingsite-biotite granite, and biotite granite. The order of intrusion, insofar as known, is from gabbro to granite.

Modes, representative averages of modes published elsewhere, are presented in Table 1. The reader should realize that these modes are averages and that values for individual specimens may depart considerably from the mean. A rough estimate of the area covered by each kind of rock is also given in this table. The area is given in per cent of the total area occupied by the White Mountain magma series. In all the modes given in Tables 1, 3, 5, and 7, potash feldspar is a term used to include orthoclase, microcline, and microperthite. The use of decimals for such minerals as apatite, zircon, and pyrite is explained below.

In some earlier papers (Billings, 1928; Kingsley, 1931) the syenites and quartz syenites were called nordmarkites, and this appellation is quite correct, if one wishes to employ names for alkalic rocks different from those used for subalkalic rocks.

The mineralogy of these rocks has been extensively studied, and more detailed information is available than for any magma series in the world (R. W. Chapman and Williams, 1935; Smith, 1940).

Microperthite is the characteristic potash feldspar of this magma series.

The olivine in the gabbro is a solid solution of 48 per cent forsterite and 52 per cent fayalite; it is absent in the intermediate rocks; in the granitic rocks it reappears in small quantities, but as a solid solution containing 90 per cent fayalite and only 10 per cent forsterite.

Pyroxene in the gabbro is a solid solution of 57 per cent diopside, 28 per cent hedenbergite, 12 per cent enstatite, and 3 per cent $FeSiO_3$. In the syenites, quartz syenites, and granites the pyroxene is a solid solution of 90 per cent hedenbergite, 10 per cent diopside. Some augite and "clinopyroxene" is reported from rocks ranging from norite to quartz monzonite. Hypersthene is found only in norite. Aegerine and aegerine-augite are confined to the nepheline-sodalite syenites and riebeckite granite.

Amphibole is "common hornblende" in the plagioclase-rich and intermediate rocks. Hastingsite and soda hornblende are the characteristic amphiboles in the syenite, quartz syenites, and granites. Riebeckite is common only in the riebeckite granites.

Biotite in the gabbro is intermediate between the iron and magnesia ends of the series but is lepidomelane (iron-rich biotite) in the granites.

It is apparent from the above description that all the ferromagnesium minerals show a striking, systematic increase in the iron-magnesia ratio progressing from the gabbro end of the series to the granitic end.

Muscovite, as Table 1 indicates, is rare in the White Mountain magma series.

Inasmuch as a great deal of the radioactivity of igneous rocks originates in the accessories (Keevil, Larsen, and Wank, 1944), a discussion of these minerals in the White Mountain magma series is necessary. As Table 1 indicates, the common accessories are opaques, apatite, zircon, sphene, fluorite, and allanite. Although quantitative data, based on heavy-mineral studies, are not available for New Hampshire,

TABLE 1.—*Average modes, White Mountain magma series*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Area*	tr	tr	tr	tr	1	tr	0.5	tr	9.2	0.3	†	5.3	5	9.4	9.2	3.0	2.0	55.0
Quartz		3		10	2	7	3	12	2			7	13	27	25	32	24	29
Plagioclase**	63_{60}	56_{45}	59_{45}	63_{45}	65_{25}	51_{43}	48_{20}	40_{20}	15_{16}		2_{27}	11_{25}	10_{20}	2_{10}	8_{20}	11_{10}	9_{20}	7_{12}
Potash feldspar	tr	4	tr	2	17	12	33	35	73	70	82	73	69	58	63	50	61	59
Olivine	10												tr	1	tr			
Pyroxene	14	16	10		4	5	1	1	2	2		1	1	2	tr	tr		
Amphibole	tr		6	9	5	13	5	6	7	8	6	7	7	6	4	6	3	tr
Biotite	5	7	17	15	5	8	6	tr	1	tr		1	tr	3	tr	1	3	5
Muscovite																		
Opaques: oxides	7	11	2		1		3	4	tr	tr	1	tr	tr		tr	tr	tr	tr
Opaques: sulphides	tr 0.16		tr 0.10		tr 0.06		tr 0.30	tr 0.16	tr 0.04	tr 0.08		tr			tr	tr		tr 0.08
Apatite	1 0.35	3 4.4	1 1.8		tr 0.28	tr	1 0.92	1 0.47	tr 0.40	tr 0.14	tr 0.33	tr 0.33	tr 0.21		tr 0.07	tr	tr	tr 0.14
Zircon			tr 0.03		tr	tr			tr	tr 0.07	tr 0.10	tr	tr 0.13		tr	tr	tr	tr 0.07
Sphene			tr		tr	tr	tr	tr		tr	2	tr	tr			tr		tr
Fluorite													tr		tr	tr		tr
Allanite									tr		tr		tr			tr		tr
Epidote						tr		tr										
			5		1	2												

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Nepheline..............										14								
Sodalite...............										6								
Analcite...............											7							

* Rough estimate, given in per cent of total area occupied by this magma series.
† Found at Pleasant Mtn., Maine; not known in New Hampshire.
** The subscript indicates the average content of anorthite.

1. Gabbro. Olivine is solid solution consisting of 48% forsterite, 52% fayalite. Pyroxene is solid solution consisting of 57% diopside, 28% hedenbergite, 12% enstatite, 3% $FeSiO_3$. Biotite is intermediate in composition, with 15.52% FeO, 14.23% MgO.
2. Hypersthene diorite (norite). Pyroxene is 6% hypersthene, 10% augite.
3. Diorite. Pyroxene is augite, amphibole is hornblende.
4. Quartz diorite. Amphibole is hornblende. Accessories stated to be 1% of rock, but not listed.
5. Monzodiorite. Pyroxene is chiefly clinopyroxene, but there is a little hypersthene. Amphibole is hornblende. Biotite has 20.88% FeO, 2.33% Fe_2O_3, and 10.04% MgO.
6. Granodiorite. Pyroxene is solid solution consisting of 63% diopside, 37% hedenbergite. Amphibole is hornblende.
7. Monzonite. Pyroxene is clinopyroxene. Amphibole is hornblende. Biotite contains 12.74% FeO, 1.31% Fe_2O_3, and 16.75% MgO.
8. Quartz monzonite. Pyroxene is clinopyroxene. Amphibole is hornblende.
9. Syenite. Pyroxene is a solid solution, consisting of 90% hedenbergite, 10% diopside. Amphibole is hastingsite in some specimens, soda hornblende in others. Biotite has high FeO/MgO ratio.
10. Nepheline-sodalite syenite. Pyroxene is aegerine augite, amphibole is hastingsite.
11. Analcime syenite from Pleasant Mountain, Maine. Amphibole is apparently hastingsite.
12. Quartz syenite. Pyroxene is hedenbergite with small amount of diopside in solid solution. Amphibole is hastingsite in most cases, but on Mt. Tripyramid it is a pleochroic brown hornblende.
13. Quartz syenite, Albany type. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite.
14. Granite porphyry. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite.
15. Amphibole granite. Olivine is fayalite, pyroxene is hedenbergite, amphibole is hastingsite in some areas, soda hornblende in others.
16. Riebeckite granite. Amphibole is riebeckite. Astrophyllite is an accessory in some specimens.
17. Hastingsite-biotite granite. Biotite is iron-rich variety; that is, lepidomelane. Amphibole is hastingsite.
18. Biotite granite. Biotite is iron-rich variety, lepidomelane.

some information has been obtained at Pleasant Mountain, Maine, by Jenks (1934a). Moreover, as shown below, chemical analysis may be used to determine the amount of some of these minerals.

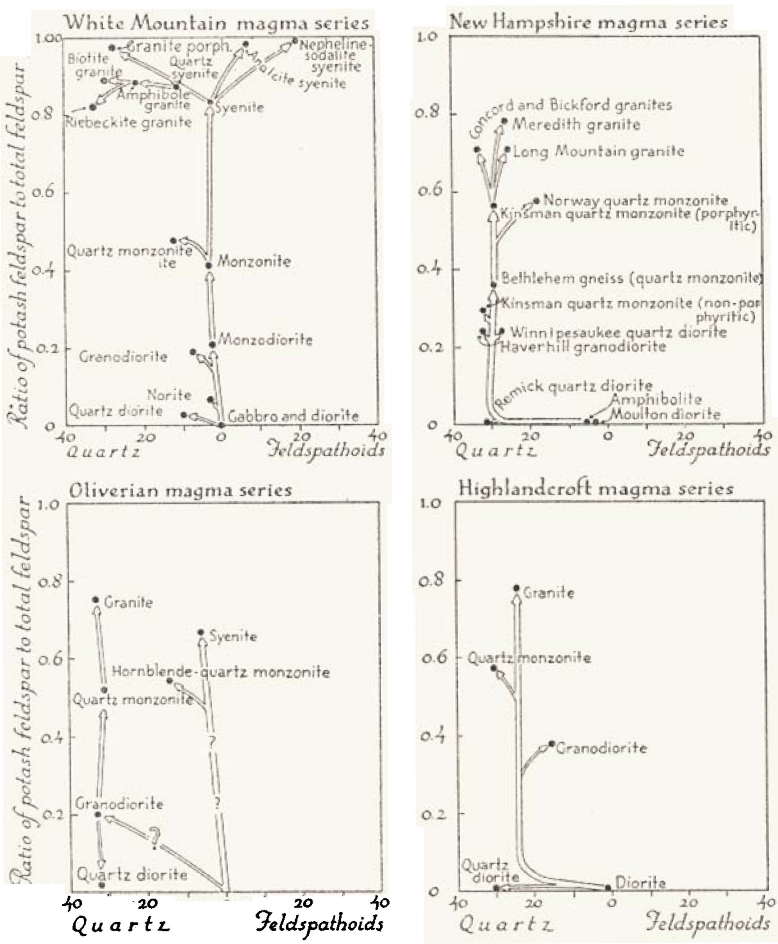


FIGURE 3.—*Graphic comparison of the four magma series*

Each magma series represented by a separate diagram. Each dot represents a rock type. Double lines with arrows represent inferred evolution, if rocks have been derived from mafic magma by fractional crystallization.

Some of the opaque minerals assume the importance of major constituents in the gabbro, norite, and diorite. Newhouse (1936), who has studied polished sections of 13 specimens of the White Mountain magma series, 8 from New Hampshire, 5 from adjacent Vermont, has identified the following opaque oxides: ilmenite; magnetite; and magnetite with exsolution lamellae of ilmenite, in some cases also containing spinel. Ilmenite dominates in the gabbro and diorite; magnetite, with or without exsolution lamellae of ilmenite, dominates in the nepheline-sodalite syenites, syenites, and quartz syenites. Granites of this magma series were not studied. Sulphides are pyrrhotite, pyrite, chalcopyrite, and pentlandite, the last two apparently confined to the gabbro and diorite. In Table 1 the amount of sulphide present is listed twice. The upper figure is based on thin-section study and is qualitative only. The lower figure is based on calculations from chemical analyses. Although the calculation was based on the formula for pyrite, the figures undoubtedly give a fair idea of the amount of sulphide present.

The amount of apatite is shown in Table 1 in a similar way, the lower figure being based on the assumption that all the P_2O_5 shown by chemical analyses is confined to this mineral. In the gabbros, diorites, monzonites, and related rocks, apatite ranges from 0.28 to 4.4 per cent; in the nepheline and analcime syenites it is 0.40 to 0.47 per cent; and in the syenites, quartz syenites, and granites it is 0.07 to 0.33 per cent.

Zircon may be similarly calculated from the amount of ZrO_2 in the analyses. Unfortunately the necessary chemical data are available for less than one-third of the rocks, but they indicate that zircon ranges from 0.03 per cent to 0.13 per cent.

Sphene has been observed in many of the rocks. Jenks (1934a) states that on Pleasant Mountain, Maine, this mineral constitutes about 0.2 per cent of the syenite (nordmarkite). Although Jenks (1934b) lists 2 per cent sphene in the modes of the analcime syenite (Table 1, column 11 of the present paper) his study of the heavy minerals indicates only 0.6 per cent of this mineral.

Allanite is a characteristic accessory in the syenites, quartz syenites, and granites. Precise data on the amounts are lacking, but there is probably about 0.1 per cent in the granites.

Fluorite is characteristic of the quartz syenites and granites. It amounts to a small fraction of 1 per cent of these rocks.

EVOLUTION

R. W. Chapman and Williams (1935, p.527) concluded that the evolution of the White Mountain magma series from a basaltic magma was controlled by fractional crystallization, but the assimilation of older siliceous rocks played an important rôle.

In Figure 3 separate diagrams are given for each of the four magma series. The ordinate is the ratio of potash feldspar to total feldspar. On the abscissa the amount of quartz is indicated to the left of the vertical median line, the amount of feldspathoids to the right. Each dot represents a rock type as listed in the modes of Table 1. In the lower two-thirds of the diagram for the White Mountain magma series the dots are close to the median line, the amount of quartz averaging less than 10 per cent. Only at the top of the diagram do the dots spread out horizontally. This fact, coupled with all the other data about the magma series, indicates that from the gabbro to the syenite stage the evolving magma stayed close to the median line, and large amounts of quartz did not develop until after the syenite stage had been reached. In a few instances feldspathoids developed to give the nepheline-sodalite and analcime syenites. The lines with arrows indicate the inferred evolution. A consideration of the mechanics of this evolution is beyond the scope of this paper, but in general the scheme set forth by R. W. Chapman and Williams (1935) is acceptable.

RADIOACTIVITY

The radioactivities of the principal rock types in the White Mountain magma series are listed in Table 2, but unfortunately specimens of some types were unavailable. In the first column is the rock name, the second column gives the number of specimens tested, the third column gives the lowest and highest radioactivity, and the fourth column gives the average radioactivity. The probable error in each average is also given in the fourth column. It has been calculated according to the equation (Keevil, 1938):

TABLE 2.—*Radioactivity of the White Mountain magma series*

Lithology	Number of specimens	Radioactivity: alpha particles emitted per milligram of rock per hour	
		RANGE	AVERAGE
MAJOR VARIETIES			
Gabbro	3	0.70–1.82	1.28 ±0.22
Norite (Hypersthene diorite)	1	0.56	0.56
Diorite	2	1.18–1.14	1.31 ±0.09
Monzodiorite	3	1.05–4.01	2.14 ±0.63
Syenite	8	0.79–5.03	2.29 ±0.34
Nepheline-sodalite syenite	1	1.17	1.17
Quartz syenite	4	1.60–3.36	2.46 ±0.29
Quartz syenite (Albany type)	5	2.69–5.12	3.49 ±0.31
Hastingsite-biotite granite	1	4.49	4.49
Hastingsite granite and soda-hornblende granite (Mt. Osceola type)	3	2.12–4.17	3.24 ±0.40
Riebeckite granite	2	2.34–3.01	2.67 ±0.22
Granite porphyry (Mt. Lafayette type)	3	4.15–5.04	4.55 ±0.06
Biotite granite (Conway type)	16	1.59–8.69	4.56 ±0.29
COMBINATIONS OF SOME OF ABOVE TYPES:			
Gabbro and norite	4	0.56–1.82	1.10 ±0.19
Syenite (including nepheline-sodalite syenite)	9	0.79–5.03	2.16 ±0.31
Quartz syenite	9	1.60–5.12	3.09 ±0.80
Amphibole granite	6	2.12–4.49	3.26 ±0.28
DIKE ROCKS			
Bostonite	1	1.75	1.75
Paisanite	1	5.61	5.61
Aplite	1	2.56	2.56
Nepheline syenite	1	0.99	0.99

$$p.e. = \pm \tfrac{2}{3} \sqrt{\frac{\Sigma(x - \bar{x})^2}{n\,(n-1)}}$$

where x is an observation, $\bar{x}$ is the average, and n is the number of observations.

The lowest average values are in the gabbro, norite, and diorite, with a general, but somewhat erratic increase to 4.56 in the biotite granite. The data are presented graphically in Figure 4. Although the abscissa could be either silica or, as Larsen (1938) has proposed, $\frac{1}{3}SiO_2 + K_2O–CaO–FeO–MgO$, neither is satisfactory when applied to the Oliverian magma series, for reasons given later. Inasmuch as one purpose of the present investigation was to compare the four magma series, an abscissa satisfactory for all the magma series was necessary. In Figure 4 the central part of the abscissa, from diorite to syenite, is based on the ratio of potash feldspar to total

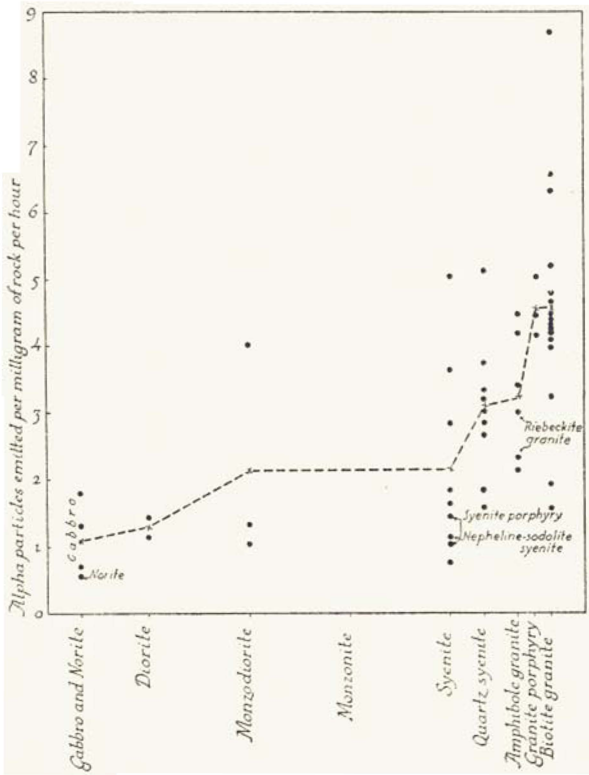


FIGURE 4.—*Radioactivity of White Mountain magma series*

Each dot represents one specimen. Each cross represents average for the rock type indicated in abscissa.

feldspar. Gabbro and norite have been placed to the left of diorite, and granites have been added to the right-hand end of the diagram. Quartz diorite has been placed a little to the right of diorite, and granodiorite, quartz monzonite, and quartz syenite have been placed to the right of their quartz-poor counterparts.

On the ordinate is plotted the radioactivity expressed in alpha particles emitted per milligram of rock per hour. Each small dot represents one specimen. Each cross is the average for a rock type.

It is clear that for each type of rock a great range in values occurs. In the biotite granite, for which 16 determinations were made, the lowest value is 1.59, whereas the highest value is 8.69. The average is 4.56. It is apparent, therefore, that a single determination for a type cannot be significant, and that a value for several specimens must be obtained in order to get a significant average.

Despite the great range shown by individual specimens, the average values show a progressive, although irregular, increase from the gabbro end of the series to the granite end. The average alpha particle emission for biotite granite is four times as great as the average value for gabbro.

The great range shown by individual specimens, despite the systematic variation shown by the averages, indicates that the source of the radioactivity is irregularly distributed through the rocks. The specimens studied, which usually contained 1 to 10 cubic inches, must be smaller than the unit that would be necessary to obtain uniform values. The size of such a unit is problematical, but it appears to be many times the size of a hand specimen.

SOURCE OF RADIOACTIVITY

In trying to find the reason for the four-fold increase in the radioactivity in progressing from gabbro to granite, we are presented with two possibilities: (1) The radioactivity of the responsible minerals may be constant, but the quantity of these minerals may increase several times; or (2) the quantity of the responsible minerals may be relatively constant, but the percentage of radioactive elements in them may increase several fold. A combination of these two possibilities should also be considered. The second hypothesis is difficult to test without separating samples of the same mineral—such as zircon—from the different rock types in the magma series; this is a time-consuming task. The first hypothesis may be tested if detailed modes are available. It should be recalled that Keevil, Larsen, and Wank (1944) discovered that in the Ayer granite the accessories accounted for half the radioactivity. Zircon, apatite, and epidote were especially radioactive. In the Lakeview tonalite of California, zircon, sphene, and apatite were the most radioactive minerals.

Whereas apatite averages only 0.2 per cent in the granitic end of the White Mountain magma series, it averages 2.2 per cent in the gabbroic end. The scanty data available suggest that zircon may average 0.09 per cent at the granitic end of the series, and only 0.03 per cent at the gabbroic end. Epidote is exceedingly rare in the White Mountain magma series. Sphene is common, but quantitative data are not available. Allanite, however, as Table 1 shows, has been recorded only in the syenites, quartz syenites, and granites; it is presumably the chief source of the high radioactivity of the granites.

Biotite, although relatively the most important mafic mineral in the biotite granite, is actually less abundant in these rocks than in gabbro, diorite, and monzonite. Potash feldspar is less common in the quartz syenites and granites than in the syenites, which have a relatively low radioactivity, hence it cannot be the explanation of high radioactivity of the granites and quartz syenites.

We conclude, therefore, that the increase in radioactivity in the granitic end of the White Mountain magma series is due primarily to the appearance of allanite, and secondarily to an increase in the amount of zircon.

NEW HAMPSHIRE MAGMA SERIES

GENERAL STATEMENT

The New Hampshire magma series is widely distributed throughout the State, extending from within 3 miles of the Connecticut River on the west (Fig. 1) to and across the Maine border on the east.

Many of the rocks of this subalkalic magma series are characterized by foliation and granulation. The individual bodies are typically great concordant sheets or lenses, tens of miles long and thousands of feet thick, but the granites occur as irregular stocks. This magma series is syntectonic with the Acadian revolution. The oldest members—diorite and amphibolite—were intruded before the main deformation and have consequently undergone regional (hydrodynamothermal) metamorphism. The rocks of intermediate composition—quartz diorites, granodiorites, and quartz monzonites—are essentially synchronous with the folding and in some instances have had a secondary lineation imposed upon them. The youngest members—Concord and Bickford—have suffered little deformation.

Although, in general, the order of intrusion was from the dioritic to the granitic end of the series, there was some reversal of order, for the Winnipesaukee quartz diorite is younger than the Meredith granite (Quinn, 1944, p. 476–477).

PETROGRAPHY

The rocks have been classified as follows, average modes being given in Table 3: Moulton diorite, amphibolite, Remick quartz diorite, Winnipesaukee quartz diorite, Haverhill granodiorite, Bethlehem gneiss (quartz monzonite), Kinsman quartz monzonite, Norway quartz monzonite, Meredith granite, Long Mountain granite, and Concord granite (equivalent to Bickford granite).

The modes in Table 3 are averages; many specimens, some of which may deviate considerably from the mean, have been averaged for some of the columns. For example, although the Bethlehem gneiss averages quartz monzonite, it is very close to granodiorite. Moreover, some specimens of Bethlehem lack potash feldspar and are quartz diorite; exceptionally the Bethlehem gneiss is granite.

The Kinsman quartz monzonite in places is nonporphyritic; elsewhere it contains variable amounts of phenocrysts of potash feldspar 2 to 5 centimeters long. Where the phenocrysts become very abundant the rock is a granite, which has been called the Meredith granite in the Lake Winnipesaukee region.

The mineralogy of this magma series is strikingly different from that of the White Mountain magma series. Olivine and pyroxene are virtually absent. Amphibole is confined to the dioritic end of the series and is "common hornblende." Biotite is the chief mafic mineral and is distinctly dominant over hornblende in all rocks except diorite and amphibolite. Muscovite, so rare in the White Mountain magma series, is a major constituent in all the rocks, except diorite, amphibolite, and quartz diorite. Potash feldspar is typically, although not exclusively, orthoclase or microcline, rather than microperthite as in the White Mountain magma series. Quartz is a very important mineral in all but the diorites and amphibolites. Quartz is important in rocks in which the ratio of potash feldspar to total feldspar is small, whereas in the White Mountain magma series quartz in large quantities is confined to rocks with a high ratio of potash feldspar to total feldspar. Quinn (1944, p. 481) has also tabulated other features in which the two magma series differ.

As shown in Table 3, the principal accessories of the New Hampshire magma series are opaques, apatite, zircon, sphene, epidote, and garnet. The opaque oxides generally occur only as a trace but approximate 1 per cent in the dioritic end of the series. The large amount listed in the Norway quartz monzonite may be in error. Newhouse (1936) states that the Concord granite contains magnetite and ilmenite, the

TABLE 3.—*Average modes, New Hampshire magma series*

	1	2	3	4	5	6	7	8	9	10	11	
Area*	1	1	2	23	tr	14	10	16	tr	8	3	
Quartz	3	5	31	27	32	29	32	29	18	26	29	33
Plagioclase	36_{8}	33_{40}	52_{14}	48_{40}	45_{30}	33_{34}	36_{27}	23_{26}	25_{23}	13_{20}	15_{20}	17_{20}†
Potash feldspar				15	14	19	15	30	33	45	37	43
Olivine												
Pyroxene	tr											
Amphibole	27	56	1	tr		1						
Biotite	1	4	12	10	5	15	12	14	20	10	17	4
Muscovite	2	tr		tr	2	3	5	4	tr	5	2	3
Opaques: oxides	tr	1	1	tr	tr	tr		tr	3	tr	tr	tr
Opaques: sulphides		tr	tr 0.06			tr 0.10	tr 0.38	tr 0.20		tr		tr 0.54
Apatite		tr	tr	tr	tr	tr 0.28	tr 0.55	tr 0.26	1	tr	tr	tr
Zircon			tr	tr	tr	tr	tr	tr	tr	tr	tr	tr
Sphene	2	tr	tr	tr	tr	tr			tr			tr
Epidote	14	tr	3	tr	1	tr	tr				tr	
Chlorite	12	1		tr					tr			
Calcite	3	tr				tr					tr	
Garnet		tr	tr	tr		tr	tr	tr		1		

* Rough estimate, given in per cent of total area occupied by this magma. About 4 per cent of area is occupied by Chatham group, for which no averages are given.

† The subscript indicates the average content of anorthite.

1. Moulton diorite. Amphibole is hornblende, muscovite is sercite, and sphene is "leucoxene".
2. Amphibolite. Amphibole is hornblende.
3. Remick quartz diorite (called tonalite in Littleton-Moosilauke report).
4. Winnipesaukee quartz diorite. The ratio of potash feldspar to plagioclase is such that this average should be called a granodiorite. In the Mt. Chocorua quadrangle, where this map unit was first called quartz diorite, there is little potash feldspar. It is possible that some of the rocks in the Winnipesaukee quadrangle carrying considerable potash feldspar should not have been assigned to the Winnipesaukee quartz diorite, but they have been entered into this average.
5. Haverhill granodiorite.
6. Bethlehem gneiss. This average is a quartz monzonite, close to granodiorite.
7. Kinsman quartz monzonite, phase without large phenocrysts of potash feldspar.
8. Kinsman quartz monzonite, phase with large phenocrysts of potash feldspar.
9. Norway quartz monzonite. This mode may be unreliable.
10. Meredith granite. Although this is a common rock in New Hampshire, only one reliable mode is available.
11. Long Mountain granite.
12. Concord granite and Bickford granite.

latter in some instances containing exsolution lamellae of hematite. In this same rock he identified pyrite and chalcopyrite. The percentage of sulphide has been calculated and entered in Table 3 for those rocks for which chemical analyses are available; the method was the same as that employed for the White Mountain magma series. Apatite, usually recorded as a trace in thin sections, is estimated from chemical analyses to range from 0.26 to 0.55 per cent, but data are available for only three of the rock types. Zircon is recorded as a trace in many thin sections. Chemical analyses of the Remick quartz diorite and the Bethlehem gneiss record ZrO_2 as 0.00, implying that the amount of zircon is less than a hundredth of 1 per cent. Sphene and garnet are generally present as traces. Epidote is abundant in the Moulton diorite, but this rock, older than the main deformation, has been subjected to low-grade metamorphism. Allanite, so common in the more siliceous rocks of the White Mountain magma series, is exceedingly rare in the New Hampshire magma series.

Kruger (1941, p. 36) has concentrated the heavy minerals from six specimens of Bethlehem gneiss from the Moosilauke quadrangle and reports that they average the following percentages of the rock: biotite, 16.30; fluorapatite, 0.13; magnetite, 0.08; unidentified opaque, 0.08; chlorite, 0.02; zircon, 0.02; and small amounts of epidote, tourmaline, hornblende, monazite, and garnet.

EVOLUTION

The average modes of the New Hampshire magma series have been plotted in one of the diagrams in Figure 3. All the rocks, with the exception of diorite and amphibolite, lie far to the left of the median line, with quartz around 30 per cent. The contrast with the White Mountain magma series is apparent.

The field evidence that the various members of the New Hampshire magma series listed in Table 3 consolidated from magma is clear, at least within the area covered by Figure 1. Dikes and sills of all these rocks cut the older schists, and inclusions of the latter are found in the igneous rocks.

An advocate of fractional crystallization might suggest that the New Hampshire magma series has been derived from basalt, and that the early appearance of large quantities of quartz is a result of the simultaneous appearance of biotite, a silica-deficient mineral, as the sole ferromagnesian mineral (Bowen, 1928, p. 84). At the present stage of our knowledge this possibility cannot be denied.

Quinn (1944, p. 482) suggests that this magma series may represent melted sial. Still a third theory, for which there is some evidence, particularly for the Bethlehem gneiss and Meredith granite, is that granitized (migmatized) schists (Billings, 1941, p. 927–932) became sufficiently mobile at depth to move as magma and to intrude schists at higher levels.

RADIOACTIVITY

The radioactivity of the New Hampshire magma series is given in Table 4. The data are presented graphically in Figure 5. Individual specimens within a rock type deviate considerably from the average. Moreover, the lowest value for the granites (1.29) is less than the highest values for the diorites (1.73). Nevertheless, as the curve for the average values shows, the granitic end of the series is several times as

TABLE 4.—*Radioactivity of the New Hampshire magma series*

Lithology	Number of specimens	Radioactivity. Alpha particles emitted per milligram of rock per hour	
		RANGE	AVERAGE
Amphibolite	2		0.59 ±0.17
Moulton diorite	3		0.90 ±0.35
Remick quartz diorite	1		0.72
Winnipesaukee quartz diorite	2		0.50 ±0.23
Bethlehem gneiss (Quartz monzonite)	9		1.94 ±0.13
Kinsman quartz monzonite	7		1.71 ±0.14
Meredith granite	1		1.46
Long Mountain granite	2		2.74 ±0.29
Concord, Bickford, and related granites	15		2.60 ±0.13
Combinations of some of above types:			
Quartz diorite	3	0.15–0.85	0.57 ±0.15
Quartz monzonite	16	0.94–2.67	1.84 ±0.09
Granite	18	1.29–4.55	2.55 ±0.12
Chatham group*	4	0.80–1.56	1.12 ±0.11

* Not entered in averages because of inadequate petrographic data.

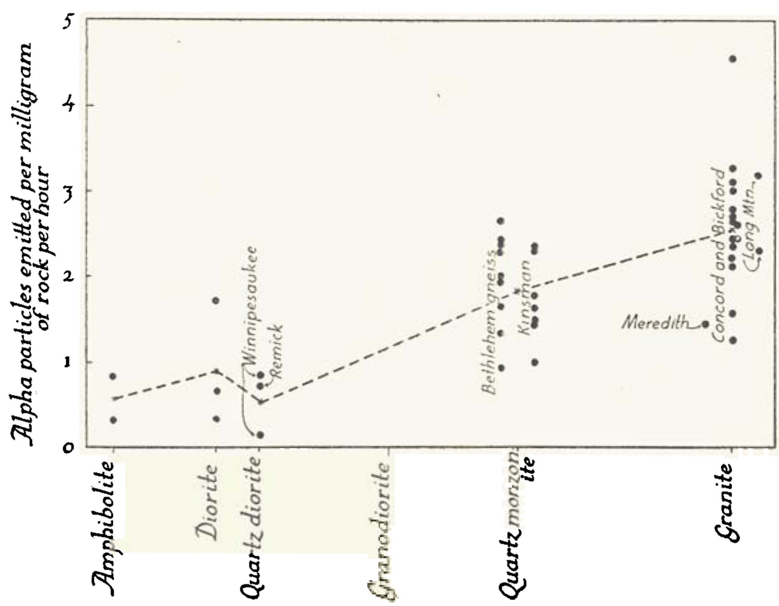


FIGURE 5.—*Radioactivity of New Hampshire magma series*

Each dot represents one specimen. Each cross represents average for the rock type indicated in the abscissa.

radioactive as the diorite-amphibolite end of the series. Comparison of Table 4 with Table 2, and Figure 5 with Figure 4, shows that the granites of the New Hampshire magma series are generally much less radioactive than the granites of the White Mountain magma series, and a similar relationship holds between the two series.

Quantitative data on the percentages of the accessory minerals in the New Hampshire magma series are insufficient to justify any attempt to explain why the granites are several times more radioactive than the diorite and amphibolite.

OLIVERIAN MAGMA SERIES

GENERAL STATEMENT

The Middle Devonian (?) Oliverian magma series is exposed principally in a belt, designated the Bronson Hill anticline, lying 10 to 15 miles east of the Connecticut River. This belt extends northeast and southwest beyond the limits of Figure 1. The French Pond and Lebanon granites (Fig. 1) originally assigned to the New Hampshire magma series (Billings, 1937) are now classified as members of the Oliverian magma series.

Many of the rocks of this subalkalic magma series are foliated, and most are granulated. The rocks are characteristically pink in contrast to the gray so typical of the New Hampshire magma series. The individual bodies, oval in plan, are 3 to 42 miles long and 1 to 9 miles wide. All the bodies in the Bronson Hill anticline possess a domical structure: a central igneous core, with outward-dipping foliation is overlain concordantly by outward-dipping Ordovician (?), Silurian and Devonian strata. Superficially, the individual bodies suggest laccoliths. Inasmuch as there is no evidence of floors each body may be the top of a "bottomless" stock, or all the bodies may belong to a single great intrusive sheet, initially horizontal, that has been buckled up into a series of domes (Billings, 1945). The French Pond and Lebanon granites, the latter described by C. A. Chapman (1939, p. 145–146, 158–159) and Kaiser (1938), are deformed stocks. The Oliverian magma series is older than the Acadian folding and is probably middle Devonian.

PETROGRAPHY

Throughout most of New Hampshire the lithology of this series is comparatively simple, and the rocks are classified as quartz diorite, granodiorite, quartz monzonite, and granite. Contacts between these various types are gradational, a fact emphasized on the quadrangle maps (Hadley, 1942; C. A. Chapman, 1939).

The average modes given in columns 1 to 5, Table 5, indicate the pertinent facts. In general, the mineralogy is not radically different from that of the New Hampshire magma series. Both series are characterized by abundance of quartz, rarity of pyroxene, and absence of olivine. Plagioclase in the Oliverian magma series is relatively uniform oligoclase; the anorthite content is about as high in granite as in quartz diorite, and the common tendency for plagioclase to become less calcic toward the granites is not observed. Biotite is the principal ferromagnesian mineral, and the dark minerals are no more abundant in the quartz diorites than in the granites. Muscovite is not as important as in the New Hampshire magma series. The potash feldspar is commonly microcline, whereas it is microperthite in the White Mountain magma series, and orthoclase is more common in the New Hampshire magma series.

In the Mt. Washington quadrangle (C. A. Chapman, Billings, R. W. Chapman, 1944) two unusual types appear. One, a hornblende-quartz monzonite (Table 5, column 6), which in places has large pink phenocrysts of potash feldspar, superficially

TABLE 5.—*Average modes, Oliverian magma series*

	1	2	3	4	5	6	7
Area*	10	30	25	15	2	5	13
Quartz	32	33	31	33	27	14	6
Plagioclase**	61_{35}	48_{22}	29_{24}	15_{20}	16_{18}	31_{33}	29_{21}
Potash feldspar	1	12	32	45	46	37	59
Olivine							
Pyroxene				tr			tr
Amphibole†	2	1		tr		12	3
Biotite	4	4	6	5	7	5	2
Muscovite	tr	tr	1	1	2		
Opaques: oxides	tr	1	tr	0.5	tr	tr	0.5
Opaques: sulphides		tr		tr 0.08	tr		
Apatite	tr	tr 0.07	tr	tr 0.05	tr	tr	tr
Zircon	tr	tr	tr 0.01	tr 0.01		tr 0.03	tr 0.06
Sphene	tr	tr	tr	tr	tr	1	tr
Epidote	tr	1	1	tr	1	tr	tr
Chlorite	tr	tr	tr	tr	1	tr	tr
Rutile	tr		tr	tr		tr	tr
Garnet	tr	tr	tr	tr			
Allanite	tr	tr	tr			tr	tr

* Rough estimate, given in per cent, total area occupied by this magma series being 100 per cent.
† Amphibole is always hornblende.
** The subscript indicates the average content of anorthite.

1. Quartz diorite.
2. Granodiorite.
3. Quartz monzonite.
4. Granite.
5. French Pond granite.
6. Hornblende-quartz monzonite.
7. Syenite.

resembles the Kinsman quartz monzonite and the Meredith granite. The second type is syenite (Table 5, column 7), composed of tabular pink crystals of potash feldspar that lie parallel to one another in many localities.

As Table 5 indicates, the accessories are opaques, apatite, zircon, sphene, epidote, garnet, rutile, and allanite. Comparatively few quantitative data are available. Magnetite, ranging on the average from a trace to 1 per cent, occurs as small octahedra 0.5 to 1 mm. in diamter. Chemical analyses of granodiorite and granite indicate, respectively, 0.07 and 0.05 per cent apatite. Unpublished spectrographic data for the Oliverian magma series in the Mt. Washington quadrangle indicate that zirconia is 0.01 per cent in quartz monzonite and granite, 0.02 per cent in hornblende-quartz monzonite, and 0.04 per cent in syenite; these figures indicate 0.01, 0.03, and 0.06 per cent of zircon, respectively in each of these three groups. Epidote, ranging from a trace to 1 per cent, is more abundant throughout the series as a whole than in the New Hampshire and White Mountain magma series.

EVOLUTION

The average modes have been plotted on one of the diagrams of Figure 3. Most of the rocks lie well to the left of the median line, the quartz content averaging about 30 per cent. In this respect, the Oliverian and New Hampshire magma series are alike. The syenite, which covers a large area in the Mt. Washington quadrangle, lies near the vertical median line.

C. A. Chapman (1939, p. 166–170) has suggested that most of the Oliverian magma series in the Mascoma quadrangle consolidated as granodiorite, much of which was later partially replaced by potash feldspar to produce quartz monzonite and granite. According to this hypothesis the series evolved from granodiorite through quartz monzonite to granite, but the process was replacement and not fractional crystallization. As Hadley (1942, p. 141) has suggested, the quartz diorite appears to represent a zone of mixed rocks between the granodiorite and the older Ammonoosuc volcanics. The parental granodiorite suggested by Chapman may have originated by melting, fractional crystallization, or some other process. Billings believes that the granite of the Mt. Washington quadrangle is not the result of replacement but consolidated from a granitic melt. In any case, as shown by the solid lines in Figure 3, the quartz monzonite and granite evolved from granodiorite, either through replacement or fractional crystallization. The quartz diorite is the result of assimilation. The syenite is well off the main line of descent and, if fractional crystallization was the principal evolutionary mechanism, must have followed a course similar to the syenites of the White Mountain magma series. The possible evolution of the Oliverian magma series from ancestral gabbro is shown in Fig. 3 by lines marked by queries.

RADIOACTIVITY

The radioactivity of the Oliverian magma series is listed in Table 6 and is presented graphically in Figure 6. The same generalizations may be made as for the younger magma series already described. Although individual specimens of a rock type show considerable range in radioactivity, the average values show a progressive increase from the quartz diorites to the granites, the latter being 2½ times as radioactive as the former. The lone determination for syenite falls considerably below the curve suggested by the other rocks, which was also true for syenite in the White Mountain magma series.

TABLE 6.—*Radioactivity of the Oliverian magma series*

Lithology	Number of specimens	Radioactivity: alpha particles emitted per milligram of rock per hour	
		RANGE	AVERAGE
Quartz diorite	4	0.61–1.60	1.04 ±0.15
Granodiorite	6	0.59–3.07	1.35 ±0.25
Quartz monzonite	4	2.59–3.00	2.76 ±0.07
Granite	11	1.29–4.49	2.67 ±0.18
Syenite	1	1.77	1.77
Hornblende-quartz monzonite	2	1.29–2.44	1.86 ±0.39
Combinations of some of above types:			
Quartz monzonite	6	1.29–3.00	2.46 ±0.52

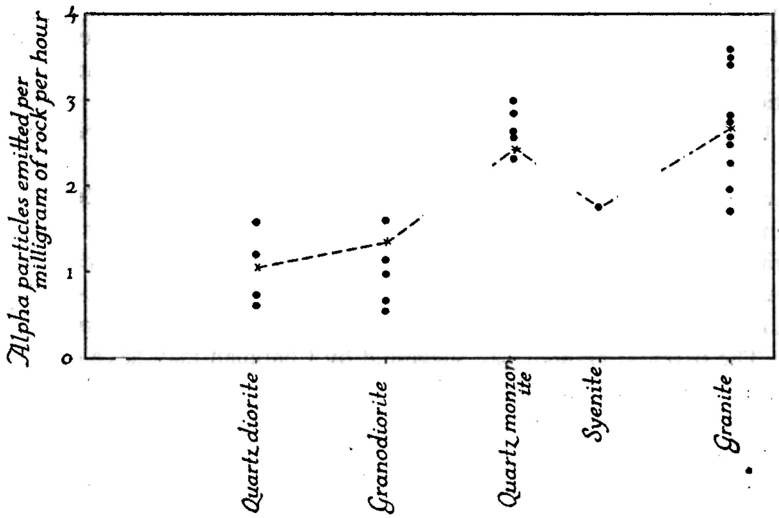


FIGURE 6.—*Radioactivity of Oliverian magma series*

Each dot represents one specimen. Each cross represents the average for the rock type indicated in the abscissa.

Quantitative data on the percentages of accessory minerals in the rocks of the Oliverian magma series are inadequate to justify any discussion of the cause of the high radioactivity of the granitic end of the series compared with the quartz diorite end.

HIGHLANDCROFT MAGMA SERIES

GENERAL STATEMENT

The late Ordovician (?) subalkaline Highlandcroft magma series occurs in three areas near the Connecticut River. In the Mt. Cube and Littleton quadrangles the plutons are 5 to 7 miles long and 2 miles wide, but some of the contacts of the mass in the Percy quadrangle are beyond the limits of the area mapped. Little is known about the original shape of these bodies, because they have been considerably modified by the Acadian folding. They are truncated on the east by the Ammonoosuc thrust, and the body in the Littleton quadrangle is overlain unconformably by Silurian strata.

TABLE 7.—*Average modes, Highlandcroft magma series*

Area*	5	30	30	30	5
Quartz	1	30	15	30	24
Plagioclase***	50_{10}	45_{10}	25_{10}	18_{10}	14_{5}
Potash feldspar			22	30	51
Olivine					
Pyroxene					
Amphibole†	20				
Biotite				9	4
Muscovite**				7	4
Opaques: oxides	2	2	tr	tr	
Opaques: sulphides					
Apatite				tr	
Zircon				tr	
Sphene			tr	tr	
Epidote††	25	4	8	4	
Chlorite		7	2	1	
Calcite	2	2	3	1	
Rutile					

* Rough estimate, given in per cent, total area occupied by this magma series being 100 per cent.
† Amphibole is always hornblende.
** Actually sericite.
†† Also zoisite.
*** The subscript indicates the average content of anorthite.

1. Diorite.
2. Quartz diorite.
3. Granodiorite. Biotite is pleochroic green, secondary mineral.
4. Quartz monzonite.
5. Granite.

PETROGRAPHY

The rocks have been classified as diorite, quartz diorite, granodiorite, quartz monzonite, and granite. The average modes, given in Table 7, reflect the fact that these rocks have undergone low-grade metamorphism. The original plagioclase, probably andesine, has been saussuritized to a mixture of albite-oligoclase, epidote, and sericite. The biotite, pleochroic in shades of green in thin section, is secondary. The hornblende and potash feldspar are primary minerals, but the chlorite and calcite are secondary. The accessories are listed in Table 7, but no supplementary data concerning them are available.

EVOLUTION

In one of the diagrams in Figure 3, the amount of quartz in this magma series has been plotted against the ratio of potash feldspar to total feldspar. The points occupy positions similar to those of the New Hampshire magma series, but somewhat nearer the median line—that is, in general the rocks of the Highlandcroft magma series have

TABLE 8.—*Radioactivity of the Highlandcroft magma series*

Lithology	Number of specimens	Radioactivity: alpha particles emitted per milligram of rock per hour	
		RANGE	AVERAGE
Diorite	1	0.59	
Quartz diorite	1	0.58	
Granodiorite	2	1.21–1.68	

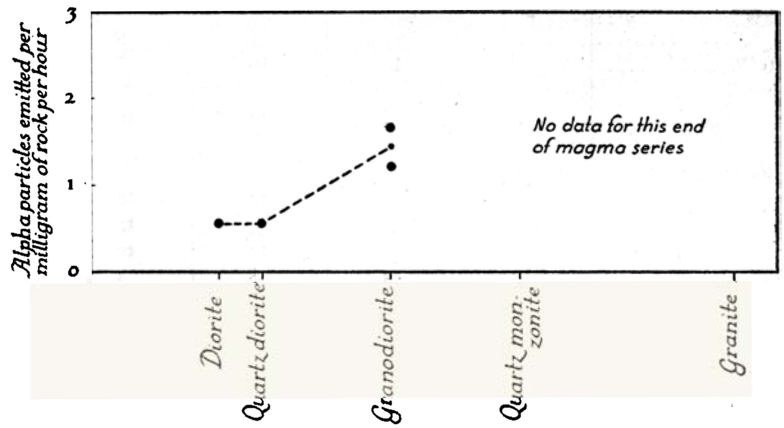


FIGURE 7.—*Radioactivity of Highlandcroft magma series*
Each dot represents average for one specimen. Asterisk is average value for granodiorite.

less quartz. A difference that this diagram does not bring out is that hornblende persists into the granodiorite stage in the Highlandcroft magma series, whereas biotite appears in the quartz diorite stage in the New Hampshire magma series.

The possible evolution of the magma series by fractional crystallization is indicated by the arrows in Figure 3.

RADIOACTIVITY

Data, available for only four specimens of the Highlandcroft magma series, are listed in Table 8 and are given graphically in Figure 7. The data indicate an increase in radioactivity from diorite to granodiorite. Specimens of quartz monzonite and granite were not available for study.

COMPARISON OF THE RADIOACTIVITY OF THE FOUR MAGMA SERIES

DATA

In Figure 8 the radioactivity curves for the four magma series have been assembled from Figures 4, 5, 6, and 7. It will be recalled from the previous discussion of the individual series that these curves are based on average values for each rock type. The curves are fairly complete except that data are unavilable for the granitic end

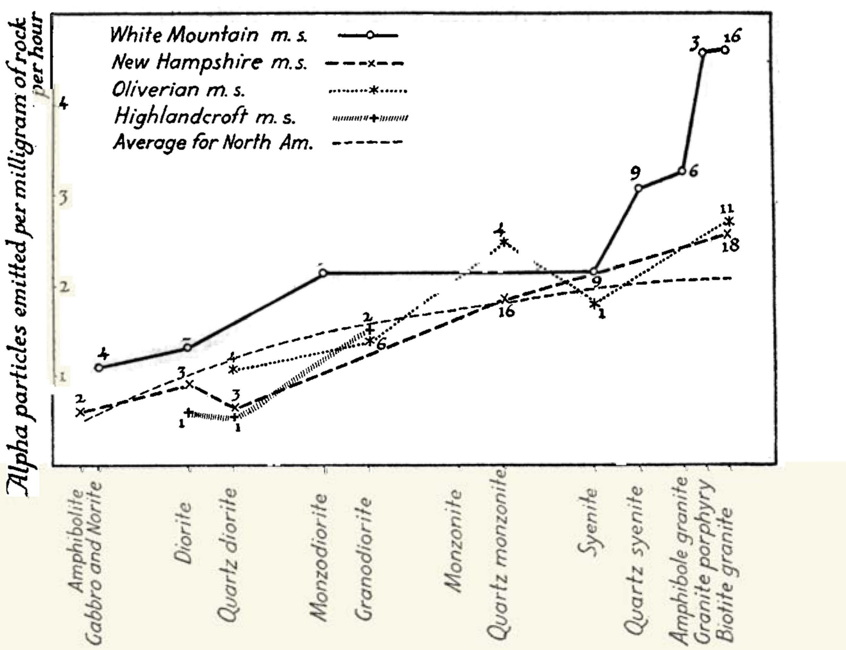


FIGURE 8.—*Comparative radioactivity of the four magma series*

Curves taken from Figures 3, 4, 5, and 6. Arabic numeral near each symbol gives number of specimens averaged to obtain value.

of the Highlandcroft magma series. A distinctive symbol, indicated in the legend, is used for each magma series. The numeral near each symbol shows the number of individual specimens averaged to obtain the value of the radioactivity. The reader can thus judge for himself how much emphasis should be placed on each point.

Smoother curves could, of course, be drawn, but, inasmuch as the data upon which they are based are averages, it seemed advisable to draw straight lines between points. Moreover, this method emphasizes the somewhat erratic character of the radioactivity. The reader can readily visualize what the smoother curves would look like.

The curves emphasize a point already brought out, the fact that the radioactivity increases from the gabbro-diorite to the granite end of each series, the increase being 4.15 times in the White Mountain magma series, 4.24 times in the New Hampshire magma series, and 2.57 times in the Oliverian magma series.

In both the White Mountain and Oliverian magma series the syenites produce a downward bend in the curve, indicating a radioactivity lower than the rest of the curve would suggest. Perhaps the curve for the New Hampshire magma series would show a similar depression if syenite were present.

The White Mountain magma series is considerably more radioactive than the other magma series. Its alpha activity averages 0.7 unit greater than that of the New Hampshire magma series. At the ends of the curves the White Mountain magma series is twice as radioactive as the New Hampshire magma series. The two curves are together only at the syenite stage, but, as pointed out in the preceding paragraph, this part of the curve for the New Hampshire magma series is not necessarily correct.

The curve for the Oliverian magma series lies, on the average, about 0.2 unit above that for the New Hampshire magma series. The greatest difference is at the quartz monzonite stage, where the curve for the Oliverian magma series is 0.62 unit above the curve for the New Hampshire magma series. At the syenite stage the Oliverian curve is actually below the New Hampshire curve, but this is not very significant, for only one specimen of the Oliverian magma series was tested, and the New Hampshire magma series lacks syenites.

The incomplete curve for the Highlandcroft magma series indicates that it is similar to the New Hampshire magma series.

REASON FOR GREATER RADIOACTIVITY OF GRANITIC ROCKS

The reasons for the progressive increase in radioactivity toward the granitic end of each of the four magma series has been discussed somewhat in the earlier sections of this paper. It is definitely not due to an increase in the content of potash. The most potassic rocks, the syenites, do not show the maximum radioactivity; in fact, they have an abnormally low radioactivity. The increased radioactivity is also not due to an increase in the biotite content of the rocks. In the White Mountain and New Hampshire magma series the radioactivity is inversely proportional to the content of biotite. Even in the Oliverian magma series the increase in biotite toward the granitic end of the series is slight. Apatite in many cases is one of the more radioactive minerals (Keevil, Larsen, and Wank, 1944). In the White Mountain magma series the content of apatite decreases as radioactivity increases. It is apparent, therefore, that the increase in radioactivity is associated with a decrease in the content of potash feldspar, biotite, and apatite.

In the White Mountain magma series it is well established that allanite, a radioactive mineral, appears in the granitic end of the series and is a conspicuous accessory. Moreover, there is an indication that the amount of zircon increases toward this end of the series. In the Oliverian magma series the few available data also indicate that the amount of apatite does not increase toward the granitic end of the series; moreover, the amount of zircon is apparently inversely proportional to the radioactivity. Therefore, except for the White Mountain magma series, data are insufficient to state whether the radioactive accessories increase in quantity toward the granitic end of the series.

It is obvious, however, that the radioactive chemical elements increase toward the granitic end of the series. It may be that some of the minerals in the granitic end of the series contain a higher percentage of radioactive elements than the same minerals possess in the gabbroic end, due to a relatively higher concentration of radioactive elements in the later magma.

To solve this problem would involve extensive spectrographic investigation, separation of accessory minerals, and a study of their radioactivity.

GREATER RADIOACTIVITY OF THE WHITE MOUNTAINS MAGMA SERIES

The White Mountain magma series averages nearly twice as radioactive as the New Hampshire magma series. Inasmuch as the White Mountain magma series is the youngest magma series in the area, we must consider the quantitative effect of the decrease in radioactivity due to age. That is, if two equally radioactive magma series were intruded a billion years apart, the older one would be less radioactive at the present time because of its greater age. Actually, this is a minor factor in considering the magma series of New Hampshire. Inasmuch as the half-life period of uranium is 4.56×10^9 years, every 100 million years approximately 1 per cent of the uranium would disintegrate and the radioactivity would decrease by 1 per cent. At first the rate of disintegration would be nearly twice this amount. The White Mountain magma series is Mississippian (?), and the New Hampshire magma series is late Devonian (?). The difference in age is therefore at the most only a few tens of millions of years. We might expect the New Hampshire magma series to be a fraction of 1 per cent less radioactive than the White Mountain magma series, whereas actually the former is half as radioactive as the latter. The half-life period of thorium is 13×10^9 years; consequently, it would "run down" much more slowly than uranium.

The White Mountain magma series is more radioactive than the other series, either because it contains a greater quantity of radioactive minerals or because its minerals contain a higher proportion of radioactive elements. The granitic end of the White Mountain magma series contains a larger percentage of radioactive accessories than the other magma series. Allanite is common at the granitic end of the White Mountain magma series but is absent or exceedingly rare in the other magma series. Moreover, chemical analyses indicate that zircon is more abundant at the granitic end of the White Mountain magma series than in the corresponding rocks of the Oliverian magma series; chemical data are absent for the New Hampshire magma series. It appears, therefore, that the granitic end of the White Mountain magma series contains a higher percentage of radioactive minerals than the other magma series, and this is why it is more radioactive.

No data are available concerning the relative abundance of radioactive accessory minerals for the gabbro-diorite end of the New Hampshire magma series, and thus a comparison with the White Mountain magma series is impossible.

The fact that the gabbro-diorite end of the White Mountain magma series is nearly twice as radioactive as similar rocks in the New Hampshire magma series implies that the greater radioactivity of the White Mountain magma series has been inherited from the original gabbro magma from which it has been derived by fractional crystallization. This in turn implies that two different levels of the crust were tapped to give the two different magma series. This is in harmony with the contrasting tectonic behavior of the two magma series, for the New Hampshire magma series is syntectonic, whereas the White Mountain magma series is post-tectonic.

RADIOACTIVITY OF ROCK TYPES WITHOUT REGARD TO MAGMA SERIES

Table 9 lists the radioactivity of each rock type regardless of magma series. The number of specimens entering the averages are also shown. These averages show, of course, the same increase toward the granites as did the individual magma series, granite being more than three times as radioactive as the gabbro and diorite.

ABLE 9.· *Average radioactivity without regard to magma series*

Rock	Number of specimens in average	Radioactivity: alpha particles emitted per milligram of rock per hour	
		Range	Average
Plutonic rocks			
Gabbro	3	0.70–1.82	1.28 ±0.22
Norite (Hypersthene diorite)	1	0.56	0.56
Amphibolite	2	0.33–0.85	0.59 ±0.17
Diorite	6	0.31–1.73	0.98 ±0.15
Quartz diorite	8	0.15–1.60	0.81 ±0.10
Granodiorite	8	0.59–3.07	1.37 ±0.19
Monzodiorite	3	1.05–4.01	2.14 ±0.63
Quartz monzonite	22	0.94–3.00	2.01 ±0.08
Syenite	9	0.79–5.03	2.22 ±0.32
Nepheline-sodalite syenite	1	1.17	1.17
Quartz syenite	9	1.60–5.12	3.09 ±0.80
Granite	55	1.29–8.69	3.36 ±0.12
Dike rocks			
Bostonite	1	1.75	1.75
Paisanite	1	5.61	5.61
Aplite	1	2.56	2.56
Nepheline syenite	1	0.99	0.99
Total	131		

4 specimens of Chatham group not included because of inadequate petrographic data

AVERAGE RADIOACTIVITY OF INTRUSIVE ROCKS IN NEW HAMPSHIRE

The average of the 135 specimens, each specimen equally weighted, is 2.44 alpha particles per milligram of rock per hour. In a second average each rock type was weighted according to the area it covers. Rough estimates of the area underlain by each rock type in each of the four magma series have been listed in Tables 1, 3, 5, and 7. For each magma series the area occupied by a rock type is given as a per cent of the total area occupied by that magma series. The White Mountain magma series is estimated to occupy 31.5 per cent of the plutonic area of Figure 1, the New Hampshire magma series occupies 42 per cent, the Oliverian magma series covers 25 per cent, and the Highlandcroft magma series occupies 1.5 per cent. The average radioactivity, weighted by area, for the terrain covered by Figure 1, is 2.45 alpha particles per milligram of rock per hour. This is almost identical with the average obtained merely by averaging the 135 specimens without regard to area. At first glance this agreement might seem to be fortuitous, but it is primarily due to the fact that the number of specimens studied for each rock type was roughly proportional to the area covered by that rock. Many specimens of rock types that cover large areas were studied, whereas comparatively few specimens of rock types covering small areas were investigated. There were a few exceptions.

TABLE 10.—*Average amounts of uranium and thorium in New Hampshire rocks in weight per cent**

	Uranium	Thorium
Gabbro	0.00020	0.00065
Norite	0.00009	0.00028
Amphibolite	0.00009	0.00030
Diorite	0.00015	0.00050
Quartz diorite	0.00012	0.00041
Granodiorite	0.00021	0.00070
Monzodiorite	0.00033	0.00109
Quartz monzonite	0.00031	0.00102
Syenite	0.00034	0.00113
Nepheline-sodalite syenite	0.00018	0.00059
Quartz syenite	0.00048	0.00157
Granite	0.00052	0.00170
Average	0.00038	0.00124
Lowest value	0.00002	0.00008
Highest value	0.00134	0.00442

* Based on the assumption that Th/U = 3.3. Although this ratio shows considerable range, the values are concentrated around 3.3 to such an extent that the error in the values given for U and Th would generally not exceed 25 per cent.

COMPARISON WITH OTHER AREAS IN NORTH AMERICA

One of the curves in Figure 8 is based on averages for several thousand igneous rocks from all of North America. It is apparent that the curve for the New Hampshire magma series lies close to the North American average. The incomplete data for the Highlandcroft magma series suggest that these rocks are also close to the average for the continent. The Oliverian magma series lies somewhat above the North American average. The White Mountain magma series, however, is twice as radioactive as the average igneous rock elsewhere in North America.

QUANTITY OF URANIUM AND THORIUM

The amount of uranium and thorium in rocks may be calculated from the alpha activity if the following assumptions are correct: (a) all the alpha particles emitted are derived from either the uranium series or the thorium series; (b) the ratio of thorium to uranium is 3:3; (c) both uranium and thorium are in equilibrium with all members of their series. The equations are:

$$U = 1.540 \times 10^{-6}\alpha \quad (1)$$
$$Th = 3.3\,U \quad (2)$$

where U = uranium in grams per gram of rock
Th = thorium in grams per gram of rock
α = number of alpha particles emitted per milligram of rock per hour.

In order to calculate the amounts of uranium and thorium in weight per cent, the factor 10^{-4} is used instead of 10^{-6}. The data are given in Table 10, where the average amount of uranium and thorium for each rock type have been calculated from the average alpha activity as given in the last column of Table 9.

CONCLUSIONS

Specimens obtained from a single rock type, such as the biotite granite (Conway granite) or the Kinsman quartz monzonite, show considerable range in radioactivity. In extreme cases the difference between the most radioactive and the least radioactive specimens from a rock type is five fold, and on the average is two to three fold. It is apparent, therefore, that a single determination for a rock type is not significant, and ordinarily several determinations of the radioactivity should be made.

Average values for each rock type show that there is a progressive, although somewhat erratic, increase in radioactivity from the gabbro end of each magma series to the granitic end, the latter being three to four times as radioactive as the former.

The reason for this increase in radioactivity toward the granitic end of the series is not always clear. It is not associated, as some results in other areas suggest, with an increase in potash feldspar, biotite, or apatite. In the White Mountain magma series the radioactive minerals, especially allanite and probably zircon, increase in quantity toward the granitic end of the series. In the other magma series no conclusive evidence was found for an increase in the quantity of the radioactive minerals. It is possible, of course, that the radioactive minerals are not more abundant in the granitic rocks, but that the radioactive elements in these minerals are more abundant because of the increased concentration of radioactive elements in the magma at the time these minerals separated.

The alkalic White Mountain magma series is twice as radioactive as the other magma series. Paradoxically, however, the most alkalic rocks within this series—nepheline-sodalite syenite and riebeckite granite—are relatively low in radioactivity; lower than usual for syenitic rocks. Apparently the ancestral magma from which this series was derived was more radioactive than the magma from which the older magma series were derived. It is possible that a different layer of the crust was tapped during the evolution of the White Mountain magma series from that tapped during the eruption of the older magma series.

REFERENCES CITED

Billings, M. P. (1928) *The petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts Sci., Pr., vol. 63, p. 67–137.

——— (1934) *Paleozoic age of the rocks of central New Hampshire*, Sci., vol. 79, p. 55–56.

——— (1937) *Regional metamorphism of the Littleton-Moosilauke area, New Hampshire*, Geol. Soc. Am., Bull., vol. 48, p. 463–566.

——— (1941) *Structure and metamorphism in the Mount Washington area, New Hampshire*, Geol. Soc. Am., Bull., vol. 52, p. 863–936.

——— (1945) *Mechanics of igneous intrusion in New Hampshire*, Am. Jour. Sci., vol. 243-A, p. 40–68.

Bowen, N. L. (1928) *The evolution of the igneous rocks, Princeton Univ. Press*, Princeton, New Jersey.

Chapman, C. A. (1939) *Geology of the Mascoma quadrangle, New Hampshire*, Geol. Soc. Am., Bull., vol. 50, p. 127–180.

———, Billings, M. P., and Chapman, R. W. (1944) *Petrology and structure of the Oliverian, magma series in the Mount Washington quadrangle, New Hampshire*, Geol. Soc. Am., Bull., vol. 55, p. 497–516.

Chapman, R. W. (1934) *Geology of the Percy quadrangle, New Hampshire*, Doctorate thesis, Harvard Univ.

——— (1935) *Percy ring-dike complex*, Am. Jour. Sci., 5th ser., vol. 30, p. 401–431.

——— (1937) *Petrology of the syenite stock at Cherry Mountain, New Hampshire*, Am. Jour. Sci. 5th ser., vol. 33, p. 174–186.

——— (1942) *Ring structures of the Pliny region, New Hampshire*, Geol. Soc. Am., Bull., vol. 53, p. 1533–1568.

——— and Williams, C. R. (1935) *Evolution of the White Mountain magma series*, Am. Mineral., vol. 20, p. 502–530.

Dale, T. N. (1923) *The commercial granites of New England*, U. S. Geol. Survey, Bull. 738, 488 pages.

Fowler-Billings, K. (1944) *Sillimanite deposits in the Monadnock quadrangle, New Hampshire*, N. H. State Planning and Devel. Comm., Mineral Res. Survey.

——— and Page, L. R. (1942) *The geology of the Cardigan and Rumney quadrangles, New Hampshire, N. H. State Planning and Devel. Comm.*, 1942.

Hadley, J. B. (1942) *Stratigraphy, structure, and petrology of the Mt. Cube area, New Hampshire*, Geol. Soc. Am., Bull., vol. 53, p. 113–176.

Hawes, G. W. (1879) *On a group of dissimilar eruptive rocks in Campton, New Hampshire*, Am. Jour. Sci., 3d ser., vol. 17, p. 147–151.

Jenks, W. F. (1934a) *Heavy minerals in the syenites of Pleasant Mtn., Maine*, Am. Mineral., vol. 19, p. 476–479.

——— (1934b) *Petrology of the alkaline stock at Pleasant Mtn., Maine*, Am. Jour. Sci., 5th ser., vol. 28, p. 321–340.

Kaiser, E. P. (1938) *Geology of the Lebanon granite, Hanover, N. H.*, Am. Jour. Sci., vol. 36, p. 107–136.

Keevil, N. B. (1938) *The application of the helium method to granites*, Roy. Soc. Canada, Tr., 3rd ser., sec. IV, vol. 32, p. 123–150.

——— (1943) *Radiogenic heat in rocks*, Jour. Geol., vol. 51, p. 287–300.

——— and Grasham, W. E. (1943) *Theory of Alpha-ray counting from solid sources*, Canad. Jour. Res., vol. A21, p. 21–36.

———, Larsen, E. S., and Wank, F. J. (1944) *The distribution of helium and radioactivity in rocks. VI. The Ayer granite-migmatite at Chelmsford, Mass.*, Am. Jour. Sci., vol. 242, p. 345–353.

Kingsley, L. (1931) *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 22, p. 139–168.

Kruger, F. C. (1941) *Structure and metamorphism of the Bellows Falls quadrangle, New Hanpshire and Vermont*, Doctorate thesis, Harvard Univ.