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RING-DIKE COMPLEX OF THE BELKNAP MOUNTAINS, NEW HAMPSHIRE

BY

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INTRODUCTION

LOCATION

The Belknap Mountains are on the southwestern shore of Lake Winnepesaukee, in central New Hampshire. The district of which the geology has been mapped is slightly over one hundred square miles in area and includes adjacent parts of the Winnepesaukee, Gilmanton, Alton, and Wolfeboro topographic sheets.

IMPORTANCE OF THE AREA AND SCOPE OF THIS PAPER

The Belknap area is of particular interest to the petrographer and structural geologist. The structure is that of a ring-dike complex; and, although similar features have been observed and described elsewhere in New Hampshire, notably in the Ossipee Mountains,[1] the Percy area,[2] and the Franconia quadrangle,[3] many features are better exposed in the Belknap area. The lithologic sequence is more readily determined, and the exposures are better. The rocks are largely igneous; the most unusual are those belonging to the White Mountain (alkaline) magma series,[4] which includes gabbro, diorite, monzodiorite, syenite, quartz syenite, and granite. A suite of crush-rocks, including mylonite, flinty crush-rock, and pseudotachylite, is also well displayed. The present paper is concerned only with the bedrock geology.

PHYSICAL FEATURES AND EXPOSURES

The Belknap Mountains are the dominant physical feature of the area. They are roughly elliptical in shape, with a northwest-southeast axis about 8 miles long and a northeast-southwest axis about 5½ miles long. The highest point is Belknap Mountain, with an elevation of 2378 feet; and the total relief in the district is 1874 feet. Careful inspection shows curvi-

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[1] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 12 (1931) p. 134-167.

[2] Randolph Chapman: *Percy ring-dike complex*, Am. Jour. Sci., 5th ser., vol. 30 (1935) p. 401-431.

[3] Marland Billings and C. R. Williams: *Geology of the Franconia quadrangle, New Hampshire*, State Planning and Development Commission, Concord (1935).

[4] Marland Billings: *Paleozoic age of the rocks of central New Hampshire*, Science, vol. 79 (1934) p. 55-56.

linear topographic patterns, which are the surface expression of the markedly annular structure of the district.

Much of the Belknap area is heavily wooded, so that the search for outcrops is greatly impeded. Generally, exposures are sufficiently numerous to permit rather accurate delineation of the rock units, but thick masses of glacial till locally conceal the bedrock. Many of the higher summits, however, are abandoned pasture lands from which much of the soil has been removed; broad, barren ledges are common.

ACKNOWLEDGMENTS

The area was suggested to the writer by Professor R. A. Daly. The work was done under the direction of Professor E. S. Larsen, who spent several days in the field with the writer, during the summers of 1929 and 1930. Professor Daly visited the gabbro stock in the northern part of the area with the writer, in the summer of 1931. The field and structural studies have been greatly aided by the interest and assistance of Professor Marland Billings, who worked in the field with the writer, for two weeks during the summers of 1930 and 1931. Field expenses for the summers of 1930 and 1931, the cost of four new chemical analyses, and the preparation of the thin-sections necessary for the investigation, were defrayed through grants from the funds of the Department of Mineralogy, Harvard University, under the bursarship of Professor Charles Palache.

Through the courtesy of Professor Adolph Knopf, of Yale University, the writer was permitted to examine the collection of rocks assembled by L. V. Pirsson and H. S. Washington [5] in connection with their investigation of the Belknap Mountains.

Professor Marland Billings, Mr. Carleton Chapman, and Mr. Walter White have aided materially in preparing this paper for publication. Mr. Edward Schmitz drafted the figures.

The writer wishes to express his sincere thanks; he gratefully acknowledges the continued inspiration and encouragement of those who have been interested in the progress of this investigation.

PREVIOUS WORK

The earliest reference to the geology of the Belknap area was made in 1844, by C. T. Jackson,[6] who noted the syenites. C. H. Hitchcock,[7] in his monumental work on the geology of New Hampshire, shows the Belknap Mountains as a body of syenite, with two included masses of

[5] L. V. Pirsson and H. S. Washington: *Contributions to the geology of New Hampshire, I. Geology of the Belknap Mountains*, Am. Jour. Sci., 4th ser., vol. 20 (1905) p. 344-352; II. *Petrography of the Belknap Mountains*, Am. Jour. Sci., 4th ser., vol. 22 (1906) p. 439-457, 493-514.

[6] C. T. Jackson: *Final report on the geology and mineralogy of the State of New Hampshire* (1844). Concord.

[7] C. H. Hitchcock: *Geology of New Hampshire*, 3 vols. (1874, 1877, 1878).

porphyritic gneiss. The suggestion is made that the syenites originated by "extrusion through a synclinal fault." Since 1906, the chief sources of detailed information have been the papers by Pirsson and Washington,[8] whose descriptions and interpretations differ greatly from the conclusions reached by the writer.

The work of Marland Billings,[9] on the petrology of the North Conway quadrangle, New Hampshire, is concerned with rocks closely related to those found in the Belknap Mountains, and has been an invaluable aid during the course of this investigation. The Ossipee Mountains, 10 miles northeast of the Belknap Mountains, across Lake Winnepesaukee, have recently been studied in detail by Louise Kingsley,[10] who has shown them to consist of an essentially circular ring-dike of Albany porphyritic nordmarkite (quartz syenite), with an interior area of subsidence composed of Moat volcanics, and a central intrusion of Conway (biotite) granite. In lithology and structure, the Ossipee Mountains bear a remarkable resemblance to the Belknap Mountains.

Since the original manuscript of this paper was written in the spring of 1933, rocks and structures similar to those in the Belknap area have been described from other districts in New Hampshire, notably the Percy area by Chapman[11] and the Franconia quadrangle by Billings and Williams.[12] Chapman and Williams,[13] moreover, have discussed the origin of the White Mountain magma series.

GENERAL LITHOLOGIC FEATURES

The complex rocks in the Belknap area belong to four major groups: (1) Rockingham schists; (2) intrusives of the New Hampshire magma series; (3) extrusive and intrusive rocks of the White Mountain magma series; and (4) glacial drift.

The Rockingham schists are intensely deformed katazonal mica schists containing such minerals as muscovite, biotite, quartz, sillimanite, andalusite, and garnet. They are believed to be of Devonian or Carboniferous age.

The New Hampshire magma series is of late Devonian or Carboniferous age and, in this area, consists of two major groups, the Chatham group (quartz diorite, granodiorite, and quartz monzonite) and the Meredith porphyritic granite.

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[8] L. V. Pirsson and H. S. Washington: *op. cit.*

[9] Marland Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 67, 137.

[10] Louise Kingsley: *op. cit.*

[11] Randolph Chapman: *op. cit.*, p. 401-431.

[12] Marland Billings and C. R. Williams: *op. cit.*

[13] R. W. Chapman and C. R. Williams: *Evolution of the White Mountains magma series*, Am. Mineral., vol. 20 (1935) p. 502-530.

The rocks of the White Mountain magma series are the most unusual in the area, not only in their variety and alkaline tendencies, but also in the structural relations of the intrusives, many of which are ring-dikes. This series is probably of Carboniferous age. Extrusive types are represented by the Moat volcanics. Intrusive types are represented by the Gilford gabbro, Endicott diorite, Ames monzodiorite, Gilmanton monzodiorite, Belknap syenite, Sawyer quartz syenite, Lake quartz syenite, Albany quartz syenite, Conway granite, and Rowes vent agglomerate. In the Pine Mountain-Rocky Mountain area, a group of quartz porphyries and granite porphyries has been mapped as a unit.

The glacial drift, of Pleistocene age, consists of both till and outwash, but has not been studied in any detail.

ROCKINGHAM MICA SCHIST

On the older geological maps,[14] the crystalline schists of the Belknap Mountains were divided into two groups, the "Rockingham mica schist" and the "Montalban series." As the present study has revealed no real difference between the schists in different parts of the area, they are here treated as a single unit, under the name Rockingham mica schist. The Montalban was originally defined by Hitchcock as a series that contained "beds" of granite and gneiss, and it is likely that good exposures of these intrusions southwest of Belknap Mountain led him to divide the schists into two series.

The age of these schists is unknown. Billings[15] has shown that the mica schists of Mt. Moosilauke are of lower Devonian age. The schists of the Belknap area do not differ materially from them, but, as yet, no one has performed the difficult task of correlation with the Belknap Mountains.

The schists usually vary considerably in composition, and the different types are interbedded in strata, a few inches to a few feet thick. Schistosity is generally parallel to the bedding. The rocks are strongly folded, and rapid variations in dip and strike are common. The essential minerals are quartz, muscovite, biotite, sillimanite, andalusite, garnet, and chlorite; the minor accessories are albite-oligoclase, sericite, zircon, spinel, titanite, corundum, pyrrhotite, and orthoclase. In general, it is a katazonal assemblage, with the exception of the chlorite and sericite, which are, in large part, probably of retrogressive origin. The modes of the various types of schists have been assembled in Table 1.

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[14] C. H. Hitchcock: *op. cit.*
L. V. Pirsson and H. S. Washington: *op. cit.*

[15] Marland Billings and Arthur Cleaves: *Brachiopods from mica schist, Mt. Clough, N. H.*, Am. Jour. Sci., 5th ser., vol. 30 (1935) p. 534.

TABLE 1.—*Modes of the Rockingham schists*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Quartz	20	55	50	50	48	50	50
Muscovite	50						
Biotite	25	35*	20	45	37	40	50*
Sillimanite	2		10	5	25	5	
Andalusite	3		5				
Sericite		7				5	
Garnet		3					
Unknown			15				
Texture	Gr; Po	Le	Gr; Fi	Gr	Fi	Gr	Le

* Includes chlorite.

Textural abbreviations: Gr-granoblastic, po-poikiloblastic, le-lepidoblastic, fi-fibroblastic.

[1] Muscovite-biotite-quartz-andalusite-sillimanite schist. Accessories: magnetite, untwinned plagioclase, sericite. Avery Mountain, north slope.

[2] Quartz-chlorite-biotite-garnet schist. Accessories: magnetite, zircon, albite-oligoclase. Pine Mountain, south slope.

[3] Biotite-andalusite-quartz-sillimanite schist. Accessories: spinel, zircon, titanite, magnetite, corundum, pyrrhotite, potash feldspar. Guinea Lake, partly submerged ledge.

[4] Biotite-chlorite-quartz-sillimanite schist. Accessories: magnetite, feldspar, zircon. Durrel Brook, elevation 890′.

[5] Biotite-sillimanite-quartz schist. Accessories: feldspar, magnetite, andalusite. Piper Mountain, west slope.

[6] Biotite-quartz-sillimanite-garnet-sericite schist. Accessories: magnetite, zircon, chlorite. Piper Mountain, west slope, interbedded with #5.

[7] Quartz-chlorite-biotite schist. Accessory: sericite. Cotton Hill.

The original sediments are inferred to have been a diverse series of sandstone, shale, siliceous shale, and feldspathic sandstone.

A detailed study of the garnet in the schists of this area has apparently never been made, so garnet from a schist at an altitude of 1390 feet on the west slope of Piper Mountain was isolated for special study. The forms are either the trapezohedron (211) alone or in combination with the dodecahedron. Most of the dodecahedron forms are only imperfectly developed, and the faces are generally small and striated. The color is violet to lavender-red, and the material fuses to a black metallic globule, at slightly above three in the scale of fusibility. The borax bead test indicates the presence of iron, and in sodium carbonate there is a faint reaction for manganese. The specific gravity is 4.23. The index of refraction for sodium light is 1.815. The chemical composition is given in Table 3.

Calculation of the analysis in terms of the various garnet molecules shows that there is a small excess of alumina, ferric oxide, and silica, above that required by the garnet; this is probably due to a small amount of fine-grained biotite contained in the garnet; without this, the percentages of the different garnet molecules are found to be as follows:

Almandite	85.3
Spessartite	11.7
Pyrope	1.9
Grossularite	1.1
	100.0

Thus, the garnet of the Rockingham schists is an almandite, with a small proportion of spessartite.

NEW HAMPSHIRE MAGMA SERIES

GENERAL FEATURES

The name New Hampshire magma series has been applied [16] to a group of intrusive igneous rocks that are younger than the Ordovician (?), Silurian, and Devonian strata of New Hampshire, but are definitely older than the Moat volcanics and the intrusive members of the White Mountain magma series. The New Hampshire magma series differs from the White Mountain magma series in that muscovite is present in many of the members, and pyroxene and amphibole are absent except in the most basic types. Olivine, fayalite, hastingsite, riebeckite, hedenbergite, nepheline, and analcime are completely lacking. Some of the members are distinctly gneissic; pegmatites are abundant. In the Belknap area, this series is represented by the Chatham group,[17] the Meredith porphyritic granite,[18] and pegmatites. These groups, although petrographically distinct, are so intimately associated in the field that it has not proved feasible to distinguish them on the geological map.

CHATHAM GROUP

In the Belknap area, the Chatham group consists of white or gray, medium-grained, massive to weakly gneissic rocks, granitic in appearance. Petrographic study shows, however, that plagioclase is more common than potash feldspar, and the rocks should be classified as quartz diorite, granodiorite, and quartz monzonite. Biotite is the only ferromagnesian mineral present. The exact relationship existing between the different petrographic types is not clear. In some cases, they may be variants of the same intrusive, but in one instance, at least, it can be demonstrated that one type intrudes another. Near Woodhaven on the Lake Shore road, opposite Minge Cove, gray quartz diorite is found as inclusions in a light-colored perthite-quartz monzonite.

[16] Marland Billings: *Paleozoic age of the rocks of central New Hampshire*, Science, n.s., vol. 79 (1934) p. 55-56.

[17] Marland Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 82.

[18] *Op. cit.*, p. 83.

Modes of the more common types are given in Table 2. The quartz diorite is found in scattered outcrops along the southwest shore of Lake Winnepesaukee, east and northeast of the Belknap Range. The microcline granodiorite exists as a distinct rock mass only on the south shore of Rattlesnake Island, where the total area exposed is about half a

TABLE 2.—*Modes of the Chatham group*

	(1)	(2)	(3)	(4)
Andesine	70			34
Oligoclase-andesine		50		
Oligoclase			30	
Microcline		15		
Perthite			40	33
Quartz	15	25	27	30
Biotite	15	10	3	3

[1] Quartz diorite, from Minge Cove; somewhat gneissic; andesine-Ab_{65} An_{35}. Accessories: apatite, sericite, chlorite, magnetite. Fabric: seriate granitic.

[2] Microcline granodiorite, from south shore of Rattlesnake Island. Plagioclase—Ab_{70} An_{30}. Accessories: zircon, sphene, sillimanite, apatite, muscovite, sericite, chlorite. Fabric: coarse granular.

[3] Perthite-quartz monzonite, from Lake Shore road opposite Minge Cove. Accessories: apatite and chlorite. Fabric: seriate granular.

[4] Perthite granodiorite. Accessories: zircon, chlorite, magnetite, muscovite-sericite, apatite. Fabric: approximately equigranular.

square mile. The perthite-quartz monzonite is in veins and irregular masses intruding the quartz diorite; several good exposures showing this relationship are on the Lake Shore road, near Woodhaven. The perthite granodiorite has been found, rather commonly, injecting the older schists lit-par-lit. Several dike-like masses also are exposed in the low saddle between Piper and Whiteface mountains.

Chemical analysis of the quartz diorite is given in Table 3 (No. 3), together with an older analysis (No. 4) by H. S. Washington,[19] of another member of the Chatham group (probably the perthite granodiorite).

MEREDITH PORPHYRITIC GRANITE

The Meredith porphyritic granite is found (a) as large masses intrusive into the older schists, the bodies on Avery Hill and Whiteface Mountain being examples of this type; (b) composing parts of the screens (long, relatively narrow, arcuate bodies) between the ring-dikes of the White Mountain magma series. One extends from West Brook Mountain to West Alton, as a great semi-circle 5½ miles long, convex toward the east. The second extends from Goat Pasture Hill, through Cedar Moun-

[19] L. V. Pirsson and H. S. Washington: *Contributions to the geology of New Hampshire, II, Petrography of the Belknap Mountains*, Am. Jour Sci., 4th ser., vol. 22 (1906) p. 446.

tain, and Woodlands as far as Ames, but only that portion of the screen southwest of Cedar Mountain is composed of Meredith granite. The granite is also found as (c) small disconnected masses in the alkaline intrusives north of Gunstock Mountain and on Straightback Mountain.

The Meredith granite is a coarse, porphyritic granite, with a coarse groundmass containing large feldspar phenocrysts which commonly show Carlsbad twinning, and which are white, oblong parallelopipedons, ranging from 1 to 5 centimeters in length, the average size being 2 to 3.5 centimeters. Microscopic study shows them to be composed of orthoclase or microcline, with some perthitic lamellae of oligoclase. The groundmass is dark, and is composed essentially of oligoclase, potash feldspar, quartz, biotite, and muscovite. Accessory minerals are pyrrhotite, magnetite, zircon, and apatite. Some of the matrix is distinctly banded and contains andalusite. The banding is attributed to the influence of an older schist, which has been largely, in some cases wholly, replaced by the invading granite. The large phenocrysts of feldspar contained in the Meredith granite are, in general, aligned approximately parallel to each other, but there is no regional trend.

PEGMATITE

Pegmatites are abundantly associated with the Meredith granite, the quartz diorite, and the perthite granodiorite. In general, they are consistently poor in ferromagnesian minerals, except those associated with the perthite granodiorite near the railroad cut, 6 miles north of Farmington, along the Alton Bay road.

WHITE MOUNTAIN MAGMA SERIES

GENERAL FEATURES

Most of the rocks in the Belknap Mountains are related to those found in the White Mountain batholith [20] and are part of what has been called the White Mountain magma series.[21] Due to the fact that, in the Belknap area, they form one of the most completely differentiated groups of these rocks yet found, the various units are described in detail.

The geological age of the series is not precisely known. Rocks belonging to this group, intrusive into the New Hampshire magma series and, therefore, younger than the lower Devonian, may be observed on the southwestern spur of Piper Mountain, at an altitude of 1550 feet. An upper age limit, other than Pleistocene, has not yet been determined.

[20] Marland Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 36.

[21] Marland Billings: *Paleozoic age of the rocks of central New Hampshire*, Science, n. s., vol. 79 (1934) p. 56.

The chronology of the White Mountain magma series in the Belknap Mountains is as follows (oldest at bottom):

Rowes vent-agglomerate
Conway granite
Albany quartz syenite
Lake quartz syenite
Sawyer quartz syenite
Belknap syenite
Gilmanton monzodiorite
Ames monzodiorite
Endicott diorite
Gilford gabbro
Moat volcanics

MOAT VOLCANICS

The extrusive phases of the White Mountain magma series have been called the Moat volcanics.[22] In the type locality, on Moat Mountain, trachyte, comendite, and rhyolitic tuffs and breccias, have an assigned minimum thickness of 11,800 feet. In the Ossipee Mountains, Kingsley [23] found basalt, andesite, and rhyolite, as flows, tuffs, and breccias. In the Belknap Mountains, the Moat volcanics are represented by a small, hitherto unnoticed area along the northern slopes of West Brook Mountain and Heater Mountain. It is approximately three quarters of a mile long, and one to two hundred yards in width; it is a remnant of a much larger body.

These extrusives are directly north of the shear zone at the northern boundary of the Heater ring-dike, and show considerable cataclastic metamorphism, which tends to obliterate characteristic extrusive textures. The study of the extrusives is further complicated by intrusive lenses of syenite porphyry, which have also undergone shearing. The syenite porphyries, however, may generally be distinguished from the extrusives by the larger size of the feldspar phenocrysts. Where the phenocrysts have been ground down by shearing, separation of the two is difficult and in places impossible. The syenite porphyry is more abundant on Heater Mountain than on West Brook Mountain.

Close study of the extrusives in the field reveals unmistakable signs of stratification, the bedding planes dipping either vertically or steeply to the north. Petrographic study shows that trachyte and rhyolitic tuffs are the chief types.

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[22] Marland Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 89.

[23] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., n. s., vol. 12 (1931) p. 134-167.

The trachyte is dense, bluish-black, with euhedral, lath-shaped phenocrysts of oligoclase, 1 to 2 millimeters long, in sub-parallel arrangement. The microscope reveals that the groundmass is dominantly potash feldspar, either as laths with a trachytic arrangement or as aggregates of anhedral grains, 0.01 millimeter in diameter. Chloritized biotite and magnetite are common; apatite and sericite are accessories. An approximate mode is as follows: orthoclase, 60 per cent; oligoclase, 20 per cent; biotite-chlorite, 15 per cent; magnetite, 5 per cent. Locally, the trachyte has recrystallized to an aggregate of interlocking grains, 2 millimeters in diameter.

TABLE 3.—*Chemical analyses of rocks and minerals from the Belknap area*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
SiO_2.....	36.21	35.88	60.68	69.76	43.94	52.95	56.66	60.75	66.14	70.45	42.73	75.65
TiO_2.....		4.17	0.64	0.36	4.13	3.90	1.55	0.63	0.51	0.69	4.30	0.05
Al_2O_3....	21.32	14.96	19.22	18.22	16.17	14.96	19.03	19.68	17.04	14.87	14.50	12.89
Fe_2O_3....	3.80	2.33	0.78	0.25	3.96	2.44	2.67	1.54	1.24	1.07	4.03	0.89
FeO.....	31.20	20.88	4.34	1.59	10.06	7.03	4.88	2.98	2.10	1.54	7.28	1.11
MnO....	5.12	0.18	0.02								0.19	n.d.
MgO.....	1.41	10.04	2.45	0.40	5.05	3.86	1.86	0.81	0.21	0.35	5.46	0.20
CaO.....	0.36	0.12	4.14	2.68	9.59	6.76	4.82	2.29	1.62	1.28	8.46	0.48
Na_2O....		0.36	3.56	4.06	2.93	4.95	4.52	4.89	4.88	4.28	3.11	3.71
K_2O.....		9.20	3.13	2.06	1.51	1.64	3.62	5.90	5.54	4.16	2.28	5.50
H_2O+...		0.80	0.91	0.50	1.42	0.55	0.60	0.08	0.41	0.65	3.08	0.15
H_2O-...				0.15	0.13	0.09		0.24		0.50	0.36	0.08
CO_2......					0.09						3.76	
P_2O_5.....			0.04		0.69	0.76			0.08	0.04	0.93	n.d
SO_3......			0.03				0.07				0.18	
ZrO_2.....						0.02						
F.......		1.58										
Total....	99.42	100.50	99.94	100.03	99.67	99.91	100.28	99.79	99.77	99.88	100.65	100.71
S.G......	4.23								2.63	2.63		

1 Garnet from mica schist, west slope of Piper Mountain, altitude 1390 feet. F. A. Gonyer, analyst.
2 Biotite from Ames monzodiorite. Separated by Randolph W. Chapman; F. A. Gonyer, analyst.[24]
3 Chatham group, quartz diorite from Minge Cove. F. A. Gonyer, analyst.
4 Chatham group, perthite granodiorite, west slope of Piper Mountain. H. S. Washington, analyst.[25]
5 Gilford gabbro, west foot of Locke's Hill. H. S. Washington, analyst.[26]
6 Endicott diorite, Locke's Hill. H. S. Washington, analyst.[27]
7 Gilmanton monzodiorite from Huckleberry Mountain. F. A. Gonyer, analyst.
8 Belknap syenite, west slopes of Mt. Belknap. H. S. Washington, analyst.[28]
9 Albany porphyritic quartz syenite from near Ox Mountain. F. A. Gonyer, analyst.
10 Conway granite from the North Conway quadrangle; red phase, Redstone, New Hampshire. W. H. Herdsman, analyst.[29]
11 Camptonite dike, Mt. Gunstock. H. S. Washington, analyst.[30]
12 Aplite dike, upper southwest slope of Mt. Gunstock. H. S. Washington, analyst.[31]

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24 R. W. Chapman and C. R. Williams: *Evolution of the White Mountain magma series*, Am. Mineral., Vol. 20 (1935) p. 512.
25 L. V. Pirsson and H. S. Washington: *op. cit.*, p. 446.
26 *Op. cit.*, p. 495.
27 *Op. cit.*, p. 455.
28 *Op. cit.*, p. 450.
29 Marland Billings: *op. cit.*, p. 123.
30 L. V. Pirsson and H. S. Washington: *op. cit.*, p. 500.
31 *Op. cit.*, p. 440.

The rhyolitic tuff is fine-grained, gray, about 60 per cent oligoclase, extensively sericitized and kaolinized. The groundmass is a dense aggregate of quartz and feldspar. Biotite, although apparently secondary, is plentiful. Apatite, magnetite, and leucoxene are accessories.

The Moat volcanics are older than the Albany quartz syenite, for the shearing that preceded the emplacement of the latter, described on a later page, has affected the volcanics. On the north slopes of West Brook Mountain, the Conway granite is in contact with the Moat rocks, at an altitude of 1820 feet; the granite near the contact is of a distinctly finer grain than most of the granite and is aplitic in texture. By removing some of the thin but tenacious soil, it was possible to observe veins and apophyses of the granite, intruding the volcanics at the contact. Thus, the extrusive rocks are shown to be older than the two plutonic masses of the White Mountains batholith with which it is in contact. The age relative to the other plutonic members of the series cannot be determined.

TABLE 4.—*Norms of the Belknap area*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Quartz	13.02	30.72		0.96	2.40	2.04	11.76	25.80		31.02
Corundum	2.45	4.28				1.02		1.63		
Orthoclase	18.35	12.23	8.90	9.45	21.13	35.03	32.80	25.02	13.34	32.80
Albite	29.87	34.58	22.01	41.92	38.25	41.39	41.39	36.15	20.44	31.44
Anorthite	20.57	13.34	26.69	13.90	20.85	11.40	8.06	6.39	18.90	1.95
Nepheline			1.42						3.12	
Diopside			13.38	12.33	2.54				13.90	0.46
Hypersthene	12.30	2.98		8.11	7.53	5.30	2.48	1.56		1.46
Olivine			10.47						7.11	
Magnetite	1.16	0.46	5.80	3.48	3.94	2.09	1.86	1.62	5.80	1.39
Ilmenite	1.22	0.76	7.90	7.45	3.04	1.22	0.91	1.37	8.21	
Apatite			1.68	1.68					2.02	
Rest			1.64	0.71					7.57	0.28
H_2O		.065				0.32				
Total	98.94	100.00	99.89	99.99	99.68	99.81	99.26	99.54	100.41	100.80

[1] Chatham group, quartz diorite, Minge Cove. II, 4, 3, 4. Tonalose.
[2] Chatham group, perthite granodiorite, west slope of Piper Mountain. I, 4, 2, 4. Lassenose.[32]
[3] Gilford gabbro. III, 5, 3, 4. Camptonose.[33]
[4] Endicott diorite. II, 5, 2, 4. Akerose.[34]
[5] Gilmanton monzodiorite. II, 5, 3, 4. Andose.
[6] Belknap syenite. I, 5, 2, 3. Pulaskose.[35]
[7] Albany quartz syenite. I, 5, 2, 3. Pulaskose.
[8] Conway granite, North Conway quadrangle, Redstone, N. H. I, 4 (1) 2, 3. Toscanose.[36]
[9] Camptonite dike, Mt. Gumstock. III, 5, 3, 4. Camptonose.[37]
[10] Aplite dike, upper southwest slope, Mt. Gunstock. I, 4, 1, 3. Liparose.[38]

[32] *Op. cit.*, p. 447.
[33] *Op. cit.*, p. 496.
[34] *Op. cit.*, p. 456.
[35] *Op. cit.*, p. 451.
[36] Marland Billings: *op. cit.*, p. 124.
[37] L. V. Pirsson and H. S. Washington: *op. cit.*, p. 501.
[38] *Op. cit.*, p. 441.

TABLE 5.—*Modes of the White Mountain magma series, Belknap Mountains area*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Quartz.........				4	3		tr		6	8	15	23	40
Labradorite....	49												
Andesine.......				72									
Oligoclase......		50	75		60	61	61						
Microperthite...				12	18	20	21	89	86	79	83	71	55
Augite.........	18	7			2	5	7						
Hornblende....	22	19	10	7	12	2	3	7	6	8	12		3
Biotite.........		20	8	3	3	10	4	2		3	tr	4	
Magnetite......	5												
Accessories.....	6	4	7	2	2	2	2	2	2	2	2	2	2

[1] Gilford gabbro. Accessories: epidote, chlorite, calcite, sphene, apatite, pyrite, sericite.

[2] Endicott diorite; average type. A little microperthite is included under oligoclase. Accessories: apatite, zircon, magnetite, chlorite, sericite.

[3] Endicott diorite; feldspar-injected type. A little microperthite is included under oligoclase. Accessories: apatite, zircon, magnetite, chlorite, sericite.

[4] Ames monzodiorite. Accessories: magnetite and zircon.

[5] Gilmanton monzodiorite, chief phase. Accessories: zircon, apatite, magnetite, sphene, chlorite, kaolin, goethite.

[6] Gilmanton monzodiorite, Piper Mountain phase. Accessories same as in #5.

[7] Gilmanton monzodiorite, Goat Pasture Hill phase. Accessories same as in #5.

[8] Belknap syenite. Accessories: magnetite, goethite, apatite, zircon, and sphene.

[9] Sawyer quartz syenite. Accessories: sphene, zircon, apatite, magnetite, and kaolin.

[10] Lake quartz syenite. Some soda-orthoclase and oligoclase are included under microperthite. Accessories: apatite, sphene, and magnetite.

[11] Albany quartz syenite. Some grains of soda-orthoclase and oligoclase are included under microperthite. Accessories: magnetite, zircon, sphene, and kaolin.

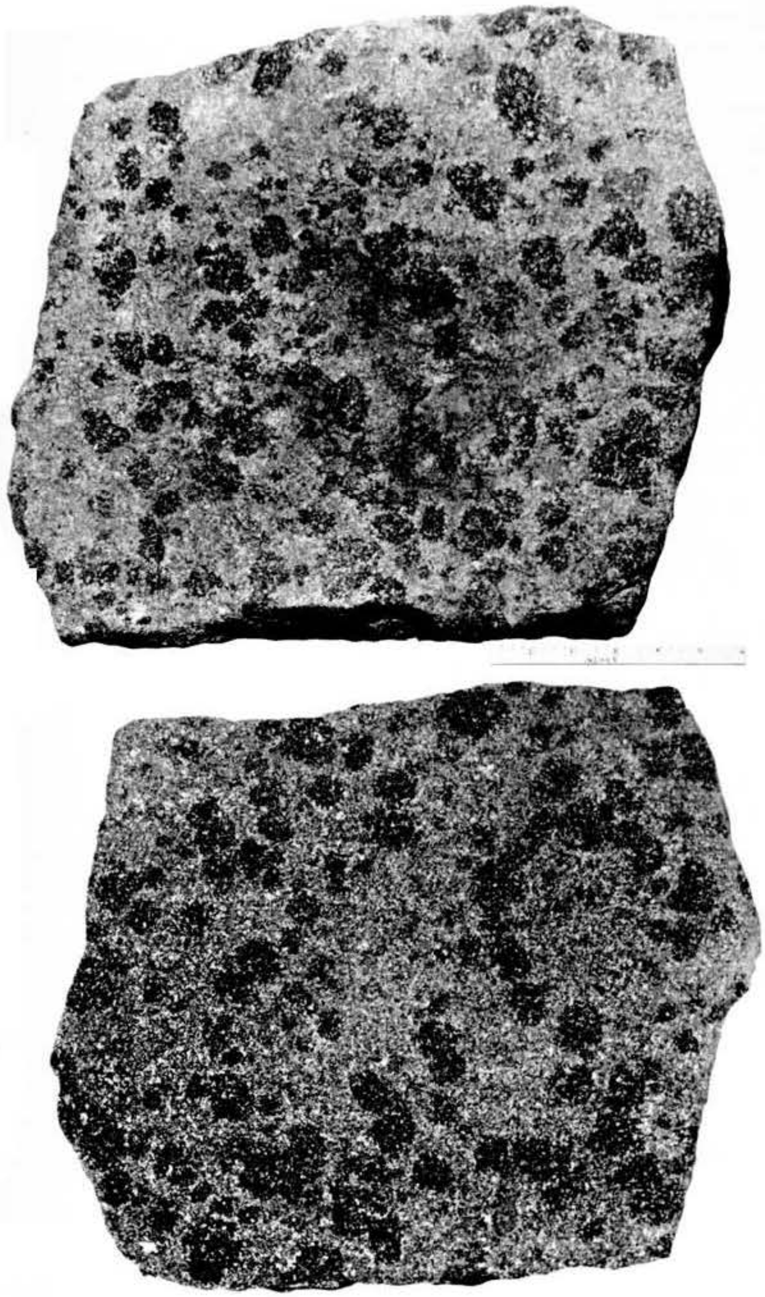
[12] Conway granite. Some oligoclase is included under microperthite, and some hornblende under biotite. Accessories: magnetite, zircon, apatite, sphene, and goethite.

[13] Pine Mountain quartz porphyry; average. Accessories: zircon, sphene, magnetite, sericite, and kaolin.

GILFORD GABBRO

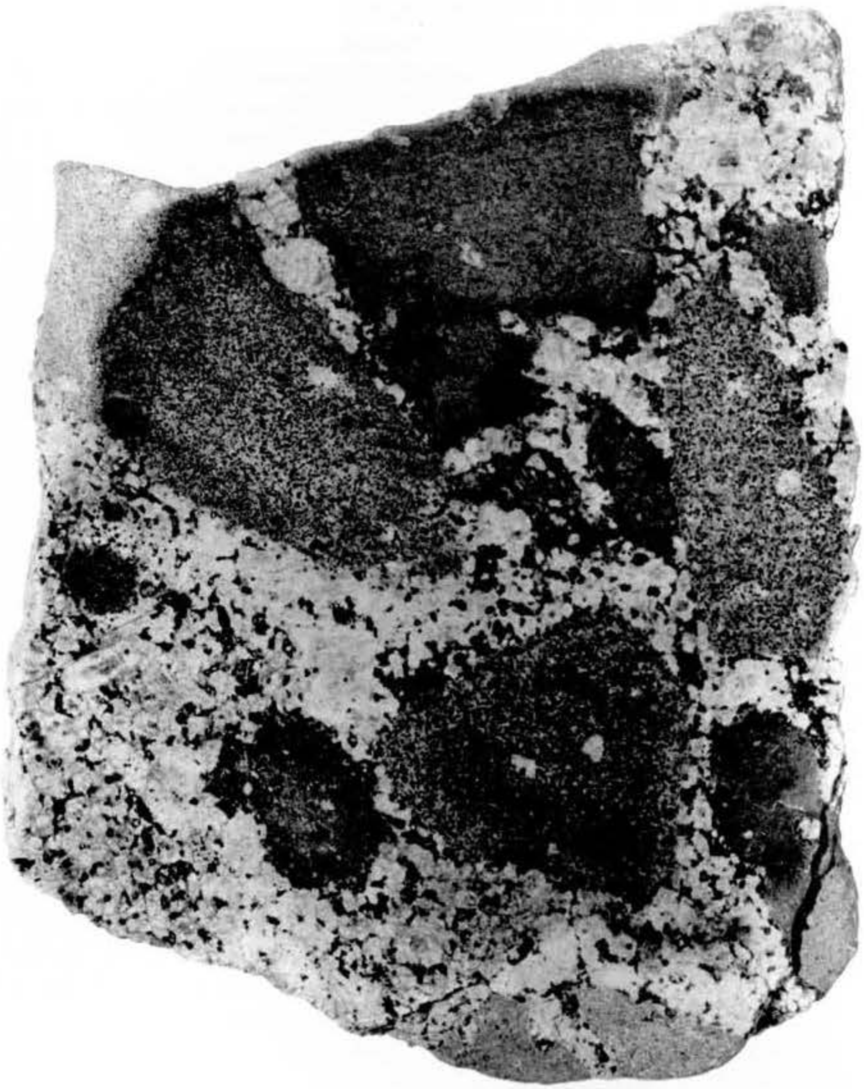
General statement.—The small Gilford gabbro mass crops out a quarter of a mile east of Gilford station, at the northwestern apex of the Belknap complex. The best exposures are to be found on a small bench (altitude, 600 feet) that forms the westernmost spur of Locke's Hill. The contacts of the gabbro with the enclosing rock are hidden by the covering of soil, and it is, therefore, not possible to outline exactly its boundaries; but exposures indicate the shape and size of the intrusive given on the geological map.

Megascopic description.—The Gilford gabbro is dark, and of unusual texture (Pl. 2). The groundmass is a diabasic intergrowth of feldspar and greenish augite, in crystals from 1 to 3 millimeters long. Set in this are large, black clot-like hornblende spheroids, commonly more than three centimeters in diameter. These spheroids constitute about 25 per cent of the rock. Each is a single crystal, but poikilitically encloses numerous crystals of feldspar, which are identical in size and shape with those in the surrounding diabasic matrix. On weathered surfaces the hornblende stands out in relief.



GILFORD GABBRO

The lower figure is a polished slab, showing spherical single crystals of hornblende. The upper specimen is a weathered surface of the same rock. x ¼.



DIORITE INCLUSIONS IN GILMANTON MONZODIORITE
Polished slab, showing inclusions of the Endicott diorite in the Gilmanton monzodiorite. x ¼.

Microscopic description.—The essential minerals are labradorite, hornblende, and pyroxene, with smaller amounts of biotite, chlorite, epidote, magnetite, calcite, sphene, pyrite, sericite, and apatite.

The brown hornblende forming the spheroids encloses poikilitically many grains, among the most common being feldspar, augite, and magnetite; sphene, green hornblende, and epidote are rarer, and generally are just outside the hornblende boundary. In places, the included grains are so abundant that the hornblende, instead of acting as host, becomes interstitial; however attenuated, it always retains its monocrystalline orientation. The primary character of the hornblende is indicated by its intergrowth with poikilitic labradorite, its optical characters, and its lack of any alteration residuals. A small amount may, however, have formed through the alteration of augite, some patches of brown hornblende in this mineral having been observed. The optical properties have been determined as follows:

Biaxial negative. Indices: $\alpha = 1.680$, $\beta = 1.693$, $\gamma = 1.710$. Optic angle (2V) = 57°. Dispersion, weak. Optical orientation: Y = b, $Z_{\wedge}c = 20°$. Pleochroism: X = light brown, Y = light brown, Z = dark brown, with $X \leqq Y < Z$.

There is also a green hornblende, secondary after augite; the replacement takes place as veins and patches of irregular character. Practically all the green hornblende shows patches and residuals of earlier augite, and most of the augite has been affected by complete or incipient alteration. Most of the augite is faintly yellow; some of it is pinkish or colorless. The crystals are prismatic in habit, 1 millimeter to 2 millimeters in length, and show distinct cleavage.

Epidote is in relatively large, stubby prisms, about 2 millimeters in length, and in nests of smaller grains, most of them concentrated at the borders of the hornblende megacrysts. It replaces feldspar, some of it completely, and, where the feldspar is euhedral, it forms a crystal pseudomorph. The epidote pseudomorph alters to chlorite, and thus is formed a chlorite pseudomorph after feldspar via an intermediate epidote stage. Epidote has also been found replacing green hornblende.

The chemical analysis, norm, and mode are given in Tables 3, 4, and 5, respectively.

ENDICOTT DIORITE

General description.—A fairly extensive area within the Belknap complex is occupied by a diorite, which has been veined and shattered by two later intrusions. Because the typical exposures are on Endicott Hill, the name Endicott diorite has been applied to this rock.

The Endicott diorite has been brecciated and intruded by the Conway granite and by the Cobble Hill phase of the Belknap syenite; in both these light-colored intrusives the diorite is found as fragments, varying from a few inches in length to masses measurable in tens of feet. The largest blocks of diorite are found in the Conway granite, along the southwestern slopes of Endicott Hill, where blocks, several hundred feet in length, are separated from each other by only a thin band of granite. There is a marked concentration of the diorite blocks within an area of the Conway granite and Cobble Hill syenite, which measures approximately 3 miles in length and three quarters of a mile in width. Blocks of the Endicott diorite are more abundant than the cementing areas of granite and syenite. The fragmental, angular nature of the blocks of diorite, and the quantitative volume relations between the intruding and the included rocks make it certain that the dioritic blocks are not basic segregations, but represent an older diorite intrusion, which has been broken and brecciated by granite and syenite. This area has, accordingly, been shown on the map as Endicott diorite breccia and, in all probability, roughly outlines, with some enlargement, the old stock of Endicott diorite.

Other areas of the Conway granite also show diorite inclusions, as, for example, the small valley between Belknap Mountain and the northern slopes of Heater Mountain, in which flows the stream tributary to Poorfarm Brook; and two, large isolated blocks on Derby Hill. These are, however, relatively unimportant in size.

Age.—The petrography of the Endicott diorite shows that it is a member of the White Mountain magma series, and therefore later than the Rockingham and the Montalban schists and the New Hampshire magma series. The relative ages of the Gilford gabbro and the Endicott diorite could not be deduced from field evidence, for no contacts were found. Application of the law of decreasing basicity seems to indicate that the diorite is younger than the gabbro. The Conway granite and the Cobble Hill syenite intrude and brecciate the diorite and are, therefore, younger.

Megascopic description.—The Endicott diorite is holocrystalline, dark-colored, and varies from fine to coarse pegmatitic varieties. In the fine-grained specimens, the constituents are less than a millimeter in size, and the habit of the minerals is not megascopically perceptible. In the most abundant type, the minerals are a millimeter in size, and consist of irregular laths of feldspar, needle-like prisms of hornblende, and some biotite. A few specks of a green augite are visible under a hand-lens. The pegmatitic varieties are characterized by thick hornblende prisms, some of which reach lengths of over two centimeters. These are randomly and abundantly distributed throughout a matrix of medium-grained feldspar.

Microscopic description.—The essential constituents of the diorite are plagioclase, hornblende, biotite, and augite, but apatite, pyrite, zircon, magnetite, sphene, microperthite, chlorite, kaolin, sericite, and goethite are present in minor amounts. The plagioclase is zoned oligoclase, an average composition being Ab_{77} An_{23}, in laths, about a millimeter in length. The amphibole is a green hornblende, which is secondary after augite, the process of replacement being clearly visible in many grains. The optical properties are as follows:

Biaxial negative. $\alpha = 1.660$, $\beta = 1.675$, $\gamma = 1.683$. Optic angle (2V) = 63°. Dispersion, medium. Optical orientation: Y = b, $Z_\wedge c = 18°$. Pleochroic formula: X = pale yellow, Y = light green, Z = grass green. Absorption, Z>Y>X.

The chemical analysis, norm, and mode are given in Tables 3, 4, and 5, respectively.

AMES MONZODIORITE

Distribution.—The Ames monzodiorite occupies a small area northwest of Ames station. Good exposures may be observed along the state highway, and along the railroad tracks. Elsewhere, the formation is completely covered, so that little of its structure and nothing of its age relations can be determined in the field. Its form may be delimited, however, by plotting outcrops of the older rocks into which it has been intruded. The Conway granite, with inclusions of diorite, abruptly cuts off the Ames monzodiorite, indicating that the latter is older.

Megascopic description.—The gray, medium-grained, Ames monzodiorite is composed primarily of feldspar and hornblende, with some biotite. Feldspar is found as euhedral to subhedral prisms, and as interlocking anhedrons. In some, a decided moonstone effect may be discerned. Hornblende is in small grains, about a millimeter in size, and, locally, in larger, lustrous black grains, showing good cleavage, and attaining lengths up to three quarters of a millimeter. Quartz is in relatively large and irregular grains, some of which are encased in a thin shell of fine-grained ferromagnesian material. In grain size and texture, it is similar to the Gilmanton formation; but this resemblance is modified by the presence of fine-grained clustered ferromagnesian particles, resembling inclusions.

Microscopic description.—The essential minerals are plagioclase, microperthite, hornblende, biotite, and quartz, with accessory amounts of magnetite and zircon. The plagioclase, an intermediate andesine (Ab_{58} An_{42}), is in laths. In some instances, it is surrounded by a shell of microperthite. Orthoclase has not been noticed in independent grains, but is found intergrown in fine-grained string and patch perthite with the plagioclase. The hornblende is corroded and embayed, and some of it contains numerous inclusions of magnetite. Quartz is in irregular grains not more than a few millimeters in size; and is angular in outline, filling interstices between grains. Magnetite is in globular and rod-like shapes, with no suggestion of crystal outline. Locally, the rods are arranged in parallel, lattice-like patterns. Sphene is in anhedral grains, associated with the magnetite.

A mode is given in Table 5.

GILMANTON MONZODIORITE

General distribution.—The Gilmanton monzodiorite, named from the township of Gilmanton, occupies a broad band along the southwestern edge of the Belknap complex, extending from Piper Mountain, on the northwest, to Goat Pasture Hill, on the southeast. The mass is roughly 2 miles long and three quarters of a mile wide.

On the south and west, the Gilmanton monzodiorite is intrusive into the older schists; and good exposures showing this relationship may be seen at an altitude of 890 feet on the southeastern slopes of Sweat Mountain, due east of the summit of Whiteface Mountain. The contact with the Albany quartz syenite trends N 85° W on the south slopes of Huckleberry Mountain; and, wherever the contact was observed, a thin band of granite, not more than a few yards in width, was found between the Gilmanton and the Albany types. As this granite is approached, the Albany quartz syenite appears to grow finer in grain; the Gilmanton monzodiorite, on the other hand, maintains the same degree of coarseness up to the very contact. This evidence, although not definite, indicates that the Gilmanton is the older of the two. The contact with the Belknap syenite is not sharp, but the structural position of the two bodies points to the Belknap syenite as being the younger.

Megascopic description.—All the rocks within this body are similar in the ratio of feldspar to dark minerals, but the ratio of plagioclase to potash feldspar, and the composition of the plagioclase vary. There are rather striking differences in texture and in the composition of the ferromagnesian minerals. The most characteristic type varies from equigranular to subporphyritic, and has a yellow to pinkish hue. Feldspar is the main constituent, with from 7 to 15 per cent of hornblende, and minor amounts of biotite. The feldspar has two habits: (*a*) oblong, euhedral crystals, elongated in the direction of the "a" axis; and (*b*) anhedral, irregularly interlocking grains. There is a great variation in size, from a millimeter to (rarely) more than 3 centimeters. Hornblende is in irregular grains and prisms, 1 to 5 millimeters in length. Megascopic quartz may, or may not, be present. On Piper Mountain, the rock is darker-colored and medium-grained, with a rather even granular texture, averaging 2 millimeters in size; biotite is the chief dark mineral. On Goat Pasture Hill, the monzodiorite is light-colored and distinctly subporphyritic. Oblong phenocrysts of white feldspar, half a centimeter long, are set in a matrix of anhedral, finer-grained feldspar. Important quantities of small augites and hornblendes average about half a millimeter in size and contrast noticeably with the white phenocrysts of feldspar, especially as many of the ferromagnesians are concentrated along the borders of the phenocrysts.

Microscopic description.—The chief constituents are oligoclase and microperthite; hornblende, biotite, and augite compose about 16 per cent of the rock, but their relative percentages vary greatly. Accessories include quartz, zircon, apatite, magnetite, sphene, chlorite, kaolin, and goethite.

The properties of the potash feldspar are difficult to determine, due to its general kaolinization. β is near 1.526. In view of the lack of the combined albite-pericline twinning characteristic of microcline, and the close approach to monoclinic symmetry, as shown by the orientation of the indicatrix, the feldspar is regarded as orthoclase rather than microcline. That considerable sodium is in solid solution is shown by the extinction angles and, in some instances, exsolved sodic plagioclase. The feldspar is, therefore, soda-orthoclase.

Hornblende is in subhedral prisms and irregular masses, up to 3.5 millimeters in size. Not commonly the hornblende contains residual patches of diopside. Deuteric alteration of the hornblende has given rise to grains showing different colors in different parts of the crystal: green in one portion, bluish green and yellow in other parts. The hornblende is notably embayed and replaced by feldspar.

Biotite is found in ragged flakes, 1 millimeter to 3 millimeters in size. Its high absorption indicates richness in iron.

Quartz is in small anhedral grains. The interstitial, crevice-filling outline of the grains marks them as the last products of crystallization of the magma.

The chemical analysis, norm, and three modes are given in Tables 3, 4, and 5, respectively.

BELKNAP SYENITE

General description.—The Belknap syenite is found in two areas. In the type locality, it forms an elliptical body, 1½ miles long and half a mile wide, on Belknap and Gunstock mountains. A second body extends 3 miles west-northwest from Cobble Hill and Corner Hill.

The contact with the older schists is exposed along the southwestern slopes of Gunstock Mountain, at an altitude of 1200 feet. The schists have been intruded by the syenite, but the latter maintains its coarse nature to the very contact. On the northwest ridge of Gunstock Mountain, angular blocks of the Belknap syenite have been found as inclusions in the Sawyer quartz syenite. The contact between the Belknap syenite and the Albany quartz syenite can be studied on the east slopes of Belknap Mountain. On the East Morril trail, the contact is at an altitude of 2180 feet. The contact can be traced southward. Several exposures show the two intrusions in direct contact, notably at altitudes of 1990 feet and 1910 feet. Both of these show the Albany quartz syenite chilled against the Belknap syenite, the chill zone being between one and two feet in width. In one exposure, a few feet high, the contact was observed to dip 33° SW.

Megascopic description.—The typical Belknap syenite is a coarse-grained aggregate of feldspar and hornblende, without visible quartz. Average grain size is more than 5 millimeters. Feldspar is, generally, in oblong euhedral prisms, cemented together by a small amount of anhedral, interlocking feldspar. In some places, the feldspar is closely intergrown, and the euhedral prismatic development is not found. The hornblende is in large irregular grains, several millimeters long, and in small grains. Some large prisms of hornblende are surrounded by fine, powdery aggregrates of the same mineral. The fracture of the rock is rough and hackly, owing to the large grain size and unoriented cleavage of the feldspars.

In the Cobble Hill body, the Belknap syenite ranges in texture from fine grain, in Poorfarm Brook, to coarse grain, in which the feldspar crystals are several centimeters across, a few hundred feet to the north.

Microscopic description.—The chief minerals are microperthite and hornblende, with smaller amounts of oligoclase, soda-orthoclase, biotite, magnetite, goethite, apatite, zircon, quartz, and sphene. The microperthite crystals have irregular outlines, and many show Carlsbad twinning. The hornblende is in prisms, which have been much corroded. Optical properties have been determined as follows:

Biaxial negative. Indices: $\alpha = 1.688$, $\beta = 1.701$, $\gamma = 1.710$. Optic angle (2V) = 75°. Optical orientation, Y = b, $Z_{\wedge}c = 20°$. Pleochroism: X = yellowish green, Y = olive green, Z = dark green, with $X<Y<Z$.

The chemical analysis, norm, and mode are given in Tables 3, 4, and 5, respectively.

SAWYER QUARTZ SYENITE

Distribution.—The Sawyer quartz syenite, so named from the farm at the west base of Gunstock Mountain, extends north from the mountain for more than 2 miles, maintaining an average width of about half a mile. Where it crops out in the series of gullies and brook slopes between Rowes Hill 2 and Rowes Hill 3, between 1050 feet and 1150 feet altitude, numerous xenoliths of schist can be observed; similar xenoliths are also found on the western spur of Rowes Hill at nearly the same altitude. At two localities, patches of a shonkinitic type of syenite were found surrounded by the quartz syenite.

Age.—As shown in the discussion of the age of the Belknap syenite, the Sawyer quartz syenite is the younger of the two. The age of the Sawyer relative to the Conway granite can be determined on Rowes Hill. Cusps of the granite, a foot deep, project into the quartz syenite, indicating the intrusive nature of the former. Moreover, inclusions of the quartz syenite are found in the granite. The Albany quartz syenite and the Sawyer quartz syenite are within a few feet of each other on Gunstock Mountain, but the exact contact has not been found by the writer. The age relations may be inferred, however, from a number of facts. The cross-cutting relation of the Albany to the Sawyer is clearly noticeable on the map. The total lack of inclusions of the Albany in the quartz syenite would be hard to explain if the quartz syenite were the younger, particularly as the Sawyer holds numerous inclusions of the older Belknap syenite. The Sawyer quartz syenite is regarded, therefore, as younger than the Gilmanton and Belknap syenites, and older than the Albany quartz syenite and Conway granite.

Megascopic description.—The Sawyer quartz syenite is a pink, medium-grained, equigranular rock. Feldspar is the predominant mineral, but there is some hornblende, and megascopically visible quartz is invariable. A few flakes of biotite are visible. Hornblende is found in rather well-developed prisms, some of which reach a few millimeters in length.

Microscopic description.—The essential minerals are microperthite, hornblende, and quartz, with accessory amounts of sphene, zircon, apatite, magnetite, and kaolin. Hornblende is of the "common" variety, but perhaps slightly darker green than usual. The quartz is in irregular grains, a millimeter or less, in size.

A mode is given in Table 5.

LAKE QUARTZ SYENITE

General statement.—The Lake quartz syenite is excellently exposed on Rattlesnake and Diamond islands, and is also found at Gerrish Point and to the north, but exposures are poor.

Megascopic description.—This is a medium-grained, subporphyritic to seriate-textured rock, with the subporphyritic aspect characteristic of most specimens. Feldspar, hornblende, and quartz are the essential minerals. Small grains of hornblende are scattered throughout the rock; some are gathered together in irregular aggregates up to half a centimeter in diameter. When these aggregates contain a feldspathic nucleus—usually a single grain—they show a concentric arrangement of the ferromagnesian particles in spherical shells. The other major constituent, feldspar, is found in subhedral prisms, 1 millimeter to 3 millimeters in length, and also in smaller, interlocking grains containing the hornblendes. The quartz syenite from Diamond Island is somewhat coarser and more equigranular in texture. At some outcrops, there are inclusions of fine-grained diorite.

Microscopic description.—The chief minerals are microperthite, hornblende, quartz, and biotite, with accessory soda-orthoclase, apatite, sphene, and magnetite. Soda-orthoclase is in clear, homogeneous grains, which act as kernels for shells of microperthite. The sizes of the grains of feldspar indicate two generations of growth, one forming subhedral grains, from 1.5 millimeters to 3 millimeters, the other developing as smaller, anhedral, particles, from 0.1 millimeter to 0.25 millimeter. The larger feldspars compose about 80 per cent of the total volume of feldspar. The green hornblende is of the "common" variety; it is in small grains, associated wth anhedral feldspar and quartz. The quartz, in small, irregular grains, was the last magmatic mineral to crystallize.

A mode is given in Table 5.

ALBANY PORPHYRITIC QUARTZ SYENITE

Distribution.—The Albany porphyritic quartz syenite is identical with the Albany porphyritic nordmarkite of the Ossipee Mountains [39] and the North Conway quadrangle,[40] and is similar to the Mt. Garfield quartz syenite of the Franconia quadrangle.[41] In the Belknap Mountains, its long, arcuate body may be traced from a point a mile east of Gilford village, across Gunstock Mountain, Belknap Mountain, Heater Mountain, Huckleberry Mountain, Straightback Mountain, and Mt. Major, and thence to Glidden Cove. As thus traced, the Albany quartz syenite is 10½ miles long, and averages about 1800 feet in width, reaching a maximum width of 4500 feet in the vicinity of Straightback Mountain. In certain areas, it is so intimately mixed with older rocks, that the mapping is, of necessity, somewhat diagrammatic. For example, 1000

[39] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains,* Am. Jour. Sci., 5th ser., vol. 12 (1931), p. 157.

[40] Marland Billings: *Petrology of the North Conway Quadrangle in the White Mountains of New Hampshire,* Am. Acad. Arts and Sci., vol. 63 (1928), p. 105.

[41] Marland Billings and C. R. Williams: *Geology of the Franconia Quadrangle, New Hampshire,* State Planning and Development Commission, Concord (1935) p. 15.

feet north-northeast of the summit of Gunstock Mountain, the Albany quartz syenite, as portrayed on the map, narrows down to a bottle-neck scarcely 250 feet wide; actually, this is an area of Belknap syenite and Sawyer quartz syenite, thoroughly cut to pieces by dikes of the Albany. Three-quarters of a mile northwest of Brookdale, two prongs of the Albany are shown as suddenly narrowing into, and ending against, the older intrusives of the New Hampshire magma series. Actually, the older rocks, for half a mile to the north-northwest, are intimately injected by the Albany. Northwest of Minge Brook, exposures of the Albany quartz syenite are not common. The most northwesterly exposure is on the little knoll along the shore of the lake, south of Glidden's Cove. Here, the Albany trends N 50° W, directly into the central granite stock and a segment, about 50 yards in length, is exposed. Its contact with the basement rocks is visible. A chilled contact zone, about a foot wide, is developed in the Albany.

Age relations.—The inner contact of the Albany quartz syenite is excellently exposed between Mt. Major and Heater Mountain, particularly on the ridges. Between Mt. Major and West Brook Mountain, the Albany is in contact with the Meredith granite; between West Brook Mountain and Heater Mountain, with the Moat volcanics. The Albany quartz syenite is clearly chilled against the other rocks. The cataclastic structures in the older rocks are described on a later page. As already stated, the Albany is younger than the Gilmanton monzodiorite, the Belknap syenite, and the Sawyer quartz syenite. The Albany, although not in contact with the Lake quartz syenite, is probably somewhat younger, for it is more siliceous. A mile southeast of Gilford, the Albany is apparently intruded by the Conway, a relationship consistent with that observed elsewhere in New Hampshire.

Megascopic description.—The Albany porphyritic quartz syenite carries abundant ovoid, white feldspar phenocrysts, from 3 to 5 millimeters in length, set in a gray, medium- to fine-grained groundmass, which consists of interlocking anhedral grains of feldspar and quartz, speckled with small ferromagnesian minerals, usually under 0.5 millimeter in size, with a few hornblende crystals, up to 2 millimeters long.

Dark, fine-grained basic inclusions are in many of the hand-specimens, especially those from the more southerly parts of the ring-dike, in the vicinity of Ox and West Brook mountains. Large prisms of lustrous black hornblende and crystals of feldspar are contained in these inclusions, seeming to indicate that these minerals are caused by impregnation. Many spheroidal biotitic shells, similar to those in the quartz syenite itself, are found.

Microscopic description.—The essential minerals are microperthite, soda-orthoclase, oligoclase, quartz, and hornblende, with smaller amounts of biotite, magnetite, zircon, sphene, and kaolin. Most of the phenocrysts are subhedral to euhedral ovoidal aggregates of soda-orthoclase and oligoclase intergrown as patch and vein perthites, together with areas of soda-orthoclase without intergrown plagioclase, randomly distributed throughout the crystal. The Federoff orientation of the optical indicatrix indicates that the soda-orthoclase contains between 20 and 40 per cent of the sodium atom in solid solution replacing potassium. The groundmass feldspar consists of microperthite, soda-orthoclase, and oligoclase (Ab_{80} An_{20}). The hornblende is in small euhedral to subhedral prismatic crystals, 0.1 to 0.5 millimeter in size. Irregular and embayed outlines convey the appearance of attack and replacement after a condition of euhedral development had been attained.

The optical properties of the hornblende have been determined as follows: Biaxial negative. Indices ($\pm$ 0.003): $\alpha = 1.680$, $\beta = 1.689$, $\gamma = 1.698$. Optic angle (2V) = 70°. Dispersion, medium. Optical orientation, Y = b, $Z \wedge c = 20°$. Pleochroic formula X = light tan, Y = olive green, Z = dark green, with $Z > Y > X$.

The chemical analysis, norm, and mode of the rock are given in Tables 3, 4, and 5, respectively.

CONWAY GRANITE

General distribution.—The Conway granite of the Belknap area is in three bodies, of which by far the largest is a pear-shaped mass that extends from Weeks Hill, in the southeast, to Locke Hill, on the northwest, a distance of 6 miles. The southern half of this body is relatively free from inclusions. The northern half, on the other hand, is so full of inclusions of diorite, that it is shown on the geological map as a diorite-granite breccia. In the vicinity of Cobble and Corner hills, moreover, the body is interrupted by a large mass of Belknap syenite. A second, not well exposed, body, half a mile east of Gilford, is 2½ miles long, but, only in a few places, is it more than 1200 feet wide. A third body, 4 miles long and at no place more than 300 feet wide, can be traced from near Mt. Major station to the south slopes of Huckleberry Mountain.

Age relations.—On the north side of West Brook Mountain, at an elevation of 1800 feet, small dikes of the Conway granite cut the Moat volcanics. The granite also cuts the Gilford gabbro and contains inclusions of it. The Endicott diorite is clearly brecciated by the granite. On Rowes Hill, the Conway granite intrudes the Sawyer quartz syenite, and, three quarters of a mile east-northeast of the village of Gilford, the granite cuts the Albany quartz syenite. Fragments of the Conway, however, are found in the Rowe agglomerate.

Megascopic description.—The Conway granite of this area is characteristically a medium- to coarse-grained pink rock, low in dark minerals, chiefly biotite, but including some hornblende. The average grain size is 2 to 3 millimeters. Feldspar is found as oblong parallelopipedons elongated parallel to "a" and also as anhedral interlocking grains. Most of the quartz is glassy and transparent, but some is smoky. On Rowes Hill, the Conway granite is somewhat coarser than elsewhere in the main body, with an average grain size of 4 to 5 millimeters. Moreover, as shown by the mode, quartz is more abundant. In the two small arcuate bodies outside the Albany quartz syenite, the Conway granite is still coarser, the feldspars averaging 7 millimeters in length. A miarolitic phase has been traced from Weeks Hill to the east slopes of Belknap Mountain, along the outer edge of the central stock. In the neighborhood of Weeks Hill, it is about 1000 feet wide and contains abundant miarolitic cavities, or druses, usually from 0.5 to 1 centimeter in diameter, although some are only 3 millimeters across. The druses contain no minerals other than the ordinary rock constituents. Projecting into the cavities are euhedral quartz and microperthite crystals, many of them covered with an earthy coating of reddish-brown limonite. Many of the druses are surrounded by this mineral stain. Many of the ferromagnesian minerals near the druse cavities, particularly the hornblende, are discolored and, in large part, altered to limonite.

Microscopic description.—The essential minerals are microperthite, soda-orthoclase, oligoclase, quartz, biotite, and hornblende, with minor amounts of magnetite, zircon, apatite, sphene, and a reddish-brown alteration product, probably goethite. The microperthite forms oblong subhedral to anhedral grains. The quartz is generally anhedral and equant, irregularly distributed among the feldspars. Oligoclase, close to $Ab_{77}An_{23}$, is found as a core in microperthite, and also in individual grains. Biotite, in small flakes and grains, shows an irregular outline due to replacement by the feldspars. The hornblende is in small grains, approximately 0.5 millimeter in size, and is subhedral to anhedral, depending on the degree of replacement. The mineral, through alteration, gives rise to a reddish-brown, translucent substance of high index and birefringence, which is probably goethite. Magnetite, also, is found as an alteration product of the hornblende.

The optical properties of the hornblende have been determined as follows: Biaxial negative. Indices: $\beta = 1.696$, $\gamma = 1.705$. Optic angle (2V) = 72°. Dispersion, medium. Optical orientation, Y = b, $Z_{\wedge}c = 21°$. Pleochroic formula: X = light yellow, Y = olive green, Z = dark green, and $Z > Y > X$.

The mode of the rock is given in Table 5, and the chemical analysis and norm of a similar rock in the North Conway quadrangle are given in Tables 3 and 4.

ROWES VENT AGGLOMERATE

One of the outstanding features of the geology of the Belknap complex is the Rowes Hill diatreme. A volcanic vent of major dimensions, filled with unbedded explosion agglomerate, and later in age than the plutonics of the White Mountains batholith, it stands as a unique structure in New England geology. The vent is over a mile in length, and on Rowes Hill, which is probably the site of the main orifice, it is almost half a mile in width. The width, however, markedly diminishes to the north, in which direction the vent tapers out into a long narrow arm. To the south, exposures are poor, and the exact outline is uncertain.

The best exposures of the vent agglomerate are provided by the broad ledges at the summit of hill 1560, 1½ miles slightly north of east of Gilford village. Rounded to angular fragments, from a few inches to a few feet across, are enclosed in a dense, dark gray matrix. By far the most abundant rock composing the fragments is the Meredith porphyritic granite; but there are a few fragments of the Sawyer quartz syenite, the Belknap syenite, and the Conway granite. The matrix itself is largely fragmental and is composed of small grains of feldspar and quartz, from 2 to 10 millimeters long, set in a dark dense groundmass.

Microscopic study shows that the matrix consists of grains of microperthite, oligoclase, and quartz, set in a groundmass of the same material, with additional hornblende and biotite. The feldspar fragments show recrystallization to a felt-like aggregate of laths, and, where albite twinning is developed, some of the grains give evidence of distortion by curvature of the twin lamellae. Both potash feldspar and plagioclase are present. Many of the quartz grains are cracked into a mosaic of smaller parts, with no change in crystallographic orientation. The groundmass consists of a fine-grained aggregate of green hornblende, either in irregular grains or in recrystallized prisms, biotite, chlorite, feldspar, quartz, and magnetite, with an average grain size not over a few hundredths of a millimeter. Microbrecciation and subsequent recrystallization have been intense.

Microscopic study shows that the few dark, dense nodules in the agglomerate consist of green hornblende, microperthite and a small amount of quartz, all with anhedral outlines. The similarity in composition with the groundmass material of the Rowes agglomerate indicates that they are probably remnants of an earlier vent-intrusion, which had solidified previous to the eruption of the rock in which they are contained.

Along the northeastern contact of the vent, there is a black, medium-grained porphyritic rock, whose relations to the enclosing rocks could not be determined. Under the microscope, it is seen to be a porphyritic augite-diorite, of augite, brown and green hornblende, biotite, and a rather calcic oligoclase. Most of the augite is colorless; but some is pink, or colorless with a distinct pink border. Magnetite, in rods forming a reticulated structure resembling Widmanstetten figures, was observed in brown hornblende.

The amount of fragmentary and recrystallized material, occupying at least 90 per cent of the total volume, is too great to permit determination of the exact character of the volcanic eruptive that formed the vent-agglomerate. However, it was probably syenitic or quartz-syenitic in composition. The rather small quantity of quartz in the cementing matrix, and the abundance of potash feldspar, strongly suggest such a composition.

From the contained fragments the Rowes vent-agglomerate is obviously younger than the Meredith granite, the Sawyer quartz syenite, the Belknap syenite, and the Conway granite, and is, thus, the youngest member of the bedrock series, with the possible exception of some of the dikes, none of which, however, has been observed to cut the agglomerate.

A small dike-like mass of agglomerate, apparently not connected with the main vent, is exposed in Poorfarm Brook, just north of the West Alton road bridge, at an altitude of 830 feet. The exposure in the brook is 140 feet long and 40 feet across, and the trend is N35°E. It recalls a similar, smaller mass described by Kingsley, from the Ossipee Mountains,[42] which contained basalt breccia and quartz-porphyry. The Poorfarm Brook outcrop is enclosed in Belknap syenite, which it brecciates, a fine-grained selvage of feldspar and hornblende, 6 inches wide, marking the contact between agglomerate and syenite. It differs from the agglomerate of the Rowes vent in that the matrix is very black.

A body of volcanic agglomerate, found along the contact between the Meredith granite and the Mt. Major granite ring-dike, on the west side of Straightback Mountain, at an altitude of 1800 feet, is believed to be contemporaneous with the Rowes vent-agglomerate.

PINE MOUNTAIN COMPLEX

One of the results of the remapping of the Belknap Mountains has been the discovery that the rocks of the Pine Mountain-Rocky Mountain area, previously regarded[43] as part of the main intrusion, belong to an inde-

[42] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 12 (1931) p. 144.

[43] L. V. Pirsson and H. S. Washington: *Contributions to the Geology of New Hampshire, I. Geology of the Belknap Mountains*, Am. Jour. Sci., 4th ser., vol. 20 (1905) p. 344-352.

pendent subsidiary stock, called the Pine Mountain complex. It is roughly circular in shape, with a diameter of 2 miles.

This stock is clearly younger than the surrounding Meredith granite and older schists, for inclusions of these rocks have been observed in the rocks of the Pine Mountain complex.

The chief rock in the stock is a granite porphyry, the groundmass of which is exceedingly dense in many localities. Porphyritic quartz syenite and granite have been observed in a few localities. In general, the exposures are so poor that it is not possible to work out the structure and relationships between the various intrusions. The complex nature of the stock is well shown in an outcrop on the interior of the Pine-Rocky Mountain Ridge, at an altitude of 1310 feet, 2 miles due west of the point where the main highway crosses the railroad at Alton, where six parallel contacts between what appear to be as many intrusions of fine-grained granite and fine-grained porphyritic syenite are found in a traverse of 40 feet, perpendicular to the trend of the contacts. These contacts are of pencil-point sharpness.

The granite porphyries are characterized by an abundance (15 to 25 per cent) of euhedral to subhedral phenocrysts of quartz, 1 to 3 millimeters in diameter. Their habit indicates crystallization in the hexagonal enantiomorphic class, and their temperature of formation was, therefore, probably above 573° C. The feldspar is variable in size, ranging from microscopic grains to phenocrysts as large as 4 millimeters. This variation in grain-size is well brought out in some of the hand-specimens, by the alternation of bands of dense material with those of medium grain. The granite-porphyries have a wide variety of colors, notably black, green, pink, and yellow.

Microscopic study shows that the phenocrysts are chiefly microperthite and quartz, both of which show resorption. The groundmass is an anhedral granular aggregate of the two minerals, with the microperthite, in grains 0.03–0.04 millimeter in length, slightly larger than the quartz (0.01 millimeter). A few grains of ragged hornblende, altering to biotite, are distributed throughout the groundmass. Accessories include zircon, sphene, magnetite, sericite, and kaolin. A mode is given in Table 5.

Porphyritic quartz syenite from the summit of Rocky Mountain is light red medium-grained, with no visible quartz, but with phenocrysts of hornblende and microperthite. About 10 per cent is interstitial material, largely fine-grained microperthite and quartz in a panallotriomorphic granular aggregate; about 8 per cent, ragged grains of green hornblende, scattered throughout the rock. The hornblende is considerably altered, different portions of a single grain showing changes from green to yellow or brown; internal decomposition, with formation of magnetite, is common.

DIKE-ROCKS

General statement.—Dike-rocks cutting the major intrusives are not uncommon in the Belknap Mountains. Several varieties have been described by Pirsson and Washington,[44] among them being aplite from the upper southwest slopes of Mt. Belknap, quartz syenite porphyry from Mt. Gunstock, quartz-bostonite from Mt. Belknap, camptonite from Mt. Gunstock and Piper Mountain, and spessartite from Mt. Belknap. The writer observed numerous dikes in other parts of the area, and presents descriptions of some of them. For convenience, they are divided into leucocratic, or light-colored, dikes and melanocratic, or dark-colored, varieties.

Leucocratic dikes.—At an altitude of 900 feet, in Moulton Brook, numerous quartz-porphyry dikes are found cutting the Gilmanton monzodiorite. At an altitude of 920 feet, a yellow, spherulitic quartz porphyry with about 20 per cent of the quartz phenocrysts set in a dense microcrystalline groundmass, trends north. Although its total width could not be determined, it is at least several yards. The quartz phenocrysts are blebs, 1 millimeter in diameter. The microscope shows quartz and orthoclase in two generations: as subhedral phenocrysts and as groundmass. Numerous spherulites of quartz and orthoclase are observed, about 0.6 millimeter in diameter. In many instances, a grain of quartz is the nucleus; some of the spherulites are outlined by a rim of ferric oxide. The rest of the groundmass is a spongy aggregate of the same two minerals, many in micrographic intergrowths.

About 200 yards upstream there are non-spherulitic quartz-porphyry dikes. Under the microscope, the same phenocrysts are seen, but the groundmass is an aggregate of fine anhedral grains of quartz and what is probably sodic orthoclase. Magnetite is a fairly abundant accessory.

A one-foot granite-porphyry dike on Piper Mountain is composed of pink feldspar, hornblende, and quartz. The thin-section shows euhedral to subhedral phenocrysts of microperthite, oligoclase, and soda-orthoclase, and hornblende in ragged and embayed grains altering to biotite. The groundmass is a granular aggregate of quartz, microperthite, and oligoclase.

Melanocratic dikes.—An augite-camptonite dike was found in Moulton Brook, a short distance from the dikes of quartz-porphyry, at an altitude of 900 feet. The hand-specimen is dark and fine-grained, with small

[44] *Ibid.*

phenocrysts of feldspar and ferromagnesian minerals, about 1 millimeter, or smaller, in size; under the microscope, the phenocrysts are seen to be labradorite, brown hornblende, and some augite.

An uncommon augite-olivine camptonite dike was found on the southwest slope of Pine Mountain. It is 15 centimeters wide and is tripartite in character. It consists of two contact zones, each 5 centimeters wide, which are fine-grained and contain a few augite phenocrysts; these are separated by a central zone, in which augite crystals increase greatly in size and number and are accompanied by a few glassy grains of green olivine. Under the microscope, the groundmass is seen to consist of labradorite laths, and an aggregate of brown and green hornblende in laths and irregular grains. In the border zones, the augite phenocrysts comprise about 20 per cent of the total volume; in the central zone, the volume increases to 50 per cent. Some of the augite crystals contain lenses and lines of magnetite in intricate patterns.

Spessartite dikes have been found on Ox Mountain, Mt. Major, and Frohock Mountain, and are undoubtedly to be found elsewhere. These rocks consist of laths and grains of andesine or labradorite, embedded in anhedral crystals of green hornblende. Another generation of green hornblende is found as subhedral phenocrysts.

Analyses of dike-rocks of the Belknap Mountains were made by Washington,[45] in connection with the earlier work on the geology of the Belknap Mountains, and were of a leucocratic and a melanocratic representative of the Belknap dikes. Chemical analyses and norm are given in Tables 3 and 4, respectively.

NATURE OF THE WHITE MOUNTAIN MAGMA SERIES IN THE BELKNAP MOUNTAINS AREA

The plutonic rocks of the Belknap Mountains area range from gabbro to granite. The complete series, arranged as nearly as possible in chronological order, is gabbro, diorite, monzodiorite (several varieties), syenite, quartz syenite (three varieties), and granite. Each type is a distinct, mappable unit, and most contacts are relatively sharp. This means that the various magmas did not form at the present surface of the earth, but at some depth, and were intruded as separate units.

The earliest of the intrusives, the gabbro, crystallized with about 40 per cent of augite and hornblende, in nearly equal amounts, together with a small amount of biotite. Nearly this same quantity of ferromagnesian minerals is found in the diorite. With the advent of the monzodiorite, the ferromagnesian content decreases to 20 per cent. Another sharp

[45] *Ibid.*

decrease marks the beginning of the syenite stage, where the amount of ferromagnesians is not more than 10 per cent, and some is less. This proportion of ferromagnesians is not changed throughout three succeeding stages—Sawyer, Lake, and Albany quartz-syenite—which are marked by variations in the quartz content. At the end stage, or period of the Conway intrusion, the ferromagnesians were reduced in quantity to 4 per cent.

Of the ferromagnesian minerals, biotite is present from the earliest crystallization stage (gabbro) onward. Augite and hornblende form a well-developed reaction pair through almost the entire differentiation series. Augite grains, in practically all stages of transformation to hornblende, are in rocks ranging in composition from gabbro to monzodiorite, and even in the Albany quartz syenite. Transformation of augite to hornblende takes place apparently not by solution of augite and precipitation of hornblende, but by a process of addition and/or subtraction of substance from the augite, and an atomic re-arrangement, which leaves the external form unaltered. The augite changes from non-pleochroic light green to dark, pleochroic green, and the birefringence is decreased. Many of the hornblende transformation zones are spread through augite grains in irregular lace-like patterns. The ease with which augite is transformed to hornblende has been explained by recent X-ray studies,[46] which reveal close structural similarities between the two substances. The physical transition from augite to hornblende involves merely the doubling of the pyroxene unit cell along the "b" axis, with the concomitant formation of double silicon-oxygen chains, and little, or no, volume change. Probably, in the later stages of differentiation, hornblende forms also by direct crystallization from the magma.

Crystallization of feldspar in the differentiation series begins by forming approximately half the bulk of the gabbro, as labradorite. The amount of feldspar gradually increases up to a point midway between the syenite and the quartz-syenite stages, after which it decreases. Decrease in feldspar content is compensated by an increasing abundance of quartz. The amount of orthoclase closely follows the variation in total feldspar content, reaching a marked maximum, and then declining. Albite is relatively small in amount in the gabbro, but upon reaching a 38 per cent content in the monzodiorite, it maintains this value throughout most of the remaining stages, with only a small decline near the end-stage of granite. Anorthite makes up 26 per cent of the gabbro and steadily declines to a value of only 6 per cent in the granite.

The Conway granite has injected and reacted upon the diorite, and its composition, therefore, cannot strictly be taken as an indicator of the

[46] B. E. Warren and D. I. Modell: *The structure of anthophyllite*, Zeit. f. Krist., Bd. 75 (1930) ss. 161-178.

trend of magmatic differentiation. It is responsible for many of the "kinks" in what would otherwise be smoother oxide variation curves. An idea as to the magnitude of the effect of reaction with the granite magma may be obtained from a comparison of the proportions of albite in the plagioclase of several members of the series, taken from the norms, as shown by the following tabulation:

Gabbro	*Diorite*	*Monzodiorite*	*Syenite*	*Granite*	*Granite*
%Ab:46	76	64	79	84	85

The plagioclase of the normal diorite should have, by extrapolation, 55 per cent of albite in the plagioclase. Reaction with the more sodic granite magma, which crystallized with 85 per cent of albite in the plagioclase, increased the proportion of albite to its present value of 76 per cent, which is checked by the petrographic determination of the plagioclase as oligoclase.

Changes in the character of the magma, which was injected in succeeding stages in the Belknap Mountains, are essentially the same, up to the quartz-syenite period, as those found in the slow and progressive crystallization of a melt having the composition of gabbro. No outside influence need be considered in order to explain the kinds of rocks present; they are the normal result of crystallization with slowly falling temperatures in the magma chamber. These intrusive bodies are a particularly good example of an igneous series produced by crystallization-differentiation. The sequence of intrusion, as far as data have been obtained, corresponds precisely to that theoretically demanded.

Magmatic history after the syenite intrusions is, in many aspects, problematical. It was formerly believed that the chief problem of the differentiation in the co-magmatic Novanglian intrusions would be to account for the production of syenite by one of the many proposed hypotheses. The real problem, however, in connection with the Belknap Mountains, is to discover in what manner the presence of a large volume of free silica in the end-stage rocks may be explained. The problem of differentiation is chiefly concerned with the production not of syenite, but of granite.

Bowen has proposed several methods for the development of free quartz in magmas of originally gabbroic composition, none of which seems wholly satisfactory. Among them are (1) early crystallization and separation of olivine, and (2) conversion of polysilicates to orthosilicates near the magmatic end-stages. Concerning the first method, it may be noted that no olivine-rich intrusives have been found in the area. Indeed, there is none that contains even the smallest percentage of this mineral. In view of the apparently complete magmatic record found in the rock series, if the separation of olivine had been an important magmatic process, it seems strange that it failed to leave any indication of its presence in the basic intrusions.

The second of Bowen's methods is strongly advocated by him. However, the Conway granite is the largest intrusive of the complex, and it contains 25 per cent of quartz, by volume. The large intrusion of Albany quartz syenite carries between 12 and 15 per cent quartz. To produce that percentage of quartz by the breaking down of polysilicate molecules to orthosilicate molecules involves the production of a large amount of orthosilicate molecules. Biotite, nepheline, and kaliophilite, however, the minerals in which these orthosilicate molecules are found, are present in only small amount, the latter two probably not at all. The biotite in the Conway granite (which carries 25 per cent of quartz) does not exceed 2 or 3 per cent. These facts offer a serious draw-back to the acceptance of the process.

Holmes [47] has shown that the intrusion of sharply contrasted acid and basic rocks, such as gabbro and granite, in the British Tertiary complexes may be explained by assuming a palingenesis, or refusion, of siliceous crustal rocks. This hypothesis has much to commend it. Holmes points out that, as it has been shown that the foci of the British Tertiary centers were at a depth of about 3 miles below the present surface, fluids must have ascended through 7 kilometers of granitic crustal rock. As judged from the exposed rocks in the Belknap Mountains, the ascending magma reservoir must have fused, or stoped, its way through rocks carrying a considerable proportion of free silica. The palingenetic magma, thereby produced, should be lighter than the more basic material below it, and should form a silica-rich fraction at the top. The intrusions of the outer ring would tap deeper portions of the cupola and, therefore, should be more basic than the inner-ring intrusion. The central stock would be expected, by that theory, to be the most siliceous intrusion. These conditions are fulfilled by the distribution of intrusions in the Belknap Mountains.

If such palingenetic action occurred, the magma resulting from fusion of the crustal rocks must have been reacted upon, to a considerable extent, by the magma of the ascending cupola, for the chemical composition of the silica-rich intrusives is not unrelated to the previous intrusions, as might have been expected if fusion alone had been operative; actually, the chemical composition fits in well with the crystallization-differentia-

[47] Arthur Holmes: *The problem of the association of acid and basic rocks in central complexes,* Geol. Mag., vol. 68 (1931) p. 241-255.

tion series of the quartz-free suite, as shown by the oxide variation diagrams.

These views represent a distinct trend to theories of syntexis as a major factor in petrogenesis, long advocated by Daly.

CATACLASTIC ROCKS IN THE BELKNAP MOUNTAINS

GENERAL FEATURES

In the central portion of the Belknap complex, extending for about a mile along the summits of Ox and West Brook mountains, there is a highly mylonized area in the older rocks north of the Albany quartz syenite (Fig. 1).

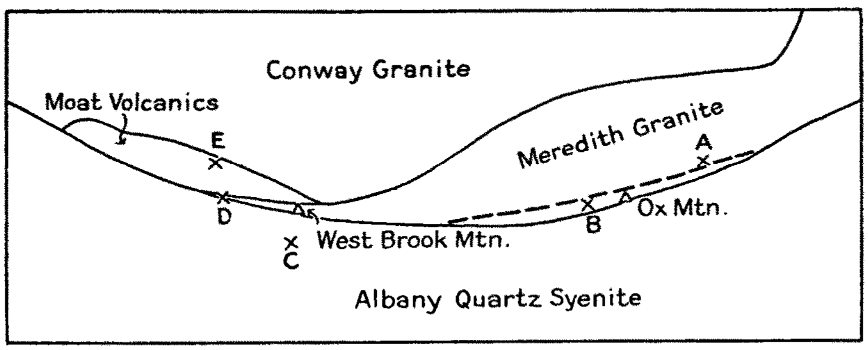


FIGURE 1.—*Sketch map of West Brook Mountain screen*
Showing location of cataclastic rocks. (*A*) Pseudotachylite-like rock is found as short dikes

CATACLASIS OF THE MEREDITH GRANITE

The cataclastic metamorphism of the Meredith granite is best observed along the summit of Ox Mountain, where the northern border of the Albany quartz syenite trends east-west. From a point 10 or 15 feet north of the Albany quartz syenite the Meredith granite becomes more and more intensely crushed as one proceeds southward, until, at many places near the contact, it is ground down to a dark, tough ultramylonite.

Three stages can be recognized in the cataclasis of the Meredith granite: (a) pre-mylonite stage, (b) mylonite stage, (c) ultra-mylonite stage. As one progresses southward, the pre-mylonite stage is first found at a point from 5 to 15 feet north of the contact with the Albany quartz syenite. The orthoclase phenocrysts, which are 3 to 5 centimeters in length, are deep pink, notably splintered and granulated, and many are veined by black strings of dense, crushed rock. The physical characteristics of the pre-mylonite are caused by fracturing and crushing, and are made especially noticeable by the porphyritic structure of the non-metamorphosed rock. Notwithstanding the fracturing and crushing, the rock is solidly welded together, and is, therefore, a pre-mylonite rather than a breccia. Under the microscope, large quartz grains and feldspar phenocrysts are seen to be veined and injected by a fine-grained powder of biotite, magnetite, quartz, and feldspar, the average size of which is 0.025 millimeter. The pink color of the feldspar phenocrysts is probably caused by oxidation of magnetite, which has been injected into them by the crushing.

In most places, the mylonite is nearer the Albany quartz syenite than is the pre-mylonite. It is a dark, fine-grained rock, containing a small proportion of pink, residual patches of pre-mylonite. The mylonite is commonly streaked, and some of the feldspar residuals have been so crushed that they resemble a foam-like network, borne up by the dark background. The microscope reveals an extremely fine-grained groundmass, average diameter approximately 0.001 millimeter, in which are set fragments of fractured quartz, recrystallized biotite, and crushed feldspar shot with fine-grained, triturated material. Magnetite is in bands and streaks composed of granules about 0.003 millimeter in diameter. In many instances, the quantity of magnetite in a given specimen is greater than that in a similar volume of unaltered granite. The groundmass consists of spongy, recrystallized feldspar, 0.05 millimeter in size, predominantly orthoclase, and clouded with biotite and magnetite dust.

The Meredith ultra-mylonite is a dark, bluish-gray, fine-grained rock, found at, or near, the contact with the Albany. It is variable in quantity; on Mt. Major, it is found only as thin streaks at the very edge of the Meredith; on West Brook Mountain, the zone is thicker. With the exception of the pseudotachylitic types, described on a later page, this is the least abundant of the crush products. Three thin sections of the ultramylonite were studied; two were collected at a point 8 inches from the Albany quartz syenite, and one from the very contact. They show a fine-grained, recrystallized aggregate of quartz and feldspar with dark streaks consisting of magnetite granules about 0.004 millimeter in size. The grain of the groundmass is about 0.01 millimeter. Biotite is in flakes, some of which show a peculiar mode of recrystallization into radial spherulitic structures, 0.002 millimeter in diameter. In certain instances, the orthoclase feldspar contains fragments of quartz, which greatly resemble the granulated particles of crushed quartz phenocrysts; they were probably incorporated in the feldspar by the intense pressure. They yield textures resembling the quartz-orthoclase micropegmatitic intergrowths, differing only in the fragmental outline shown by the quartz. They have a pseudoeutectic structure. In some specimens, angular residuals of quartz and feldspar are clouded by small particles of biotite and magnetite. Magnetite, sphene, and zircon are not distributed evenly throughout the groundmass, but show a distinct tendency to remain associated with each other in patches, strings, and irregular masses. The cataclasis in these types of Meredith granite produced predominant recrystallization; they are, therefore, ultra-mylonites.

CATACLASIS OF SYENITE AND SYENITE PORPHYRY

The cataclasis of syenite and syenite porphyry is to be observed at, and slightly north of, the summit of West Brook Mountain, where thin lenses of syenite and syenite porphyry intrude the Moat volcanics and the Meredith granite. The syenites show all stages in the progression from pre-mylonite to mylonite, and, in addition, furnish examples of flinty crush-rocks.

The unaltered syenite is pink, rather distinctly porphyritic, and consists of oligoclase and orthoclase with about 7 per cent hornblende and a small amount of biotite and quartz. The earliest signs of shearing are the darkening of the rock and a streaked appearance. One specimen in the type collection shows the development toward the mylonite type; the feldspar phenocrysts are contained in a black angular network of fine-grained crush particles. Further crushing produces somewhat darker colors and accentuates the light-colored residuals of the original phenocrysts. These are never, in the syenite, completely obliterated by the cataclasis; all specimens of the crushed syenite contain areas of residual material, differing in this respect from the typical pseudotachylite examples from Ox Mountain.

In thin section, the syenitic pre-mylonites and mylonites show the usual crushing and granulation of the feldspar and quartz, with the presence of small recrystallized hornblende and biotite flakes. Some of the biotite is altered to a colorless chlorite. The groundmass varies from 0.05 to 0.005 millimeter in size. The feldspar consists of both orthoclase and oligoclase, with the orthoclase comprising about 60 per cent of the total feldspar. The phenocrysts of feldspar contain a dust of sphene, biotite, and magnetite, which is also distributed throughout the groundmass. In many instances, the quantity of magnetite, sphene, biotite, and a zircon-like mineral in the mylonites seems in excess of that contained in the undisturbed syenite.

The syenitic flinty crush-rock is characterized by textures resembling those produced in anhydrous melts. In the hand-specimen, it is dark, fine-grained, bluish-black, and contains residuals of feldspar phenocrysts averaging 3 to 4 millimeters in size. The feldspar residuals are blotchy and irregular and, in places, contain visible grains of ferromagnesian minerals; many of them are drawn out and distorted.

Microscopic study shows that most of the feldspar phenocrysts have recrystallized into laths approximately 0.12 millimeter in size, similar to the textures obtained from feldspar in a dry melt; such textures have not been observed in the unaltered syenites. This texture is believed to signify that the original feldspar phenocrysts of the syenite were actually melted and then recrystallized. These recrystallized phenocrysts are clouded with particles of ferromagnesian minerals. Some of the phenocrysts have been only partly melted and recrystallized, and those parts that have not been recrystallized lack the ferromagnesian minerals. Moreover, the boundary between the two areas is sharp. Some of the feldspar phenocrysts are clearly embayed by the groundmass, and, as such a feature has not been observed in the unaltered syenite, it is believed to have occurred during crushing.

The groundmass is a felt of orthoclase and albite laths, highly charged with small shredded biotite flakes and magnetite granules.

Of the various kinds of cataclastic rocks in the Belknap Mountains, this type presents the closest similarity to the British flinty crush-rocks. A specimen from the crushed Lewisian gneiss of the Isle of Tiree has been examined by the writer.

PSEUDOTACHYLITE

A few feet north of the Albany quartz syenite on Ox Mountain, several dikes of a dense, black to blackish-green rock intrude the Meredith granite. The dikes are about half a foot in width and resemble the lamprophyric dikes that are ordinarily found throughout the Belknap Mountains. Close examination, however, reveals certain peculiarities. Although dark and dense, the dikes are peculiarly mottled; they persist for no great distance, sometimes being so short as to become only an irregular mass. Their appearance suggests that, instead of an ordinary lamprophyre, they might be highly altered crush-rock derived from the cataclasis of the Meredith granite, an assumption that laboratory investigation has shown to be essentially correct. Thin sections of this rock reveal composition and texture unlike that of a lamprophyre; the texture shows marked similarity to that of some of the pseudotachylites illustrated by microphotographs in the Shaler Memorial volume on "The Vredefort Mountain Land." [48] The Belknap rock is believed to be analogous to the pseudotachylites and will, therefore, be referred to by that name.

Microscopically, the Belknap pseudotachylite is a dense aggregate of

[48] A. L. Hall and G. A. F. Molengraaff: *The Vredefort Mountain Land in the Southern Transvaal and the Northern Orange Free State,* Shaler Memorial Series, Kon. Akad. Wetenschap. Amsterdam (1925).

orthoclase, oligoclase, biotite, hornblende, and lesser amounts of magnetite, apatite, sphene, and zircon. Some of the feldspars are 0.20 millimeter long, but, generally, they are smaller; the larger ones are euhedral, and some are arranged in a manner that suggests trachytic structure. The biotite and hornblende are distributed throughout the thin section, in flakes and needles varying from 0.01 millimeter to 0.2 millimeter in size. Exceptionally, a few large crystals of feldspar and biotite are observed and are interpreted as remnants of the original rock; in one of these feldspar residuals, biotite flakes had penetrated along numerous cleavage surfaces without fracturing the grain. In the biotite residuals, they almost invariably show spherulitic recrystallization. One example of other feldspar residuals showed that it had undergone complete replacement by magnetite granules and apatite and was now a pseudomorph; another showed interwoven veins and concentrations of magnetite granules in intricate networks. Sphene and zircon are in close association with magnetite, in some places forming streaks and irregular areas of concentration. It is not unlikely that some of the sphene, zircon, and magnetite, together with what appears to be an excess of biotite and hornblende, may have been hydrothermally introduced at the time of the crustal disturbance that produced the pseudotachylite.

Field observations showed that the only mylonized rock near the pseudotachylite is the Meredith granite. The Albany quartz syenite, to the south, is quite unsheared. It, therefore, seemed likely that the Meredith granite was the source of dikes of pseudotachylite. Microscopic examination, however, destroys this hypothesis, for the thin sections show no quartz. The pseudotachylite resembles much more closely in its general composition the syenite and syenite prophyry that were observed on West Brook Mountain, as small lenses in the Meredith granite and the Moat volcanics. After such lenses had been injected, they were completely crushed and converted to pseudotachylite.

TECTONICS OF THE BELKNAP MOUNTAINS

GENERAL STRUCTURAL FEATURES

The geological map of the Belknap Mountains shows an igneous complex, marked by a notable annular arrangement of its units. The Albany quartz syenite forms an arcuate, almost oval-shaped, intrusive ribbon. Symmetrically grouped along the western edge of the complex are arcuate masses of quartz syenite, syenite, and monzodiorite. The Lake quartz syenite continues the arcuate trend of this latter group eastward, across Alton Bay, across Black Point headland, and through Rattlesnake and Diamond islands. In the southeastern part of the Belknap complex, two arcuate remnants of the schists and intrusives older than the White Mountain magma series further accentuate the structure.

This dominance of annular arrangement is too marked to be the result of chance distribution of intruding magmas. From the petrological distribution pattern alone, the conclusion must be drawn that a specialized tectonic mechanism—that of ring-intrusions—has been operative.

As further confirmation of such a theory, the structure of the Ossipee Mountains, across Lake Winnepesaukee from the Belknap Range, has been shown to be the result of ring-intrusion tectonics. Kingsley [49] demonstrated the existence of a ring-dike of Albany quartz syenite, identical with that in the Belknap Mountains.

SHAPE OF THE INTRUSIVE BODIES

Kingsley [50] was able to show in the Ossipee Mountains that the Albany quartz syenite is not only circular, but has steep, practically vertical contacts. What data are available in the Belknap Mountains indicate that, in general, the contacts, with one exception, are steep. The best exposed contact is the inner one of the Albany quartz syenite, which may be traced over barren ledges, from Mt. Major to Heater Mountain, without deviation. Between Ox Mountain and West Brook Mountain, the contact crosses a valley, 500 feet deep, without any change in strike on opposite sides of the valley bottom. This clearly demonstrates a vertical contact. Wherever the contact is exposed in small cliff faces, this fact is confirmed.

Although the outer contact of this body is not so well exposed, it crosses the south ridge of Huckleberry Mountain—a ridge that rises about 500 feet above the valleys on either side—without a change in strike. Farther east, the same relations hold. On the east slopes of Belknap Mountain, however, the contact, in a cliff a few feet high, was observed to dip about 33° SW. Although this may be a local variation from a vertical dip, the relation of the contact to the topography, for a mile to the south and half a mile to the north, suggests that this low dip may be of more than local significance.

In general, therefore, the Albany quartz syenite is arcuate in plan and has nearly vertical contacts, with the exception of 1½ miles of the outer contact. It is a true ring-dike.

The relations on the south side of Rattlesnake Island show that the contact of the Lake quartz syenite with the older intrusives of the Chatham group must be relatively steep.

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[49] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol. 12 (1931) p. 134-167.

[50] *Op. cit.*, p. 145, 146.

The contacts of the central stock of Conway granite must be steep. The contact crosses the ridge connecting Weeks Hill with Straightback Mountain but does not change in strike, although northeast of the ridge, the contact drops 800 feet. Also between Rowes Hill and Joy Hill, the contact crosses a valley, 300 feet deep, without perceptible deviation.

In summary, the intrusive bodies—with the exception of the central stock—are arcuate in plan and, although the data are, perhaps, not as complete as could be wished, have steep, probably vertical contacts. They fit the definition of ring-dikes.

That the Albany quartz syenite was actually intruded along an arcuate or circular fault is demonstrated by the cataclastic rocks so well exposed along the crest of Ox Mountain and West Brook Mountain. Here, the contact between the Albany quartz syenite and the Meredith granite is a fault plane, which has been cemented by the intrusion of the former. A steep, arcuate fracture must have originally cut the Meredith granite; movement along the walls is shown by the associated mylonite and flinty crush-rock. That the Albany quartz syenite was intruded parallel to the surface of the fault is shown by the persistence with which the quartz syenite clings to the fault line as its lateral boundary. A chill zone, varying from several feet to several yards in width, forms a sharp contact with the Meredith granite screen. These data on the mode of intrusion are similar to those described for the ring-dikes of the classic areas of western Scotland; undoubtedly the Belknap igneous complex was formed by some similar tectonic mechanism.[51]

The block inside the arcuate fault has subsided, for the youngest lithologic unit in the district, the Moat volcanics, lies inside the fault. A similar relationship between the Moat volcanics, the older rocks, and the Albany quartz syenite has been noted by Kingsley in the Ossipee Mountains,[52] by Billings in the North Conway quadrangle,[53] and by Billings and Williams in the Franconia quadrangle.[54]

THEORY OF CENTRAL COMPLEXES

The theory of central complexes is sufficiently well known from the Mull and Ardnamurchan Memoirs [55] and the papers by Richey [56] and

[51] C. T. Clough, H. B. Maufe, and E. B. Bailey: *The cauldron subsidence of Glen Coe*, Geol. Soc. London, Quart. Jour., vol. 65 (1909) p. 611-678.

[52] Louise Kingsley: *op. cit.*, p. 162.

[53] Marland Billings: *Petrology of the North Conway Quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 128.

[54] Marland Billings and C. R. Williams: *Geology of the Franconia Quadrangle, New Hampshire*, State Planning and Development Commission, Concord (1935) p. 23.

[55] C. T. Clough, H. B. Maufe, and E. B. Bailey: *op. cit.*

J. E. Richey: *The geology of Ardnamurchan, northwest Mull, and Coll*, Geol. Surv. Scotland, Mem. (1930).

[56] J. E. Richey: *Tertiary ring structures in Britain*, Geol. Soc. Glasgow, Tr., vol. 19, pt. 1 (1932) p. 42-140.

Kingsley,[57] so that only that portion of the theory that deals with the formation of ring-dikes and the associated screens, needs consideration here. A paraboloidal magma reservoir is assumed to exist at a depth of several miles. When the magmatic pressure becomes less than the hydrostatic pressure on the roof, the stresses are relieved by a series of outwardly dipping fractures with superimposed tension planes parallel to the outline of the magma chamber (Fig. 2). Subsidence of a central block and intrusion of magma between it and the country rock produce a ring-dike.

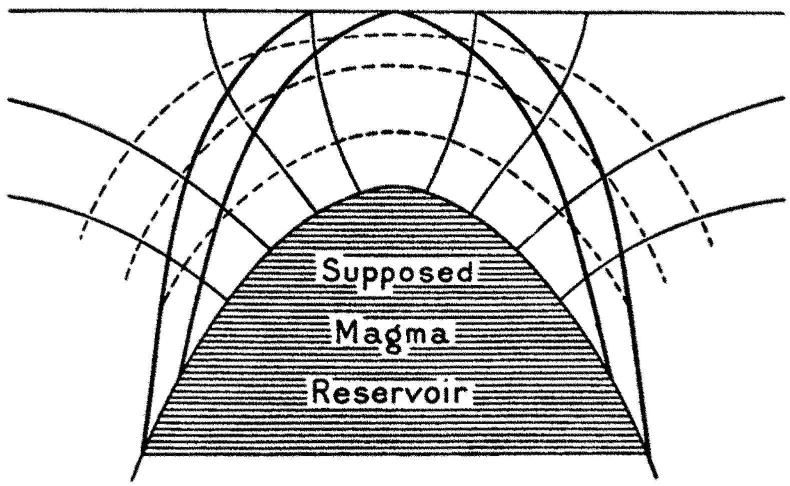

FIGURE 2.—*Dynamic relations of ring-fractures*
(After the Geological Survey of Scotland)

The ring-dike of the Ossipee Mountains is the only one as yet mapped which forms a complete circle. All others form partial circles or, more properly speaking, arcs.

Where the initial fissure forms a complete circle, the facts are as follows: (1) If the subsiding block has the same form in all cross sections, and if the subsiding block drops directly down, a complete ring-dike with uniform breadth of outcrop (in any given horizontal plane) should develop (Fig. 3, a). (2) If the subsiding block does not sink directly down, but crowds toward one wall, an incomplete ring-dike may form (Fig. 3, b). (3) If the initial fracture dips much more steeply on some parts of the circle than on others, the ring-dike varies in thickness, and, if the fracture is vertical, no intrusion may form (Fig. 3, c). (4) If the outward dip of

[57] Louise Kingsley: *op. cit.*

the initial fracture varies greatly, the ring-dike may have closely spaced variations in its breadth of outcrop (Fig. 3, d). (5) A younger intrusion, either another ring-dike or a stock, may destroy an older, complete ring-dike (Fig. 3, e). Chapman believes that this is probably the explanation of the discontinuity of the incomplete Park Brooks ring-dike of the Percy

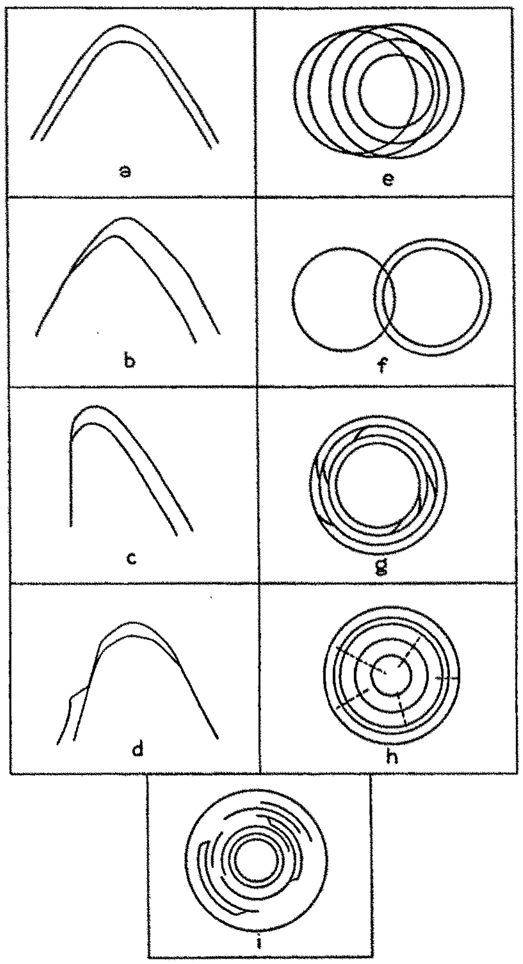

FIGURE 3.—*Formation of incomplete ring-intrusions*

(*a*) Complete ring-dike, (*b*) crowding to wall, (*c*) unsymmetrical dip, (*d*) variable dip, (*e*) later intrusion, (*f*) intersection, (*g*) two tangential fractures intersecting two concentric fractures, (*h*) two radial fractures intersecting two concentric fractures, (*i*) cavity left by subsidence of small slab between two arcuate fractures.

area,[58] and Billings and Williams believe the Mt. Garfield ring-dike of the Franconia quadrangle [59] is cut out by younger intrusives. (6) If the initial fracture is essentially vertical, the intrusive may make room for itself largely by piece-meal stoping, in which case, it may be markedly irregular and even incomplete. Billings and Williams believe that such a process is important in the White Mountains.[60] (7) As the result of the intersection of two circular fractures, a more or less arcuate slab may subside, and magma well up to fill the potential cavity (Fig. 3, f). (8) Two tangential (Fig. 3, g) or two radial (Fig. 3, h) fractures might intersect two concentric fractures, and the block so bounded might subside, and the magma well up to fill the potential cavity. This type of subsidence, as well as the preceding type, may be called slab-subsidence.

It is entirely possible, however, that the initial fracture may not form a complete circle, and, obviously, incomplete ring-dikes will result. (9) The magma might force the walls apart as in the normal type of dike; such dikes would probably be only a few hundred feet wide. (10) A small slab, caught between two arcuate fractures, might subside, and the magma well up to fill the potential cavity (Fig. 3, i). (11) Piecemeal stoping might be concentrated along an incomplete fracture.

OUTER FRAME

Outside the Belknap complex is a frame of older rocks, consisting of the Rockingham mica schists, the Meredith granite, and the Chatham group.

RATTLESNAKE COMPOSITE RING-DIKE

This structure extends from a point a third of a mile northwest of Ames, through Diamond Island, Rattlesnake Island, Gerrish Point, Goat Pasture Hill, Sweat Mountain, Piper Mountain, Belknap Mountain, and Gunstock Mountain to a point a mile northeast of the village of Gilford. It is interrupted between the last point and Ames by the central stock. It is a composite ring-dike, for it contains Ames monzodiorite, Gilmanton monzodiorite, Belknap syenite, Sawyer quartz syenite, and Lake quartz syenite. The angular, brecciated blocks of syenite in the quartz syenite near their contact indicate that (a) the intrusives of the ring-dike were not erupted simultaneously; (b) differentiation did not occur *in situ;* and (c) the dike was not intruded as a heterogeneous magma. On the basis of Anderson's theory of central subsidence, [61] it is necessary to picture the formation of the ring-intrusion as follows: (a) central subsidence along a ring-fracture, with the emplacement of an arcuate intrusive mass;

[58] Randolph Chapman: *Percy ring-dike complex,* Am. Jour. Sci., 5th ser., vol. 30 (1935) p. 417.
[59] Marland Billings and C. R. Williams: *op. cit.,* p. 24.
[60] *Op. cit.,* p. 25.
[61] C. T. Clough, H. B. Maufe, and E. B. Bailey: *op. cit.,* p. 11.

(b) solidification of the magma; (c) re-opening of the fracture, central subsidence, and intrusion of a new magma; (d) intrusion congeals, in turn, and process is repeated in other intrusions.

MT. MAJOR RING-DIKE

The regular outline of the inner ring-dike of Albany quartz syenite and its petrographic homogeneity throughout its length indicate a typical ring-dike intrusion. The lithologic homogeneity of the intrusive is characteristically porphyritic in texture. Observations along the Ox Hill section of the dike, and its trend across the topography, show that the dip of the fracture along which the intrusive rose is practically vertical. Central subsidence accounts well for its emplacement; a view strengthened by the fact that the ring-dike of the Ossipee Mountains, formed of an Albany quartz syenite, has been shown to have formed by central subsidence.[62]

CEDAR MOUNTAIN AND WEST BROOK MOUNTAIN SCREENS

A ring-complex containing arcuate strips of basement rocks is an expected result of the tectonic theory of ring-dike formation. The mode of formation is shown in Figure 4. Two such structures are in the Belknap complex. One, the Cedar Mountain screen, lies between the inner and the outer ring-dikes, and may be traced from Ames, Sleepers Island, Woodlands, and Cedar Mountain to a point just north of Goat Pasture Hill, where it ends at the point of convergence of the two ring-dikes.

The West Brook Mountain screen lies between the Mt. Major ring-dike and the central stock; it extends from Glidden Cove, through Weeks Hill, as far as Heater Mountain. The Moat volcanics occupy the west end of this screen, and must have reached their present position through subsidence of the interior cylinder, outlined by the inner ring-dike fracture. In the section extending northeast-southwest through the mass of Moat volcanics, the geologic structure of the Ossipee Mountains is exactly repeated. In both areas, the geologic sequence was as follows: (a) cauldron subsidence of the Moat volcanics, (b) emplacement of a ring-dike of Albany quartz syenite, and (c) intrusion of a central stock of Conway granite. A somewhat similar section is found, also, where the Moat volcanics are preserved in the Franconia quadrangle.[63]

CENTRAL STOCK AND RING-DIKES OF CONWAY GRANITE

The problem of the mode of intrusion of the Conway granite presents several puzzling features. The central stock of Conway granite could

[62] Louise Kingsley: *Cauldron subsidence of the Ossipee Mountains*, Am. Jour. Sci., 5th ser., vol 12 (1931) p. 134-167.

[63] Marland Billings and C. R. Williams: *op. cit.*, p. 23.

not very well have been formed by an unmodified process of central subsidence, for a large part of it is really an older, brecciated stock, which, by the subsidence theory, should have disappeared. Stresses on the roof above the magma chamber probably caused the formation of several arcuate fractures in the central part of the complex. Slabs of the roof rock, outlined by these arcuate fractures, sank into the magma, brecciating the diorite to the north by its rupture from it. A strong upwelling of granite magma then (a) completed the shattering of the diorite, forming an intrusion breccia with it; (b) filled in the space formerly occupied by

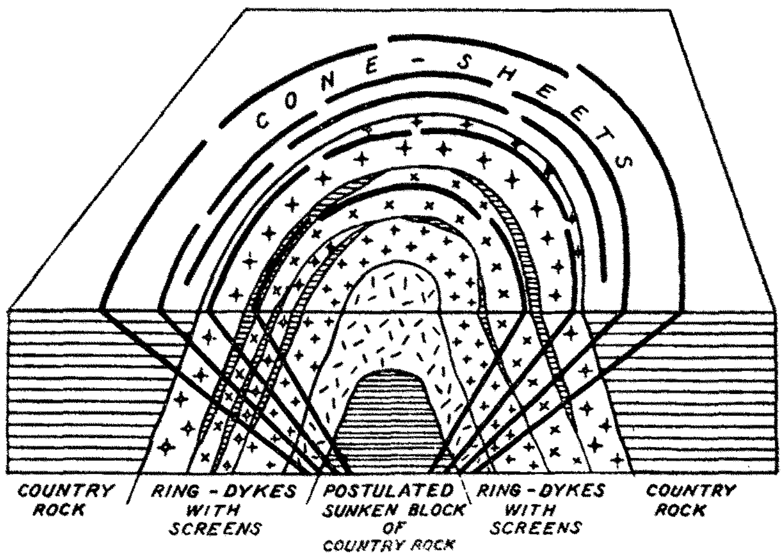

FIGURE 4.—*Stereometric view of an ideal ring-complex*
(After the Geological Survey of Scotland)

the subsided arcuate slabs; and (c) forced its way up the most southerly of the arcuate fractures along the northern border of the Cedar Mountain screen, forming the ring-dike of the Conway granite.

LATE VOLCANIC VENTS

The Rowes volcanic vent, already described, is slightly arcuate in outline, and is filled with unbedded vent agglomerate. The body of volcanic breccia along the southern contact of the West Brook screen, along the western slopes of Straightback Mountain, probably also represents a small late volcanic conduit.

GENESIS OF THE BELKNAP COMPLEX

The genesis of the Belknap Mountains may be summarized as follows: (1) The Rockingham mica schists were deposited as muds, sandy muds, and muddy sandstones, probably during the Devonian, or possibly in the Carboniferous. (2) The sediments were intensely folded either in late Devonian or in late Carboniferous. In the latter stages of this orogeny, intrusives of the New Hampshire magma series rose into the crust, and the sediments were metamorphosed to crystalline schists. (3) A long period of erosion exposed these formations.

The White Mountain magmatic cycle was probably initiated by the extrusion of the Moat volcanics on a surface composed of the older rocks. Strictly speaking, all that can be proved in the Belknap Mountains is that the Moat volcanics are older than the Albany porphyritic quartz syenite; possibly, some of the earlier intrusions may actually be older than the Moat volcanics. At Pleasant Mountain, however, Jenks[64] has demonstrated that the volcanics are older than the syenites, and Althea P. Smith has found fragments of basalt in a quartz monzonite of the White Mountain magma series on Tripyramid Mountain.[65] Although such facts suggest that the Moat volcanics are relatively old members of the magmatic cycle, Billings[66] and Kingsley[67] have pointed out that the volcanic and the plutonic phases of the activity may have been coextensive.

The first stage in the plutonic cycle was the intrusion of the small stock of Gilford gabbro.

Next was the emplacement of a large body of diorite. As in the case of the gabbro, there is no evidence to suggest fault-intrusion; the diorite is considered to have been intruded as a large stock, occupying essentially the same position as the mass of diorite-granite breccia.

The underlying magma reservoir then exerted stress of such a nature on its roof that a crudely circular fracture zone was formed. Individual fractures within this zone had steep dips. Possibly, at least one major fracture formed a complete circle, along which subsidence occurred. The fracture zone extended through Diamond Island, Rattlesnake Island, Gerrish Point, Goat Pasture Hill, Piper Mountain, Mt. Belknap, and Mt. Gunstock. Into this fracture zone, there was intruded successively the Ames and Gilmanton monzodiorites, the Belknap syenite, the Sawyer quartz syenite, and the Lake quartz syenite. These bodies may have

[64] W. F. Jenks: *Petrology of the alkaline stock at Pleasant Mountain, Maine*, Am. Jour. Sci., 5th ser., vol. 28 (1934) p. 321-340.

[65] A. P. Smith: Geology of the Sandwich Range. In preparation.

[66] Marland Billings: *Petrology of the North Conway quadrangle in the White Mountains of New Hampshire*, Am. Acad. Arts and Sci., Pr., vol. 63 (1928) p. 67-137.

[67] Louise Kingsley: *op. cit.*

been emplaced either by successive subsidences along the zone of weakness, or by overhead stoping along this same zone, as the Rattlesnake composite ring-dike was formed.

A new ring-fracture, smaller than the first, developed next. The center of this fracture was at least a mile northwest of the center of the older fracture zone, implying migration of the underlying magma reservoir. Because the central block subsided, the Moat volcanics were dropped to their present position, the Albany quartz syenite was intruded along the fracture, and a large screen of the older basement rocks was left between the two ring-dikes.

Further stresses were relieved by arcuate cracks in the central part of the area. Rupture and sinking of blocks formed, together with an influx of granite magma, shattered and brecciated the diorite to form a diorite-granite breccia. The rupture and subsidence of the central blocks left behind a thin strip of the old basement rocks (principally the Meredith porphyritic granite) to form the West Brook screen. Farther from the center, two incomplete ring-dikes of granite were injected along the outer edge of the younger of the two ring-dikes.

The explosion of a volcanic vent marked the next phase of igneous activity; this eruption was localized in an area between the quartz syenite and the Cobble Hill area of the Belknap syenite. The volcanic pipe left as a relic of this disturbance is approximately a mile in length; it is filled with rubble of the Meredith granite and other rocks, forming a typical vent-agglomerate. Simultaneously, volcanic activity occurred along the southern part of the Albany quartz syenite and the West Brook screen, giving rise to other volcanic breccias.

A period of dike injection closed the history.

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