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STRUCTURE AND METAMORPHISM IN THE MOUNT WASHINGTON AREA, NEW HAMPSHIRE

BY

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The Mt. Washington area of New Hampshire contains the highest peaks in the northern Appalachian Mountains. The metamorphic rocks belong to four stratigraphic units: the Ordovician (?) Ammonoosuc volcanics, chiefly fine-grained biotite gneiss; the Ordovician (?) Partridge formation, largely gneiss derived from shale; the Silurian Fitch formation, consisting of lime-silicate granulite and schist; the Devonian Littleton formation, mostly quartzite and schist.

The oldest intrusive rocks are quartz monzonites and granites belonging to the Devonian (?) Oliverian and New Hampshire series. Granite, syenite, tuff, and breccia belong to the Mississippian (?) White Mountains magma series.

The chemical composition of some of the minerals differs with the formation. Pyroxene and amphibole in the Fitch formation are magnesia-rich and iron-poor, whereas in the Ammonoosuc volcanics the reverse is true. Oligoclase characterizes the Partridge formation, Littleton formation, and Bickford granite; andesine is typical in the Ammonoosuc volcanics; and bytownite is common in the Fitch formation. Biotite and muscovite are relatively uniform, except for magnesia-rich biotite in the Fitch formation.

The Mt. Washington area is on the southeast flank of a large dome, the center of which is occupied by the intrusive Oliverian magma series. The folds in the Presidential Range trend north and northeast. The major folds are *en echelon,* and upon them are superimposed many minor folds. Schistosity, due to platy minerals, parallels the bedding. Fracture cleavage is essentially parallel to the axial planes of the minor folds. The Pine Mountain fault is the largest of several normal faults.

Metamorphism is high-grade (katazonal). Original shales are now andalusite schist, coarse rough pseudo-andalusite schist, fine grained pseudo-andalusite schist, and staurolite schist. Contrasting metamorphic history explains the various types. Metamorphism was syntectonic, and the coarser schists show three major stages in the paragenesis. Many rocks, particularly paraschists, suffered no significant chemical change. Potash was introduced into some of the coarser schists. Many of the gneisses are derived from shale by metamorphic differentiation, and less than 1 per cent of soda, lime, and potash has been introduced. Four or five per cent of soda, lime, and potash has been added to shale to form the lighter colored gneisses.

INTRODUCTION

The Mt. Washington area, as defined for this paper, covers about 100 square miles somewhat north of the center of New Hampshire (Fig. 1). The mapped area is mostly in the southern half of the Mt. Washington quadrangle, but includes a few square miles in the southwestern part of the Gorham quadrangle and the northern part of the Crawford Notch quadrangle.

Brief mention of the geology was made by C. T. Jackson (1844) and H. D. and W. B. Rogers (1846; 1848). The most thorough investigation of the bedrock geology was by C. H. Hitchcock (1877, p. 113-127). R. W. Chapman (1937) has described the syenite stock on Cherry Mountain (Mt. Martha). No attempt was made in the present investigation to consider all phases of the geology. The study was concerned with the lithology, stratigraphy, structure, and metamorphism. The physiography and glaciation have been so thoroughly studied by J. W. Goldthwait (1916), A. C. Lane (1921), I. B. Crosby (1924), E. Antevs (1932), and R. P. Goldthwait (1940), that the present writer did no work on these subjects.

The field work occupied one month in the summer of 1936 and three months each during the summers of 1938 and 1939. On topographic maps, enlarged to about 3 inches to the mile, all observations were plotted, and a complete outcrop map was prepared. Location was made largely by barometer, inasmuch as all streams, ridges, and trails are shown on the map. A few pace-and-compass traverses were made but it was not necessary to use this method as extensively as in the Littleton-Moosilauke area (Billings, 1937, p. 466-469). The laboratory investigation was carried on during the winters from 1937 to 1940. Two hundred and thirty thin sections were used and a great deal of optical mineralogy was essential. Nine chemical analyses were made by the Rock Analysis Laboratory at the University of Minnesota.

After the field work had been completed, it became obvious that the results could be most satisfactorily presented in a series of papers. The dike rocks, although variable and interesting, have no particular relationship to the stratigraphy, metamorphism, and structure and will be considered in a separate paper by Katharine Fowler-Billings. The Oliverian magma series consists of several mappable units. However, these rocks are also extensively developed in the northern half of the Mt. Washington quadrangle, now being studied by R. W. and C. A. Chapman, and will be considered in a joint paper. The stock of syenite on

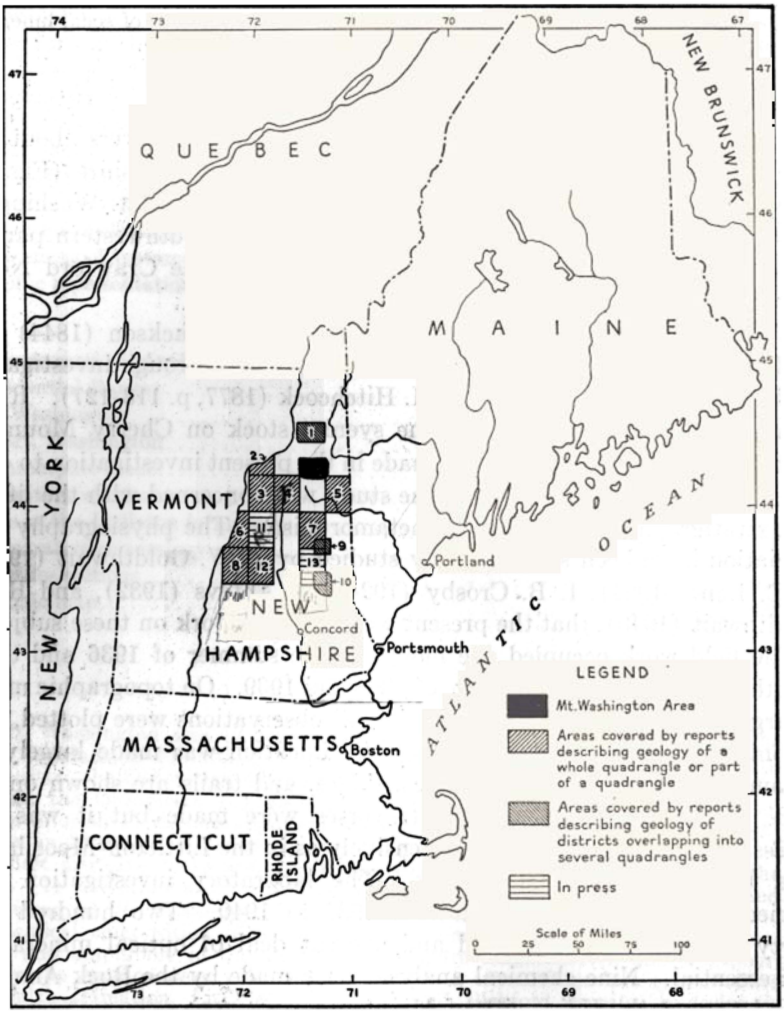

FIGURE 1.—*Index map*

Shows location of the Mt. Washington area in solid black. Other areas studied in the present investigation of New Hampshire are: 1 = Percy area (R. W. Chapman, 1935); 2 and 3 = Littleton and Moosilauke quadrangles (Billings, 1937); 4 =Franconia quadrangle (Williams and Billings, 1938); 5 = North Conway quadrangle (Billings, 1928); 6 and 8 = Mt. Cube and Mascoma quadrangles (Hadley and C. A. Chapman, 1939; C. A. Chapman, 1939); 7 = Mt. Chocorua quadrangle (Smith, Kingsley, and Quinn, 1939); 9 = Ossipee Mountains (Kingsley, 1931); 10 = Belknap Mountains (Modell, 1936); 11 = Rumney quadrangle (Page, in preparation); 12 = Cardigan quadrangle (Fowler-Lunn and Kingsley, 1937); 13 = Winnepesaukee quadrangle (Quinn, in preparation). Red Hill (Quinn, 1937) lies west of the Ossipee Mountains.

FIGURE 1. AERIAL VIEW FROM THE SOUTH IN WINTER
The highest peak is Mt. Washington. (Photo by H. Bradford Washburn, Jr.

FIGURE 2. AERIAL VIEW FROM THE WEST
Peaks from left to right: A—Mt. Adams; J—Mt. Jefferson; C—Mt. Clay; W—Mt. Washington; B—Boott Spur; M—Mt. Monroe; P—Pleasant Dome, which is not within the area covered in Plate 1. Open fields in foreground are Bretton Woods. Lowland is underlain by Bickford granite. (Photo by H. Bradford Washburn, Jr. Courtesy of The Flume Reservation, Franconia Notch, New Hampshire)

PRESIDENTIAL RANGE

FIGURE 1. AERIAL VIEW FROM THE EAST
B—Boott Spur; W—Mt. Washington; C—Mt. Clay; S—Gulf of the Slides; T—Tuckerman Ravine; H—Huntington Ravine; G—Great Gulf. (Photo by H. Bradford Washburn, Jr. Courtesy of the Flume Reservation, Franconia Notch, New Hampshire)

FIGURE 2. AERIAL VIEW OF TUCKERMAN RAVINE FROM THE EAST
Shows axis depression just above the headwall. To the left (south) of the Ravine the folds plunge north; above the headwall they are horizontal; and to the right they plunge south. (Photo by H. Bradford Washburn, Jr.)

MT. WASHINGTON

Cherry Mountain (Mt. Martha) has been described by R. W. Chapman (1937). The Conway granite in the southwestern part of the quadrangle is so similar to its continuation in the Franconia quadrangle (Williams and Billings, 1938) that a detailed description is unnecessary. Two preliminary papers on the area have already been published (Billings, 1938b; 1939).

ACKNOWLEDGMENTS

The writer is greatly indebted to numerous organizations and individuals for aid. The cost of the study was partially financed by grants from the Associates in Science of Harvard University and from the Penrose Bequest of The Geological Society of America. Robert Williams assisted in the field in 1936, F. B. Loomis, Jr. in 1938, and W. P. Fuller, Jr. and R. F. Story in 1939. Mr. Loomis mapped the area bounded on the south by Ammonoosuc River, on the west by the Cherry Mountain road, on the east by the Jefferson Notch road, and on the northwest by a northeast-southwest line 1 mile northwest of Pine Mountain. Katharine Fowler-Billings was my co-worker in the field throughout the summer of 1938. Mr. Fuller gave valuable laboratory assistance during the winter of 1939-40.

Mr. Elliott Libby, of Gorham, New Hampshire, kindly allowed us to use the automobile road on Mt. Washington without charge. Due to the great hurricane of September, 1938, large portions of the White Mountain National Forest were closed to all entry during the summer of 1939 because of great fire-hazard. Mr. C. L. Graham, Forest Supervisor, kindly granted permits to enter closed areas, and the district rangers, N. D. Shirley and H. C. Waldo were most cordial. Oblique aerial photographs by H. Bradford Washburn, Jr. proved useful in planning accessible routes and in locating outcrops. The original manuscript has been extensively revised in accordance with suggestions made by C. A. Chapman and R. W. Chapman. Photographs accompanying this paper, unless otherwise acknowledged, are by Katharine Fowler-Billings, R. F. Story, and W. P. Fuller, Jr. Edward Schmitz has done the drafting.

TOPOGRAPHY AND DRAINAGE

The Mt. Washington area (Pl. 1), containing the highest peaks in the northern Appalachian Mountains, has a maximum difference in elevation of somewhat greater than 5000 feet. The Presidential Range (Pls. 2, 3), which occupies the eastern half of Plate 1, trends north-south but is convex toward the west. The principal summits, from south to north, are: Boott Spur, Mt. Monroe, Mt. Washington (altitude 6288 feet), Mt. Clay, Mt. Jefferson, Mt. Adams, and Mt. Madison. To the east of the

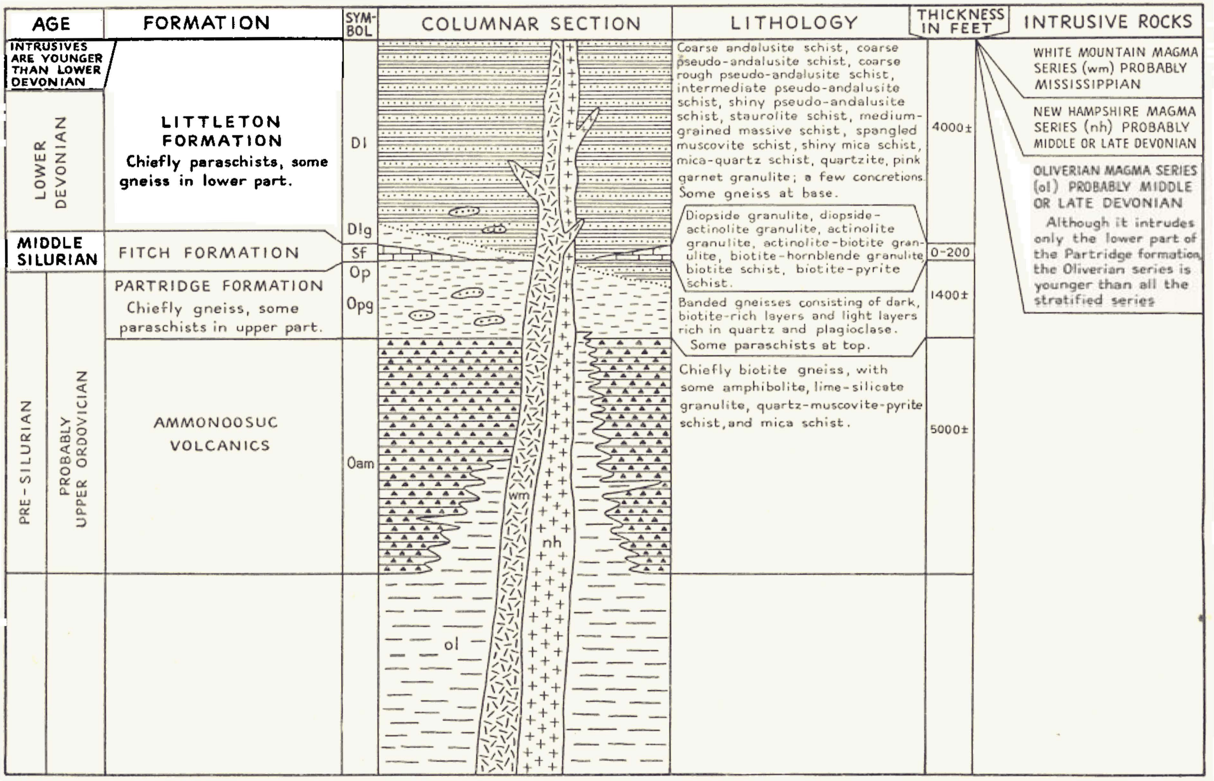

FIGURE 2.—*Columnar section for Mt. Washington area*

Shows sequence, character, and thickness of the metamorphic rocks and the sequence of igneous intrusion. The Oliverian magma series (ol) at the base of the column is not part of the stratified series, but a huge intrusive sheet, the top of which varies considerably in stratigraphic position.

Presidential Range are the Peabody and Ellis rivers, which flow northeast and south respectively. Pinkham Notch (altitude 2032 feet) is at the divide.

The Dartmouth Range lies in the central part of the area, trends northeast, and contains the following principal peaks: Millen Hill, Mt. Dartmouth (altitude 3721 feet), Mt. Deception, and Little Mt. Deception. Cherry Mtn., the principal summit of which is known as Mt. Martha, is in the west-central part of the area. Moose and Israel Rivers drain the northern part, and the Ammonoosuc River drains the southwestern part.

The area is heavily forested, except for the higher parts of the Presidential Range (Pl. 4, fig. 2). Timberline (Pl. 4, fig. 1) is at about 4500 to 4800 feet, although locally it is lower. Outcrops are not abundant above timberline, due to extensive late-glacial or postglacial frost action. Bedrock is well exposed in cirques, along many of the streams, on landslides, and in numerous outcrops scattered in the forest. As a whole, outcrops are fairly good, but are scarce on the northern slopes of the Dartmouth Range.

GENERAL LITHOLOGIC FEATURES

Metamorphic and plutonic rocks compose the Mt. Washington area. Their sequence, age, lithology, thickness, and a graphical representation of the geological history are given in Figure 2.

The oldest rocks, probably upper Ordovician, are the Ammonoosuc volcanics. Above is the Partridge formation, also probably upper Ordovician. It is largely gneiss, but locally is schist and quartzite. The middle Silurian Fitch formation is a thin, discontinuous unit above the Partridge formation. It has been derived from impure dolomites and is distinctive because it contains diopside, actinolite, calcic plagioclase, and magnesia-rich biotite. The highest stratigraphic unit is the lower Devonian Littleton formation, which is largely quartzite and schist. The lower part of the formation has been locally converted to gneiss. The total thickness of the metamorphosed sedimentary and volcanic rocks is about 10,500 feet.

These stratified rocks are intruded by plutonic rocks belonging to three of the four magma series of New Hampshire. The Oliverian magma series is younger than the stratified rocks but is slightly older than the orogeny, probably middle or late Devonian. The New Hampshire magma series is represented by the Bickford granite, probably injected just after the folding and thus late Devonian. The White Mountain magma series is represented by the syenite on Cherry Mountain (Mt. Martha), the Conway granite around Mt. Oscar, and small volcanic vents. This series is probably Mississippian.

Over 100 basic dikes, belonging partly to the White Mountain magma series and partly younger, have been observed, but will be described in a separate paper. Glacial drift hides much of the bedrock.

AMMONOOSUC VOLCANICS (ORDOVICIAN?)

GENERAL STATEMENT

Along the lower slopes of the northern flank of the Presidential Range the Ammonoosuc volcanics occupy a belt which trends east-northeast and is almost 1½ miles wide (Pl. 1). The rocks are well exposed along streams from south of Bowman to southwest of Randolph. Southwest of Mt. Bowman, however, exposures of the Ammonoosuc volcanics are rare. South of Randolph the belt of Ammonoosuc volcanics is interrupted by a stock of Bickford granite and by glacial drift. Isolated exposures are found, however, along the railroad 2 miles east of Randolph. The small belt of Ammonoosuc volcanics shown 1 mile north of Mt. Deception is based on float; no outcrops have been observed. The small belt 2½ miles west of Mt. Deception is well exposed, and the intrusive relations of the surrounding granites of the Oliverian magma series are well established.

The best exposures of the Ammonoosuc volcanics are along Israel River, Moose River, and several streams not shown on Plate 1, especially The Mystic, Cold Brook, and Snyder Brook.

LITHOLOGY

General character.—The Ammonoosuc volcanics are classified as follows: (1) amphibolite, including quartz amphibolite; (2) biotite gneiss, derived from tuffs with the composition of rhyolite, quartz latite, and dacite; (3) lime-silicate granulite and schist; (4) quartz-muscovite-pyrite schist; and (5) miscellaneous rocks of sedimentary origin, including mica schist, biotite-feldspar schist, and quartz-chlorite-plagioclase gneiss.

Amphibolite.—Amphibolites are not common in the Ammonoosuc volcanics of the Mt. Washington area. Megascopically they are dark, speckled, medium-grained rocks composed of black hornblende and white plagioclase. A weak schistosity is generally present, and in some cases the aligned hornblende needles give a distinct lineation.

Under the microscope the amphibolites are granoblastic; hornblende, 0.1 to 1.0 millimeters in diameter, is distinctly larger than andesine, which is 0.25 to 0.2 millimeters. Accessory minerals are quartz, magnetite, and sphene. Modes[1] are given in Table 1.

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[1] All modes are estimates and are in volume per cent. Those calculated from chemical analyses are in weight per cent.

The plagioclase, many grains of which are slightly zoned, commonly shows albite twinning and, to a lesser extent, Carlsbad twinning. The composition ranges from intermediate andesine (An_{40}) to andesine-labradorite (An_{50}).[3] Optical data indicate that the amphibole is common hornblende, similar to that analyzed from an intrusive amphibolite in the Littleton-Moosilauke area (Table 10, column 18). A chemical analysis of amphibolite from the Mt. Washington area is given in Table 10, column 11.

Amphibolite, sufficiently rich in quartz, is classed as quartz amphibolite. The texture is granoblastic. These rocks (Table 1, column 2) differ from the more common amphibolites in containing orthoclase and pyroxene as well as quartz. Andsesine (An_{40}), is mostly untwinned although some shows albite twinning. The relative proportions of quartz and feldspar were determined by Dodge's (1936) method. The amphibole is common hornblende.

Biotite gneiss.—Biotite gneisses are the most abundant rocks in the Ammonoosuc volcanics of the Mt. Washington area. Megascopically they are gray and fine-grained, with variable amounts of biotite. In general they are even-grained, but some specimens show grains of feldspar and quartz several millimeters across set in a finer groundmass.

Microscopically the biotite gneisses consist essentially of quartz, plagioclase, potash feldspar, and biotite, with such minor accessories as muscovite, hornblende, apatite, garnet, and epidote. Modes are given in Table 1. The plagioclase is oligoclase and andesine, in which the anorthite content is constant in each specimen but ranges from 12 to 40 per cent in different specimens. Potash feldspar and plagioclase are present in all proportions.

Optical data indicate that most of the biotite is nearer annite than phlogopite, the weight per cent of iron equaling or exceeding the weight per cent of magnesia. The epidote, although not abundant, apparently is a primary metamorphic mineral. It occurs in small fresh anhedra, with about 13 per cent $HCa_2Fe_3Si_3O_{13}$, that is, 8 per cent Fe_2O_3. Muscovite is essentially $H_4K_2Al_6Si_6O_{24}$, similar to the analysis in Table 10, column 19.

By analogy with the Ammonoosuc volcanics in the low-grade metamorphic zone of the Littleton-Moosilauke area (Billings, 1937, p. 477), the biotite gneisses are considered to have been derived from pyroclastics. Many specimens show no trace of volcanic textures, but subhedral grains of feldspar and quartz, similar to those found in crystal tuffs, have been noted. No textures suggesting volcanic breccias or conglomerates were observed, but experience in the Littleton-Moosilauke area indicates that with increasing metamorphism such features tend to disappear. Assuming no important change in composition during metamorphism, rhyolites (Table 1, columns 3, 3a), quartz latites (column 4), and dacites (column

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[3] In the laboratory study critical optical data were obtained for the principal minerals in every specimen for which a thin section was available; the data included the indices as determined by the immersion method. In a preliminary manuscript these data were recorded but have been omitted from the published manuscript. However, they are summarized graphically in Plate 8.

TABLE 1.—*Approximate modes—Ammonoosuc volcanics*

	1	1a	2	3	3a	4	5	6	7	8	9	10	11	12	13	14	15
Number of thin sections	2	..	1	2	..	1	2	1	1	2	1	2	1	2	1	1	1
Quartz	3	6	21	33	37	40	37	40	10	4	35	36	..	71	50	10	45
Orthoclase*	..	..	5	45	46	20	3	..	..	..	25	31	10	..	..	20	..
Plagioclase	27	37	43	10	10	33	44	40	58	45	32	23	17	5	32	35	12
Hornblende	68	55	25	..	..	1	..	..	8	tr	2	6	52	..	..	..	..
Pyroxene	..	..	5	..	..	..	..	..	20	27	1	..	..	..	..	..	..
Muscovite	..	..	..	1	2	..	3	2	..	..	..	..	..	20	3	..	15
Biotite	..	..	..	11	5	6	13	..	..	..	..	2	..	..	..	35	25
Garnet	..	..	..	tr	..	..	..	3	..	1	1	1	..	tr	..	..	3
Apatite	..	tr	tr	tr	tr	tr	tr	tr	..	tr	..	..	..	..	..	..	..
Epidote	..	..	..	..	..	tr	tr	..	3	22	4	tr	..	..	..	..	..
Chlorite	..	..	..	..	..	..	..	15	..	..	..	tr	18	..	15	..	..
Magnetite	1	2	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..
Sphene	1	..	1	..	..	tr	..	..	1	1	..	1	1	..	tr	..	..
Pyrite	..	..	..	..	tr	..	..	..	..	..	..	..	..	4	..	..	..
Carbonate	..	tr	..	..	..	..	..	..	..	..	..	..	1	..	..	..	..
Sillimanite	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	tr
Per cent of anorthite in plagioclase																	
Average	45	52	40	12	10	35	32	13	40	45	35	57	46	5	38	30	15
Range	40–50	52	40±	12–13	10	35	25–40	13	40	40–50	35	35–90	46	5	38	30	15
Grain size millimeters	0.05-1.00	0.05-1.00	0.10-0.30	0.10-0.50	0.10-0.80	0.05-0.50	0.05-0.80	0.05-0.08	0.05-2.00	0.05-0.40	0.05-0.20	0.05-1.00	0.05-0.40	0.05-1.50	0.10-0.30	0.10-0.60	0.05-1.00

* Includes microcline and microperthite

1. Amphibolite.
1a. Amphibolite, calculated from chemical analysis (W 56).
2. Quartz amphibolite.
3. Biotite gneiss, originally rhyolite.
3a. Biotite gneiss, originally rhyolite, calculated from chemical analysis (W 26).
4. Biotite gneiss, originally quartz latite.
5. Biotite gneiss, originally dacite.
6. Chloritized biotite gneiss.
7. Pyroxene-hornblende granulite.
8. Pyroxene-epidote granulite.
9. Hornblende-epidote granulite.
10. Hornblende-biotite granulite.
11. Edenite-chlorite schist.
12. Quartz-muscovite-pyrite schist.
13. Quartz-chlorite-plagioclase gneiss.
14. Biotite-feldspar schist.
15. Mica schist.

5) are represented. Admixture of terrigenous material is suggested by the relatively high quartz or biotite content of some specimens.

A chemical analysis of biotite gneiss, which is metamorphosed rhyolite, is given in Table 10, column 14.

Lime-silicate granulite.—Granulites carrying hornblende and pyroxene, are not particularly abundant, but they are distinctive and have received special study. Moreover, megascopically they resemble lime-silicate granulites in the Fitch formation.

Megascopically the lime-silicate rocks are white to gray in weathered outcrops, gray to green in fresh exposures. Generally they are hard, resistant, and lack a good schistosity. Alternating bands, 1 to 10 millimeters thick differ in mineral composition. Pink garnets, black hornblende, and black pyroxene may be commonly recognized.

In the field these lime-silicate rocks are distinguished from the biotite gneisses by a lack of schistosity and the presence of hornblende and pyroxene. Their lighter color distinguishes them from the amphibolites. Some specimens closely resemble lime-silicate rocks of the Fitch formation. The means of distinguishing rocks from the two formations is discussed later.

Microscopically the lime-silicate rocks are granoblastic, although the hornblende commonly encloses the other minerals poikiloblastically. The individual minerals range considerably in size, but the pyroxene and hornblende are commonly 0.1 to 2.0 millimeters long, whereas the quartz and plagioclase are 0.05 to 0.2 millimeter. Modes are given in Table 1.

The pyroxene is a member of the diopside-hedenbergite series, and the content of diopside varies from 35 to 45 per cent. In most specimens the amphibole is common hornblende similar to that found in the Littleton-Moosilauke area. One specimen (Table 1, column 11) containing an amphibole with optical properties similar to edenite (Larsen and Berman, 1934, Table 6, No. 56), has obviously undergone hydrothermal alteration. Epidote, in subhedral to euhedral grains, appears to be contemporaneous with pyroxene, hornblende, and andesine. There is no evidence that it is a later hydrothermal alteration product. Optical data indicate 10 to 15 per cent of $HCa_2Fe_3Si_3O_{13}$.

The plagioclase is generally andesine, ranging from An_{35} to An_{50}, but in one specimen it is An_{90}. Chlorite from the edenite-chlorite schist is a later hydrothermal derivative from biotite, and its optical properties indicate that it is prochlorite (Winchell, 1933, p. 280).

The pyroxene-epidote granulites and probably the pyroxene-hornblende granulites were basaltic flows or tuffs. The edenite-chlorite schist, although considerably altered, also seems to have been originally a basalt. The hornblende-epidote and hornblende-biotite granulites, with their relatively high content of quartz and potash feldspar and low content of dark minerals, were presumably quartz latites.

The lime-silicate granulites of the Ammonoosuc volcanics superficially resemble the lime-silicate granulites of the Fitch formation. However, a distinction may be readily made microscopically. In the pyroxene of the Fitch formation γ is close to 1.708, whereas in the Ammonoosuc volcanics it averages 1.730. In the amphibole of the Fitch formation γ averages 1.648, whereas in the Ammonoosuc volcanics it is higher, ranging from 1.660 to 1.700. These differences are shown in Plate 8.

Quartz-muscovite-pyrite schist.—Although these rocks are not abundant, they are conspicuous and distinctive. In natural exposures they are rusty schists, stained deep brown by the alteration of pyrite to limonite. Fresh specimens are pure white, lustrous schists dotted with pyrite grains. Muscovite flakes are as much as 2 millimeters in diameter.

Under the microscope they are lepidoblastic to granoblastic, the grain size ranging from 0.05 to 1.50 millimeters. Quartz, muscovite, and pyrite are most conspicuous, with albite (An_5), garnet, and an unknown mineral as accessories. Modes are given in Table 1. The muscovite does not differ greatly from that found in the other formations.

These rocks apparently represent argillaceous sandstones interbedded with the volcanics. The pyrite was probably introduced hydrothermally during the metamorphism.

Mica schist and other schists.—Some of the Ammonoosuc volcanics are of sedimentary origin or represent mixtures of terrigenous and volcanic material. A coarse mica schist, containing small quantities of sillimanite (Table 1, column 15), was collected in the Moose River at an altitude of 1625 feet. The biotite is intermediate between phlogopite and annite. The muscovite is essentially $H_4K_2Al_6Si_6O_{24}$. This specimen carries sillimanite, indicating that the Ammonoosuc volcanics of the Mt. Washington area belong to the high-grade zone of metamorphism rather than to the middle-grade zone.

In a volcanic series composed dominantly of water-laid tuffs and breccias (Billings, 1937, p. 476) some admixture of terrigenous material is to be expected. The biotite-feldspar schist (Table 1, column 14), because of its high biotite content, is considered to represent a quartz latite tuff contaminated by argillaceous material. The quartz-chlorite-plagioclase gneiss (Table 1, column 13), is believed to represent a dacite contaminated by terrigenous quartz and argillaceous material. Furthermore, this specimen has undergone retrograde metamorphism. Some of the lime-silicate granulites and some of the biotite gneisses may be volcanics contaminated by sedimentary quartz.

RETROGRADE PROCESSES

In some specimens retrograde metamorphism is manifested primarily by the conversion of biotite to chlorite. Three specimens found within 100

FIGURE 1. TIMBERLINE
Looking north across mouth of Tuckerman Ravine toward Huntington Ravine. Shows transition from heavy timber through scrub timber into treeless zone.

FIGURE 2. ABOVE TIMBERLINE
Looking south toward Mt. Monroe from the south slope of Mt. Washington. Lakes of the Clouds in the right foreground. The Fitch formation occupies the depression at the foot of Mt. Monroe.

ON MT. WASHINGTON

FIGURE 1. PARTRIDGE FORMATION
Alternating light and dark bands typical of the variety of gneiss which has been derived from shale without much change in chemical composition.

FIGURE 2. LITTLETON FORMATION
Coarse rough pseudo-andalusite schist. Large pseudo-andalusite crystals, which now consist of sillimanite, muscovite, and quartz, with a little staurolite.

FIGURE 3. LITTLETON FORMATION
Interbedded quartzite and spangled muscovite schist.

METAMORPHIC ROCKS

feet of each other at an altitude of 1550 to 1560 feet on Moose River, contain considerable prochlorite or ripidolite. One of these specimen is also rich in edenite. The three specimens lie within the Pine Mountain fault zone. Presumably fractures permitted the access of hydrothermal solutions necessary for these retrograde changes.

THICKNESS

The Ammonoosuc volcanics in the Mt. Washington area attain a maximum thickness of 5000 feet; the base, however, is not exposed because of the intrusive relations of the Oliverian magma series. A fairly complete section along Israel River shows dips almost exclusively to the southeast, although some northwesterly dips may be observed. As shown in section CC′ of Plate 11, the thickness approximates 5000 feet. Along the headwaters of Moose River the thickness is likewise 5000 feet. On other streams the range is from 3500 to 5000 feet.

A rough estimate of the relative abundance of the various types is as follows: amphibolite 3 per cent; biotite gneiss 93 per cent; lime-silicate granulites 1 per cent; quartz-muscovite-pyrite schist 3 per cent; mica schist, trace.

PARTRIDGE FORMATION (ORDOVICIAN?)

GENERAL STATEMENT

The Partridge formation overlies the Ammonoosuc volcanics and occupies two areas (Pl. 1), one of which extends northeasterly from Mt. Deception through Mt. Bowman to the northeast corner of the map. The second area, forming a great irregular semicircle, may be traced along the east side of the map from Dolly Copp Camp to Pinkham Notch, thence westward to Mt. Franklin and northwesterly to Millen Hill.

Good exposures may be seen in many places, especially at: (1) Peabody River, at and below the junction with the West Branch; (2) West Branch of the Peabody River, for 1 mile above the junction with the main stream; (3) Cutler River, just above Pinkham Notch; (4) summit of Mt. Clay; (5) summit of Mt. Monroe.

LITHOLOGY

General character.—The Partridge formation consists of two major types: paraschists and gneisses. The paraschists are quartzites and mica schists, derived respectively from sandstones and shales. The gneisses, which are typically composed of alternating dark and light bands, have also been derived from shales. Closely associated with the gneisses are small bodies of granitoid rocks. The gneisses are far more common than the paraschists. However, in places, notably along the lower part of the West Branch of the Peabody River and the Cutler River just west of

Pinkham Notch, the formation is paraschist rather than gneiss. Because of the scale of the map (Pl. 1) not all the details of distribution of the lithologic types could be illustrated.

Gneiss.—The gneiss is composed of alternating light and dark layers (Pl. 5, fig. 1). The dark layers consist essentially of biotite, muscovite, quartz, and accessories, whereas the light layers are primarily plagioclase and quartz, with only minor amounts of biotite and muscovite. Individual layers range in thickness from 0.5 to 3 centimeters. The ratio of dark to light material differs greatly. Wherever the lighter material comprises only a small percentage of the whole rock, the plagioclase-quartz aggregate occurs as short pods which in cross section appear to be from 1 to 10 centimeters long. Where the light and dark constituents are equal in amount, both are discontinuous, mutually interfingering layers. With a still greater increase in the lighter constituents, the dark layers are short and discontinuous. In the North Conway quadrangle (Fig. 1) large areas of such rocks are mapped as part of Chatham granite (Billings, 1928, p. 82-83). In the present paper they are mapped as the gneissic portion of the Partridge formation.

The individual minerals range in diameter from a fraction of a millimeter to 5 millimeters. The muscovite flakes are the largest and most conspicuous. The dark, biotite-rich layers are schistose parallel to the gneissic banding. The light-colored, plagioclase-quartz aggregates, however, are massive and typically granitoid. Two lines of evidence indicate that the banding is parallel to the original bedding. First, the banding is parallel to the bedding in the underlying Ammonoosuc volcanics and overlying paraschists of the Partridge, Fitch, and Littleton formations. Second, the bedding in small patches of paraschist preserved within the gneiss is parallel to the gneissic banding.

Locally, the gneissic banding is thrown into folds which are similar to those in the paraschists of the Partridge and Littleton formation. The folding must have preceded the final recrystallization, as the individual minerals are not granulated and the light-colored layers are typically granitoid.

The mineralogical composition of the gneiss is summarized in Table 2. Column 1 gives its composition as a whole; column 2 represents the dark portion; and column 3 gives the light portion.

In those specimens in which the light constituents are in isolated lenses, the dark portions are black to gray mica schists that do not differ greatly from some of the paraschists. Biotite, muscovite, quartz, garnet, and sillimanite are important. More commonly, where the light and dark bands are approximately equal, although the alternating layers are clearly defined in the hand specimens, the dark layers contain considerable plagioclase.

The light layers consist largely of plagioclase and quartz with minor amounts of biotite and muscovite. The texture is essentially hypidiomorphic granular. Within the limits of a thin section the segregation into dark and light layers may not be apparent.

The anorthite content of plagioclase ranges from 15 to 30 per cent in different specimens. In all the specimens of gneiss studied microscopically, not one grain of orthoclase or microcline has been observed. Muscovite is similar to those obtained in other formations. The biotite is not greatly different from that in the paraschists of the Partridge and Littleton formations.

A chemical analysis of gneiss in which the dark and light layers are about equal is given in Table 10, column 10.

Granitoid rocks.—Patches of granitic rocks too small to be shown on Plate 1 occur in the gneiss at the following localities: (1) Peabody River, between altitudes of 1700 and 1800 feet; (2) one mile southwest of Pinkham Notch, on New River, between altitudes of 2780 and 2970 feet and between 3270 and 3370 feet.

They are massive, homogeneous, gray rocks composed of plagioclase, quartz, biotite, and muscovite, with conspicuous garnet in some specimens. The characteristic grain-size is 1 to 3 millimeters but in the exposures on the Peabody River large muscovite flakes, up to 1 centimeter across, flash conspicuously in the sunshine. The muscovite encloses other minerals poikiloblastically. These granitoid rocks resemble the nonporphyritic phase of the Kinsman quartz monzonite of the Littleton-Moosilauke area (Billings, 1937, p. 506-507).

Three modes are given in Table 2, columns 4, 5, and 6. One is quartz diorite, a second is granodiorite, and a third is quartz monzonite. In naming these rocks the Johannsen system has been followed, except that muscovite has been treated as if it were potash feldspar. The average mineral composition is not greatly different from that of the gneiss.

That these granitoid rocks are younger than the gneiss of the Partridge formation may be demonstrated southwest of Pinkham Notch. At an altitude of 2850 feet on New River, angular inclusions of gneiss occur in a granitoid rock.

Paraschists.—The original sediments of the Partridge formation have not all been converted to gneiss. West of Pinkham Notch, along the lower part of the West Branch of Peabody River, and northeast of Boott Spur, the upper part of the Partridge formation consists of paraschists. Moreover, within the areas mapped as gneiss are small bodies of paraschist, too small to show on the map (Pl. 1).

The paraschists are lithologically identical with many of the types found in the Littleton formation and include: (1) shiny fine-grained

TABLE 2.—*Approximate modes—Partridge formation and associated plutonic rocks*

Type	1	1a	2	3	4	5	6	7	8	8a	9	10	11	12	13	14
Number of thin sections	10	..	5	5	1	1	1	1	2	..	1	2	2	2	1	1
Quartz	37	36	33	40	35	30	47	12	42	36	35	56	52	88	73	54
Plagioclase	36	17	17	47	49	45	18	..	3	15	..	5	5	6	..	32
Biotite	15	29	27	5	10	15	6	20	14	29	..	8	5	5	7	..
Muscovite	11	12	19	7	3	10	20	63	29	9	10	18	27	1	12	..
Garnet	1	1	3	tr	..	tr	1	..	..	1	1	1	..	tr	tr	5
Sillimanite	tr	5	1	1	..	..	tr	5	..	10	3	1	..	..	..	..
Magnetite	tr	..	tr	tr	..	..	tr	tr	..	..	3	1	..	tr	..	..
Apatite	tr	tr	tr	tr	..	tr	..	tr	..	tr	..	tr	tr	tr	..	..
Staurolite	..	..	..	..	..	..	..	tr	..	..	..	..	..	..	tr	..
Tourmaline	..	..	..	tr	..	..	..	tr	tr	..	..	..	tr	tr	tr	..
Chlorite	tr	..	tr	tr	..	..	8	..	3	..	16	10	2	tr	8	..
Pyrite	tr	tr	..	..	3	tr	..	..	4	tr	..	..	8	tr	..	..
Sericite	tr	..	..	..	..	..	..	..	5	..	32	..	1	tr	..	..
Sphene	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	1
Zircon	tr	..	tr?	..	..	..	tr	..	..	..	..	..	..	tr	tr	..
Hornblende	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	8
Per cent of anorthite in plagioclase																
Average	19	19	22	20	21	26	15	..	n.d.	24	..	16	40	15	..	92
Range	15-30	19	18-30	16-30	21	26	15	..	n.d.	24	..	16	40	15	..	92
	0.03–6.00	0.03–4.00	0.10–6.00	0.10–6.00	0.30–4.00	0.20–0.50	0.50–6.00	0.50–4.00	0.05–0.80	..	0.05–3.00	0.10–4.00	0.05–1.00	0.05–1.50	0.10–2.50	

1. Gneiss.
1a. Gneiss, calculated from chemical analysis, specimen W215.
2. Dark portion of gneiss.
3. Light portion of gneiss.
4. Quartz diorite.
5. Granodiorite.
6. Quartz monzonite.
7. Muscovite—rich knot in a coarse rough pseudo-andalusite schist.
8. Shiny fine-grained pseudo-andalusite schist.
8a. Shiny fine-grained pseudo-andalusite schist, calculated from chemical analysis, specimen W229.
9. Medium-grained massive schist.
10. Spangled muscovite schist.
11. Shiny fine-grained mica schist.
12. Quartzite.
13. Quartz conglomerate.
14. Lime-silicate concretion.

pseudo-andalusite schist; (2) medium-grained massive schist; (3) spangled muscovite schist; (4) shiny fine-grained mica schist; (5) quartzite; and (6) a few thin beds of fine-grained quartz conglomerate. Modes of the various types are given in Table 2. A detailed description is unnecessary, as similar rocks are described under the Littleton formation. Because of variations in the conditions of metamorphism certain types found in the Littleton formation—notably those containing staurolite, large andalusite crystals, or pseudomorphs after large andalusite crystals—are not found in the paraschists of the Partridge formation. On Millen Hill, however, there is a small area underlain by coarse rough pseudo-andalusite schist, which is similar to rocks in the Littleton formation.

A chemical analysis of shiny fine-grained pseudo-andalusite schist is given in Table 10, column 4.

THICKNESS

The thickness of the Partridge formation can be determined most satisfactorily along the Israel River, northeast of Mt. Bowman and along some of the small streams for a mile to the northeast. This is the only place in the whole area where the Partridge formation is in contact with the overlying and underlying stratigraphic units. The formation here consists entirely of gneiss. The structure is comparatively simple, for the foliation of the gneiss, as well as the bedding of the overlying and underlying formations, dips uniformly southeast. The thickness of the gneiss is approximately 1400 feet, but the thickness of the original shale from which the gneiss has been derived is conjectural. Considerable tectonic thinning may have occurred; on the other hand, there may have been some thickening by the introduction of magmatic material.

FITCH FORMATION (SILURIAN)

GENERAL STATEMENT

The Silurian Fitch formation, although comparatively thin, is a great aid in solving the geological structure of the Presidential Range. This unit is best developed south of Mt. Washington and on the west side of the Peabody River valley between Pinkham Notch and Dolly Copp Camp. Unusually good and accessible localities to see the formation are: (1) West Branch of the Peabody River, 1620 to 1635 feet; (2) Cutler River, 2170 feet, between the Appalachian Mountain Club bridge and the foot of Crystal Cascade; (3) pass 1000 feet northeast of summit of Mt. Monroe; and (4) headwall of Oakes Gulf. In general the Fitch formation is 20 to 50 feet thick. Locally it is 200 feet thick but is absent at the appropriate horizon on the northern slopes of Mount Adams and Mount Madison.

LITHOLOGY

General character.—The rocks of the Fitch formation consist primarily of diopside, actinolite, biotite, plagioclase, microcline, and quartz, with such accessories as hornblende, sphene, clinozoisite, apatite, garnet, pyrite, zircon, muscovite, and tourmaline. On the basis of equilibrium relations the rocks may be classified as diopside granulite, diopside-actinolite granulite, actinolite granulite, actinolite-biotite granulite, biotite schist, and biotite-pyrite schist. Modes of rocks microscopically studied are in Table 3. In general the various types are in relatively thin beds, a fraction of an inch to 3 inches thick. Locally, however, the beds may be 3 feet thick, and some of the biotite schists are 10 feet thick.

The granulites, because of the diopside and actinolite, are believed to have been derived from dolomitic sandstones and shales (Billings, 1937, p. 486, Table 6). The schists are believed to represent calcareous shales.

Diopside granulite.—The diopside granulites weather pure white and on hasty inspection resemble quartzite. Fresh specimens are white with a slight green tinge and have a fine-grained, granular texture, the individual grains averaging a fraction of a millimeter to 2 millimeters in diameter. The dominant and diagnostic mineral is diopside, whereas plagioclase and microcline are of variable importance. Accessories include sphene, actinolite, and biotite. Modes are given in Table 3.

Diopside-actinolite granulite.—Eight of the rocks studied microscopically are diopside-actinolite granulites. In some of these specimens green needles of actinolite, 1 to 3 millimeters long, lie in a greenish-gray groundmass. The needles tend to parallel the bedding and the long axes are aligned, giving the rock a distinct lineation. In other specimens, more uniformly greenish-gray, the actinolite needles are less conspicuous as they are only a millimeter long, but inspection with the hand lens shows them clearly. In these specimens the needles parallel the bedding; but in some they are diversely oriented within these planes, in others the long axes are aligned.

Microscopic study shows that in addition to actinolite and diopside, the essential minerals are microcline, plagioclase, and quartz, with such accessories as biotite, sphene, and clinozoisite. Modes are given in Table 3. The texture is granoblastic, except for the poikiloblastically developed actinolite which is in larger needles (1 to 4 millimeters) than the other minerals (0.1 to 1.0 millimeter).

Actinolite granulite.—The actinolite granulites do not differ megascopically from the diopside-actinolite granulites. In some, conspicuous dark-green actinolite needles, 1 to 3 millimeters long, are set in a greenish-gray groundmass. In others, the rock is a uniform greenish-gray, and a hand lens is necessary to discern actinolite needles a millimeter long.

Microscopic studies show the important constituents to be plagioclase, microcline, and quartz with such accessories as sphene, clinozoisite, biotite, and apatite. The texture is essentially granoblastic but the actinolite needles surround the other minerals poikiloblastically.

TABLE 3.—*Approximate modes—Fitch formation*

		2	3	4		6
Number of thin sections averaged	2	8	4	3	7	1
Quartz	....	11	21	22	27	40
Microcline	9	22	16	....	13	3
Plagioclase	19	10	31	13	25	10
Diopside	69	29	....	....	....	....
Actinolite	tr	23	29	34	....	....
Biotite	1	4	1	26	32	32
Sphene	2	1	2	2	tr	tr
Garnet	....	....	tr	1	1	5
Clinozoisite	....	tr	tr	....	....	....
Apatite	....	....	tr	tr	tr	tr
Pyrite	tr	....	tr	2	1	10
Zircon	....	....	tr	....	....	....
Magnetite	....	....	....	tr?	....	....
Muscovite	....	....	....	....	1	....
Tourmaline	....	....	....	....	tr	....
Per cent of anorthite in plagioclase:						
Average	70	82	53	77	34	92
Range	55–86	55–92	20–86	77	28–47	....
Grain size in millimeters	0.05–2.00	0.05–4.00	0.05–1.50	0.05–1.00	0.05–2.00	0.05–0.10

(1) Diopside granulite.
(2) Diopside-actinolite granuli
(3) Actinolite granulite.
(4) Actinolite-biotite granulite
(5) Biotite schist.
(6) Biotite-pyrite schist.

Actinolite-biotite granulite.—The actinolite-biotite granulite is a brownish or purplish rock, interbedded with thin layers of actinolite granulite. The elliptical biotite flakes have parallel long axes, producing a distinct lineation. The rock is granoblastic; its mode is shown in Table 3.

Biotite schist.—The biotite schists are black to brownish-gray schistose rocks, usually with a well-marked lineation due to the parallel long axes of elliptical biotite plates.

Microscopic study confirms the lepidoblastic texture. Biotite and quartz are essential constituents; plagioclase is present in varying amounts. Microcline occurs in some specimens. Accessories include muscovite, garnet, and tourmaline. Modes are given in Table 3.

Biotite-pyrite schist.—The biotite-pyrite schists are conspicuous in the field because of their rusty brown color, due to limonitization of the pyrite. Fresh surfaces are gray, and the rock has a fair schistosity on which lineation is evident, due to the elliptical flakes of biotite. A mode is given in Table 3.

BLE 4. *Thickness of the Fitch formation*

Locality	Measured thickness (in feet)	Probable thickness (in feet)
West Branch of Peabody River, 1620-1635 feet	136	200?
1600 feet on stream, 2800 feet NW. of Glen House	25	50?
Emerald Pool, ½ mile SW. of Glen House	27	27
Peabody River, 2380 feet..............	15±	15±
Cutler River, 2200 feet, just below Crystal Cascade	65	65
Headwall of southern amphitheatre of Tuckerman Ravine	10 5/6	12+
500 feet SW. of Boott Spur	Present only in the float	100?
Headwall of Oakes Gulf	38.5	50?
4445 feet on east branch of stream flowing north from BM 5305 on Mt. Washington Auto Road	28.5±	28.5
Ravine of the Castles, ½ mile east of Mt. Bowman	30±	30±

MINERALOGY

Diopside is remarkably uniform in the 10 specimens in which it was found. Optical data indicate from 16 to 22 per cent of hedenbergite in solid solution (Winchell, 1933, p. 226). Actinolite is likewise remarkably uniform in the 15 specimens in which it was found. Optical data indicate from 18 to 25 per cent of $CaFe_3Si_4O_{12}F$ in solid solution (Winchell, 1933, p. 246). Biotite of the Fitch formation is more variable in composition than the actinolite and diopside. In those rocks carrying diopside and actinolite, however, the indices are systematically lower and the pleochroic colors less intense than in rocks devoid of those minerals. In rocks with actinolite and diopside the biotite averages 72 per cent phlogopite, and the range is 69 to 78 per cent (Winchell, 1933, p. 274). In specimens without lime silicates, the biotite is apparently richer in iron, and the data suggest an average phlogopite content of 59 per cent, ranging from 50 to 67 per cent. Although the indices of biotite

TABLE 5.—*Measured Sections of the Fitch formation*

(1) WEST BRANCH OF PEABODY RIVER

800 feet downstream from the Osgood bridge, altitude 1620-1635 feet. (Stratigraphically highest units, which are at the southwest end of the outcrop, are at top of table)

	Thickness (feet)
Green actinolite granulite *	17
Black biotite schist	6
Green actinolite granulite *	3
Biotite schist	8
Green actinolite granulite *	2
Dark biotite schist	6
Green actinolite granulite *	5
Dark biotite schist	3
Green actinolite granulite *	½
Biotite schist	9
Biotite schist, some beds containing small white needles 2 to 6 millimeters long	13
Interbedded white diopside granulite and green actinolite granulite *, the individual beds about 1 inch thick	15
Dark biotite schist	1
Interbedded white diopside granulite and green actinolite granulite*	½
Biotite schist	22
Interbedded white diopside granulite and green actinolite granulite*	5
Biotite schist	5
Actinolite granulite *	3
Interbedded biotite schist and actinolite granulite *	12
Total	136

(2) CUTLER RIVER

2200 feet, just below Crystal Cascade.

		Thickness (feet)
	Mica schist above Fitch formation	. .
Fitch formation	Lime-silicate granulites	20
	Interbedded lime-silicate granulites and biotite schists	40
	Rusty biotite-pyrite schist	5
	Granite and pegmatite	
	Total	65

(3) TUCKERMAN RAVINE

400 feet southwest of where Tuckerman Ravine Trail crosses the "Little Headwall' ½ mile northeast of Boott Spur.

		Thickness (feet)
	Spangled muscovite schist above Fitch formation	
Fitch formation	Biotite schist	0.5
	Thin-bedded actinolite-biotite granulite	4
	Gray biotite gneiss	1
	Thin-bedded actinolite granulite	1
	Gray mica schist	1.2
	Pegmatite sill	3.5
	Biotite schist	0.1
	Pegmatite sill	6
	Actinolite-diopside granulite	3
	Base not exposed.	
	Total	10.8†

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* Rocks classified as actinolite granulite in the field undoubtedly contain diopside, but inasmuch as no microscopic study was made of these particular rocks, definite data are unavailable. The actinolite granulites of this table correspond therefore to the diopside-actinolite and actinolite granulites of Table 3.

† Pegmatites are not included in totals.

Table 5.—*Measured Sections of the Fitch formation—Continued*

(4) Altitude of 4750 feet

Headwall of Oakes Gulf, 2800 feet southeast from the Lakes of the Clouds.

		Thickness (feet)
	Quartzite and muscovite schist above Fitch formation	..
Fitch formation	Biotite schist	5
	Platy diopside-actinolite granulite and some biotite schist	10
	Fine-grained biotite schist	1.5
	Biotite schist, somewhat injected	2
	Actinolite-diopside granulite	7
	Gap	5
	Biotite schist	3
	Pegmatite	0.5
	Actinolite-diopside granulite	2.5
	Gray biotite schist	1.5
	Dark biotite schist	1
	Base not exposed.	
	Total	38.5 †

(5) Altitude 4445 feet

On east branch of stream flowing north from BM 5305 on Mount Washington Auto Road.

		Thickness (feet)
	Gneiss in Littleton formation	..
Fitch formation	Actinolite granulite	0.9
	Gneiss	17.3
	Actinolite granulite	5.5
	Interbedded quartzite and actinolite granulite	23.0
	Quartzite in Partridge formation	
	Total	46.7

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† Pegmatites are not included in totals.

are not very reliable in determining chemical composition, they indicate the trend in composition.

Plagioclase, as noted in Table 3, differs in composition, the anorthite content ranging from 20 to 92 per cent. The amount in the plagioclase is independent of the other minerals present. Muscovite is found in only two of the specimens, and the optical data indicate essentially pure $H_4K_2Al_6Si_6O_{24}$.

THICKNESS AND MEASURED SECTIONS

The thickness of the Fitch formation was determined in a number of localities. In some of these either the top or the bottom of the formation is not exposed so that the measured thickness is a minimum value. In Table 4 the measured thickness is given in one column, the probable thickness in a second column. In places, notably on the northern slopes of Mt. Adams and Mt. Madison, the Fitch formation is absent at the appropriate horizon. The maximum measured thickness is 136 feet, and the maximum probable thickness is 200 feet. The arithmetical mean of the "probable thickness" is 60 feet. Several stratigraphic sections were measured and the data are given in Table 5.

LITTLETON FORMATION (DEVONIAN)

GENERAL STATEMENT

The Littleton formation, the highest stratigraphic unit in the area, occupies a large portion of the eastern part of the geological map (Pl. 1) and is the bedrock on most of the higher summits of the Presidential Range. Only locally, as in the vicinity of Mt. Clay, are other formations found.

Excellent exposures may be seen: (1) along the Mt. Washington Auto Road; (2) Mt. Madison; (3) ridge south of Cutler River; (4) Tuckerman Ravine; (5) Huntington Ravine; (6) half a mile northeast of Mt. Monroe; (7) pass south of Mt. Jefferson; (8) pass north of Mt. Jefferson; (9) ridge 1½ miles southwest of Dolly Copp Camp.

The Littleton formation consists largely of paraschists; gneiss occurs locally in the lower part of the formation. Many of the schists and gneisses are so similar to those in the Partridge formation that a distinction can be made only by stratigraphic relations—that is, whether the beds lie above or below the Fitch formation.

PARASCHISTS

General statement.—The paraschists of the Littleton formation consist of schists and quartzites. In many localities bedding is conspicuous, due to alternating layers of different types (Pl. 5, fig. 3). The thickness of the strata ranges from an inch or less up to 10 feet. The schistosity characteristically parallels the bedding, but locally fracture cleavage at an angle to the bedding is prominent.

The argillaceous types, originally shale, are varied primarily because of differences in the metamorphic conditions and secondarily because of differences in the original rock composition. They may be most conveniently classified as: (1) coarse andalusite schist; (2) coarse pseudo-andalusite schist; (3) coarse rough pseudo-andalusite schist; (4) intermediate pseudo-andalusite schist; (5) shiny fine-grained pseudo-andalusite schist; (6) staurolite schist; and (7) medium-grained massive schist. Less aluminous shales are now (8) spangled muscovite schist, and (9) shiny fine-grained mica schist. The original arenaceous shales or argillaceous sandstones are now (10) mica-quartz schist. The original sandstones are (11) quartzites; (12) pink garnet granulites, although thin, are conspicuous.

Coarse andalusite schist.—The coarse andalusite schists and coarse pseudo-andalusite schists occupy several square miles northwest of Pinkham Notch (Fig. 3). The least altered andalusite schists have large, unoriented porphyroblasts of andalusite, 1 to 8 centimeters long and a half

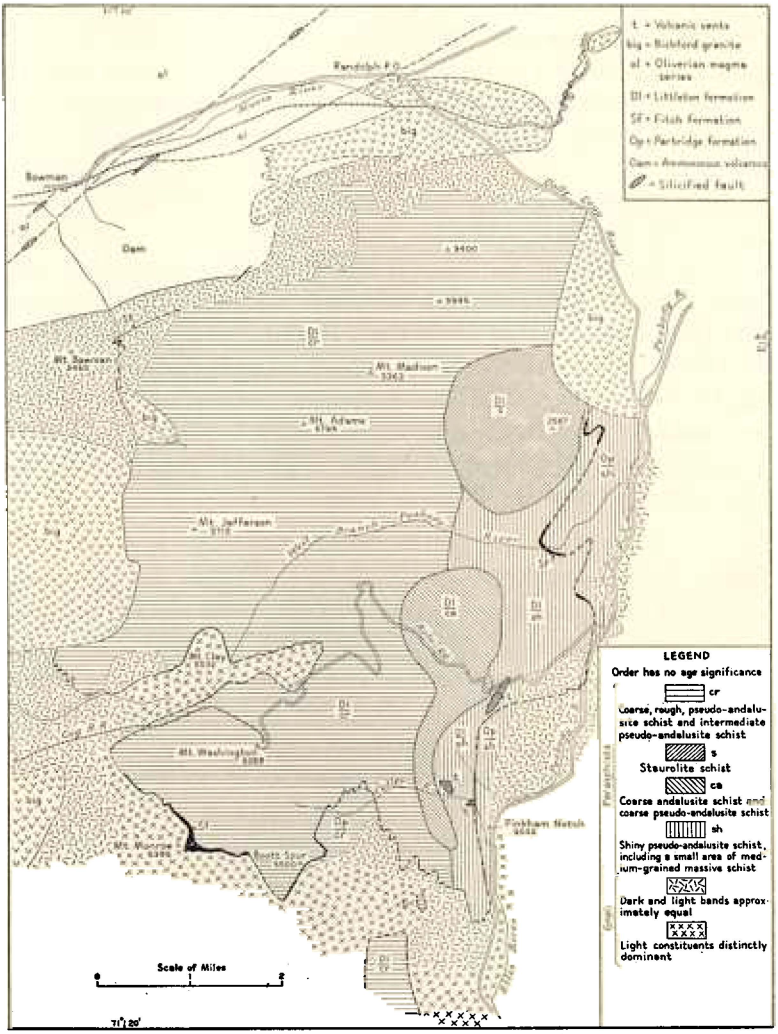


FIGURE 3.—*Metamorphic subzones in Mt. Washington area*

Sediments that were originally the same kind of shale now vary greatly in appearance because of differences in mineralogy or texture, inasmuch as the character of the metamorphism was not the same everywhere. The legend in the lower right-hand corner, by pattern and letter, shows the present character of the original shale. The legend in the upper right-hand corner shows, by letters, the formation to which the rocks belong. In the letter-symbols on the map the letters above the line indicate the formation, the letters below indicate the present character of original shales.

to 1 centimeter thick, set in a fine-grained shiny matrix of mica schist (Pl. 6, fig. 1). Andalusite has well-developed prismatic cleavage and is flesh-colored except for a darker central core. Even in the least altered specimens, an outer shell has been converted to muscovite, with some associated staurolite. Some specimens show sillimanite closely associated with andalusite, particularly as an outer shell. The matrix is shiny mica schist composed of muscovite, biotite, quartz, and garnet. A mode of the coarse andalusite schist appears in Table 6, column 1.

Coarse pseudo-andalusite schist.—The coarse pseudo-andalusite schist differs megascopically from the coarse andalusite schist in the gray, greasy lustrous color of the large columnar pseudo-andalusite crystals. Microscopic study shows the andalusite to be completely sericitized. The groundmass is lustrous mica schist, strongly crumpled in many localities.

Table 6, column 2 represents the mineralogy of these rocks. In one specimen the muscovite is in two generations. Many of the larger flakes (0.5 to 1.0 millimeter across) and all the smaller ones (0.03 to 0.02 millimeter across) have replaced andalusite. Sillimanite is associated with the smaller muscovite flakes, but the exact amount is hard to determine because the birefringence and character of the elongation of sillimanite and muscovite are similar.

Coarse rough pseudo-andalusite schist.—The coarse rough pseudo-andalusite schists characterize the higher parts of the Presidential Range. Large knots, from 2 to 20 centimeters long and a half to 2 centimeters wide, are irregularly distributed in a schistose matrix (Pl. 5, fig. 2, Pl. 6, fig 2.). The knots are muscovite and sillimanite, with lesser amounts of staurolite and sericite. The individual muscovite flakes are 2 to 10 millimeters across, and the sillimanite crystals 5 to 20 millimeters long. Generally the sillimanite is in the interior of the knot, whereas the muscovite forms the outer shell. Staurolite, in crystals 1 to 2 millimeters long, is locally associated with the muscovite in the outer part of the knot but more commonly is irregularly distributed through the matrix of the rock. These "knots" are pseudomorphs after andalusite. Not only do they have the form of andalusite, but the description of the coarse andalusite schist, already given, makes it clear that all stages in the transition from andalusite to the knots may be observed.

The groundmass of the coarse rough pseudo-andalusite schist is typical mica schist, composed of muscovite, biotite, garnet, tourmaline, and quartz. Modes are given in Table 6, columns 3 and 3a; a chemical analysis appears in Table 10, column 5.

Intermediate pseudo-andalusite schist.—The intermediate pseudo-andalusite schists are extensively developed northeast of Mt. Monroe. The pseudo-andalusite crystals, which are 1 to 4 centimeters long and 2 to 5 millimeters wide (Pl. 6, fig. 3), are smaller than those in the coarse rough pseudo-andalusite schist.

Characteristically, but not necessarily, the long axes of the crystals parallel one another, giving the rock a distinct lineation parallel to the pitch of the fold axes. The pseudo-andalusite crystals are largely irregular patches of sillimanite associated with muscovite. Large irregular flakes of muscovite 5 to 10 millimeters across are distributed through the rock. The groundmass, essentially quartz, muscovite, and biotite, contains stubby crystals of black tourmaline 1 to 7 millimeters long. Column 4 of Table 6 illustrates this variety of schist.

Shiny fine-grained pseudo-andalusite schist.—With progressive diminution in the size of the pseudo-andalusite crystals the intermediate variety passes into the shiny variety. The shiny pseudo-andalusite schists are typically developed on the eastern slopes of the Presidential Range (Fig. 3); excellent exposures occur in the Cutler River, above Crystal Cascade, and on Peabody River, between altitudes of 2400 and 2900 feet.

These rocks are characterized by shiny planes of schistosity which glisten in the sunlight. Although the fresh surfaces are invariably gray and the weathered surfaces usually so, some beds are rusty brown due to oxidation of pyrite. Schistosity, parallel to the bedding, is generally well developed and in many localities has been thrown into a series of small crinkles or folds with a wave length of 3 to 10 millimeters and an amplitude of 1 to 2 millimeters.

Small white crystals of pseudo-andalusite, 5 to 10 millimeters long, 2 to 4 millimeters wide, and a half to 1 millimeter thick, lie with their greatest and intermediate axes in the plane of schistosity; in many instances the long axes are parallel and give the rock a distinct lineation. On fresh surfaces the pseudo-andalusite has a greasy lustre, and in sections perpendicular to the lineation it has the appearance of augen.

Inspection with the hand lens shows that the groundmass of the rock contains considerable biotite and muscovite 0.1 to 3 millimeters across. Subhedral garnets up to 0.5 millimeters are present in some specimens. Locally these schists are greenish-gray due to chloritization of biotite.

An average mode of the shiny fine-grained pseudo-andalusite schist is given in Table 6, column 5. The texture is lepidoblastic, with the pseudomorphs of andalusite in distinct augen. Microscopic study shows these crystals to be chiefly sericite with lesser amounts of sillimanite and muscovite. Unaltered andalusite has not been observed but that this was the original mineral is demonstrated by similar relations in the coarse pseudo-andalusite schists. Sillimanite, present in the pseudomorphs

FIGURE 1. COARSE ANDALUSITE SCHIST
Large clear crystals of pink andalusite in a groundmass of fine-grained mica schist. Scale in inches.

FIGURE 2. COARSE ROUGH PSEUDO-ANDALUSITE SCHIST
Shows large pseudo-andalusite crystals similar to Figure 2 of Plate 5.

FIGURE 3. INTERMEDIATE PSEUDO-ANDALUSITE SCHIST
Long, slender, pseudo-andalusite crystals, now sillimanite, muscovite, and some staurolite. Note excellent lineation.

FIGURE 4. BICKFORD GRANITE
Shows typical hypidiomorphic granular texture.

LABORATORY SPECIMENS

Figure 1. Series of Minor Folds
Axial planes are nearly vertical and axes have gentle plunge.

Figure 2. Plunging Fold
Axial plane dips away from reader and axis plunges 25 degrees to left.

Figure 3. Close-up of Fold
Axial plane is steep and plunge of axis is gentle.

Figure 4. Coarse Rough Pseudo-andalusite Schist
This fold shows folded and bent pseudo-andalusite crystals.

FOLDS IN THE LITTLETON FORMATION

after andalusite, also occurs in small needles throughout the rock. Locally the pseudomorphs consist exclusively of sillimanite. Some specimens have undergone retrograde metamorphism, so that all the biotite is now chlorite.

Staurolite schist.—The staurolite schists are exposed on the lower eastern slopes of Mt. Madison (Fig. 3). The best exposures are on the ridge 1½ miles southwest of Dolly Copp Camp. Small euhedral to subhedral porphyroblasts of staurolite, 1 to 5 millimeters long, are set in a light-gray to dark-gray matrix. Cruciform twins, on (032) which gives a rectangular cross, and on (232) which gives a cross at 60 degrees, are present. Rarely the staurolite is surrounded by a thin shell of sericite 0.1 millimeter thick.

Some specimens contain andalusite or pseudomorphs after andalusite 1 to 10 centimeters long and 4 to 8 millimeters wide. Some crystals have a core of gray andalusite surrounded by a shell of flesh-colored andalusite, outside of which is a replacement shell composed of muscovite, staurolite, and grains of quartz 1 to 3 millimeters long. In many cases the andalusite has been completely replaced by this aggregate. The gray shiny groundmass of these schists is biotite, muscovite, and quartz, with some garnet. A mode is given in Table 6, column 6.

Medium-grained massive schists.—In a small area west of the Glen House, extending up to the Mt. Washington Auto Road to an altitude of 2400 feet (Fig. 3), the schists are massive rather than schistose and have an average grain size of several millimeters. The essential minerals are muscovite in conspicuous flakes, biotite, and quartz. Sillimanite, in stubby crystals 4 to 8 millimeters long, is prominent in some specimens and in places displays a distinct lineation. Retrograde processes are indicated by sericitization of the sillimanite, and chloritization of the biotite.

These massive schists do not differ chemically from the shiny fine-grained pseudo-andalusite schists. The differences, one schistose, the other massive, are due to tectonic reasons. The shiny fine-grained pseudo-andalusite schists were in an area of strong rock flowage, whereas the massive schists were not.

Spangled muscovite schist.—All of the paraschists of the Littleton formation described in the preceding pages were initially of the same chemical composition, inasmuch as they were aluminous shales. Aluminous minerals, such as andalusite, pseudo-andalusite, sillimanite, and staurolite, are conspicuous. Less aluminous shales have been metamorphosed to spangled muscovite schist and shiny mica schist. These rocks are not devoid of aluminous minerals, but such minerals are not common.

The spangled muscovite schists are best developed in areas occupied by the coarse rough pseudo-andalusite schists, the intermediate pseudo-andalusite schists, the coarse andalusite schists, and the coarse pseudo-andalusite schists.

Typically, the spangled muscovite schists have large porphyroblasts of muscovite, 2 to 10 millimeters in diameter, in a gray massive to schistose groundmass of biotite, muscovite, and quartz, with small amounts of garnet and tourmaline. All transitions to the coarse rough pseudo-andalusite schists exist, and hand specimens of the two rocks may not differ much in appearance. However, the spangled muscovite schist lacks the pseudomorphs after andalusite characteristic of the coarse rough pseudo-andalusite schist. A mode is given in Table 6, column 8.

Shiny fine-grained mica schists.—The shiny fine-grained mica schists occur in the same areas as the shiny fine-grained pseudo-andalusite schists and represent the less aluminous shales. Fresh surfaces are always gray, but weathered surfaces of many specimens are rusty brown due to oxidation of pyrite. The essential minerals are muscovite, biotite, and quartz. The schistosity, which parallels the bedding, displays a well-defined lineation, due to the alignment of the long axes of oval-shaped grains of biotite or to small crinkles or folds with a wave length of 2 to 3 millimeters and an amplitude of 0.2 to 0.5 millimeter. In some specimens muscovite porphyroblasts, 2 to 3 millimeters across, lie within the plane of schistosity, and the rock similates the spangled muscovite schist. A mode is given in Table 6, column 9.

Mica-quartz schist.—Following the usage employed in the Littleton-Moosilauke area (Billings, 1937, p. 472), rocks with 60 to 80 per cent quartz (or quartz plus feldspar, if the feldspar is not abundant) are termed mica-quartz schists and were derived from arenaceous shales. Massive, gray, granular rocks, with prominent porphyroblasts of muscovite from 1 to 5 millimeters across, differ from the spangled muscovite schists primarily in having more quartz and secondarily in having less muscovite and in being more massive. The groundmass consists of biotite, muscovite, quartz, and some plagioclase. A mode is given in Table 6, column 10.

Quartzite.—The massive gray granular quartzites are composed of quartz, with some biotite and muscovite. Modes are given in Table 6, columns 11 and 11a. The grains are relatively small, minerals over 1 millimeter in diameter being comparatively rare. A chemical analysis is given in Table 10, column 9.

Garnet granulite.—Thin pink beds, seldom over 1 millimeter thick, are a rather distinctive feature of the paraschists, particularly near the Fitch formation. A microscopic study has not been made, but megascopic study indicates that the grain size is 0.1 millimeter, and that the essential minerals are garnet and quartz, with lesser amounts of biotite and muscovite. Hadley (1941) reports 5 per cent apatite from similar rocks in the Mt. Cube area.

MINERALOGY OF THE PARASCHISTS

For almost every specimen β, γ, and the optic angle of muscovite were obtained. The data are constant and indicate essentially pure $H_4K_2Al_6Si_6O_{24}$. An analysis of muscovite with nearly identical optical properties is given in Table 10, column 19. The γ index of biotite was obtained for nearly every specimen and the optic angle for some. Although the indices alone are not sufficient to determine the precise character, they indicate an intermediate biotite in which the phlogopite-eastonite series makes up 30 to 50 per cent and the annite-siderophyllite series make up to 70 to 50 per cent. Optical data on staurolite were obtained for only a limited number of specimens, but they are remarkably uniform. Moreover, they are very similar to the data for the staurolite from the Littleton-Moosilauke area, a chemical analysis of which is available (Table 10, column 17).

All of the chlorite is of retrograde origin, either replacing biotite or garnet. The optical data are rather uniform, and indicate an iron-rich end of the chlorite series, with 80 per cent of the iron molecule and only 20 per cent of the magnesian molecule (Winchell, 1933, p. 278). Oligoclase, ranging from 15 to 30 per cent anorthite, averages only 2 per cent of the formation.

The garnets are difficult to study, because they are rare, are always small grains, and generally have impurities. In no case is it possible to obtain garnet in sufficient quantities and proper purity for chemical analysis. Five rock specimens were studied. In material from a single hand specimen the index of refraction is constant, but the specific gravity varies, due to impurities, such as quartz, muscovite, and chlorite. Therefore, only the highest value for the specific gravity is significant. The figures range from 4.100 to 4.245, the average being 4,200; the average of the maximum values determined for each hand specimen is 4.230, and this is undoubtedly the more significant figure. The values for the indices of refraction range from 1.798 to 1.807, averaging 1.803.

From Winchell's (1933, p. 176) Figure 93 it is apparent that the garnets belong to the almandite-spessartite series, with perhaps limited amounts of andradite, grossularite, and pyrope in solid solution. Using his more detailed graphs, Figures 97, 98, and 99, the gravity readings suggest that the composition is near the almandite end of the series, whereas the indices are near the spessartite end. In the blowpipe studies the manganese reaction is weak to fair, indicating a limited content of manganese. The garnets of the Mt. Washington area are probably not very different from the analysed almandite from the Belknap Mountains (Table 10, column 16).

GNEISS

Locally the basal portion of the Littleton formation has been converted gneiss. Three such areas are of sufficient size to show on the geological ap (Pl. 1). One is 1½ miles north of Pinkham Notch, a second is 1 mile est of Mt. Clay, and a third is 1 mile east of Mt. Bowman. Moreover,

TABLE 6.—*Approximate modes of the Littleton formation*

Type	1	2	3	3a	4	5	6	7	8	9	10	11	11a	
Number of thin sections	1	2	5	..	1	6	3	3	6	3	4	5	..	
Quartz	48	37	23	29	46	45	57	39	52	55	66	87	72	
Microcline	..	..	..	..	..	tr	..	..	..	..	..	..	..	
Plagioclase	..	..	2	10	..	2	..	3	tr	tr	3	3	6	
Biotite	20	17	20	24	15	15	24	9	21	4	14	8	13	
Muscovite	20	27	40	21	20	25	12	15	20	23	16	2	4	
Chlorite	..	7	4	..	..	3	..	13	1	13	1	tr	..	
Sericite	..	9	4	..	8	6	..	16	1	..	..	tr	..	
Andalusite	8	..	..	..	..	..	..	..	..	..	..	..	..	
Sillimanite	..	2	3	11	7	2	..	2	2	..	tr	tr	4	
Staurolite	..	..	1	2	1	tr	5	..	1	..	tr	..	..	
Garnet	4	1	3	3	2	1	2	2	1	1	tr	tr	1	
Magnetite	..	tr	tr	..	..	tr	..	1	1	tr	tr	tr	tr	
Tourmaline	tr	tr	tr	..	1	tr	tr	tr	tr	1	tr	tr	..	
Pyrite	..	..	tr	..	..	1	..	tr	..	3	..	tr	..	
Apatite	..	..	tr	tr	..	..	tr	tr	tr	tr	..	tr	tr	
Zircon	..	..	..	..	..	..	..	..	tr	..	..	tr	..	
Ilmenite	..	..	tr	..	..	..	..	..	tr	..	..	..	..	
Hornblende	..	..	..	..	..	..	..	..	..	..	..	..	..	
Carbon ?	..	..	..	..	..	..	1	..	..	..	..	..	..	
Per cent of anorthite in Plagioclase:														
Average	..	..	20	5	..	22	..	18	..	..	15	12	8	90
Range	..	..	15–25	5	..	15–30	..	18	..	..	10–20	10–15	8	90
Grain size in millimeters	0.05–80.0	0.05–1.00	0.05–8.00	0.10–4.00	0.50–10.0	0.05–3.00	0.10–3.50	0.05–3.00	0.03–10.00	0.05–1.50	0.05–6.00	0.05–2.00	0.05–2.00	0.20–1.00

1. Coarse andalusite schist.
2. Coarse pseudo-andalusite schist.
3. Coarse rough pseudo-andalusite schist.
3a. Coarse rough pseudo-andalusite schist, calculated from chemical analysis, specimen W 223.
4. Intermediate pseudo-andalusite schist.
5. Shiny fine-grained pseudo-andalusite schist.
6. Staurolite schist.
7. Medium-grained massive schist.
8. Spangled muscovite schist.
9. Shiny fine-grained mica schist.
10. Mica-quartz schist.
11. Quartzite.
11a. Quartzite, calculated from chemical analysis, specimen W 222.
12. Lime-silicate concretion.

within the area shown as paraschist, there are numerous localities where the paraschists might be classed as incipient gneisses. Inasmuch as the gneisses do not differ from those in the Partridge formation, a separate description seems unnecessary.

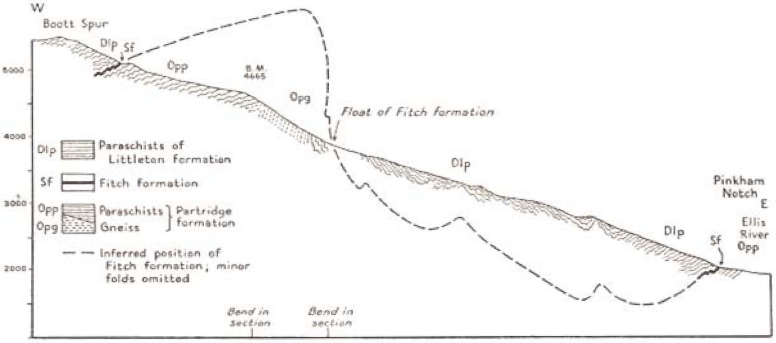


FIGURE 4.—*Structure section along ridge south of Cutler River*
Between Boott Spur and Pinkham Notch. Horizontal scale same as vertical.

THICKNESS

In many localities the Littleton formation has been so extensively folded that even approximate figures of the thickness are difficult to obtain. Elsewhere, the structure is comparatively simple, and reasonably accurate figures for part of the formation may be determined. On the ridge south of the Cutler River between altitudes of 2000 and 2700 feet, the lower part of the formation is 1200 feet thick (Fig. 4). Along the headwaters of Peabody River (Pl. 1) and the north fork of Cutler River the beds dip gently westward and 2000 feet of paraschists are exposed above the Fitch formation. On the valley slopes of the West Branch of the Peabody River and on Mt. Adams and Mt. Madison even higher strata in the Littleton are exposed, and structure sections indicate that the formation is about 4000 feet thick (Pl. 9, sections BB′, CC′, DD′).

OLIVERIAN MAGMA SERIES (DEVONIAN?)

GENERAL STATEMENT

The Oliverian magma series occupies the northwestern and northern parts of the area (Pl. 1), and extends far to the west, north, and northeast beyond the limits of the map. Inasmuch as these rocks are to be discussed fully in a forthcoming joint paper with R. W. Chapman and C. A. Chapman, detailed consideration here is not necessary. The following types have been recognized: (1) biotite gneiss; (2) porphyritic biotite gneiss; (3) coarse granite; (4) coarse syenite; (5) hornblende-quartz monzonite; and (6) fine-grained gray monzonite.

AGE RELATIONS

The Oliverian magma series is younger than the Ammonoosuc volcanics. The relations of the biotite gneiss to the Ammonoosuc volcanics are best displayed 2½ miles west-southwest of Randolph on Cold Brook, not shown on Plate 1. Between altitudes of 1400 and 1480 feet biotite gneiss of the Oliverian series contains inclusions of amphibolite from the Ammonoosuc volcanics. At 1490 feet, the main body of the Ammonoosuc volcanics begins, but there is at least one dike of biotite gneiss.

Two and one-half miles west of the summit of Mt. Deception, near a narrow belt of Ammonoosuc volcanics, reworked inclusions of the volcanics are common in the porphyritic biotite gneiss; moreover, dikes and sills of the porphyritic biotite gneiss intrude the volcanics.

Although in the Mt. Washington area it is impossible to determine the age of the Oliverian magma series relative to the formations younger than the Ordovician (?), in the Mascoma quadrangle C. A. Chapman (1939, p. 168) has shown that the Oliverian series intrudes the Silurian Clough formation. On structural evidence Billings (1937, p. 502) as well as C. A. Chapman and J. B. Hadley (1939) consider the Oliverian to be younger than the Devonian Littleton formation.

BICKFORD GRANITE (DEVONIAN?)

GENERAL STATEMENT

Many square miles of the Mt. Washington area are underlain by the Bickford granite. Four principal bodies have been distinguished. The Bretton Woods body is the largest and lies west of Mt. Monroe, extending from the lower slopes of the Presidential Range west to Bretton Woods. A large appendage extends northeasterly beyond Jefferson Notch. The second area is 1¼ miles southeast of Mt. Bowman. A third, irregular area lies south of Randolph, and a fourth, east of Mt. Madison, centers about Dolly Copp Camp.

Accurately portrayal of the shapes of these bodies of Bickford granite is difficult, partly because of the lack of exposures in some places. This is notably true of the Randolph body, where large areas are devoid of outcrops. Another difficulty arises in large areas where the older schists are cut by numerous dikes and sills of Bickford granite, south of Mt. Deception and Mt. Dartmouth. Wherever exposures are poor it is difficult to decide whether an outcrop of granite belongs to a large body or is merely a sill or dike in a much larger area of gneiss or schist. Thus the contact around Mt. Dartmouth and Mt. Mitten is poorly defined. One and a half miles southwest of Randolph, outcrops of Bickford granite alternate with the Ammonoosuc volcanics. On the geological map these outcrops have been arbitrarily joined to the main part of the Randolph body.

Good and accessible exposures may be seen at the following localities: (1) Ammonoosuc River, upstream from Bretton Woods; (2) Ammonoosuc River, between 2080 and 2260 feet; (3) the trail on the south slope of Little Mt. Deception.

LITHOLOGY

Megascopic description.—The Bickford is a white to gray binary granite (Pl. 6, fig. 4). The texture is equigranular, locally porphyritic, and platy textures are rare. The chief minerals are feldspar, quartz, muscovite, and biotite. The white subhedral to anhedral feldspar grains show Carlsbad twins and, less commonly, albite twins. Quartz is milky white. Biotite and muscovite constitute 2 to 7 per cent each.

The only significant difference between specimens of the Bickford granite is the grain size. In the coarsest specimen collected the feldspar crystals range from 3 to 15 millimeters in length, the quartz and micas 1 to 3 millimeters. In the finest grained specimens the individual grains range from 0.3 to 1.0 millimeter. All transitions between these extremes have been observed. The coarser varieties are characteristic of the larger bodies, the finer are found in the small bodies.

Microscopic description.—The essential minerals of the Bickford granite are quartz, potash feldspar, oligoclase, biotite, and muscovite, with such accessories as apatite and garnet. The quartz in many cases has undulatory extinction. Carlsbad twinning is particularly noticeable in the larger crystals of potash feldspar. Most grains have the cross-twinning characteristic of microcline. The oligoclase has both Carlsbad and albite twinning, and some crystals are weakly zoned with more calcic cores.

The average of 10 modes given in Table 7, column 1, is quartz monzonite, but lies so near the borderline with granite, that it seems advisable to call the whole unit granite. Some specimens are quartz monzonites; others are granites.

As Table 7 shows, the anorthite content of the plagioclase is relatively uniform, ranging in different specimens from 12 to 24 per cent, and averaging 17.5 per cent. The muscovite is relatively uniform, with γ averaging 1.601 and ranging from 1.599 to 1.604; 2V averages 36 degrees, with a range from 34 to 37½ degrees. For biotite γ averages 1.651, with a range of 1.645 to 1.658; 2V is generally small but in one case is 21 degrees.

Under the microscope the Bickford granite shows a poorly defined hypidiomorphic granular texture, with strong granulitic tendencies. Many grains of plagioclase, potash feldspar, and mica are subhedral, but other grains of these minerals and all the quartz are distinctly anhedral. A little myrmekitic intergrowth of quartz and plagioclase was noted in several specimens.

AGE RELATIONS

The Bickford granite is younger than the metamorphic rocks and the Oliverian magma series but is older than the White Mountain magma series. Being undeformed, it must be younger than the main orogenic period. It is the youngest member of the New Hampshire magma series, but has been silicified and sericitized near the Pine Mountain fault.

TABLE 7.—*Approximate modes—Bickford granite*

	1	2	3	4
Number of thin sections	10	1	1	1
Quartz	30	42	35	40
Microcline*	38	....	39	....
Plagioclase	24	35	20	....
Muscovite	4	17	2	5
Biotite	4	2	4	....
Apatite	tr	tr	tr	....
Garnet	tr	....	....	....
Chlorite	....	4	....	....
Sericite	....	....	....	55
Leucoxene	....	....	....	tr
Per cent of anorthite in plagioclase:				
Average	17.5	16	16	....
Range	12–24	....	....	....
Grain size in millimeters	0.1–15.0	0.5–3.0	0.1–1.0	

* Includes orthoclase.

1. Bickford granite.

2. Binary granite, A. M. C. bridge over Cutler River.

3. Binary granite, north slope of Pine Peak, 2400 feet.

4. Granitic rock, adjoining shear zone and showing effect of shear, from top of 2980 knob, approximately 1 mile SW. of Pine Peak.

Dikes and sills of Bickford granite cut the Ammonoosuc volcanics on several of the brooks 1 to 2 miles southwest of Randolph. On Plate 1 a special symbol is used for those areas where dikes and sills of the Bickford granite cut the Partridge and Littleton formations. The Oliverian magma series, being more deformed and granulated, is believed to be older than the Bickford granite. Moreover, for reasons discussed elsewhere (Billings, 1937, p. 535-536) the Oliverian series is considered to be older than the folding.

No data are available in this area bearing on the age of the Bickford granite relative to the syenite of Cherry Mountain and the Conway granite. However, blocks of binary granite similar to the Bickford have been found in the Moat volcanics (Billings, 1928, p. 99-100), which are older than the syenites and the Conway granite of the White Mountain magma series (Billings, 1928, p. 88). Hence the Bickford granite is considered older than the White Mountain magma series.

WHITE MOUNTAIN MAGMA SERIES (MISSISSIPPIAN?)

The Mississippian (?) White Mountain magma series is represented by the syenite at Cherry Mountain (Mt. Martha), the Conway granite in the southwest corner of the map (Pl. 1), and small volcanic vents composed of tuff, breccia, and diabase. R. W. Chapman (1937) has given a complete description of the syenite so that further discussion is unnecessary. The Conway granite is like that in the adjacent Franconia quadrangle (Williams and Billings, 1938). The volcanic vents will be considered in a forthcoming paper by K. F. Billings describing the dike rocks.

CORRELATIONS AND AGE OF FORMATIONS

GENERAL STATEMENT

In the preceding pages the lithologic units have been described under names based on correlation with the Littleton-Moosilauke area (Billings, 1937) and elsewhere. No proof of the correlations adopted or of the ages assigned has been given.

In the Mt. Washington area certain standard methods of correlation can not be used. Paleontological methods fail, as fossils have not been found. The writer believed that possibly one or more stratigraphic units could be followed northeasterly from the Littleton-Moosilauke area to the Mt. Washington area (Fig. 1). The western half of the area covered by Plate 1 was mapped chiefly for that purpose. As the map shows, the project failed because the southwest corner of the Mt. Washington area is underlain by plutonic rocks. The Oliverian magma series, however, can be followed from the Littleton-Moosilauke area to the Mt. Washington area.

Correlation between these areas must be based on lithologic similarity and a similar sequence of rock types, including the thickness of the units involved. The correlation is made with the Littleton-Moosilauke area because that is the only place in New Hampshire where fossils—middle Silurian and lower Devonian—have been found. Moreover, the stratigraphic sequence was first established there (Billings, 1937). The rocks in that locality show a progressive increase in metamorphism toward the southeast and were classified as belonging to the low-grade, middle-grade, and high-grade metamorphic zones.

LITHOLOGIC SIMILARITY

Ammonoosuc volcanics.—The thick sequence of metamorphosed volcanics on the northern slopes of the Presidential Range was correlated with the Ammonoosuc volcanics early in the field work. Not only are the rocks similar to those found in the Littleton-Moosilauke area, but they are very thick. Although volcanics similar to those in the Ammonoosuc formation are found in the Littleton formation in the Littleton and Moosilauke quadrangles, they are comparatively thin. Moreover, the metamorphosed volcanics in the Mt. Washington area occupy the same structural position as the Ammonoosuc volcanics in the Franconia and Moosilauke quadrangles. In both localities they form the roof of an intrusive dome of the Oliverian magma series. Although it is impossible to trace the Ammonoosuc volcanics from one area to another, the outcrops are on the same strike. A small area of Ammonoosuc volcanics 3 miles north of Mt. Oscar (Pl. 1) lies between the two localities.

TABLE 8.—*Stratigraphic column of the Littleton-Moosilauke area*

AGE	FORMATION	INFERRED ORIGINAL LITHOLOGY	THICKNESS (feet)
Lower Devonian	Littleton formation	Sandstone and shale, with some thin volcanic members	5000
Middle Silurian	Fitch formation	Limestone, arenaceous limestone, dolomitic shale, arenaceous dolomite, dolomitic sandstone, calcareous shale, sandstone, shale	400–700
Lower or middle Silurian	Clough formation	Quartz conglomerate and sandstone	0–150
Upper Ordovician (?)	Partridge formation	Shale and sandstone	0–2000
	Ammonoosuc volcanics	Tuffs, breccias, and conglomerates, with only a few flows, of the composition of soda-rhyolite (quartz latite), andesite, basalt	
	Albee formation	Sandstone and shale	4000±

Fitch formation.—The Fitch formation is unique in west-central New Hampshire because of its original content of calcareous and dolomitic beds. In the higher metamorphic zones of the type locality these rocks contain such distinctive minerals as diopside, actinolite, calcic plagioclase, magnesian biotite, and sphene. Similar rocks are unusual and striking in the monotonous succession of schists of the Mt. Washington area. When they were first observed their similarity to the Fitch formation of the Littleton-Moosilauke area was at once recognized. One difference, however, should be noted: marbles are characteristic, although not abundant in the Fitch formation of the Littleton-Moosilauke area, but they are absent from the Mt. Washington area.

Littleton formation.—The paraschists of the Presidential Range are lithologically similar in most respects to the Littleton formation around Mt. Moosilauke. In the Mt. Washington area, however, large andalusite and pseudo-andalusite crystals are prominent, but this is due to a difference in the metamorphic history. The original sediments were shales and sandstones in both areas.

TABLE 9.—*Stratigraphic sequence in the Mt. Washington area.*

UNIT	ORIGINAL LITHOLOGY	THICKNESS (feet)
d.	Sandstone and shale	4000
c.	Dolomitic shale, dolomitic sandstone, arenaceous dolomite, sandstone, shale, calcareous shale	0–200
b.	Shale and sandstone	1400±
a.	Tuffs—and perhaps breccias and conglomerates—with the composition of quartz latites, rhyolites, andesite, and basalt	5000±

SIMILAR SEQUENCE

Correlations based on lithologic similarity alone are not necessarily convincing. However, the sequence in the Mt. Washington area is similar to that in the Littleton-Moosilauke area, the sequence for which is summarized in Table 8. The lithology is given in terms of the original sediments, and, although inferred, is essentially the same as that found in the low-grade zone. The thicknesses are also given.

Table 9 gives the sequence in the Mt. Washington area, the lithology likewise in terms of the original sediments. The columns in Tables 8 and 9 match satisfactorily. At the top of both columns is a thick series of shale and sandstone, and "d" of Table 9 corresponds to the Littleton formation of Table 8. Next lower in the Mt. Washington area is a comparatively thin series of metamorphosed dolomitic and calcareous beds, which correspond to the Fitch formation.

The Clough formation is absent from the Mt. Washington area, but this situation is expectable. This formation is not present in the northeast portion of the Littleton-Moosilauke area, "for the formation was deposited as a thin sheet overlapping from the southwest" (Billings, 1937, p. 48). The thinness of the Fitch formation in the Mt. Washington area compared with the Littleton-Moosilauke area, is presumably due to the same overlapping of the Silurian seas from the southwest.

Unit "b" of the Mount Washington area agrees in position, lithology, and thickness with the Partridge formation. Finally, unit "a" of Table 9 agrees in position and lithology with the Ammonoosuc volcanics, although it is considerably thicker around Mount Washington.

PLUTONIC ROCKS

Oliverian magma series.—The correlation of this series is based on several facts: (1) some units are mineralogically and texturally similar to Oliverian rocks elsewhere; (2) the attitude of the foliation indicates a great dome, as in the type locality of the Oliverian series; and (3) this dome is located in the center of the Bronson Hill anticline, a feature characteristic of the Oliverian series elsewhere.

Bickford granite.—The binary granite south and east of the Dartmouth Range is similar to the Bickford granite of the type locality in the Franconia quadrangle (Williams and Billings, 1938). These rocks also resemble the Concord granite at Concord, New Hampshire, and Hitchcock (1877, p. 161) applied this name in the Mt. Washington area. However, this distant correlation may be incorrect, so that it seems advisable to use a name from a nearby locality. The term Randolph granite (Billings, 1928, p. 81) was also used for these rocks but should be abandoned because of prior use elsewhere (Wilmarth, 1938, p. 1770-1771).

AGE

The geologic age of the lithologic units has been discussed in previous papers, so that a thorough consideration is unnecessary. Fossils from the vicinity of Littleton, New Hampshire, place the Fitch formation in the middle Silurian and the Littleton formation in the lower Devonian (Billings and Cleaves, 1934). The Ammonoosuc volcanics and the Partridge formation are probably upper Ordovician, as they lie unconformably beneath the Silurian and are apparently above the middle Ordovician of Vermont (Billings, 1937, p. 475). The Oliverian magma series and the Bickford granite are younger than the lower Devonian and are probably late Devonian. The White Mountains magma series is tentatively considered Mississippian.

COMPARATIVE MINERALOGY

GENERAL STATEMENT

Special attention was given in the present study to the chemical composition of the minerals in the metamorphic and igneous rocks. This was deduced from optical data. No new analyses of minerals were made, for

TABLE 10.—*Chemical analyses of rocks and minerals*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	(20)	(21)	
SiO_2	58.92	58.14	66.36	61.40	56.23	66.68	57.43	86.91	82.56	62.87	50.91	51.64	49.06	75.93	72.80	36.21	27.81	44.18	46.31	56.0	59.4	
TiO_2	0.93	0.65	1.03	0.92	1.11	0.87	0.94	0.50	0.64	0.92	1.68	1.33	1.36	0.18	0.33	n.d.	n.d.	1.23	0.79			
Al_2O_3	18.55	21.00	15.75	19.04	23.15	18.17	21.68	6.34	8.22	17.43	16.00	17.62	15.20	12.61	13.49	21.32	54.00	10.34	38.52	24.7	17.7	.575
Fe_2O_3	0.94	0.33	1.16	0.63	1.17	0.90	0.08	0.59	0.50	0.55	1.17	1.14	5.38	0.21	1.45	3.80	2.76	3.02	tr	0.5	0.6	
FeO	6.63	6.32	5.37	6.90	6.94	4.98	6.82	2.03	3.22	6.67	8.81	7.80	6.37	1.13	0.88	31.20	12.48	13.90	n.d.	6.1	4.0	
MnO	0.08	0.06	0.08	0.07	0.12	tr	0.28	0.02	0.04	0.23	0.21	0.12	0.31	0.03	0.08	5.12	n.d.	tr	n.d.	0.2	0.2	
MgO	3.24	3.41	2.50	2.10	2.21	1.42	2.02	0.58	1.02	2.71	6.85	7.74	6.17	0.58	0.38	1.41	1.92	11.39	0.18	2.2	2.6	
CaO	0.48	0.32	0.52	0.90	0.26	0.76	0.72	0.08	0.26	0.59	9.99	6.44	8.95	0.38	1.20	0.36	n.d.	12.31	0.46	0.7	5.2	.001
Na_2O	1.49	1.10	1.68	1.30	1.14	0.74	0.53	0.14	0.72	1.71	2.27	4.52	3.11	2.76	3.38	n.d.	n.d.	1.11	1.56	1.1	0.5	.015
K_2O	3.74	3.85	3.23	3.74	4.53	2.89	6.32	1.32	1.69	4.08	0.69	0.25	1.52	5.87	4.46	n.d.	n.d.	0.82	8.03	5.6	3.5	.025
H_2O+	3.90	4.47	1.95	2.89	2.75	1.75	2.80	1.23	0.91	2.10	0.97	1.29	1.62	0.21	1.47	n.d.	1.70	1.57	4.46	3.0	1.4	
H_2O-	0.11	n.d.	0.06	0.06	0.09	0.40	0.20	0.08	0.05	0.08	0.05	n.d.		0.01		n.d.	n.d.	n.d.				
CO_2	0.25	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.02	0.07	0.00	*	0.00	*	n.d.	n.d.	0.00	n.d.			
ZrO_2	n.d.	0.04	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	*	n.d.	*	n.d.	n.d.	n.d.	n.d.			
P_2O_5	0.14	0.00	0.17	0.08	0.18	tr	tr	0.04	0.07	0.11	0.20	0.09	0.45	0.02	0.08	n.d.	n.d.	0.00	n.d.			
S	0.17	0.09	0.03	0.08	0.02	0.05	tr	0.05	0.02	0.04	0.03	tr	*	0.02	*	n.d.	n.d.	0.00	n.d.			
C	n.d.	n.d.	n.d.	n.d.	n.d.	0.29	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	*	n.d.	*	n.d.	n.d.	n.d.	n.d.			
BaO	n.d.	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	*	n.d.	*	n.d.	n.d.	n.d.	n.d.			
O−S Corr.	−0.06	....	−0.01	−0.03	−0.01	....	....	−0.02	−0.01	−0.02	−0.01	....	....	−0.01	....	....	....	....	....			
Total	99.51	99.78	99.89	100.09	99.90	99.90	99.82	99.94	99.92	100.09	99.89	99.98	100.00	99.93	100.00	99.42	100.76	99.86	100.31			
S. G.	2.75	2.777	2.83	2.75	2.91	....	....	2.69	2.72	2.83	2.92	2.901	....	2.61	....	4.23	3.775	....	....			

* Not included in Daly's average analyses.

1. (W 219) Slate, Littleton formation, low-grade zone, quarry at Slate Ledge, approximately 2¾ miles west of Littleton, N. H. "Several of your samples, contain appreciable amounts of graphitic carbon, especially the slate, W 219. This probably accounts for the rather low summation of that analysis." (Letter from R. B. Ellestad, May 8, 1940). G. Kahn, analyst.

2. (L 489) Slate, Littleton formation, low-grade zone, quarry at Slate Ledge, approximately 2¾ miles west of Littleton, N. H. (Billings, 1937, p. 556). F. A. Gonyer, analyst.

3. (L 494) Biotite-garnet-staurolite schist, Littleton formation, middle-grade zone, 0.5 mile south of Northey Hill, Moosilauke quadrangle. "Some difficulty was encountered with sample L 494, the staurolite schist, in connection with the ferrous iron determination. This mineral is extremely resistant to the $HF-H_2SO_4$ attack used in the usual method for FeO determinations in silicates. Consequently, in the figures reported, the FeO in the staurolite would be counted as ferric oxide. In order to get an idea of the error involved, I determined the total iron content of the residue left after the usual FeO determination, and found 0.62% Fe_2O_3. If this were all present as FeO originally, the reported figure for Fe_2O_3 would be high by 0.62%, while the reported figure for FeO would be low by 0.62 × 0.9, or 0.56%." (Letter from R. B. Ellestad, May 17, 1940). G. Kahn, analyst.

4. (W 229) Shiny fine-grained pseudo-andalusite schist, Partridge formation, high-grade zone, 2.5 miles S. 75° E. from Mt. Washington (Cutler River, 2135 feet). G. Kahn, analyst.

5. (W 223) Coarse rough pseudo-andalusite schist, Littleton formation, high-grade zone, 2.1 miles N. 32° E. from Mt. Washington (Chandler Ridge, 4000 feet). G. Kahn, analyst.

6. Sillimanite schist, Littleton formation, high-grade zone, 0.2 mile NW. of summit of South Peak of Loon Mountain, Franconia quadrangle, N. H. (Billings, 1938a, p. 292). W. H. Herdsman, analyst.

7. Muscovitized schist, Littleton formation, high-grade zone, summit of South Peak of Loon Mountain, Franconia quadrangle, N. H. (Billings, 1938a, p. 292). W. H. Herdsman, analyst.

8. (W 220) Sandstone, Littleton formation, low-grade zone, 0.3 mile SE. of quarry at Slate Ledge, Littleton quadrangle, N. H. G. Kahn, analyst.

9. (W 222) Quartzite, Littleton formation, high-grade zone, 2.1 miles N. 32° E. from Mt. Washington (Chandler Ridge, 4060 feet). G. Kahn, analyst.

10. (W 215) Gneiss, Partridge formation, high-grade zone, 1.6 miles N. 5° E. from Glen House, Mt. Washington area. G. Kahn, analyst.

11. (W 56) Amphibolite, Ammonoosuc volcanics, high-grade zone, 0.2 mile S. 65° E. from Bowman, Mt. Washington area. G. Kahn, analyst.

12. (L 418) Fine-grained amphibolite, volcanic member of the Littleton formation, middle-grade zone, 1 mile above the mouth of the Gale River, Littleton quadrangle, N. H. (Billings, 1937, p. 556). F. A. Gonyer, analyst.

13. Average basalt, analysis No. 58, from Daly (1933, p. 17).

14. (W 26) Biotite gneiss, Ammonoosuc volcanics, high-grade zone, 0.6 mile south of Bowman, Mt. Washington area. G. Kahn, analyst.

15. Average rhyolite, analysis No. 5, from Daly, 1933, p. 9.

16. Garnet from mica schist, west slope of Piper Mountain, altitude 1390 feet, Belknap Mountains area. (Modell, 1936, p. 1896). F. A. Gonyer, analyst.

17. Staurolite from Littleton formation, middle-grade zone, probably from 0.8 mile due west of Garnet Hill, Moosilauke quadrangle. S. L. Penfield and J. H. Pratt (1894).

18. Common hornblende from amphibolite sill, 0.6 mile S. 75° E. from summit of Garnet Hill, Moosilauke quadrangle. (Billings, 1937, p. 556).

19. Muscovite from high-grade schist, Clove quadrangle, New York (Barth, 1936, p. 780).

in many cases the relation between optics and chemical composition is known. In other cases, such as the biotite group, where the relation is not so definite, new analyses did not seem advisable. Even under the best circumstances a certain amount of contamination occurs, and the presentation of analyses of such material would be misleading.

Optical data, including indices, were obtained on all the essential minerals in all the rocks for which thin sections were available. For comparison such data were plotted on graphs. The indices of refraction are the most significant data, and γ is the abscissa in Plate 8. Each lithologic unit is shown by a distinctive line. The ordinate could be based on the total number of determinations, but such a method would not be useful for comparative purposes. The ordinate represents, therefore, the percentage of the total number of readings falling within a given range of indices. The range chosen was 0.005. For example, in the ~~plagioclase~~ amph diagram, the curve for the Fitch formation reaches 55 per cent at the value of 1.6475. This means that of all the determinations made, 55 per cent fell between 1.645 and 1.650.

In some cases, notably plagioclase and the actinolite-tremolite series, where only two end members are involved, it is possible to relate the curves directly to chemical composition, as has been done in Plate 8.

The graphs serve two purposes. They show the extent to which one mineral varies in composition within a single unit and also how much one mineral varies from unit to unit.

COMPOSITION OF MINERALS

Plagioclase.—The composition of the plagioclase differs between formations. In the paraschists of the Littleton and Partridge formations 60 per cent of the plagioclase is close to An_{10}, and none is more calcic than An_{35}. In the gneisses of these same formations the plagioclase is more calcic; the maximum on the curve is at An_{22} and none is more calcic than An_{45}. The plagioclase in the Fitch formation is very calcic in many specimens. The maximum is near An_{90}, but there is a distinct submaximum at An_{30}.

In the Ammonoosuc volcanics, which in this area consist almost exclusively of biotite gneisses and related types derived from rhyolite and quartz latites, the crest of the curve is at An_{45}. None is more calcic than An_{55}, but some are very sodic.

In the Bickford granite the maximum covers the range from An_{10} to An_{22}, and varieties as calcic as An_{25} are unknown.

In order of increasing anorthite content of the maximum the lithologic units are, as shown by Plate 8: paraschists of the Littleton and Partridge formations (An_{10}), Bickford granite (An_{10} to An_{22}), gneisses of the Littleton and Partridge formations (An_{20}), Ammonoosuc volcanics (An_{45}), and the Fitch formation (An_{90}).

Muscovite.—The muscovite in the Mt. Washington area has constant optical properties. For the Bickford granite and the paraschists and gneisses of the Littleton and Partridge formations, γ in more than 75 per cent of the specimens lies between 1.600 and 1.605. The optic angle was measured for every hand specimen and the average value for 2V is 37½ degrees. Barth (1936, p. 780) gives an analysis (Table 10, column 19 of the present paper) of muscovite with similar optical properties.

In the Ammonoosuc volcanics the maximum is a little higher, between 1.605 and 1.610; 2V averages 37½ degrees. The composition would differ very slightly from the other formations.

Biotite.—The maximum for γ of biotite from the Fitch formation is much lower than for the other units. In nearly 50 per cent of the specimens γ lies between 1.610 and 1.620. This indicates that the biotite is nearer the magnesian than the iron end of the series, and that phlogopite-eastonite molecules constitute approximately 65 per cent of the mineral.

For biotite in the Bickford granite, as well as the paraschists and gneisses of the Littleton and Partridge formations, γ reaches a maximum between 1.640 and 1.650. These data indicate that the biotite is nearer the iron end of the series, suggesting approximately 60 per cent of annite-siderophyllite.

Amphibole.—Amphibole occurs abundantly only in the Fitch formation, and to a lesser extent in the Ammonoosuc volcanics. In the Fitch formation over 50 per cent of the amphibole has γ close to 1.647, and the remainder does not differ greatly. Complete optical data show that the amphibole is actinolite with about 80 per cent of the tremolite molecule, and about 20 per cent of the $CaFe_3Si_4O_{12}$ molecule (Winchell, 1933, p. 246). The γ index of the amphibole in the Ammonoosuc volcanics is on the average distinctly higher than in the Fitch formation and covers a range from 1.663 to 1.701. Complete data indicate that it is common hornblende.

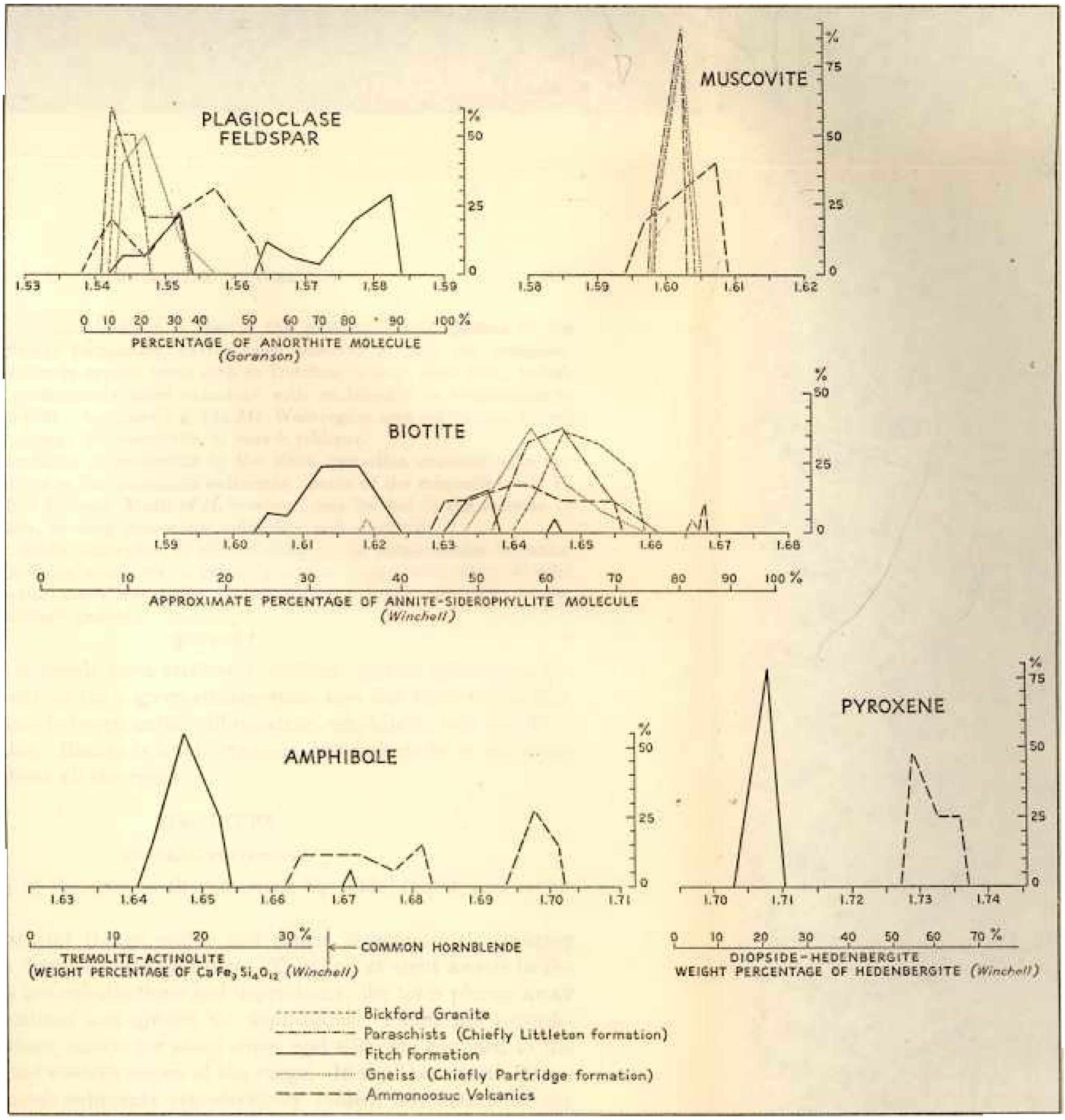
Pyroxene.—Pyroxene occurs only in the Fitch formation and the Ammonoosuc volcanics. In the Fitch formation γ is very uniform, more than 75 per cent of the specimens lying between 1.705 and 1.710. Complete data indicate diopside-hedenbergite with about 20 per cent hedenbergite and 80 per cent diopside (Winchell, 1933, p. 226).

Pyroxene is not abundant in the Ammonoosuc volcanics. It is distinctly richer in iron than in the Fitch formation, and the average content of hedenbergite is 55 per cent. The range is from 50 to 70 per cent.

The data concerning diopside and actinolite in the Fitch formation are significant for a number of reasons. They show that within the Mt. Washington area these two minerals have a rather limited range in composition, and indicate that the amount of the ferrous molecule in solid solution with the magnesia molecule is essentially the same for both minerals. Moreover, the data are the same as for the middle-grade lime-silicate rocks of the Fitch formation in the Littleton-Moosilauke area (Billings, 1937, p. 486), where the diopside carries 20 per cent of hedenbergite in solid solution and the actinolite 20 per cent $CaFe_3Si_4O_{12}$.

Garnet.—Although garnet is found in several of the lithologic units, it is nowhere abundant, and significant data are difficult to obtain. In the paraschists of the Littleton formation the garnet is almandite with considerable spessartite in solid solution.

Staurolite, sillimanite, and andalusite.—Andalusite and staurolite are largely confined to the paraschists of the Littleton formation, although some andalusite is also found in the Partridge formation. Staurolite has uniform optics and hence a constant composition (Table 10, column 17). No special optical study was made of the andalusite. Sillimanite is found in the paraschists and gneisses of the Partridge and Littleton formation, as well as a small body of gneiss in the Ammonoosuc volcanics. No special optical study was made.



COMPARATIVE MINERALOGY

In all cases the abscissa is the γ index, the ordinate the percentage of the determinations falling within each 0.005 block. Beneath the abscissa in most cases there is also a second scale to show the approximate composition of the mineral. The graphs show how each mineral varies within a given formation and also how each mineral varies from one formation to another.

Potash feldspar.—Potash feldspar is rare in the paraschists and gneisses of the Littleton and Partridge formations, having been observed in only one specimen. This is striking because in certain areas such as Dutchess county, New York, potash feldspar becomes progressively more abundant with an increase in metamorphism (Barth, 1936, p. 825-832). Apparently in the Mt. Washington area not enough potash was introduced to change the muscovite to potash feldspar.

The relative abundance of microcline in the Fitch formation contrasts with the lack of potash feldspar in the aluminous sediments. Some of the microcline may be recrystallized detrital feldspar. Much of it, however, may be due to the reaction of sericite and dolomite, forming microcline, actinolite, and anorthite.

Potash feldspar, chiefly microcline, is characteristic of the Ammonoosuc volcanics. As in the Littleton-Moosilauke area, it probably carries considerable albite in solid solution, but no optical study was made. Potash feldspar, chiefly microcline, is also common in the Bickford granite.

SUMMARY

Many of the minerals have relatively uniform optical properties and chemical compositions for a given stratigraphic unit but show rather systematic differences between units. Plagioclase, amphibole, and pyroxene are good examples. Biotite is a fair example, but muscovite is relatively constant throughout all the rocks.

STRUCTURE

GENERAL STATEMENT

The structure of the area is characterized by folds, faults, and intrusions.

In the Presidential Range major and minor asymmetrical, plunging en echelon folds dominate the structure. Trending at right angles to the axes of the folds are culminations and depressions; the folds plunge away from the culminations and toward the depressions. Faults are subordinate, and intrusions, except for small dikes and sills, are confined to the lower northern and western slopes of the range. In the Dartmouth Range the metamorphosed sediments are obviously folded, but details of the structure have not been solved.

The northeasterly trending Pine Mountain fault crosses the northwestern slopes of the Dartmouth Range and probably continues to a point north of Randolph. It is apparently a gravity (normal) fault with the downthrow on the southeast. Some of the many minor faults are shown on the geological map (Pl. 1).

Large igneous intrusions occupy the northwestern, western, and southwestern parts of the Mt. Washington area. The rocks of the Oliverian magma series in the Mt. Washington area are generally foliated, and although several different lithologic units are represented, the mass as a whole shows a distinct anticlinal structure. The New Hampshire magma series is represented by the Bickford granite, a massive binary granite, rarely foliated, and in part, at least, cross-cutting. The White Mountain magma series is represented by parts of two stocks, the Cherry Mountain stock in the west, and a body of Conway granite in the southwest.

JEFFERSON DOME

The foliation of the Oliverian magma series shows a major anticline (Pl. 10; Pl. 9, section HH′), called the Jefferson dome, from the township of that name. The crest of this anticline lies 1.8 miles N. 30° E. from the summit of Hardwood Ridge (Pl. 10). Northwest of the anticlinal axis the foliation dips 10° to 30° NW., whereas south of the axis the dip is 16° to 30° SE. The intrusive rocks on the southeast limb have a breadth of 3 miles and dip southeast at angles of 30 to 90 degrees. The variations in dip are probably due to rolls in a southeasterly-dipping limb; there is no evidence of closed, isoclinal folding. From north of Hardwood Ridge, the axis must extend west-southwest toward Mt. Martha. The Oliverian magma series north of the syenite stock on Mount Martha is obviously part of the northern limb of the anticline. The occasional steep northerly dips southeast of the syenite are presumably due to local overturning of a steeply dipping limb. The symbols east of the syenite stock indicate deformation of the foliation. These exposures are probably near the crest of the anticline. The deformation may be older than the intrusion of the syenite stock or contemporaneous with it.

PRESIDENTIAL RANGE

Minor folds.—The Presidential Range is replete with minor folds. Although in many outcrops the attitude of the bedding is relatively constant, in others it has been contorted into small folds, the amplitude and wave length of which range from a few inches to scores of feet. Under favorable conditions such folds may be photographed (Pl. 7), otherwise small sketch maps can be prepared (Fig. 9).

In recording such folds, the attitude of two features, the axial plane and the axis must be measured. The strike and dip of the axial plane are recorded, as well as the strike of the horizontal projection of the axis and the plunge of the axis. In most papers only the attitude of the axis is recorded, but this information alone is insufficient to define the fold. Suppose the horizontal projection of the axis strikes north and the plunge is zero. A fold with a vertical axial plane striking north could satisfy this condition; or asymmetrical and overturned folds with the axial plane dipping at any angle to either the east or west could satisfy the conditions. It is apparent, therefore, that the attitude of both the axial plane and the axis should be recorded. The objection may be made that the axial plane is an imaginary surface and its attitude can not be properly measured.

Even though precise measurements may be difficult, the structural picture is incomplete without such information.

The attitude of the minor folds is given on Plate 10. In many places where more data were obtained than could be shown on the map, the symbol is an average of several folds. In the Presidential Range the axial planes usually dip steeply to the northwest. However, in an area that extends from 1 mile southwest of Pinkham Notch as far north as the Auto Road (Pl. 10) the axial planes dip steeply to the east. Moreover, on the northwest flanks of the Presidential Range the axial planes commonly dip to the southeast.

The direction of plunge of the minor folds is more variable. Nevertheless, over large areas the plunges are systematic both in direction and value. Between Pinkham Notch and Mt. Monroe gentle northerly plunges prevail. Around the summit of Mt. Washington the plunges are southerly, but on the north slope of Mt. Clay they are northerly. Near the Halfway House the minor folds plunge toward the north at high angles, but to the south the plunge is nearly zero. Around the summit of Mt. Madison the minor folds plunge systematically southwest at low angles, with few exceptions. Between the Glen House and Dolly Copp Camp the plunge of the minor folds is toward the west and southwest.

Wherever data are available, the minor folds have essentially the same plunge as the major folds. Consequently, in those places where the larger structure is obscure, the attitude of the minor folds may aid in reconstructing the major folds.

Major folds.—Whereas the minor folds may be observed directly, the major folds are inferred from various data. As shown in Plate 9, sections BB′ and CC′, the Presidential Range is on the southeast flank of the Jefferson dome. Within the Presidential Range the strata are thrown into a series of major folds associated with which are countless minor folds. In Plate 9 the attitude of the minor folds is accurately shown, but it has been necessary to magnify the size and decrease the number because of the scale employed.

The major folds are shown in Plate 9 and even more completely in Figure 5, which is a structure-contour map of the altitude of the Fitch formation above sea level. The contour interval is 1000 feet and no attempt has been made to show the minor folds.

The axes of the major and minor folds trend north-south in the southern part of the Presidential Range, but toward the north they swing into northeasterly trends. The en echelon pattern is shown on the structure-contour map. Many of the folds can be traced for only 1, 2, or 3 miles before dying out.

Several of the major folds are asymmetric, and in all cases the southeast limb of the anticline is the steeper. These relations are shown by the anticline at Mt. Clay, the anticline northeast of Mt. Clay, the syncline 4 miles northeast of Mt. Washington, and the limb 1½ miles north of Mt. Adams. Large scale overturning does not occur.

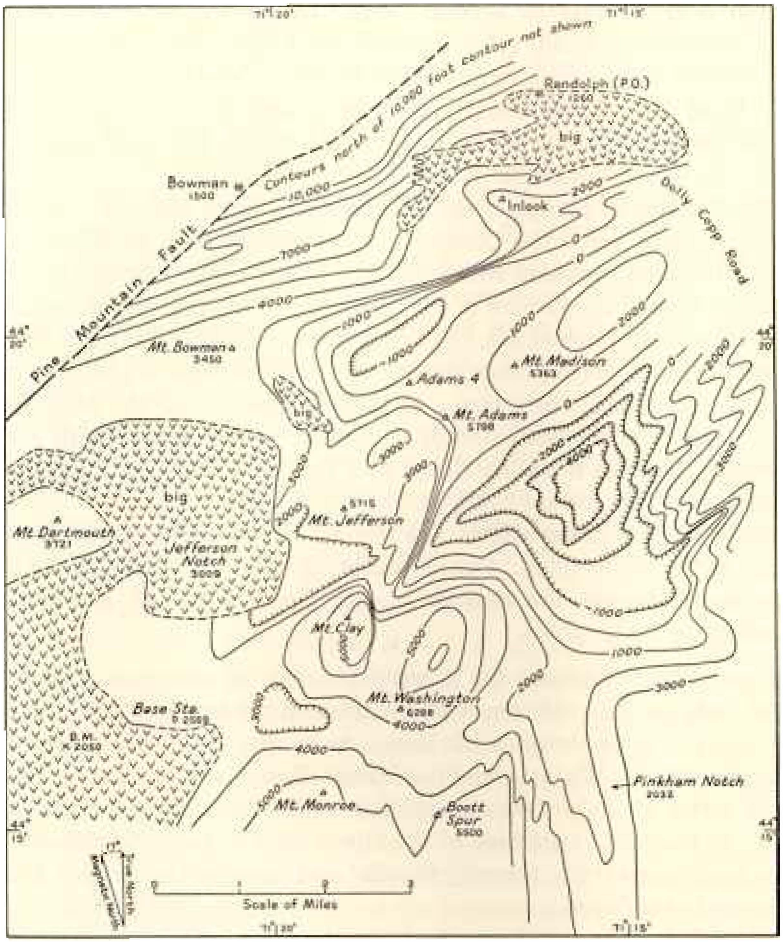


FIGURE 5.—*Structure-contour map of the Presidential Range*

Contours show altitude relative to sea level of the base of the Fitch formation. The contour interval is 1000 feet. big = Bickford granite.

The axis of one major syncline lies half a mile west of Pinkham Notch. The attitude of the bedding on the ridge half a mile south of Cutler River is shown on Plate 10, and a structure section based on additional field data is given in Figure 4.

The east limb of this fold is also exposed on Cutler River and the headwaters of Peabody River.

The axis of a major anticline is 1½ miles west of Pinkham Notch. The east limb is the west limb of the syncline just described. The west limb of the anticline is exposed on the north wall of Tuckerman Ravine, and on the east slope and summit of Boott Spur. This anticline plunges north and can be followed toward the north for only a mile. Further west, in the vicinity of Mt. Monroe, another anticline plunging gently north is exposed on the headwall of Oakes Gulf.

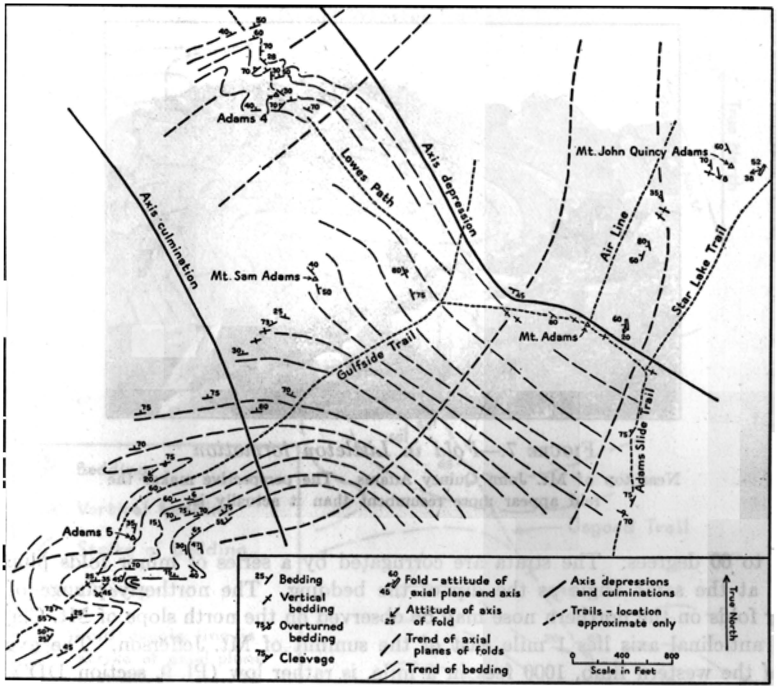


FIGURE 6.—*Sketch map of area around Mt. Adams*

The trend of the axial planes of the folds, shown by the heavy long broken lines, ranges from east to north. The cleavage parallels the axial planes of the folds and dips 35 to 70 degrees northwest. An axis culmination lies between Adams 4 and Adams 5. On Adams 4 the folds plunge northeast. On Adams 5 the folds plunge slightly south of west. On Mt. Adams the beds strike northwest and are essentially vertical. They are considered to be on the northeast nose of a fold with a vertical plunge. The folds to the northeast plunge gently south and an axis depression lies just northeast of the summit of Mt. Adams.

A doubly plunging anticline lies near the summit of Mt. Washington (Fig. 5). The east limb, greatly modified by minor folds, is exposed in Huntington Ravine and the west limb, accompanied by some minor folds, may be seen on the headwall of Great Gulf. The southern nose, on which the summit of Mt. Washington is located, is characterized by strata dipping to the south and minor folds plunging in the same direction (Pl. 10). The northern nose is shown in the vicinity of the Halfway House by beds dipping north and folds plunging in the same direction (Pl. 10). The anticlinal structure of Mt. Washington is also shown in Plate 9, section FF'.

Another doubly plunging anticline centers about Mt. Clay. The attitude of the steeply dipping eastern limb on the eastern slope of the mountain is shown principally by the Fitch formation. The southern nose is particularly well exposed south of the Cog Railroad (Pl. 10), where the beds strike east-west and dip south at angles of 25 to 60 degrees. The strata are corrugated by a series of minor folds plunging south at the same angle as the dip of the bedding. The northerly plunge of the minor folds on the northern nose may be observed on the north slope of Mt. Clay.

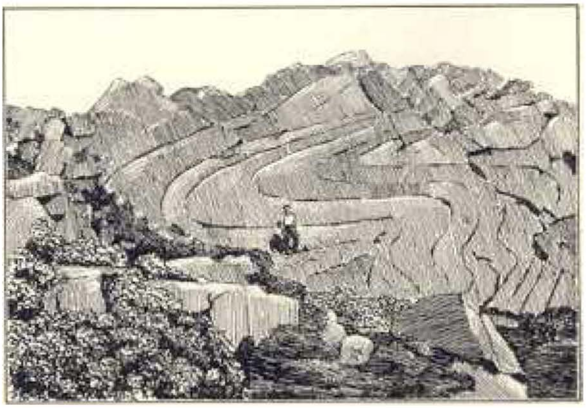


FIGURE 7.—*Fold in Littleton formation*

Near top of Mt. John Quincy Adams. The perspective makes the fold appear more recumbent than it actually is.

An anticlinal axis lies 1 mile east of the summit of Mt. Jefferson. The average dip of the western limb, 1000 feet in a mile, is rather low (Pl. 9, section DD'), but countless minor folds are so abundant that no regional dip is apparent in the field. The minor folds on the southwest flank of this fold plunge southwest and are well displayed on the southern slopes of Mt. Jefferson.

Another anticline is located 1 mile northeast of the summit of Mt. Jefferson. Field data for this area are given in Figure 6. On Adams 4, which lies 0.6 mile northwest from Mt. Adams, the structural relations are unusually clearly displayed (Fig. 6). The strata are thrown into a series of folds which plunge 25° to 40° NE., and the axial planes dip steeply to the northwest. A well-defined cleavage, which cuts across the bedding, strikes northeast, and dips 70° NW., is essentially parallel to the axial planes of the folds.

The beds around the summit of Mt. Adams present what at first appears to be an anomalous attitude. They strike west-northwest and dip very steeply, 10 degrees either side of the vertical. Inasmuch as these beds strike directly toward those of Adams 4, they probably occupy a similar structural position on the nose of a northeasterly plunging anticline; but the plunge is vertical. Three quarters of a mile southwest of Mt. Adams it is equally apparent that the folds plunge to the west and southwest (Fig. 6) at an average of 45 degrees.

On Mt. John Quincy Adams, 0.3 mile northeast of the summit of Mt. Adams, minor folds which plunge 15 to 32 degrees south are common (Fig. 7). Similar southerly plunges are found only 400 feet east of the summit of Mt. Adams.

Mt. Madison is on the nose of a southwesterly plunging anticline. The minor folds, well exposed on the upper 300 feet of the mountain, plunge southwest (Pl. 10), although there are a few exceptional northeasterly plunges. The characteristic southwesterly plunges are found a mile northeast of the summit. The complexity of the crest of this anticline is indicated by the structure exposed on Osgood Ridge, between altitudes of 4440 and 4830 feet (Fig. 8). Considerable variation in the attitude of the bedding exists and minor folds may be observed. The cleavage, striking uniformly northeast and dipping northwest at angles of 45 to 60 degrees, is considered to be

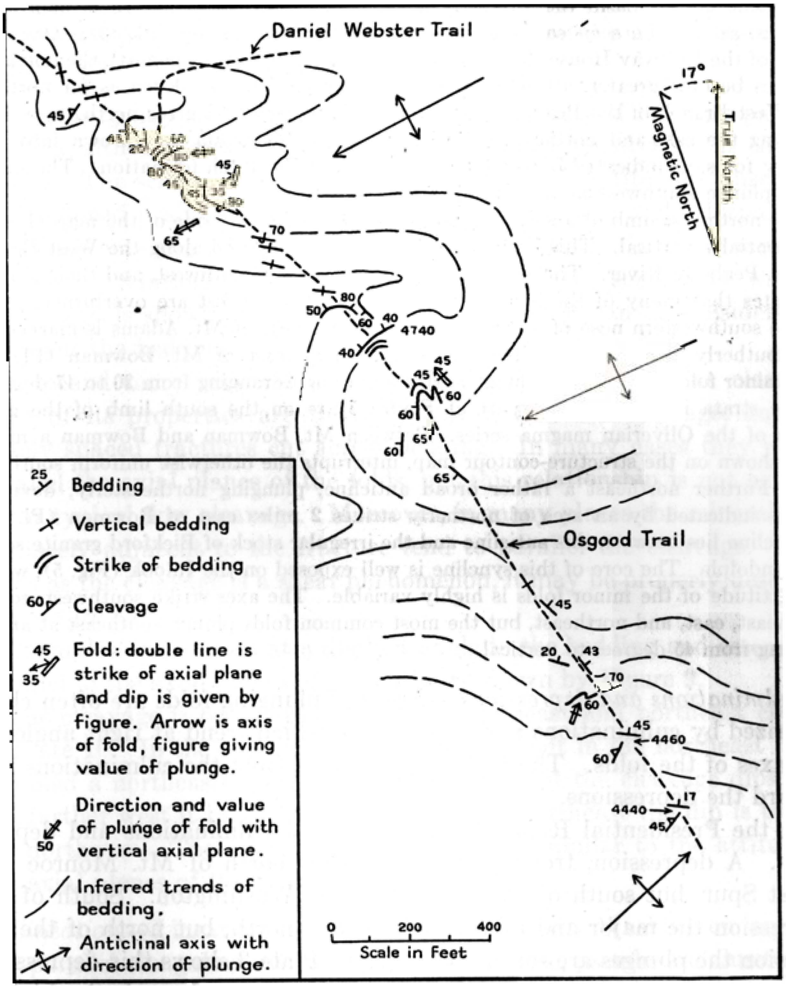


FIGURE 8.—*Structure on Osgood Ridge*

Osgood Ridge extends southeast from the top of Mt. Madison. The inferred trend of the bedding is shown by the long broken lines.

parallel to the axial planes of the folds. At the southeast end of the ridge the folds plunge northeast, at the northwest end they plunge southwest.

A broad syncline, in which the Fitch formation is more than 4000 feet below sea level, lies 1½ miles southeast of Mt. Adams and Mt. Madison (Fig. 5). On the south side of this basin the strata dip north and northeast, at angles as high as 70 degrees, as may be seen east and west of the Halfway House (Pl. 10). One mile south of the Halfway House the plunge averages zero. Toward the north the northerly plunges become greater, attaining a maximum of 60 degrees. Even as far north as the West Branch of the Peabody River the folds plunge 38 degrees north.

Along the east and northeast sides of this basin the strata are thrown into subsidiary folds, as indicated by the outcrop pattern of the Fitch formation. The minor folds plunge southwest at angles as high as 60 degrees.

The northwest limb of a subsidiary syncline along the east side of the map (Fig. 5) is essentially vertical. This limb is particularly well exposed along the West Branch of the Peabody River. The minor folds plunge steeply southwest, and their pattern indicates that many of the beds which dip steeply northwest are overturned.

The southwestern nose of a syncline 1 mile northwest of Mt. Adams is marked by the southerly trend of the Fitch formation, 1 mile east of Mt. Bowman (Pl. 10). The minor folds in this area plunge northeast at angles ranging from 20 to 47 degrees.

The strata in the northern part of Figure 5 are on the south limb of the great dome of the Oliverian magma series. Between Mt. Bowman and Bowman a minor fold, shown on the structure-contour map, interrupts the otherwise uniform southerly dip. Further northeast a rather broad anticline, plunging northeasterly, develops and is indicated by an area of northerly strikes 2 miles east of Bowman (Pl. 10). A syncline lies between this anticline and the irregular stock of Bickford granite south of Randolph. The core of this syncline is well exposed on the Inlook (Fig. 5), where the attitude of the minor folds is highly variable. The axes strike southwest, south, southeast, east, and northeast, but the most common folds plunge southeast at angles ranging from 45 degrees to vertical.

Culminations and depressions.—Areas of plunging folds are often characterized by culminations and depressions, which trend at right angles to the axes of the folds. The folds plunge away from the culminations and toward the depressions.

In the Presidential Range there are several culminations and depressions. A depression, trending east-west, lies north of Mt. Monroe and Boott Spur, but south of Mt. Clay and Mt. Washington. South of the depression the major and minor folds plunge north, but north of the depression the plunges are south. Figure 2 of Plate 3 shows this depression.

A culmination, likewise striking east-west, passes through the highest parts of the anticlines near Mt. Washington and Mt. Clay. A depression trends northwest between Adams 4 and Mt. Madison and extends southeast to the limits of the map but dies out toward the northwest. A poorly defined culmination, which lies 1½ miles northeast of Mt. Madison, strikes west-northwest.

The major folds of the Presidential Range plunge in unison. The structurally highest area is near Mt. Washington and Mt. Clay. The folds, with some minor oscillations, plunge northeast for 3 miles, where a structural low is reached. Still further to the northeast the folds rise again to a culmination, which, however, is not as high as that around Mt. Washington. The folds also plunge south from the highest culmination around Mt. Washington and a mile to the south reach a depression, south of which they rise again.

Schistosity and cleavage.—Schistosity is well-marked in many parts of the area, although on the upper slopes of the range massiveness is characteristic. The schistosity is due to parallel plates of biotite and muscovite, and flattened grains of other minerals, such as quartz and feldspar. In most instances the schistosity parallels the bedding. In those outcrops where such relations could not be demonstrated, the schistosity was recorded and is shown on Plate 10. In most cases it can be considered to represent the bedding.

A second more restricted structure may be referred to as cleavage. Most of its properties are those typical of fracture cleavage, and the closely spaced fractures cut across bedding. In many cases they nearly parallel the axial planes of the folds, but this relationship is not as close as for typical flow cleavage. Moreover, in many places the minerals immediately adjacent to the fracture tend to parallel the cleavage. Inasmuch as the cleavage is a shear phenomenon, it may be properly described as fracture cleavage.

Examples of cleavage at a distinct angle to the bedding and essentially parallel to the axial planes of the folds are shown by Figure 9.

The cleavage is best developed in the southeast and northeast corners of Plate 10. In the southeast it strikes north, but in the northeast it has assumed a northeasterly trend. In the southeast the cleavage dips east, but farther west it becomes westerly. In the northeast the dip is toward the northwest. The attitude of the cleavage is similar to the attitude of the axial planes of the folds.

Lineation.—Lineation is represented in the Mt. Washington area by (1) parallel elongate minerals, such as sillimanite, pseudo-andalusite, and hornblende; (2) parallel streaks of such platy minerals as biotite; and (3) "crinkles," which are small folds with an amplitude and wave length of a fraction of an inch. Elongated pebbles are absent, for the original strata were either devoid of conglomerates or metamorphism has obliterated the pebbles.

The lineation generally parallels the axes of the folds. In those areas where the minor folds are absent, the lineation may offer an important clue to the structure, although this is rarely necessary in the Mt. Washington area because minor folds are so abundant. In some cases two or even three sets of "crinkles" may be displayed on a single bedding plane. The younger sets are generally related to minor fractures and are not parallel to the axes of the folds.

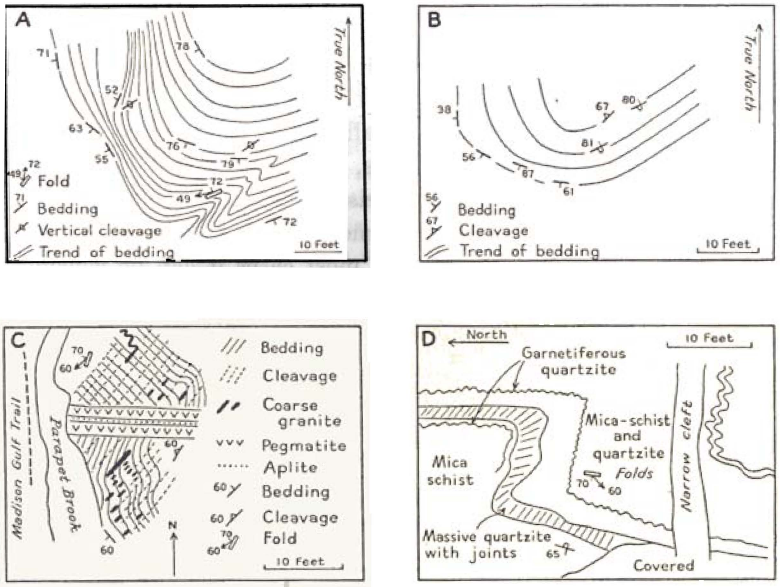


FIGURE 9.—*Sketch maps showing cleavage parallel to axial planes of folds*

A = ridge south of Culhane Brook, altitude 1600 feet; both A and B are about 1 mile south-southwest of Dolly Copp Camp. B = ridge south of Culhane Brook, altitude 1540 feet. C = Parapet Brook, altitude of 4150 feet; Parapet Brook drains the south slope of Mt. Madison. D = West Branch of Peabody River, altitude 1750 feet; 100 feet below the Osgood Ridge.

FAULTS

General statement.—Faults are recognized primarily by silicified zones. The major fault is the Pine Mountain fault, but several smaller ones have also been mapped (Pl. 1).

Pine Mountain fault.—On the northern slopes of the Dartmouth Range are a number of isolated silicified zones, where the rocks have been almost completely replaced by silica and are cut by innumerable quartz veins. The individual zones strike northeast, wherever data are available, and are aligned in a northeasterly trending zone. Elsewhere in New Hampshire silicified zones are located along faults (Billings, 1937, p. 528; C. A. Chapman, 1939, p. 165).

The most prominent silicified zone is found on Pine Mountain (Pl. 1), and the shiny white outcrops at the top of the mountain are conspicuous even from the

Presidential Range. The silicified zone, forming the summit of the mountain is bordered on the southeast by a 100-foot cliff. The zone strikes N. 40° E., is at least 80 feet wide, and crops out for several hundred feet along the strike.

There is a second exposure nearly a mile to the southwest. The silicified zone, exposed on top of a small knob, apparently strikes northeast and is 15 feet wide. A third exposure, 2.4 miles southwest of Pine Mountain, holds up a distinct terrace, and is at least 100 feet wide. A fourth exposure, 3.5 miles southwest of Pine Mountain, is a small, inconspicuous outcrop on the trail at an altitude of 2640 feet. The most southwesterly exposure, 4 miles southwest of Pine Mountain, is a silicified zone about 20 feet wide, striking N. 62° E.

The precise course of the fault northeast of Pine Mountain is uncertain. In the vicinity of Bowman there are several silicified zones. On the geological map the central one has been correlated with the Pine Mountain fault. The northern exposure, however, might have been chosen with equal justification. An isolated exposure of silicified rock 3 miles northeast of Bowman has been shown as representing the continuation of the fault.

There is, of course, important stratigraphic evidence of faulting. South of Bowman the Ammonoosuc volcanics, occupying a belt 1.3 miles wide, abut against the fault and have not been observed to the west. This type of evidence, however, is not as imposing in the field as the geological map would suggest. The section of the Ammonoosuc volcanics along the Israel River is reasonably good and complete. However, west of here exposures of the volcanics are lacking, except north of Mount Bowman, near the contact with the Partridge formation. Similarly, in the triangle bounded by the Israel River, the South Branch of the Israel River, and the fault, the Oliverian magma series has been mapped on the basis of float and doubtful exposures.

The southeast side of the fault is downthrown. Higher structural units, such as the Ammonoosuc volcanics and the gneiss of the Partridge formation, lie on the southeast side of the fault, whereas a lower structural unit, the Oliverian magma series, lies to the northwest. Nothing is known about the dip of the fault; the fact that the trace is independent of topography indicates a steep dip.

Minor faults.—The best-exposed minor fault, 2.2 miles S. 65° E. from Bowman, strikes N. 55° E., dips 65° SE., and displays a 1-foot slickensided zone. The minor irregularities on the fault plane indicate a normal fault. Gneiss of the Partridge formation on the southeast side has been dropped against Ammonoosuc volcanics and Bickford granite on the northwest side. No direct data concerning the amount of displacement are available, but it has probably been slight. No silicification has occurred along this fault.

The silicified zone 2.3 miles S. 80° W. from Bowman, at an altitude of 1460 feet on the South Branch of the Israel River, strikes N. 50° E., being 100 feet long and 20 feet wide. The principal shear planes strike N. 45° E. and dip 60° SE.

The silicified zone 1 mile N. 80° E. of Bowman is exposed in a small brook between altitudes of 1430 to 1460 feet. Fault planes within this zone strike from N. 40° E. to N. 58° E. and dip 55° SE. Striations pitch 48 degrees in a direction N. 83° E. The hanging wall has apparently gone down; the faulting is normal, and, assuming that the striations indicate the average direction of motion, there has been an easterly component to the downward movement.

Many small silicified zones have been observed in the Presidential Range. In many cases they are zones of weakness and are followed by small gulleys.

Generalizations.—Certain generalizations may be made concerning the faults and silicified zones, including the Pine Mountain fault: (1) they strike northeast, although data are lacking for two faults; (2) they dip 55° to 65° SE., in the two instances where data are available; and (3) in two cases the southeast side is downthrown, as is probably true in a third —in others data are not available. It is probable that these faults are all part of one set. From analogy with the minor faults the Pine Mountain fault is probably a normal fault dipping southeast.

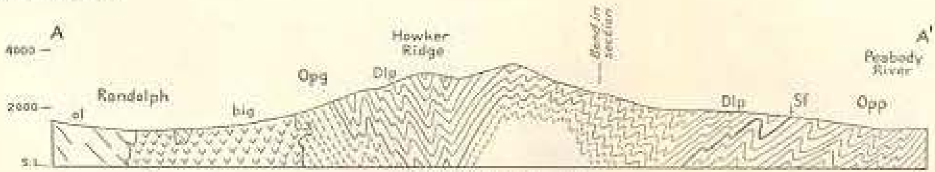
DARTMOUTH RANGE

General statement.—Study of the structure of the Dartmouth Range, which extends from Deception Brook to the South Branch of Israel River, is difficult (Pl. 1). On the northern slopes exposures are rare and this portion of the map is an approximation. Although exposures on the southern slopes, particularly in the streams, are reasonably good, the lack of a key bed handicaps structural interpretation.

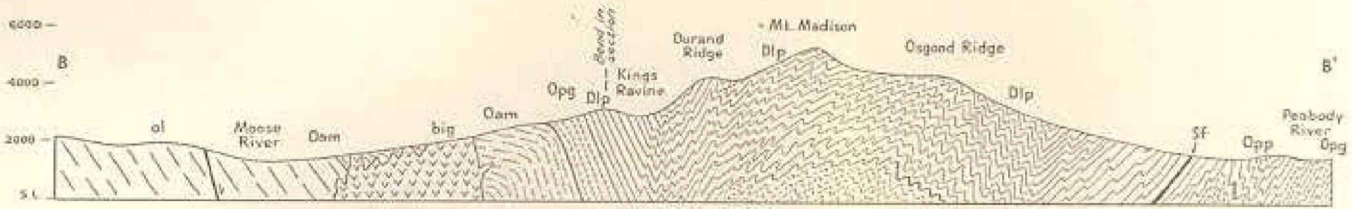
Southeast of the Pine Mountain fault.—Southeast of the Pine Mountain fault the Dartmouth Range is composed of gneiss and Bickford granite. The gneiss is the southwesterly continuation of a belt which can be traced through Mt. Bowman from the northern slopes of the Presidential Range. The gneissic structure in general strikes east-northeast, and dips range from 50° to 80° SE. The trend of the range is parallel to the strike of the gneissosity, so that on Mt. Dartmouth, where the average strike of the gneissosity is northwest, the range likewise trends northwest. Locally the gneissosity varies from the usual trend, implying some folding.

Practically no other data are available. One minor fold has been recorded near the top of Mt. Deception. It is apparent, both from the tectonic map (Pl. 10) and the structure sections (Pl. 9, section HH′), that the Dartmouth Range is on the southeast limb of a great anticlinal dome formed by the Oliverian magma series.

Presumably the gneissosity parallels the original bedding, as in the Presidential Range. If the Dartmouth Range, southeast of the Pine Mountain fault, is the limb of a major fold unmodified by minor folds, the gneiss is at least 5000 feet thick. In that case the Fitch formation should appear somewhere in the range. Moreover, the pattern of the Fitch (Pl. 1) suggests that the gneiss of the Dartmouth Range is stratigraphically beneath it. If this is so, and the Partridge formation is only 1400± feet thick, the gneiss of the Dartmouth Range must be thrown into a series of isoclinal folds, the axial planes of which dip southeast. The structure has been so shown in section HH′ of Plate 9, but the representation is strictly diagrammatic.



SECTION A - A'



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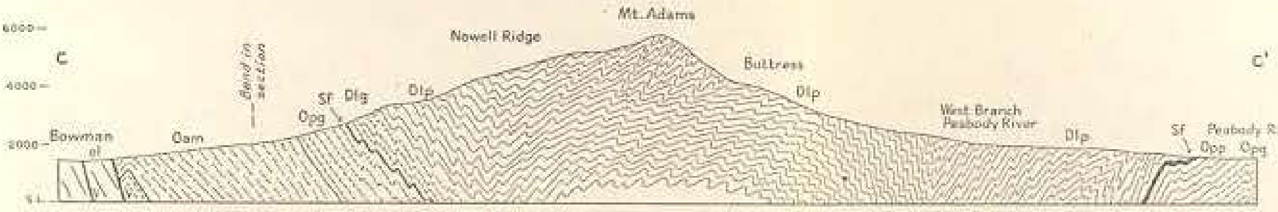

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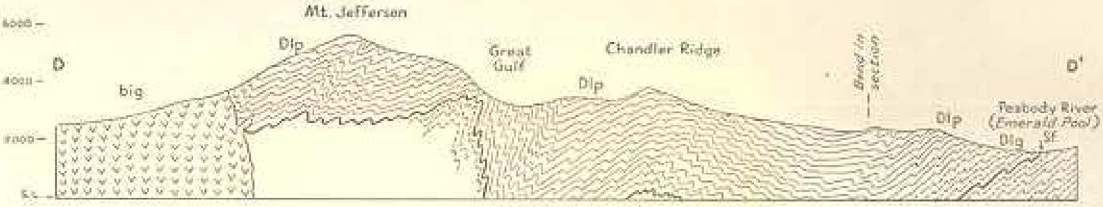
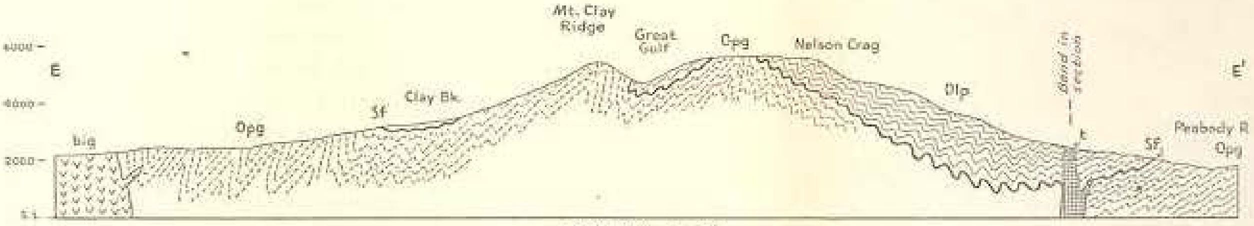


SECTION D - D'



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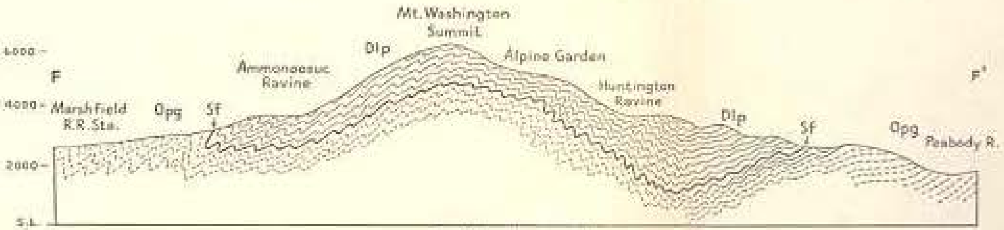

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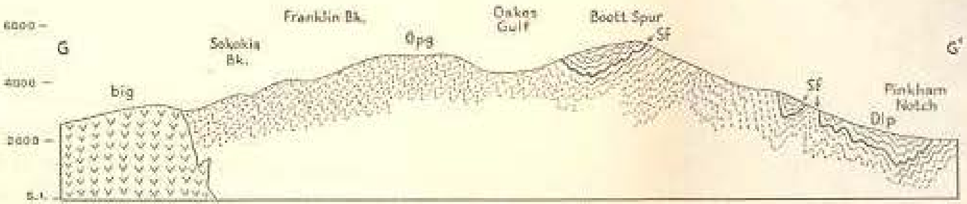

SECTION G - G'

SECTION H - H'

STRUCTURE SECTIONS

Taken along lines shown in Plate 1. Vertical scale in feet; horizontal scale same as vertical scale. Oam = Ammonoosuc volcanics; Opg = gneiss of Partridge formation; Opp = paraschists of Partridge formation; Sf = Fitch formation; Dlg = gneiss of Littleton formation; Dlp = paraschists of Littleton formation; ol = Oliverian magma series; big = Bickford granite; t = tuff and breccia of volcanic vents.

Northwest of the Pine Mountain fault.—Data are scanty on the northwestern slopes of the Dartmouth Range, especially northwest of the Pine Mountain fault. On the northwestern slope of Mt. Deception the gneiss is exposed at altitudes as low as 2600 feet. The dip of the gneissosity ranges from 40° to 70° SE., and the rocks are probably thrown into a series of isoclinal folds trending east-northeast and overturned toward the northwest. Whether there is a belt of Ammonoosuc volcanics between the gneiss of the Partridge formation and the granitoid rocks of the Oliverian magma series is questionable. The critical area without exposures is 2000 feet wide, and this is the maximum possible width of such a belt. The erratics and float, however, indicate a narrow belt of Ammonoosuc volcanics as shown on the geological map. Apparently the rocks of the Oliverian magma series have injected higher stratigraphic units here than east of Bowman, and the Ammonoosuc volcanics have been nearly entirely eliminated.

BICKFORD GRANITE

The Bickford granite occurs in several stocks. A large one envelops the Dartmouth Range on the west, south, and east. One small stock is in the Ravine of the Castles, in the headwaters of the Israel River. A stock of intermediate size lies south of Randolph. Another is located near Dolly Copp Camp. The older rocks surrounding these stocks are commonly injected by numerous dikes and sills of the Bickford granite. The granite of the stocks is typically massive, suggesting that it is younger than the major orogenic period. Moreover, undeformed dikes of this rock cut the folded paraschists and gneisses.

Although the Bickford granite is essentially massive, a planar structure was observed in a few localities (Pl. 10). This structure is due to the parallelism of feldspar crystals or less commonly to parallel plates of biotite. Reference to the tectonic map reveals that this planar structure in general strikes parallel to the regional trend lines, suggesting that it resulted from compressive stresses in operation during the waning stages of the orogeny.

The mechanics of intrusion of the Bickford granite, particularly of the largest stock, deserves consideration. In several places the contact is discordant (Pl. 10), as, for example, 1 mile south of Jefferson Notch, 1 mile south of Mount Deception, and 1 mile southeast of Pine Mountain. Concordant relations exist only where the contact parallels the regional trend of the structures. The discordant relations suggest stoping. The manner in which the Bickford granite has shattered the surrounding rocks indicates that the country rock was relatively brittle at the time of intrusion. All the conditions were favorable for the stoping of the country rock. Xenoliths have been observed in the Bickford granite but are not especially abundant.

On the other hand, reference to either the geological map (Pl. 1) or the tectonic map (Pl. 10), shows that the trend lines in the country rock wrap around the major stock of Bickford granite. Northwest of the stock the structures trend east-northeast; east of the stock the structures trend nearly north-south. Such relations suggest that the Bickford granite inserted itself like a great wedge, shoving apart the older rocks.

It is concluded that the Bickford granite forced its way into the older brittle rocks. The rocks surrounding the rising magma were mechanically shattered and broken, and countless dikes and sills of magma forced into the fractures. Blocks of country rock, engulfed by the magma, were assimilated, the extent of the assimilation depending upon whether the blocks were incorporated in the early or late stages of the rise of the magma.

The relative importance of the two major processes involved cannot be evaluated at present. Additional work in the Mt. Washington area might shed more light on the subject, but it is felt that most of the critical data available have been obtained. Study in the surrounding areas may aid in attempts to reach a more definite conclusion.

AGE OF THE STRUCTURAL FEATURES

The main orogenic period is considered to have been Acadian (middle or late Devonian). Two methods of attack lead to this conclusion.

The deformation is obviously younger than the metamorphosed sediments involved, which are Ordovician (?), Silurian, and lower Devonian. In the Franconia quadrangle, the Moat volcanics rest unconformably on the paraschists of the Littleton formation (Williams and Billings, 1938, p. 1025). Sufficient time elapsed between the deposition of the lower Devonian Littleton formation and the eruption of the Moat volcanics for folding, metamorphism, intrusion of the Oliverian and New Hampshire magma series, and deep erosion. Hence it is unlikely that the Moat volcanics are older than Mississippian. They are the extrusive phase of the White Mountain magma series, which is consanguineous with the pre-Pennsylvanian Quincy-Blue Hill group of the Boston region (LaForge, 1932, p. 37). Therefore, the Moat volcanics cannot be younger than Mississippian, and the orogeny is younger than the lower Devonian, but older than the Mississippian.

A second fact bearing on the age of the folding relates to the Littleton-Moosilauke area where evidence shows that the Bethlehem gneiss was syntectonic (Billings, 1937, p. 537). Subsequently Shaub (1938) demonstrated that some of the pegmatites derived from the Bethlehem gneiss in the Cardigan quadrangle contained uraninite of Devonian age.

Evidence has been offered elsewhere (Billings, 1937, p. 535-536) that the intrusive domes of the Oliverian magma series of the Littleton-Moosilauke and Mascoma areas preceded the folding but are younger than the lower Devonian. Hence they are considered to be early Acadian.

The Bickford granite, which belongs to the New Hampshire magma series, is younger than the main deformation, but it apparently felt the waning effects of the compressive stresses.

The Pine Mountain fault is younger than the Ammonoosuc volcanics, the Partridge formation, the Oliverian magma series, and the Bickford granite, as all these rocks are cut by the fault. There is no evidence that the fault cuts the Conway granite or displaces the contact of the Conway granite. Although such evidence is not very significant because of the poor exposures, it is probable that the fault is older than the Conway granite. If so, the fault is late Devonian or early Mississippian.

METAMORPHISM

GENERAL STATEMENT

The original sedimentary rocks of the area have been thoroughly recrystallized and metamorphosed into a variety of crystalline schists. The rocks involved in these transformations were originally shale, sandstone, dolomitic sandstone, calcareous shale, basaltic tuff, quartz latite tuff, and rhyolite tuff. All of the metamorphic rocks, with the possible exception of those in a small area east of Mt. Madison, lie in the high-grade zone of metamorphism. However, there are several subzones.

The minerals in the paraschists of the Littleton and Partridge formations did not form simultaneously, and a definite paragenesis may be established. The problem of chemical changes during the metamorphism is given special consideration. To what extent have new elements been added to the rocks and how much material has been taken away by moving solutions? In particular, what is the origin of the gneiss in the Partridge formation and at the base of the Littleton formation? It is generally recognized that regional metamorphism of the type here considered is associated with a period of orogeny. In the Mt. Washington area this is true, and the stages in the recrystallization can be correlated with the orogenic stages.

ZONING AND SUBZONES IN THE PARASCHISTS

All rocks in the area, with the exception of one small region, lie in the high-grade zone of metamorphism, corresponding to the sillimanite zone of the British (Harker, 1939) and the katazone of Grubenmann and

Niggli (1924). The index mineral of the high-grade zone, sillimanite, is generally present throughout the Presidential Range in the paraschists and gneisses. Moreover, the groundmass of the rocks is much coarser grained than in typical middle-grade schists.

No direct criteria determine whether the actinolite and diopside granulites of the Fitch formation belong in the high-grade or middle-grade zone. As this unit is thin and is overlain and underlain by typical high-grade schists, it must be high-grade. Similarly, the Ammonoosuc volcanics, being nonaluminous, carry no index minerals for distinguishing between middle-grade and high-grade metamorphism. On the headwaters of Moose River, at an altitude of 1625 feet, and well within the area of Ammonoosuc volcanics, mica schist containing sillimanite is interbedded with the typical volcanics, indicating that the Ammonoosuc volcanics are high-grade.

In the description of the paraschists of the Littleton and Partridge formations it has been pointed out that original argillaceous sediments have recrystallized to rocks which differ greatly in their physical appearance and somewhat in their mineral composition. For descriptive purposes these rocks have been classified as: (1) coarse andalusite schists; (2) coarse pseudo-andalusite schist; (3) coarse rough pseudo-andalusite schist; (4) intermediate pseudo-andalusite schist; (5) shiny fine-grained pseudo-andalusite schist; (6) staurolite schist; and (7) medium-grained massive schist. In Figure 3 two varieties in several cases have been grouped under one symbol.

On the summits and upper slopes of the Presidential Range the original argillaceous sediments have been converted to coarse rough pseudo-andalusite schists. Lower down on the slopes, the rocks are not as coarse and are designated as intermediate pseudo-andalusite schist.

The coarse andalusite schists and the coarse pseudo-andalusite schists occupy an area extending from half a mile west of Pinkham Notch to a point 2½ miles to the north. The coarse andalusite schists are not extensive, because in most areas the andalusite has been completely altered to sericite or muscovite, forming the coarse pseudo-andalusite schists. Where the andalusite is partly altered the rocks constitute a transitional variety.

On the west side of the valley at Pinkham Notch the original argillaceous sediments are now shiny pseudo-andalusite schists, traceable north-northeast for 4½ miles. In the vicinity of the Mt. Washington Auto Road and the Glen House are local areas of medium-grained massive schist.

The staurolite schists occupy slightly more than a square mile southeast of Mount Madison. Although the coarse rough pseudo-andalusite schist and the intermediate pseudo-andalusite schist carry staurolite, they also carry the index mineral sillimanite and are relatively coarse. The staurolite schists have no sillimanite and the matrix is fine-grained. Such being the case, these rocks should be considered middle-grade.

The distribution of the different varieties is not due to any difference in stratigraphic position, as is quite apparent from Figure 3. In the vicinity of Mt. Clay coarse, rough pseudo-andalusite schist directly overlies the Fitch formation. Around Mt. Monroe and Boott Spur the intermediate pseudo-andalusite schist is directly above the Fitch formation. On the Cutler River, however, shiny pseudo-andalusite schist lies on the Fitch. Near summit 2587, 2 miles east-southeast of Mt. Madison, staurolite schist overlies the Fitch formation. Thus the varieties are not due to stratigraphic position but to differences in physical conditions during metamorphism. Variations in the character of moving solutions may have played a role. What these differences were is discussed in a later section.

PARAGENESIS IN THE PARASCHISTS

Sequence.—In the paraschists of the Littleton formation, particularly the coarser varieties, it is apparent that the minerals are not contemporaneous. The general sequence is shown in Fig. 10. At least three major stages may be recognized: andalusite belongs to the first; sillimanite, staurolite, garnet, tourmaline, and much of the muscovite and biotite belong to a second; and chlorite and sericite belong to the third stage. Some muscovite and biotite may belong to the first stage, although direct evidence is lacking. Quartz presumably belongs to both the first and second stages.

Evidence.—The evidence on which the paragenesis has been determined is comparatively simple and clear. ! Andalusite is older than muscovite, sillimanite, and staurolite; in many instances andalusite is surrounded by a pseudomorphic shell of one or more of these minerals. Staurolite and muscovite are considered to outlast sillimanite. There is no evidence for this in the Mt. Washington area, but in the Littleton-Moosilauke area shells of staurolite and muscovite surrounding sillimanite are common (Billings, 1937, p. 551). Muscovite, however, outlasted staurolite, for pseudomorphic shells of muscovite around staurolite are common in the staurolite schists.

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Garnet is apparently older than staurolite. In many specimens euhedral crystals of staurolite are associated with irregular corroded grains of garnet, indicating that garnet was out of equilibrium and was dissolving when staurolite was forming. Biotite is believed to be essentially contemporaneous with muscovite, chiefly because it shows essentially the same amount of deformation. Tourmaline is considered to be contemporaneous with staurolite as it likewise occurs in euhedral grains.

Sericite and chlorite belong to the third stage. Much of the andalusite is completely sericitized. Moreover, the staurolite has thin pseudomorphic shells of sericite, and in many specimens a sericitized andalusite is surrounded by a muscovite shell. This implies that the outer part of an andalusite crystal was replaced by muscovite and subsequently that part of the andalusite not already altered was converted to sericite. Chlorite is younger than biotite and garnet, as both of these minerals are extensively chloritized. Chlorite and sericite are associated along planes of fracture cleavage and are apparently contemporaneous.

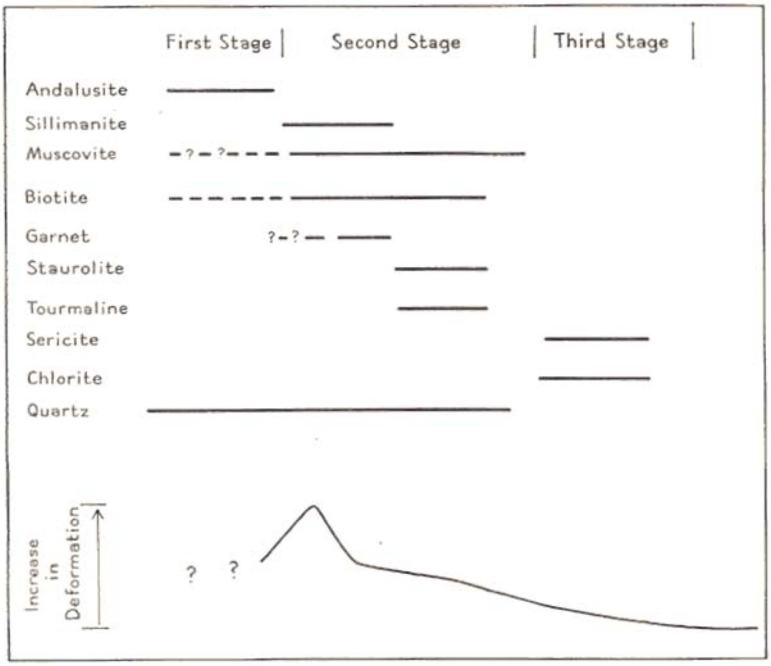

FIGURE 10.—*Paragenesis of metamorphic minerals*

Refers primarily to the coarse rough pseudo-andalusite schist of the Littleton formation
The abscissa represents time, the younger minerals appearing to the right.

CORRELATION OF PARAGENESIS AND DEFORMATION IN THE PARASCHISTS

Problem.—The chronological relation between paragenesis and deformation is an important problem. In general the recrystallization was syntectonic, but some minerals are older than the culmination of the orogeny, others are younger. Conceivably the deformation was not simultaneous throughout the region, and the same may be true of the recrystallization. Consequently some rather complicated relations may occur.

Coarse rough pseudo-andalusite schist.—In these rocks many of the andalusite pseudomorphs have been folded with the strata (Pl. 7, fig. 4). In some thin sections the sillimanite which partially replaces andalusite is folded and broken. In such cases it is evident that the minor folds are younger than the andalusite and sillimanite. There is some evidence, to be discussed later, that the large folds had already developed when andalusite and sillimanite formed.

The muscovite generally occurs as large undeformed plates, but locally it is broken by sharp flexures. This indicates that some deformation outlasted the recrystallization, but it is distinctly a subordinate phenomenon. The biotite shows relations similar to muscovite. Staurolite and tourmaline are in euhedral grains which lie in diverse orientations. They are considered, therefore, to be relatively late minerals.

Intermediate pseudo-andalusite schist and shiny pseudo-andalusite schist.—In these rocks the pseudomorphs after andalusite show a distinct lineation in many localities. Likewise the biotite in the shiny pseudo-andalusite schists may show a linear parallelism. The nature of the lineation indicates that it is syntectonic, not mimetic. In these rocks, therefore, the andalusite and biotite, and probably other minerals, are contemporaneous with the deformation. Little crinkles, however, which are due to small folds in the schistosity, parallel the lineation shown by the elongation of the minerals. These crinkles indicate that deformation outlasted recrystallization.

Fitch formation.—Many specimens of this unit show an excellent lineation. The actinolite in the granulites is in stubby grains which lie parallel to one another, indicating that they formed contemporaneously with the deformation.

Conclusions.—The recrystallization of the Fitch formation and the shiny pseudo-andalusite schists was contemporaneous with the formation of the minor folds. In the coarse rough pseudo-andalusite schist, however, the recrystallization largely outlasted the development of the minor folds.

METAMORPHISM, STRUCTURE, AND TOPOGRAPHY

A comparison of the structure-contour map (Fig. 5) with the map of the metamorphic subzones (Fig. 3) shows that there is a rather close correlation between the anticlines with closure and the coarsest schists. The coarse rough pseudo-andalusite schist and the intermediate pseudo-andalusite schist are characteristically developed on the anticlines on

Mt. Washington, Mt. Clay, Mt. Jefferson, Mt. Adams, and Mt. Madison. Conversely the fine-grained schists, such as the shiny fine-grained pseudo-andalusite schist, medium-grained massive schist, and staurolite schist, are characteristically found in the synclines and on the flanks of folds. Schists of this type are characteristic of the syncline west of Pinkham Notch—particularly the east limb—and the large syncline 3 miles northeast of Mt. Washington.

Why there should be such a structural control of the metamorphism is problematical. A possible explanation is that the development of large crystals—particularly andalusite—was favored by hot aqueous solutions. Such solutions would tend to be concentrated and trapped on the crest of anticlines with closure.

There is an interesting correlation between metamorphism, structure, and topography. The height of the Presidential Range is due to the exceedingly tough, coarse-grained schists of which it is composed. Such rocks are rare in New Hampshire, but wherever similar schists are found in the state they hold up relatively high mountains—Moosilauke, Kearsarge, Monadnock. In the Mt. Washington area, at least, the nature of the metamorphism has been controlled by the structure. Consequently the topography is closely related to the structure and the individual mountains are anticlinal. The anticlinal structure alone, however, would not suffice to cause the location of mountains. Rather, the relation is an indirect one, for the topography is controlled by the character of the metamorphism, which in turn has been controlled by the structure.

CAUSES OF SUBZONES IN THE PARASCHISTS

The subzones of metamorphism of the Mt. Washington area result from variations in the metamorphic history in different sections. There is no evidence that the subzones were buried at different depths. The temperature, however, may well have differed from place to place. Moreover, the time of maximum temperature and time of maximum deformation may have been synchronous in some localities, but elsewhere either one might have preceded the other. In the folding of strata, moreover, strong differential movements are often confined to special zones, in which highly schistose rocks may be expected.

Those rocks with large andalusite and large pseudo-andalusite crystals went through a stage which did not affect the other rocks. It was essentially a contact metamorphism, but the causative igneous body is not known.

In a later phase of the metamorphic history temperature and stress conditions favored the formation of sillimanite throughout most of the area, and this mineral either partially replaced andalusite or formed about new centers of crystallization. However, in one area now occupied by the staurolite schists (Fig. 3) the physical conditions did not permit the formation of sillimanite.

With falling temperature, accompanied by decreasing intensity of deformation, conditions favored the formation of staurolite throughout the region. In those areas where coarse andalusite or sillimanite were present, the staurolite, along with muscovite, formed as small shells replacing the older aluminous minerals. Where these minerals had not previously formed, the staurolite developed as independent crystals.

A massive rather than a schistose structure may be due to one of two reasons. The rock may have formed in a region which was not affected by strong differential movements; or the recrystallization may have followed the deformation. The medium-grained massive schists are believed to have developed in preference to the shiny fine-grained pseudo-andalusite schists because of lack of strong differential movements.

The subzones are due, therefore, to a complicated interplay of the various factors involved in the metamorphism.

CHANGES IN CHEMICAL COMPOSITION

General statement.—One of the primary purposes of the present investigation was to ascertain the extent of chemical changes during metamorphism. This is always difficult, as primary differences may not be readily distinguished from changes due to metamorphism. Moreover, there is the danger of unconsciously selecting material with which to prove a preconceived idea.

Fitch formation.—The abundance of minerals rich in lime and magnesia, such as actinolite, diopside, and calcic plagioclase, make it clear that many of the rocks in the Fifth formation have been derived from arenaceous and argillaceous dolomites or limestones. Marble has not been observed, and even calcite is rare. There are two possible ways to explain the origin of these rocks. They may have been arenaceous and argillaceous dolomites, and the metamorphism may have taken place with little change in chemical composition, except the loss of CO_2 and perhaps H_2O; or the initial rocks may have been arenaceous and argillaceous limestone, and much of the iron and magnesia may have been introduced from extraneous sources. The first hypothesis is more likely correct, although direct proof is lacking. In the Littleton-Moosilauke area it was possible to demonstrate that the actinolite and diopside granulites were derived from arenaceous and argillaceous dolomites, for granulites are no commoner in the higher zones than dolomites in the low-grade zone (Billings, 1937, p. 547). Moreover, in the Littleton-Moosilauke area, thin beds of marble are interbedded with the granulites, and the contacts are sharp. These relations would not be consistent with an explanation involving extensive metasomatism.

Ammonoosuc volcanics.—In the Littleton-Moosilauke area it was believed that the Ammonoosuc volcanics were metamorphosed without important compositional changes. The same is true in the Mt. Washington area.

Amphibolites are rare, but a chemical analysis was made of one specimen W56 (Table 10, column 11). The composition is similar to typical basalt (Table 10, column 13). It is a thin layer interbedded with the biotite gneisses and must be a bed of tuff.

The biotite gneisses are abundant, but the ratio of plagioclase to orthoclase varies considerably. Some, like the one listed in Table 1, column 4, do not differ much in chemical composition from some of the soda-rhyolites of the low-grade metamorphic zone of the Littleton-Moosilauke area (Billings, 1937, Table 19, column 6; Table 3, line 2). Others, such as the one listed in Table 1, column 5, compare favorably in their chemical composition with those listed in Table 3, line 3, of the Littleton-Moosilauke paper. Thus, many of the biotite gneisses of the Mt. Washington area have apparently been derived from the original volcanics without much chemical change.

Volcanics with a distinct dominance of potash feldspar, such as those listed in Table 1, columns 3 and 3a, and Table 10, column 14, have not been observed in the low-grade zone. It might be proposed, therefore, that such rocks indicate the introduction of potash. It is equally possible, however, that such rocks represent original rhyolites, which are absent from the low-grade zone or were not observed during the field work.

Paraschists.—In the high-grade zone of the Franconia quadrangle many schists derived from argillaceous sediments have been enriched in potash (Billings, 1938). Pseudomorphic shells of muscovite surrounding sillimanite constitute the field evidence, and chemical analyses supported this interpretation.

Two analyses are available for the low-grade slates from the Littleton area. Specimen W219 (Table 10, column 1) is the less aluminous type and does not differ significantly from an analysis of the shiny fine-grained pseudo-andalusite schist, Specimen W229 (Table 10, column 4). The schist is slightly richer in silica and poorer in total iron and magnesia, suggesting a slightly more arenaceous original rock. However, potash is identical in the two rocks, and soda is actually somewhat less in the schist. Apparently alkalies have not been added to this particular rock during the metamorphism.

A second analysis of slate, L489, is a more aluminous variety (Table 10, column 2). Compared to the coarse rough pseudo-andalusite schists, it is somewhat richer in silica, but poorer in alumina and potash. The field evidence suggests that some potash has been introduced into the schist, for part of the muscovite is pseudomorphous after large andalusite crystals, now completely replaced by muscovite, staurolite, and sillimanite. The analysis is consistent with this hypothesis, as the coarse rough pseudo-andalusite schist contains 0.68 per cent more potash than the slate.

The shells of muscovite surrounding andalusite in the coarse andalusite schist and the coarse rough pseudo-andalusite schist and enveloping staurolite in the staurolite schist, indicate addition of potash at a relatively late stage in the paragenesis.

Much of the andalusite has been replaced by sericite. Some specimens of pseudo-andalusite have an outer shell of muscovite and a core of sericite. Moreover, euhedral staurolite crystals, which are rather late in the paragenesis, have narrow shells of sericite, indicating that the potash in the sericite was introduced rather late in the paragenesis. In any case, a tremendous difference in the size of the muscovite and the sericite indicate a distinct difference in age. The relations with staurolite indicate that the sericite is younger.

In order to see how much change took place in the metamorphism of impure sandstone to quartzite, two analyses were prepared. One, W220 (Table 10, column 8), is a low-grade sandstone from the Littleton area; the second, W222 (Table 10, column 9), is a quartzite from the Mt. Washington area. Systematic differences exist between the analyses. The sandstone is richer in silica but poorer in the other important oxides. Contrasts between the analyses could be due to differences in the original sediments, the sandstone having had more quartz and less clay than the rock from which the quartzite was derived. This interpretation, rather than ascribing the differences to changes during metamorphism, is preferred because of the evidence offered by the graphic representation described on a later page.

Gneiss.—The gneisses so common in the Partridge formation consist, over large areas, of alternating dark and light streaks in about equal proportions. The dark streaks are primarily biotite, with minor amounts of quartz, plagioclase, and muscovite (Table 2). The light layers are primarily quartz, plagioclase, and muscovite, with subordinate amounts of biotite.

After studying these gneisses in the adjacent North Conway quadrangle (Fig. 1) the writer concluded that they were injection gneisses (Billings, 1928, p. 85-86).

> "Juices from the invading Chatham granite soaked through the folding sediments, greatly augmented the tendency to rock flowage, and caused recrystallization. As the granite moved up into a given horizon of the metamorphosed zone it first intruded the schists in lit-par-lit fashion and then gradually ripped them to pieces, strewing the shreds throughout the granite."

The dark portions of the gneiss were considered to be remnants of the older schists, modified by moving solutions, whereas the light-colored portions of the gneiss were believed to have been injected as thin sheets of magma.

During the present investigation a chemical analysis has been made of a gneiss composed of about equal parts of light and dark constituents (Pl. 5, fig. 1; specimen W215, Table 10, column 10; Table 2, column 1a). Such a specimen is typical of much of the gneiss (Fig. 3). The chemical composition is essentially the same as that of some of the slate (W219, Table 10, column 1), suggesting that slate has been transformed *in situ* into gneiss with little change in chemical composition. The gneiss is a little richer in soda and potash than the slate. This may mean the introduction of some alkalies, but the differences are so slight that too much significance should not be attached to them. As the metamorphic processes increased in intensity the light and dark constituents segregated into alternating bands. Turner (1940) has recently discussed this process in an admirable paper. In general the streaks followed the original bedding. A good example, however, of the light constituents concentrating along the cleavage is shown by Figure 9.

Such an explanation is inadequate for predominately light-colored gneisses (Fig. 3). The gneisses in which the dark and light constituents are equal contain only 17 per cent plagioclase, 1.71 per cent soda, and 0.59 per cent lime. The average gneiss, however, contains 36 per cent plagioclase, about 3.7 per cent soda, and about 1.4 per cent lime. Some of the light-colored gneisses contain up to 50 per cent plagioclase, and a correspondingly greater amount of soda and lime. Apparently as much as 4 or 5 per cent of soda, potash, and lime have been introduced into the light-colored gneisses.

Graphic representation.—Many devices have been employed to represent graphically the chemical relations between rocks. One of the most common systems involves the use of triangular diagrams which are unsatisfactory, inasmuch as only a limited number of the essential oxides can be incorporated. Four components can be shown on a tetrahedron, but the perspective may be confusing and even misleading.

In Figure 11, applying only to original shales or sandstones, the various oxides have been plotted against silica as the abscissa, as in the ordinary variation diagram for igneous rocks. At first this method may seem arbitrary and unjustified for rocks of sedimentary origin. For shales and sandstones derived from thoroughly weathered older rocks, however, this method might be satisfactory. Such rocks are composed essentially of two parts, a clay portion and grains of quartz. Inasmuch as the clay portion would presumably have a uniform composition, all the other oxides would vary inversely to the silica. The other oxides should intersect the base of the plot at 100 per cent silica.

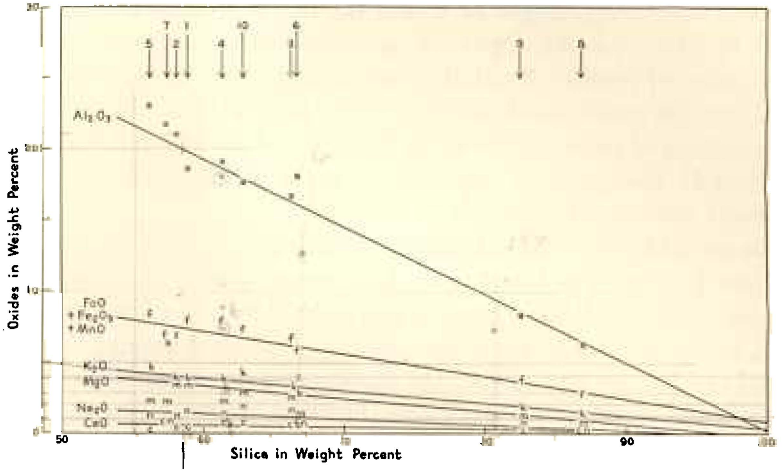

FIGURE 11.—*Graphic representation of chemical changes during metamorphism*

a = alumina; f = FeO + Fe_2O_3 + MnO, (Fe_2O_3 recalculated to FeO); k = K_2O; m = MgO; n = Na_2O; c= CaO. Numbers are the same as in Table 10. Low-grade rocks: 1 and 2 = slate. Middle-grade rock: 3 = staurolite schist. High-grade rocks: 4 = shiny fine-grained pseudo-andalusite schist; 5 = coarse rough pseudo-andalusite schist; 6 = medium-grained massive schist; 7 = muscovitized schist; 8 = sandstone; 9 = quartzite; 10 = gneiss.

Figure 11 dispels any doubts of the theoretical justification of the method. The curves are remarkably straight and the various points are relatively close to the appropriate curve,—much better than in most variation diagrams of igneous rocks.

The curves (Figure 11) have been constructed on the analyses from the low-grade zone, for which two analyses of slate and one of sandstone are available. Although these few points may seem a rather weak basis for statistical comparisons, the fact that the points for rocks from the high-grade zone lie very close to these curves justifies the principle involved. Moreover, all the curves intersect the base close to 100 per cent silica.

In comparing the high-grade with the low-grade metamorphic rocks, any oxide which has changed notably will lie off the curves. In analysis 7 of Figure 11, potash lies several per cent above the curve. This is a muscovitized schist from the Franconia quadrangle (Billings, 1938a), where field evidence indicates addition of potash. In analysis 5, the coarse rough pseudo-andalusite schist, potash is somewhat above the curves, suggesting the possible addition of some potash. Although the amount is slight and might be within the limits of error of the method, the field data—pseudomorphs of muscovite after andalusite—indicate introduction of potash. Similarly, some potash seems to have been introduced into the gneiss (analysis 10). There is no evidence for an increase in the content of potash in the shiny fine-grained pseudo-andalusite schist (analysis 4), the quartzite (analysis 9), or the sillimanite schist from the Franconia quadrangle (analysis 6).

Soda seems to show no systematic variation except for an increase of less than 1 per cent in the gneiss. Iron seems to have increased, but in this case the left end of the curve seems to be a little too low, because the curve, as drawn through the control points, strikes the base of the plot to the right of 100 per cent silica. On an adjusted curve iron does not show any systematic variation. Magnesia, however, shows a systematic loss, amounting to over 1 per cent in some cases. Alumina seems to show an increase. However, it is more likely that analysis 1 is abnormally low in alumina, so that if the curve were based on analysis 2 alone, this oxide would show no systematic change.

Summary of chemical changes.—Changes in chemical composition during the metamorphism have been investigated by field, microscopic, and chemical methods. In general the changes in the Ammonoosuc and Fitch formations have not been great. Even in the Partridge and Littleton formations, as shown by Figure 11, many rocks seem to have undergone little or no change; this is notably true of the shiny fine-grained pseudo-andalusite schist (analysis 4), massive medium-grained schist (equivalent to analysis 6), and quartzite (analysis 9).

Potash has been added to some schists, such as the coarse rough pseudo-andalusite schist (analysis 5), but not to the same extent as the muscovitized schist of the Franconia quadrangle (analysis 7). Less than 1 per cent each of soda and potash have been added to the gneiss (analysis 10), but 3 per cent of soda and 1 per cent lime and 1 per cent potash have been added to some of the light-colored gneiss for which chemical analyses are not available.

A systematic loss of magnesia has occurred. The relative abundance of tourmaline suggests the addition of boron, and the conversion of such minerals as andalusite to muscovite indicates the addition of water.

Mechanics of the chemical changes.—The changes in chemical composition described in preceding sections were accomplished by moving solutions which added and removed material. In some rocks no changes are apparent; in others, where the changes were slight, pseudomorphs of muscovite and sericite formed after aluminous minerals. In regions of even greater alterations the introduced materials participated in the selective fusion or solution of the rocks. The solutions so generated gathered into irregular light-colored streaks, which, although they constitute 50 per cent of the rock, include less than 1 per cent of added material. In the areas of most intense alteration, where 4 or 5 per cent of soda, lime, and potash were introduced, the whole rock became a molten mush similar to magma.

The gneisses resulting from the processes described above would be called migmatites by many (Tyrrell, 1930, p. 331). However, the writer has intentionally refrained from the use of this term because it is used differently by various investigators. The process itself is similar to anatexis, metatexis, palingenesis, and granitization (Barth, Correns, and Eskola, 1939, p. 226). These terms also have been used with different meanings by geologists.

The gneisses of the Mt. Washington area formed by processes identical to those postulated for central Massachusetts by Larsen and Morris (1933). The process is similar to that described by Currier (1937) in the Chelmsford-Westford district of Massachusetts and at Milford, New Hampshire. Similar interpretations have been given to granitic rocks in other parts of North America during the last few years. Goodspeed (1939) has discussed this subject and gives an excellent list of references.

Within the gneiss small bodies of typical granitoid rocks, a few feet to several hundred feet across, have relatively sharp contacts with the gneiss and locally contain angular inclusions of gneiss. Such granitoid rocks apparently consolidated from magma injected into the gneiss. Probably these magmas were derived from deep-seated sources and are apophyses of a larger mass below.

In principle, a clear distinction should be made between gneiss which has originated *in situ* and granitoid rocks which have consolidated from magma derived from below; in practice the distinction may be difficult. Where exposures are poor or the observer is not aware of the situation, the gneiss may appear to grade imperceptibly into the granitoid rocks. Where exposures are good, however, a relatively sharp discontinuity may be recognized.

On the accompanying maps (Pl. 1; Fig. 3) the areas shown as gneiss of the Partridge and Littleton formations contain rocks of two different origins. The most abundant are gneisses derived from shales by selective solution accompanied by the introduction of alkalies and lime. Less common, but equally important rocks occupy bodies which vary from a few feet to several hundred feet across, too small to show on the scale employed. These rocks consolidated from magma of distant origin.

SUMMARY OF GEOLOGIC HISTORY

GEOSYNCLINAL PHASE

The geological record begins with the accumulation of the Ammonoosuc volcanics, probably during late Ordovician. Not less than 5000 feet of pyroclastics, chiefly rhyolite, quartz latite, and dacite, but including some andesite and basalt, were deposited, accompanied by minor amounts of sedimentary material. The volcanic cycle was followed by the deposition of 1400 feet of sandstone and shale to form the Partridge formation. Evidence elsewhere in New Hampshire indicates a mild period of orogeny near the end of the Ordovician, accompanied by uplift and followed by erosion.

In a middle Silurian sea, which moved in from the southwest, the dolomitic sandstones and shales of the Fitch formation, not over 200 feet thick, were deposited. Late Silurian history is obscure, but during early Devonian 4000 feet or more of sandstone and shale were deposited to form the Littleton formation.

OROGENIC PHASE

Deformation.—During middle or late Devonian the strata were caught in a major orogenic paroxysm. Even before the deformation, or at least in its early stages, successive injections of the Oliverian magma series formed a large intrusive dome. This northeasterly-trending dome is in the northwestern part of the area and was inserted beneath or within the Ammonoosuc volcanics. The Ordovician (?), Silurian, and Devonian strata of the southwestern part of the area were thrown into a series of doubly plunging, en echelon folds, the axes of which trend north and northeast. Associated with the major folds are countless minor folds, the amplitudes and wave lengths of which are measured in feet, tens of feet, and scores of feet. Schistosity, parallel to the bedding, formed during the earlier stages of the orogeny. A lineation, well marked in many places, formed contemporaneously with the minor folding. Fracture cleavage, which is essentially parallel to the axial planes of the minor folds, formed during the later stages of the deformation.

Metamorphism.—The metamorphism is syntectonic. Recrystallization began sometime after folding had commenced. The major structure must have already developed because the character of the metamorphism is controlled by the larger structural features. Locally recrystallization was contemporaneous with a later phase of the orogeny, during which many minor folds developed. Elsewhere, however, crystallization, notably of andalusite, preceded this later phase of minor folding, but many of the other minerals crystallized afterwards. On the whole, recrystallization was syntectonic, but some preceded the intensive minor folding, some followed.

Some rocks recrystallized without any significant change in chemical composition, such as the amphibolite and biotite gneiss in the Ammonoosuc volcanics, the shiny pseudo-andalusite schist in the Partridge and Littleton formations, and probably the actinolite and diopside granulites of the Fitch formation—except for the loss of CO_2. Potash was added to some schists, notably the coarse andalusite schist, the coarse pseudo-andalusite schist, and the coarse rough pseudo-andalusite schist. Potash was added in two stages; in an earlier high temperature stage the aluminous minerals were converted in whole or in part to muscovite. In a later, lower temperature stage sericite replaced the unaltered andalusite, and chloritization of biotite and garnet took place. Magnesia was in part removed during the metamorphism.

The gneiss originated in part through selective solution *in situ,* accompanied by the introduction of soda, lime, and potash. Where the light-colored constituents constitute a high percentage of the gneiss, 4 or 5 per cent of soda, lime, and potash have been added to produce granitic-looking rocks.

The gneiss formed near the end of the orogeny, because some of the light-colored material has concentrated along cleavage planes parallel to the axial planes of the folds. The orogeny was in an advanced state when the segregation occurred; although the gneiss is locally thrown into small folds, the crystallization is later than the folding. The rocks show no evidence of strain, such as would be expected if they were folded subsequent to the crystallization of the light-colored material.

LATE-OROGENIC AND POSTOROGENIC HISTORY

After the main orogenic movements had ceased, the Bickford granite intruded the relatively brittle older rocks. It made space for itself partly by forcing aside the country rocks, but partly by stoping. Subsequently a series of northeasterly trending normal faults, the largest of which is the Pine Mountain fault developed. The last phase in the construction of the bedrock was the intrusion of the White Mountain magma series, to which may be assigned the syenite on Cherry Mountain, the Conway granite, tuffs and breccias in volcanic vents, and small dikes.

WORKS TO WHICH REFERENCE IS MADE

Antevs, Ernst (1932) *Alpine zone of Mt. Washington Range,* 118 pages, Auburn, Maine.

Barth, T. F. W. (1936) *Structural and petrologic studies in Dutchess County, New York; part II, petrology and metamorphism of the Paleozoic rocks,* Geol. Soc. Am., Bull., vol. 47, p. 775-850.

———, Correns, C. W., and Eskola, P. (1939) *Die Entstehung der Gesteine,* 422 pages, Berlin.

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

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

——— (1938a) *Introduction of potash during regional metamorphism in western New Hampshire,* Geol. Soc. Am., Bull., vol. 49, p. 289-302.

——— (1938b) *Geology in the Presidential Range,* Mount Washington Observatory, News Bull., no. 4, p. 8-11.

——— (1939) *Chemical changes during regional metamorphism in the Presidential Range of New Hampshire* (abstract), Geol. Soc. Am., Bull., vol. 50, p. 1900.

———, and Cleaves, A. B. (1934) *Paleontology of the Littleton area, New Hampshire,* Am. Jour. Sci., 5th ser., vol. 28, p. 412-438.

———, — ——— (1935) *Brachiopods from mica schist, Mt. Clough, New Hampshire,* Am. Jour. Sci., 5th ser., vol. 30, p. 530-536.

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

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

——— (1937) *Petrology of the syenite stock at Cherry Mountain, New Hampshire,* Am. Jour. Sci., 5th ser., vol. 35, p. 174-186.

Crosby, I. B. (1924) *The physiographic history of Pinkham Notch,* Appalachia, vol. 15, p. 462-468.

Currier, L. W. (1938) *Regional granitization and metamorphism in New England* (abstract), Geol. Soc. Am. Pr. 1937, p. 75.

Daly, R. A. (1933) *Igneous rocks and the depths of the earth,* 598 pages, New York.

Dodge, T. A. (1936) *A rapid method for distinguishing quartz from untwinned oligoclase-andesine,* Am. Mineral., vol. 21, p. 531-532.

Fowler-Lunn, Katharine, and Kingsley, Louise (1937) *Geology of the Cardigan quadrangle, New Hampshire,* Geol. Soc. Am., Bull., vol. 48, p. 1363-1386.

Goldthwait, J. W. (1916) *Glaciation in the White Mountains of New Hampshire,* Geol. Soc. Am., Bull., vol. 27 p. 263-294.

——— (1925) *The geology of New Hampshire,* N. H. Acad. Sci., Handbook no. 1, 86 pages.

Goldthwait, R. P. (1940) *Geology of the Presidential Range,* N. H. Acad. Sci., Bull. 1, 41 pages.

Goodspeed, G. S. (1939) *Pre-Tertiary metasomatic processes in the southeastern portion of the Wallowa Mountains of Oregon,* 6th Pacific Sci. Congr., Pr., p. 399-422.

Grubenmann, U., and Niggli, P. (1924) *Die Gesteinsmetamorphose,* 539 pages, Berlin.

Hadley, J. B. (1941) *Stratigraphy, structure and metamorphism of the Mt. Cube area, New Hampshire* (in press).

Hadley, J. B., and Chapman, C. A. (1939) *The geology of the Mt. Cube and Mascoma quadrangles, New Hampshire,* State Planning and Development Commission, 28 pages.

Harker, Alfred (1939) *Metamorphism,* 360 pages, London.

Hitchcock, C. H. (1877) *Geology of New Hampshire,* vol. II, 684 pages, Concord, N. H.

Jackson, C. T. (1844) *Final report on the geology and mineralogy of the state of New Hampshire,* 376 pages, Concord, N. H.

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

LaForge, L. (1932) *Geology of the Boston Area, Massachusetts,* U. S. Geol. Survey, Bull. 839, 105 pages.

Lane, A. C. (1921) *White Mountain physiography,* Am. Jour. Sci., 5th ser., vol. 1, p. 349-357.

Larsen, E. S., and Berman, H. (1934) *The microscopic determination of the nonopaque minerals,* U. S. Geol. Survey, Bull. 848, 266 pages. USGS Bu

———, — Morris, F. K. (1933) *Origin of the schists and granite of the Wachusett-Coldbrook tunnel, Massachusetts,* Geol. Soc. Am., Bull., vol. 44, p. 92.

Modell, D. I. (1933) *Ring-dike complex of the Belknap Mountains, New Hampshire,* Geol. Soc. Am., Bull., vol. 47, p. 1885-1932.

Page, L. R. (in preparation) *Geology of the Rumney quadrangle, New Hampshire.*

Penfield, S. L., and Pratt, J. H. (1894) *On the chemical composition of staurolite, and the regular arrangement of its carbonaceous inclusions,* Am. Jour. Sci., 3d ser., vol. 47, p. 81-89. Am [illegible]

Quinn, A. W. (1937) *Petrology of the alkaline rocks at Red Hill, New Hampshire,* Geol. Soc. Am., Bull., vol. 48, p. 373-402.

——— (in preparation) *The geology of the Winnepesaukee quadrangle, New Hampshire.*

Rogers, H. D., and Rogers, W. D. (1846) *On the geological age of the White Mountains,* Am. Jour. Sci., 2d ser., vol. 1, p. 411-421.

———, — ——— (1848) *Fossils in the White Mountains,* Am. Jour. Sci., 2d ser., vol. 5, p. 116.

Shaub, B. M. (1938) *The occurrence, crystal habit, and composition of the uraninite from the Ruggles Mine, near Grafton Center, New Hampshire,* Am. Mineral., vol. 23, p. 334-341. Am Min

Smith, A. P., Kingsley, L. and Quinn, A. W. (1939) *The geology of the Mt. Chocorua quadrangle, New Hampshire,* State Planning and Development Commission, 24 pages.

Turner, F. J. (1941) *The development of pseudo-stratification by metamorphic differentiation in the schists of Otago, New Zealand,* Am. Jour. Sci., vol. 239, p. 1-16. AmJ

Tyrrell, G. W. (1934) *The principles of petrology,* 3d. ed., 349 pages, London.

Williams, C. R., and Billings, M. P. (1938) *Petrology and structure of the Franconia quadrangle, New Hampshire,* Geol. Soc. Am., Bull., vol. 49, p. 1011-1044.

Wilmarth, M. G. (1938) *Lexicon of geologic names of the United States,* U. S. Geol. Survey, Bull. 896, 2396 pages.

Winchell, A. N. (1933) *Elements of optical mineralogy, part II,* 459 pages.

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