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BY

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ABSTRACT

Middle-grade and high-grade metamorphic rocks, derived from sediments and volcanics, which range from Middle Ordovician to Lower Devonian, comprise half the rocks in the Mascoma quadrangle. The Orfordville formation (probably Middle Ordovician) is a new formation. Biotite gneiss of the Oliverian and New Hampshire magma series comprise the rest of the rocks.

The outstanding structural features are domes of metamorphic rocks with cores of the Oliverian magma series. Evidence indicates these bodies are laccoliths. A primary foliation is believed to have developed in these igneous rocks parallel to the contacts and a schistosity produced parallel to the bedding in the roof rocks. Bedding, schistosity, and foliation are thus all parallel. Field and laboratory studies indicate that considerable microcline later replaced some of these igneous and metamorphic rocks, producing rocks with the composition of granite.

The Mt. Clough pluton of Bethlehem gneiss with a marked primary foliation paralleling its contacts is a later major feature. It was intruded probably in the late Devonian as a huge sheet essentially parallel to the regional structure. Field evidence indicates that it forced its way over two of the Oliverian domes while buried beneath several thousand feet of rock.

The area sheds considerable light on metamorphic problems. Chlorite (amesite) is stable in the presence of muscovite in the garnet zone. Kyanite forms in the lower part of the middle-grade zone. Disequilibrium rocks are believed to be common. Rotated porphyroblasts indicate a post-metamorphism deformation. Two distinct periods of metamorphism are evinced by the fact that the schistosity formed by laccolithic intrusion has in places been highly folded and a second schistosity superimposed.

INTRODUCTION

The Mascoma quadrangle, in west-central New Hampshire (Fig. 1), was mapped in 1927 by the topographic branch of the United States Geological Survey, on a scale of 1:62,500 and with a contour interval of 20 feet. The earliest studies in bedrock geology of the area include those of C. H. Hitchcock (1874, 1877, 1878, and 1909), but more recent studies have been made by J. W. Merritt (1921), J. W. Goldthwait (1925), and E. P. Kaiser (1938). In recent years considerable detailed work in stratigraphy, structural geology, and petrology has been done in New Hampshire. Much of this was of considerable aid in the study of the present problem. Of particular importance is the work of M. P. Billings (1937) in the Littleton and Moosilauke quadrangles. Other important works will be found in the list at the end of this report.

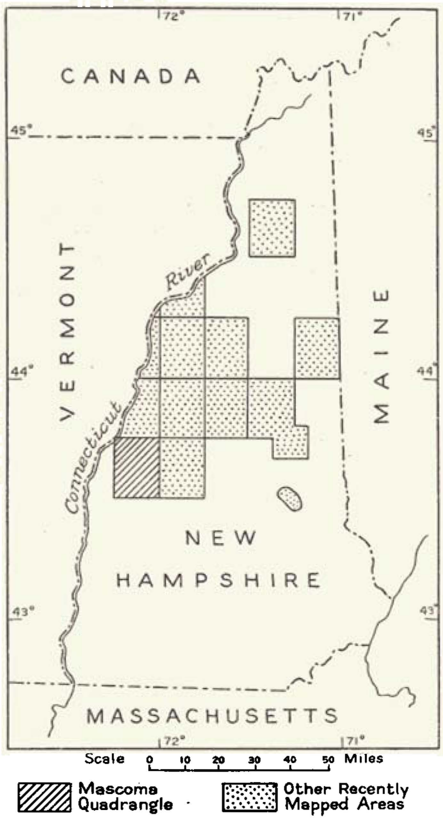


FIGURE 1.—*Index map*

Showing location of Mascoma quadrangle and other recently mapped areas.

METHOD OF WORK AND ACKNOWLEDGMENTS

The field work, which occupied 26 weeks, was carried on during the summers of 1935 and 1936. The 1932 edition of the United States Geological Survey topographical sheet was enlarged three times to a scale of 3 inches to 1 mile, and used as a base map in the field. All critical points were accurately located by means of pace-and-compass traversing or by an aneroid barometer, and all outcrops were recorded on maps. About five weeks were spent in making detailed pace-and-compass maps (scale of 800 feet to the inch) in regions where the structure was relatively complex or where it was desired to trace contacts accurately.

Welcome coöperation was received from field parties working in adjoining areas; Doctors K. Fowler-Lunn and L. Kingsley (1937) in the

AGE		FORMATION	LITHOLOGY	THICKNESS	SYMBOL	COLUMNAR SECTION
DEVONIAN	Lower	LITTLETON FORMATION	Mica schist, quartz-mica schist, staurolite schist, sillimanite schist, and quartzite, with volcanic member of biotite gneiss (Dlv)	4000'±	Dlv Dl	Section east of Northey Hill Thrust
SILURIAN	Middle	FITCH FORMATION	Diopside-hornblende granulite	0-100'	Sf	
	Lower or Middle	CLOUGH FORMATION	Quartz conglomerate and quartzite with mica schist and mica-quartz schist	200'-1200'	Sc	
		Unconformity				
ORDOVICIAN ?	Upper?	AMMONOOSUC VOLCANICS	Amphibolites with some biotite gneiss	2000'±	Oam	Section cut out by Northey Hill Thrust
	Upper?	ALBEE FORMATION	Mica schists and quartzite	4000'±	Oal	
	Middle?	ORFORDVILLE FORMATION	Mica-quartz schist, mica schist, garnet schist, and quartzite, with Hardy Hill quartzite (Ooh) and Post Pond volcanics (Oop) and a few lenses of volcanics (Oov)	4000'±	Oo Ooh Oov Oop	Section west of Northey Hill Thrust

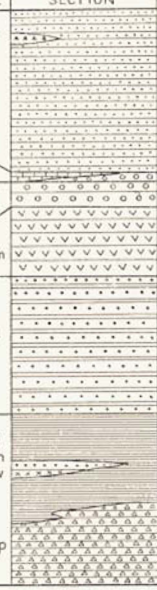


FIGURE 2.—*Columnar section of Mascoma quadrangle*

Cardigan quadrangle, Dr. J. B. Hadley (1938) in the Mt. Cube quadrangle, Dr. L. R. Page in the Rumney quadrangle (1937), and Mr. E. P. Kaiser (1938) in the Mascoma and Hanover quadrangles.

Sincere thanks are due Professor Marland Billings of Harvard University, for supervision of field and laboratory work and valuable assistance in the preparation of this paper, and to Professor E. S. Larsen, Jr., for the many helpful suggestions and criticisms. The writer was assisted in the field by Mr. B. F. Chapman, Mr. R. Vosburgh, and Mr. E. Breed, Jr., and for shorter periods by Dr. R. W. Chapman, Mr. W. E. Richmond, and Dr. J. B. Hadley. To these men the writer wishes to express his indebtedness. He also wishes to express his sincere thanks to Professor Charles Palache and the Department of Mineralogy and Petrography, Harvard University, for money obtained from the Holden Fund to finance field expenses and pay for thin sections; to Professor J. W. Goldthwait and Mr. F. E. Everett who obtained funds necessary for publishing the colored geological map; and to Dr. E. B. Dane, Jr., for the numerous photomicrographs used in this paper.

METAMORPHIC ROCKS

GENERAL STATEMENT

The metamorphic rocks of the Mascoma quadrangle consist of a great number of lithologic types, of sedimentary and volcanic origin. They range in age from Middle Ordovician (?) to Lower Devonian (Fig. 2). Except for a small area of high-grade schists in the southeastern part of the quadrangle, they all belong to the middle-grade zone of metamorphism.

ORFORDVILLE FORMATION

Correlation.—The Orfordville formation was named by Hadley (1938) for a group of black schists and volcanics, which underlie the Albee formation in the Mt. Cube quadrangle. This formation consists of a lower volcanic member, the Post Pond volcanics, and an overlying series of black schists, in the middle of which is the relatively thin Hardy Hill quartzite member (Fig. 2).

Black schists.—The black schists which lie above the Post Pond volcanics are continuous with identical types studied by Hadley in the Mt. Cube quadrangle, and are represented on the geological map (Pl. 6) by the letter symbol *Oo*. They are fine-grained, thinly-bedded rocks with a well-marked schistosity. Field and laboratory studies show that, although all transitions exist, they may be classified as quartzite, quartz-mica schist, mica-quartz schist, and mica schist.[1] Interbedded with these schists are small lenses of volcanic material, one of which, near Etna Highlands School in Hanover Township, is large enough to map. Several modes of the black schists are given in Table 1.

Quartzite, though uncommon, occurs as a fine-grained, dark gray rock possessing only a slight trace of cleavage.

Mica-quartz schist is abundant. It contains biotite porphyroblasts which lie at all angles to the schistosity. The biotite contains inclusions of fine carbonaceous material in streaks and bands which probably represent bedding. The highly crumpled character of the rock is well shown by wavy bands of these inclusions (Pl. 4, fig. 1). Garnet occurs in small euhedral crystals, in rounded grains, and in large skeletal crystals nearly a centimeter across (Pl. 4, fig. 2). Its specific gravity is 4.15, and its refractive index is 1.806 ± 0.003. The composition, therefore, is almandite. The schists are black due mainly to the presence of about one per cent of finely divided carbonaceous material.

Mica schist differs from the mica-quartz schist only in having more mica and a better schistosity.

Hardy Hill quartzite.—The name Hardy Hill quartzite is proposed for the quartzite and quartz conglomerate member near the top of the Orfordville formation. The thickness of this member ranges from 0 to 250 feet. The cause of the great variation in thickness within short distances is

[1] For convenience in nomenclature metamorphic rocks consisting largely of mica and quartz, with some feldspar, are classified as follows: (1) mica schist, less than 60 per cent quartz and feldspar; (2) mica-quartz schist, 60 to 80 per cent quartz and feldspar; (3) quartzite and quartz-mica schist, over 80 per cent quartz and feldspar.

TABLE 1.—*Modes of the Orfordville formation*

	Black Schists						Post Pond Metamorphosed Volcanics								Post Pond Metamorphosed Sediments									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Large Crystals:*																								
Quartz							15								10									12
Oligoclase							20			5					5		5			3				
Porphyroblasts:																								
Oligoclase	10																							
Biotite			2	10	9															2		9		
Hornblende											1	20												
Garnet			2			20																		
Kyanite																							35	7
Groundmass:																								
Quartz	55	70	65	47	55	65	20	35	33	30	7	10	20	5	72	55	57	65	42	50	45	60	60	43
Microcline							43	25																
Oligoclase								15	40	40	50	42	45	23	5	30	5	7	25	22	25	tr.		5
Muscovite	26	4	15	25	33		1	15	17	5						7	30	7		23	9	30	5	15
Biotite		15	8	12			tr.	2		10			13		3	tr.	tr.	17	15		18			
Chlorite	8	2	5			11				3	15	15		3	5	7	1	3	15		tr.	1		17
Calcite								3	8		12	7		10		tr.								
Epidote	tr.							4		tr.	15	3	20	20					1	tr.	tr.			tr.
Garnet		7																tr.	1		2	tr.		
Carbon	1	2	1	3	2	1																		
Hornblende						tr.								37										
Kyanite																								
Tourmaline	tr.	tr.		tr.	tr.			1					1					1						
Magnetite	tr.	tr.	1		tr.	3						3	1					tr.	1	tr.	1	tr.		
Sphene	tr.						tr.		tr.	tr.				tr.		tr.	tr.		tr.	tr.				tr.
Zircon	tr.	tr.	tr.	tr.	tr.	tr.											tr.	tr.			tr.			
Pyrite				3			tr.	tr.	2	7	tr.				tr.		tr.							
Apatite									tr.	tr.											tr.			
Rutile							tr.																tr.	tr.
Structure	S	S	S	S	S	S	G	S	S	G	S	G	S	S	G	S	S	S	S	S	S	S	S	S
Size, Large Crystals in mm.							0.50-5.00			0.20-1.00					0.10-0.50					0.20-0.80				0.50-1.50
Size, Porphyroblasts in mm.	0.10-0.70		0.50-1.50	0.10-0.40	0.10-0.50	0.50-2.00					0.10-3.00	0.50-10.00								0.20-0.80		0.10-1.50	1.00-15.00	0.50-1.50
Size, Groundmass in mm.	0.01-0.05	0.01-0.10	0.01-0.03	0.01-0.02	0.01-0.03	0.02-0.10	0.02-0.05	0.03-0.20	0.02-0.20	0.02-0.10	0.02-0.15	0.02-0.05	0.02-0.30	0.01-0.30	0.01-0.05	0.01-0.10	0.03-0.30	0.03-0.10	0.02-0.08	0.01-0.05	0.03-0.10	0.02-0.07	0.03-0.40	0.01-0.03

* Includes large crystals or fragments of intratelluric origin which were deposited with the original volcanics. G = Granoblastic. S = Schistose.

1. Mica-quartz schist from elevation 1360 feet three-quarters of a mile south of North Neighborhood School in Hanover.
2. Mica-quartz schist from elevation 1000 feet east of the "S" in "Signal Hill" in Lebanon.
3. Mica-quartz schist from one-quarter mile southwest of the "A" in "LEBANON."
4. Mica schist from near road half a mile west of Potato Hill School in Enfield.
5. Mica schist from one mile southwest of North Neighborhood School in Hanover.
6. Garnet-chlorite schist from elevation 1150 feet five-eighths of a mile southeast of Hardy Hill School in Lebanon.
7. Quartz-oligoclase-microcline gneiss from near north boundary of area, one mile east of the Connecticut River.
8. Quartz-oligoclase-microcline schist from northernmost knoll of Signal Hill in Lebanon.
9. Quartz-oligoclase-muscovite schist from road-cut a mile east of Lebanon village.
10. Quartz-oligoclase-biotite-muscovite schist from near side road three-quarters of a mile southwest of Hayes Hill.
11. Quartz-oligoclase-biotite schist from brook near Hough School in Lebanon.
12. Quartz-oligoclase-hornblende schist from hill one mile northwest of Gleason Cemetery in Plainfield.
13. Quartz-oligoclase-biotite schist from Mink Brook at Etna.
14. Amphibolite from just east of the "E" in "LEBANON."
15. Quartzite from hill half a mile northeast of Gleason Cemetery in Plainfield.
16. Feldspathic quartzite from hill one-eighth of a mile north of Gleason Cemetery in Plainfield.
17. Mica-quartz schist from elevation 1300 feet half a mile southwest of Hayes Hill in Hanover.
18. Mica-quartz schist from near road one mile due east of Pinneo School in Hanover.
19. Mica-quartz schist from brook one-quarter of a mile east of Pinneo School in Hanover.
20. Mica-quartz schist from hill three-quarters of a mile west of Arvin School in Hanover.
21. Mica-quartz schist from brook near Pinneo School in Hanover.
22. Mica schist from elevation 1000 feet on Bass Hill in Lebanon.
23. Kyanite schist from one-quarter of a mile south of the "S" in "Signal Hill" in Lebanon.
24. Kyanite schist from elevation 1140 feet near the "F" in "PLAINFIELD."

in part sedimentary and in part structural. The member consists predominantly of gray to white quartzite and quartz conglomerate, with minor amounts of interbedded quartz-mica schist and mica schist. Bedding planes are conspicuous; the individual beds range from a few inches to a few feet in thickness. The conglomeratic character is not always well shown because the pebbles have about the same composition as the matrix, and recrystallization has been intense. The pebbles which are from one to three inches long are composed of nearly pure vein quartz and quartzite, and have been greatly deformed during folding and metamorphism.

Post Pond volcanics.—The name Post Pond volcanics is given by Hadley (1938) to the rocks, mostly metamorphosed volcanics, which occur in the lower part of the Orfordville formation in the Mt. Cube quadrangle. In the Mascoma quadrangle the Post Pond member consists of metamorphosed sediments as well as metamorphosed volcanics.

The metamorphosed volcanics are medium to fine-grained gneiss and schist, probably derived from volcanic tuff. No true lava flows were observed. The following lithologic types are present: (1) quartz-oligoclase-microcline gneiss and schist (originally rhyolite), (2) quartz-oligoclase-biotite-muscovite schist (originally quartz latite), (3) quartz-oligoclase-biotite schist (originally dacite), and (4) amphibolite (originally basalt). Several modes are given in Table 1.

The quartz-oligoclase-microcline gneiss and schist, originally rhyolite, are light colored rocks. Large crystals of quartz and albite-oligoclase (intratelluric phenocrysts), up to half a centimeter long, constitute 25 per cent of these rocks. The large quartz crystals have been granulated and recrystallized into mosaics. The plagioclase crystals, on the other hand, are fractured and bent, but in a few cases are granulated and recrystallized (Pl. 2, fig. 1). The groundmass is composed of quartz and microcline with very minor amounts of albite-oligoclase.

Quartz-oligoclase-biotite-muscovite schist, originally quartz latite, is abundant. The coarser and more gneissic type has preserved its large crystals better than the schistose type. Intratelluric crystals of quartz, up to four millimeters long, make up 10 per cent of the rock (Pl. 2, fig. 2). Green or red-brown biotite usually occurs in small flakes, but in some specimens it is in large flakes, poikiloblastically enclosing quartz and feldspar.

The quartz-oligoclase-biotite schist, originally dacite, is equally common with the quartz-oligoclase-biotite-muscovite schist and closely resembles the latter. Biotite and chlorite are important constituents, whereas muscovite is usually absent. A blue-green hornblende is present in some specimens in slender, euhedral crystals up to one centimeter long. The centers of these crystals are filled with inclusions of feldspar, epidote, and quartz (Pl. 2, fig. 4).

Amphibolite, originally basalt, is relatively scarce in the Post Pond volcanics of the Mascoma quadrangle. It is a medium to fine-grained rock, ranging in color from dark green or gray to black. Blue-green hornblende is the principal dark mineral, and it commonly shows a linear orientation. Oligoclase and epidote constitute most of the rest of the rock.

Among the metamorphosed sediments are the following types: (1) quartzite, (2) mica-quartz schist, (3) mica schist, and (4) kyanite schist. The modes of these rocks are given in Table 1.

The quartzite, though relatively scarce, is in most instances feldspathic. It is fine-grained, gray and locally possesses a poor cleavage.

The mica-quartz schist is fine-grained, and commonly contains 25 per cent of oligoclase or andesine. The biotite is brown, and is considerably altered to chlorite. Poorly formed porphyroblasts up to two millimeters across are seen in some thin sections. Garnet is present in small crystals which contain minute inclusions of quartz and other minerals.

Mica schist is as common as the mica-quartz schist. Reddish-brown biotite may be present either in fine flakes or in porphyroblasts up to two millimeters across. Some specimens contain as much as 20 per cent garnet in small anhedral crystals whose centers are filled with minute inclusions. This rock may be distinguished as garnet-mica schist. In other specimens the high content of calcite justifies the name calcareous mica schist.

Kyanite schist is characteristic of the top of the Post Pond member. It may be subdivided into two types, that with chlorite and that without chlorite. The chloritic type occurs mainly in Plainfield Township, and consists of a fine-grained, muscovite-chlorite schist with 5 or 10 per cent of kyanite. Quartz occurs in small grains (0.03 millimeter) with minor amounts of oligoclase. Rounded quartz grains, many of which are over one millimeter long, are abundant (Pl. 2, fig. 3). These have been slightly granulated and recrystallized. The non-chloritic type on Signal Hill in Lebanon Township, is coarser-grained, and may contain 35 per cent of kyanite in crystals an inch or more in length. Much of the kyanite has been hydrothermally altered to muscovite. In thin section the kyanite crystals show a feathery outline, and poikiloblastically enclose quartz. The groundmass is composed mainly of quartz with smaller amounts of muscovite. The mineralogical composition of these rocks and their association with quartzite and mica-quartz schist strongly favor the idea that the kyanite schist was derived from sediments rich in alumina and extremely low in iron, and, in the case of the non-chloritic type, extremely low in magnesium.

Age.—The Orfordville formation is overlain by the Albee, Ammonoosuc, Partridge, Clough, Fitch, and Littleton formations in ascending order (Fig. 2). The Fitch contains middle Silurian fossils, and the Clough, since it grades into the Fitch, is either lower or middle Silurian. There is an unconformity beneath the Clough (Billings, 1937, p. 483). Billings and Hadley (personal communication) are of the opinion that the Partridge, Ammonoosuc and Albee formations, and certain slates and sandstones in eastern Vermont, which are to be correlated with the Orfordville, overlie the fossiliferous Deepkill and Normanskill (Richardson, 1919, p. 51) of eastern Vermont. Hence the Orfordville is probably upper Middle Ordovician and the Albee and Ammonoosuc Upper Ordovician.

Thickness.—Due to the intense crumpling, it is difficult to measure the true thickness of the Orfordville. The extreme upper part of the formation is cut out by the Northey Hill thrust. It is estimated, however, that the total thickness exposed in the Mascoma quadrangle is 4000 $\pm$ 2000 feet. About one-half of this thickness is represented by the Post Pond member and the other half by the black schists and Hardy Hill quartzite member. The Hardy Hill quartzite is absent in some places; elsewhere it is 250 feet thick.

MISSING FORMATIONS

The Albee formation (Billings, 1935, p. 9) which occurs farther northeast, in New Hampshire, is absent in the Mascoma quadrangle, because of thrust faulting. It is mentioned here, however, to make the stratigraphic column complete. In the middle-grade zone of metamorphism it consists of a thick series (4000 $\pm$ feet) of quartzite and schist, and overlies the Orfordville formation and underlies the Ammonoosuc volcanics. As will be shown, most of the Ammonoosuc volcanics and part of the Littleton formation are missing in the Mascoma quadrangle, also for tectonic reasons.

AMMONOOSUC VOLCANICS

Correlation.—The name Ammonoosuc volcanics has been given by Billings (1935, p. 10) to a group of volcanic rocks in the Littleton and Moosilauke quadrangles in western New Hampshire. In the Mt. Cube quadrangle there is a belt of rocks which Hadley has identified from stratigraphic relations and lithologic character as Ammonoosuc volcanics, and which can be traced southward into the Mascoma quadrangle. In view of these facts, certain volcanic rocks of the Mascoma quadrangle are correlated with the Ammonoosuc volcanics which they resemble very closely in the Littleton and Moosilauke areas.

Lithology and petrography.—The rocks of this formation consist essentially of amphibolite with small amounts of biotite gneiss. They are believed to have been derived from volcanic tuffs, breccias, and conglomerates, but it is possible that a few may have been true lavas. Metamorphism has destroyed most of the original textures and structures of these rocks, but in some exposures these still persist. Breccias are found in Dorchester Township, near the bridge over the Mascoma River; farther down the river, some of the rocks still retain their tuffaceous characteristics. Bedded structure expressed by alternating light and dark layers is locally preserved. Modes will be found in Table 2.

Amphibolite constitutes about 80 per cent of the formation. It is a dark, fine to medium-grained rock, composed essentially of hornblende and plagioclase. The hornblende is in needles or stubby crystals many of which poikiloblastically enclose small grains of feldspar. The optics of several specimens of hornblende, given in Table 3, closely resemble those of an analyzed hornblende from the Littleton-Moosilauke area (Billings, 1937, p. 513). The optics and chemical analysis of this hornblende are as follows: $\alpha = 1.654$. $\beta = 1.667$, $\gamma = 1.676$; optically negative; $2V = 71°$; $Y = b$, $Z \wedge c = 19°$; $X = Y =$ yellowish green, $Z =$ bluish green; $X = Y < Z$:

SiO_2	44.18
TiO_2	1.23
Al_2O_3	10.34
Fe_2O_3	3.02
FeO	13.90
MnO	tr.
MgO	11.39
CaO	12.31
Na_2O	1.11
K_2O	.81
H_2O	1.57
	99.86

Feldspar ranges in composition from intermediate andesine to sodic bytownite, and in some sections shows strong zoning. Epidote is not usually a major constituent of the amphibolite, but in some specimens it composes 45 per cent of the rock. Sphene, in some instances, makes up as much as 5 per cent of the rock.

The biotite gneiss is a gray, metamorphosed volcanic rock (mostly dacite), composed essentially of quartz, sodic plagioclase, and biotite, with smaller amounts of garnet, amphibole, and muscovite. Feldspar ranges from intermediate oligoclase to sodic andesine, and is present in round or elongate grains. Biotite is in well-oriented, green or reddish-brown flakes which are usually less than one millimeter across.

TABLE 2.—*Modes of the Ammonoosuc volcanics*

	1	2	3	4	5	6	7	8	9	10	11	12
Phenocrysts:												
Quartz	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	10	.....
Oligoclase	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	25	.....
Labradorite	.....	.....	.....	.....	.....	.....	10	.....	.....	.....	.....	.....
Groundmass:												
Quartz	.....	.....	.....	.....	5	.....	.....	.....	15	35	25	20
Oligoclase	.....	.....	.....	.....	.....	.....	.....	10	65	45	35	.....
Andesine	.....	.....	.....	.....	45	60	.....	.....	.....	.....	.....	60
Labradorite	20	.....	40	50	.....	.....	45	.....	.....	.....	.....	.....
Bytownite	.....	40	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Hornblende	75	60	45	45	45	38	40	45	15	.....	2	1
Muscovite	.....	tr.	.....	.....	.....	.....	tr.	.....	.....	7	.....	.....
Biotite	.....	.....	.....	tr.	tr.	.....	.....	tr.	2	12	2	7
Chlorite	.....	.....	tr.	4	.....	.....	.....	tr.	tr.	tr.	tr.	5
Epidote	2	.....	15	.....	.....	.....	2	45	.....	tr.	tr.	.....
Garnet	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	5
Apatite	.....	.....	.....	.....	tr.	tr.	.....	.....	tr.	1	tr.	tr.
Magnetite	.....	.....	.....	1	.....	1	tr.	.....	.....	.....	.....	tr.
Sphene	1	.....	tr.	.....	4	1	tr.	tr.	.....	.....	1	tr.
Pyrite	.....	.....	.....	.....	tr.	.....	.....	.....	3	tr.	.....	1
Calcite	.....	.....	.....	.....	.....	.....	3	.....	.....	.....	.....	.....
Zircon	.....	.....	.....	.....	.....	.....	.....	.....	tr.	.....	.....	.....
Rutile	.....	.....	.....	tr.	.....	.....	.....	.....	.....	.....	.....	.....
Structure	S	S	S	S	G	S	S	S	G	S	G	G
Size phenocrysts in mm	.....	.....	.....	.....	.....	.....	1.00–4.00	.....	.....	.....	0.50–4.00	.....
Size groundmass in mm	0.05–3.00	0.05–5.00	0.05–5.00	0.10–3.00	0.10–3.00	0.10–2.00	0.10–0.50	0.02–0.30	0.03–0.30	0.05–0.30	0.05–0.20	0.10–0.70

G = Granoblastic S = Schistose

1. Amphibolite from near outlet of Crystal Lake in Canaan.
2. Amphibolite from elevation 1120 feet in Mascoma River in Dorchester.
3. Amphibolite from half a mile north of triangulation point on East Hill in Canaan.
4. Amphibolite from main road a mile west of Canaan village.
5. Amphibolite inclusion from hill northeast of Enfield Center.
6. Amphibolite from just south of the "E" in "EAST HILL" in Enfield.
7. Amphibolite from elevation 1180 feet in Mascoma River in Dorchester.
8. Amphibolite from elevation 1950 feet just southeast of North Peak in Hanover.
9. Biotite-hornblende gneiss from brook near the "S" in "Skinner Brook" in Grantham.
10. Biotite gneiss from elevation 2000 feet half a mile northeast of North Peak in Hanover.
11. Biotite gneiss from elevation 1620 feet half a mile northeast of North Peak in Hanover.
12. Biotite gneiss from elevation 1540 feet in brook near the "G" in "GRANTHAM."

Age.—The age has been discussed under the Orfordville formation.

Thickness.—The total thickness of the Ammonoosuc volcanics in the Littleton and Moosilauke quadrangles (Billings, 1935, p. 12) is 2000 feet, but only the upper few hundred feet of the formation are exposed in the

TABLE 3.—*Optical properties of hornblendes of the Ammonoosuc volcanics*

	1. From specimen 2 of Table 2	
α = 1.651	r > v perc.	X = yellow
β = 1.663	2V = 80°–85°	Y = green
γ = 1.674	Y = b	Z = greenish blue
Optically (	Z ∧ c = 21°	Z > Y > X
	2. From specimen 3 of Table 2	
α = 1.660	r > v perc.	X = yellow
β = 1.674	2V = 70°–75°	Y = deep green
γ = 1.681	Y = b	Z = greenish blue
Optically (·	Z ∧ c = 19°	Z > Y > X
	3. From specimen 5 of Table 2	
α = 1.657	r > v perc.	X = yellow
β = 1.670	2V = 80°	Y = green
γ = 1.680	Y = b	Z = greenish blue
Optically (−)	Z ∧ c = 20°	Z > Y > X
	4. From specimen 7 of Table 2	
α = 1.660	r > v perc.	X = yellow
β = 1.673	2V = 80°	Y = yellowish green
γ = 1.682	Y = b	Z = greenish blue
Optically (·	Z ∧ c = 19°	Z > Y > X
	5. From specimen 9 of Table 2	
α = 1.659	r > v perc.	X = yellow
β = 1.672	2V = 85°	Y = yellowish green
γ = 1.683	Y = b	Z = greenish blue
Optically (·	Z ∧ c = 20°	Z > Y > X
	6. From specimen just north of the "O" in "DORCHESTER"	
α = 1.650	r > v perc.	X = yellow
β = 1.663	2V = 80°	Y = green
γ = 1.673	Y = b	Z = greenish blue
Optically (·)	Z ∧ c = 20°	Z > Y > X

Mascoma quadrangle due to the intrusion of certain igneous masses. The total thickness of the formation exposed does not exceed 600 feet.

CLOUGH FORMATION

Correlation.—The name Clough formation has been given by Billings (1935, p. 13) to the interbedded quartz conglomerate and quartzite, which underlie the Fitch formation in the Littleton and Moosilauke quadrangles. Similar quartzites and quartz conglomerates, in the Mascoma quadrangle, occupy the same stratigraphic position, and are, therefore, correlated with the Clough formation.

Lithology and petrography.—The Clough formation consists of quartzite and quartz conglomerate interbedded with mica schist. The schist constitutes less than 25 per cent of the formation. The modes of several types are given in Table 4.

TABLE 4.—*Modes of the Clough formation*

		2	3	4
Porphyroblasts:				
Albite......		....	....	12
Garnet......		....	3	2
Groundmass:				
Quartz..........	97	80	70	60
Oligoclase..........	....	12	....	....
Muscovite..........	3	tr.	15	15
Biotite..........	tr.	4	....	9
Chlorite..........		tr.	8	1
Epidote..........		2	tr.	tr.
Apatite..........	tr.	....	tr.	tr.
Garnet..........		1	....	
Zircon..........	tr.	tr.	tr.	tr.
Magnetite..........		tr.	4	1
Sphene..........		....	....	tr.
Tourmaline..........	tr.	tr.	tr.	tr.
Structure..........	G	G	S	S
Size Porphyroblasts in mm..........	....	....	0.50–1.50	0.50–4.00
Size Groundmass in mm..........	0.10–1.50	0.10–0.40	0.10–0.30	0.10–0.50

G = Granoblastic S = Schistose

1. Quartzite from near top of Moose Mountain east of Ruddsboro School in Hanover.
2. Feldspathic quartzite from elevation 1720 feet north of North Peak in Hanover.
3. Mica-quartz schist from top of Moose Mountain east of Ruddsboro School in Hanover.
4. Feldspathic mica schist from top of Moose Mountain, east of Mascoma village.

The quartz conglomerate is a massive, coarse-grained, white to bluish-gray rock, composed of pebbles up to eight inches long set in a matrix of relatively pure quartzite. The pebbles, chiefly vein quartz and white or gray quartzite, were tremendously distorted during metamorphism.

Microscopic study of the quartzite shows quartz to be inequigranular with granoblastic texture, and the grain-size to range from a few tenths of a millimeter to a few millimeters. The feldspar consists of highly sericitized oligoclase grains molded between the quartz. Biotite, if present, and muscovite are in small, well-orientated flakes.

The mica schist and mica-quartz schist are medium to fine-grained, and consist principally of quartz and muscovite. Biotite, plagioclase and garnet, however, are less abundant. Garnets up to 2 millimeters across contain elongate inclusions of quartz, tourmaline, and magnetite. The discordance between the orientation of the elongated grains in the garnet and those in the schist indicates a slight rotation of these porphyroblasts some time after they had captured their inclusions. Albite may be present in rounded masses 5 millimeters across with irregular and indistinct boundaries, and enclosing grains of quartz, magnetite, tourmaline, muscovite, biotite, and garnet.

Age.—Billings (1935, p. 15) concludes that the Clough is of middle or lower Silurian age, since it underlies the Fitch formation, which contains middle Silurian fossils, and because it is separated from the underlying formations by an unconformity.

Thickness.—Billings (1935, p. 15) considers the original thickness of the Clough, in the Littleton and Moosilauke quadrangles, to range from 0 to 150 feet. Hadley (personal communication) believes that southwest along the strike, in the Mt. Cube quadrangle, the thickness varies from 350 to 1200 feet. In the Mascoma quadrangle the maximum thickness is, perhaps, 1200 feet. The minimum thickness, where not cut out by igneous intrusions, is about 200 feet.

FITCH FORMATION

Correlation.—The term Fitch formation was given by Billings (1935, p. 15) to a series of limestones and lime-silicate rocks occurring between the Clough and Littleton formations in the Littleton and Moosilauke quadrangles. This formation can be traced, nearly continuously, southwestward to the Mascoma quadrangle. A group of lime-silicate rocks occurring at this stratigraphic position in the Mascoma quadrangle are correlated with the Fitch formation farther northeast. Only two small patches of the Fitch formation are shown on the geological map; one at the north end of Moose Mountain in Hanover Township, and the other is 1½ miles southwest of Smith Pond in Enfield Township.

Lithology and petrography.—The Fitch formation of the Mascoma quadrangle consists mainly of lime-silicate rocks. These rocks are medium to fine-grained, and are commonly in alternating green and gray bands an inch thick.

The green bands are composed of diopside (33%), epidote (45%), microcline (12%), and a little sphene and magnetite. The diopside has the following optical properties: $\alpha = 1.693$, $\beta = 1.701$, $\gamma = 1.718$; optically positive; $2V = 60°$; dispersion perceptible, $r > v$; $Y = b$, $Z \wedge c = 40°$. According to Winchell (1933, p. 226) the composition would be diopside$_{60}$–Hedenbergite$_{40}$. The gray bands are rich in microcline which makes up over 50 per cent of the layers. Amphibole is present in crystals 1 to 2 millimeters long and poikiloblastically encloses other minerals. The optics show it to be a hornblende. $\alpha = 1.648$, $\beta = 1.668$, $\gamma = 1.683$; optically negative; $2V = 85°$; dispersion perceptible, $r > v$; $Y = b$, $Z \wedge c = 18°$; X = yellow, Y = yellowish-green, Z = bluish green; $X < Y < Z$. Epidote and diopside are less abundant.

Age.—According to Billings and Cleaves (1934, p. 415), the age of the Fitch formation is Niagaran (Middle Silurian).

Thickness.—The thickness of the Fitch in the Littleton and Moosilauke quadrangles (Billings 1935, p. 16) is calculated to be between 400 and 700 feet. In the Mt. Cube quadrangle, it is somewhat less, and in the Mascoma quadrangle it varies from 0 to 100 feet. Three hypotheses will be considered to explain this apparent thinning of the Fitch formation toward the south.

There may be an unconformity at the base of the Littleton formation. In the Mt. Cube quadrangle the very top of the Fitch formation is characteristically composed of a diopside and actinolite rock. This is the type of rock present in the Mascoma quadrangle, and probably represents the extreme upper part of the Fitch formation. Therefore, if the top of the Fitch were deposited to the south as well as to the north, the apparent thinning of the formation can not be explained as being due to an unconformity, since the upper beds would be the first to be removed in the production of such an unconformity.

It is possible that the apparent thinning may be due to a fault. However, since field evidence is lacking such a fault would be purely hypothetical.

The lower part of the Fitch in the Littleton and Moosilauke area contains beds closely resembling the Clough lithologically. Hadley (personal communication) finds evidence in the Mt. Cube quadrangle for assuming that rocks of the Clough lithology were being deposited to the south at the same time that rocks of the Fitch type (lime-silicate rocks) were being deposited farther north. This would suggest that, as one proceeds southward, more and more of the lower part of the Fitch is represented by the Clough facies. Therefore, in the Mascoma quadrangle only the very top beds are of the true Fitch facies. This hypothesis also helps to explain some of the thickening of the Clough formation toward the south, as there the Fitch type of sediment has given place to the Clough type. This hypothesis is considered the best by the writer, and the boundary between the Fitch and Clough formations is mapped on the basis of lithology and not on chronology.

LITTLETON FORMATION

Correlation.—The name Littleton formation has been given by Billings (1935, p. 17) to a series of low-grade, metamorphosed, dark slates and sandstones northwest of the Ammonoosuc thrust, in the Littleton and Moosilauke quadrangles. Two other belts of the Littleton formation, one of medium-grade and the other of high-grade metamorphism, are found to the southeast of the fault. The belt of medium-grade rocks consists of mica, garnet, and staurolite schists, and can be traced from the Moosilauke quadrangle to Cornish, in the Mascoma quadrangle. The schists in the southeastern part of the Mascoma quadrangle are also correlated with the Littleton formation, because they lie in the belt of high-grade rocks which can be traced southward from the Moosilauke quadrangle.

Lithology and petrography.—The rocks of the Littleton formation belong to two zones of metamorphism. The western belt of Littleton is in the middle-grade zone, and is composed dominantly of fine to medium-grained schists most of which contain porphyroblasts of biotite, garnet, and staurolite. Amphibolite sills are common but metamorphosed volcanics occur only sparingly, and were probably originally siliceous tuffs. The eastern belt of schists belongs to the high-grade zone of metamorphism, and is composed of coarse-grained rocks with porphyroblasts of garnet and sillimanite. The rocks of the Littleton formation, containing considerable amounts of staurolite and sillimanite, were undoubtedly de-

TABLE 5.—*Modes of the Littleton formation*

	1	2	3	4	5	6	7	
Porphyroblasts:								
Biotite	5	....	....	10	....	3	3	
Garnet	....	5	....	....	....	....	1	3
Groundmass:								
Quartz	63	60	65	60	75	55	50	40
Oligoclase	....	....	....	5	....	....	....	....
Andesine	....	....	....	....	....	....	....	6
Muscovite	20	15	20	15	15	25	40	25
Biotite	....	4	....	....	1	....	....	20
Chlorite	10	15	15	10	8	18	2	....
Sillimanite	....	....	....	....	....	....	....	6
Epidote	....	tr.	....	....	....	tr.	tr.	....
Apatite	tr.	tr.	....	tr.	....	tr.	....	tr.
Magnetite	....	1	....	tr.	tr.	2	3	....
Ilmenite	2	....	tr.	....	....	....	....	tr.
Sphene	....	....	tr.	....	....	....	....	tr.
Garnet	....	....	....	tr.	....	tr.	....	....
Zircon	....	tr.	....	tr.	....	....	....	....
Tourmaline	tr.	tr.	tr.	tr.	tr.	tr.	....	tr.
Structure	S	S	S	S	S	S	S	S
Size Porphyroblasts in mm	0.50–3.00	0.10–0.30	....	0.50–1.20	....	0.50–1.50	0.50–1.50	1.00–1.50
Size Groundmass in mm	0.02–0.20	0.02–0.05	0.02–0.10	0.05–0.20	0.02–0.07	0.03–0.15	0.01–0.10	0.10–1.00

S = Schistose.
1. Mica-quartz schist from brook east of the "H" in "SHAKER MOUNTAIN."
2. Mica-quartz schist from trail due west of Hyde Hill in Plainfield.
3. Mica-quartz schist from hill one mile northwest of Hyde Hill in Plainfield.
4. Mica-quartz schist from near BM 1167 northwest of Montcalm School in Plainfield.
5. Mica-quartz schist from near road-fork north of Ruddsboro School in Hanover.
6. Mica schist from near the "E" in "SHAKER MOUNTAIN."
7. Mica schist from road-cut one mile west of Enfield village.
8. Sillimanite schist from half a mile south of the "D" in "SPRINGFIELD."

rived from sediments relatively rich in alumina and poor in alkalis, whereas the biotite and garnet rocks were probably originally more normal shales and impure sandstones. Several modes are given in Table 5.

Quartzite is relatively scarce in the Littleton formation. It is fine-grained, ranging in color from white to buff or gray. The mica-quartz schist is fine-grained, medium gray, and constitutes a large percentage of the Littleton formation. Some types possess a perfect cleavage, whereas others split with a more irregular fracture. Chlorite and micas may be uniformly distributed through the quartz mosaic or concentrated into bands and layers. Biotite commonly occurs as porphyroblasts a millimeter across, oriented at all angles to the schistosity; and garnet appears in crystals ranging up to a millimeter in diameter, but it is not an abundant constituent. Mica schist is probably as abundant as the mica-quartz schist, and closely resembles the latter.

Staurolite schist makes up much of the Littleton formation from Shaker Mountain to Cornish Township. The rock is medium to fine-grained resembling the mica schist but with porphyroblasts of staurolite up to several inches in length. The staurolite makes up about 15 per cent of the rock and usually contains abundant inclusions of quartz and magnetite. As a result of alteration, most of the crystals are enclosed in a thick shell of secondary muscovite and chlorite (Pl. 3, fig. 1). There is a marked increase in the size of the porphyroblasts from west to east.

There is a volcanic member near the top of the Littleton formation, which extends from near the crest of Shaker Mountain to Methodist Hill. This member has a maximum thickness of about 300 feet, and is composed of fine to medium-grained, buff colored biotite gneiss (probably originally volcanic tuff) the composition of which ranges from rhyolite to quartz latite.

The rocks of high-grade metamorphism include medium to coarse-grained mica schist and mica-quartz schist many of which contain sillimanite. The coarseness of grain marks these rocks as distinct from those of middle-grade metamorphism. Quartz grains are irregular and show slight straining. Calcic oligoclase or sodic andesine is present in small amounts, but muscovite makes up 25 or 30 per cent of the rock. Biotite is nearly as abundant, and occurs in red-brown flakes a millimeter across. In hand specimen, crystals of sillimanite are abundant; and attain the length of several millimeters. In thin section, the sillimanite appears in sheaves of fine needles a few tenths of a millimeter long, and replaces mica and garnet. Garnet usually constitutes less than 5 per cent of the rock.

Age.—Billings and Cleaves (1934, p. 419) have shown the Littleton to be of Oriskany (Lower Devonian) age.

Thickness.—It is almost impossible to calculate the thickness of the Littleton formation with any degree of accuracy as the detailed structure of it is unknown in most of the area. A rough estimate would be 4000 feet; but it should be noted that this estimate does not represent the total thickness of the formation, as the upper part is cut out by the Northey Hill thrust.

PLUTONIC, SILL, AND DIKE ROCKS

GENERAL STATEMENT

Intrusive igneous rocks constitute about half the rocks of the Mascoma quadrangle. They are nearly all medium to coarse-grained, plutonic gneisses, ranging in composition from granite to quartz diorite. The relative abundance of each of these rock types is estimated to be as follows, in decreasing order: granodiorite, quartz monzonite, quartz diorite, and granite. These gneisses may be divided into two groups, on the basis of age; an older, belonging to the Oliverian magma series, and a younger, belonging to the New Hampshire magma series. A few small bodies of intrusive rocks are younger than the gneisses and belong to the White Mountain magma series.

OLIVERIAN MAGMA SERIES

Correlation.—The term Oliverian magma series was given by Billings (1935, p. 26) to a series of intrusive rocks in the Moosilauke quadrangle, which occurs in a domical structure (Owls Head dome), and is younger than Lower Devonian, but older than the period of folding. Six similar domes, with the same igneous series, have been studied in western New Hampshire since the original mapping of the Owls Head dome. The distribution of only the completely mapped bodies of this series may be seen in Figure 3. In the Mascoma quadrangle the plutonic rocks of the Mascoma, Smarts Mountain, Croydon, and Lebanon domes belong to the Oliverian magma series.

Mascoma group.—The term Mascoma group is proposed for the plutonic rocks of the Mascoma dome. This group occupies the central part of the Mascoma quadrangle, and consists of fine- to medium-grained, gray rocks. Where considerable potash feldspar is present, however, the rock may be sub-porphyritic with a light pink color. Most specimens show a foliation due to parallel arrangement of small biotite flakes. The composition of the group ranges from quartz diorite to granite, and the areal distribution of these various types is shown on the geological map (Pl. 6). The dotted boundaries indicate that the types are somewhat gradational. Modes are given in Table 6.

Quartz diorite includes the finest-grained types, many of which are border phases. Plagioclase (An_{13} to An_{30}) and quartz constitute most of the rock and give it a granoblastic structure. Biotite is present in small flakes and usually in minor amounts. One characteristic feature more commonly seen in the quartz diorite than in the other rock types is the presence of granulated and recrystallized quartz phenocrysts.

The granodiorite is the most abundant rock in the Mascoma group. It is slightly coarser than the quartz diorite, and has a little more biotite. There is a tendency for biotite, and euhedral crystals of epidote to segregate into masses about half a centimeter across, so as to give these light-gray rocks a spotted appearance. Some varieties are sub-porphyritic with crystals of microcline up to one centimeter long. A little microcline is also present in the groundmass. Plagioclase has the same composition as in the quartz diorite (An_{13} to An_{30}), and quartz is a little less abundant. Small quantities of myrmekite are present, usually replacing potash feldspar.

The texture and grain size of the quartz monzonite and granite are like those of the granodiorite, but the gneissic structure is less perfectly developed. The pink color of much of the quartz monzonite and granite is due to the abundance of microcline in large crystals, commonly a centimeter long. Upon first glance these crystals appear to be phenocrysts, but detailed study, particularly in thin section, disclosed several lines of evidence which point strongly to the idea that they are metacrysts, introduced subsequent to the consolidation of the original rock. Plagioclase ranges in composition from An_{15} to An_{30}, and quartz constitutes 20 to 35 per cent of the rock. Some of the potash feldspar is replaced by myrmekite which may constitute as much as 10 per cent of the rock.

Smarts Mountain group.—The term Smarts Mountain group is used for the plutonic rocks of the Smarts Mountain dome, most of which is exposed in the Mt. Cube quadrangle. A few square miles of this dome are exposed in the northeastern part of the Mascoma quadrangle. The group consists predominantly of quartz diorite with smaller amounts of granodiorite; both rocks closely resemble their equivalent types in the Mascoma group. (See Table 6.)

Croydon group.—The term Croydon group is proposed for the plutonic mass of the Croydon dome. Only the northwestern part of the Croydon

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

	Mascoma Group												Croydon Group			Smarts Mtn. Group			Lebanon Group					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Quartz	30	45	37	35	38	35	25	33	25	32	20	27	25	40	35	26	30		10	20	20	20	30	35
Microcline	....	....	5	9	15	20	25	30	45	44	50	50	1	2	2	....	5		5	....	5	28	55	5
Oligoclase	66	54	55	50	45	43	40	35	25	20	20	20	64	53	58	65	60		....	60	33	30	10	30
Andesine	....	....	....	....	....	....	....	....	....	....	....	....	....	...	....	....	....		25	....	....	....	....	....
Muscovite	tr.	....	....	1	tr.	....	tr.	....	tr.	1	2	tr.	....	tr.	....	....	....		....	2	....	4	2	3
Biotite	3	2	3	4	2	2	5	1	3	3	6	3	7	5	5	1	5		10	15	23	8	1	15
Chlorite	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	....		....	....	2	....	tr.	....
Epidote	tr.	tr.	tr.	....	....	....	5	1	tr.	tr.	2	tr.	tr.	tr.	tr.	tr.	tr.		10	3	12	4	2	12
Calcite	....	....	....	....	....	....	....	....	....	....	....	....	....		....	....	....		....	....	5	5	....	....
Hornblende	....	....	....	....	....	....	....	....	....	....	....	....	tr.		....	7	....		50				....	
Garnet	....	....	....	tr.	....	....	....	....	....	....	....	....	2		....	tr.	....						....	
Apatite	....	tr.	tr.	tr.	....	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.				tr.	....	tr.
Sphene	....	tr.	tr.	tr.	....	....	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.				tr.	tr.	
Magnetite	tr.	tr.	....	tr.	tr.	tr.	....	....	tr.	tr.	....	tr.	....		tr.	tr.	tr.	tr.				tr.	tr.	
Pyrite	....	....	tr.	tr.	....	....	....	....	....	....	tr.	....	....		....	....	....						....	
Zircon	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	tr.	....	tr.	tr.	tr.	tr.						tr.	tr.
Rutile	tr.	....	....	....	....	....	....	....	....	....	....	....	....		....	....	....						....	
Tourmaline	....	....	....	....	....	....	....	....	....	....	....	....	....		....	....	....					1	....	
Allanite	....	tr.	tr.	....	....	tr.	tr.	tr.	....	....	tr.	tr.	tr.		....	tr.	....						....	

1. Quartz diorite from road three-quarters of a mile north of Washburn corner in Springfield.
2. Quartz diorite from hill one and one-half miles north of Canaan Center.
3. Granodiorite near the "H" in "Shaker Hill" in Enfield.
4. Granodiorite from road three-quarters of a mile north of the triangulation station on East Hill in Canaan.
5. Granodiorite from southeastern knoll on Town Hill in Canaan.
6. Granodiorite from elevation 1260 feet on unimproved road west of Clark Pond in Canaan.
7. Quartz monzonite from road one mile south of Tunis School in Hanover.
8. Quartz monzonite from hill one and three-quarters miles north of Tunis School in Hanover.
9. Quartz monzonite from hill one and three-quarters miles north of Tunis School in Hanover.
10. Granite from top of South Peak in Hanover.
11. Granite from near the second "O" of "MOOSE MOUNTAIN" in Hanover.
12. Granite from near Goss Neighborhood School in Hanover.
13. Quartz diorite from top of hill north of the first "A" in "GRANTHAM."
14. Quartz diorite from elevation 1900 feet three-quarters of a mile south of the "G" in "GRANTHAM."
15. Quartz diorite from road near "H" in "GRANTHAM."
16. Quartz diorite from elevation 1920 feet half a mile north of the "T" in "DORCHESTER."
17. Quartz diorite from elevation 1720 feet one-quarter of a mile south of the second "E" in "DORCHESTER."
18. Quartz diorite from contact southwest of Pollard Hill in Dorchester.
19. Amphibolite (gabbro) from knoll north of the western Hanover reservoir.
20. Quartz diorite from east knoll of Lords Hill in Hanover.
21. Granodiorite from hill three-quarters of a mile northeast of Etna.
22. Quartz monzonite from elevation 1000 feet on western slope of northern knoll of Signal Hill in Lebanon.
23. Granite from southern knoll on Rix Ledges in Lebanon.
24. Inclusion of border gneiss in Lebanon granite from northern knoll of Rix Ledges in Lebanon.

dome is exposed in the Mascoma quadrangle. The rocks of the Croydon group closely resemble those in the Mascoma dome (See Table 6). For the most part, potash feldspar is scarce and, as in the Smarts Mountain group, quartz diorite is the predominating rock type. This type occupies the outer part of the igneous body. Although exposures are poor near the center of the mass a few outcrops of granodiorite and quartz monzonite have been found.

Lebanon group.—The term Lebanon group is proposed for the plutonic rocks of the Lebanon dome, which were originally described by Hitchcock (1877, p. 353) as "protogene gneiss", and were grouped under the general term "Bethlehem gneiss". In a more recent work (1909, pp. 139-186), however, he considered the igneous mass as intrusive into the surrounding metamorphic rocks. More detailed studies of this dome have been made by Merritt (1921, p. 1-36), Goldthwait (1925, p. 7), and Kaiser (1938, p. 27) all three of whom recognize the igneous rocks as an intrusive which domes the surrounding rocks. As the Lebanon group intrudes the Orfordville formation, it is probably younger than Middle Ordovician; and as these igneous rocks have suffered the effects of regional metamorphism, they must be older than the metamorphism. In view of these facts and the marked similarity between the Lebanon dome and other domes, the writer considers the Lebanon group consanguineous with the Oliverian magma series.

There are two more or less distinct igneous rock types in the dome, a coarser-grained granitic core surrounded by a finer-grained, more mafic border-phase. The core-rock is a weakly gneissic, pink granite termed the Lebanon granite. The border-phase is, in general, rather different from the granite; the term "border gneiss", used by Goldthwait and Merritt, will be used here when referring to this rock. As the two types are somewhat gradational near their contacts, they have been separated on the geological map by a dotted boundary. Several modes are given in Table 6.

The border gneiss is dark-gray, medium-grained, and ranges in composition from gabbro to quartz monzonite. In most places it possesses a well developed foliation, but in some localities only a pencil structure is observable. Quartz is granulated, and recrystallized into irregularly shaped grains which are commonly seen to be assembled into bands and streaks. Plagioclase ranges in composition from An_{12} to An_{25}. The crystals are bent, fractured, and granulated, and are filled with abundant inclusions of epidote, calcite, and sericite, all of which are probably alteration products of their host. Microcline is most commonly present in small grains. Flakes of olive-green biotite, 0.5 millimeter across, are segregated with sphene into bands and streaks. Hornblende may take the place of biotite as the dark mineral in the rock, but it usually occurs in amounts subordinate to biotite. There are two areas of amphibole-rich rock which contains up to 50 per cent of this blue-green hornblende. One is on the east slope of Pinneo Hill in Hanover Township, and the other is on the hill north of Hanover reservoir. A mode of the rock from the last named locality is given in Table 6. It was probably originally a gabbro. The feldspar has the composition An_{37}, and is more calcic than any other found in the dome. The optics of the hornblende in this amphibolite are as follows: $\alpha = 1.640$, $\beta = 1.655$, $\gamma = 1.667$; optically negative; $2V = 80°$; dispersion perceptible, $r > v$; $Y = b$, $Z \wedge C = 22°$; $X =$ greenish yellow, $Y =$ light green, $Z =$ bluish green; $X < Y < Z$.

The Lebanon granite is medium- to coarse-grained, pink, and commonly subporphyritic. The granite in the Mascoma quadrangle has a poor gneissic structure, principally because of the low biotite content, but just west of Rix Ledges, in the Hanover quadrangle, the granite possesses a more definite foliation. Microcline is the most abundant mineral, and occurs in broken and partly granulated phenocrysts usually less than a centimeter long, or in smaller grains 0.2 to 0.3 millimeter in diameter. The larger crystals are usually perthitic. Only small amounts of plagioclase are found, and this is usually sodic oligoclase. Very little, however, is primary, some having been introduced to form replacement perthite, and some occurring in the myrmekite which replaces potash feldspar. Quartz constitutes about a third of the rock, but biotite, muscovite, and epidote are scarce.

Age of intrusions.—The domes (not including the Lebanon dome) are younger than Lower Devonian, because during the intrusion of their igneous cores, the Littleton formation was displaced. From his work in the Moosilauke quadrangle, Billings (1935, p. 34) concluded that the intrusion of the Owls Head group preceded the period of folding. The author has come to the same conclusion for the other Oliverian domes, and detailed consideration of the effects of regional folding upon these domical structures is given later. The age of the Lebanon dome has been considered in the description of the Lebanon group.

NEW HAMPSHIRE MAGMA SERIES

General statement.—The term New Hampshire magma series was given by Billings (1935, p. 26) to a series of plutonic rocks, usually foliated, and characterized by muscovite and biotite. The series was intruded during the late stages of folding or shortly thereafter. The Bethlehem gneiss of the Mascoma quadrangle belongs to this series.

Bethlehem gneiss.—The term Bethlehem was originally used by C. H. Hitchcock (1877, p. 104-111) for a group of igneous rocks in the township of Bethlehem, N. H. Billings (1935, p. 27) has found it advisable, however, to restrict the term to one particular phase. The largest body of this gneiss extends southwest from the Franconia quadrangle through the eastern part of the Mascoma quadrangle and for an unknown distance into the Sunapee quadrangle (Fig. 3). The total length is at least 65 miles. Along the eastern contact of the gneiss, numerous sills of fine-grained Bethlehem have been intruded into the Littleton formation. These sills, however, are not found more than a few hundred feet from the contact. Along this same contact is a zone of pegmatites which is several thousand feet wide, and confined mainly to the Littleton schists.

The Bethlehem gneiss is a medium- to coarse-grained gneiss, composed essentially of quartz, andesine, microcline, biotite, and a little muscovite. It ranges in composition from granodiorite to granite, and may locally contain phenocrysts of potash feldspar up to four inches in length. The gneiss possesses a foliation brought out principally by the marked orientation of the large mica flakes. The foliation gives place to a lineation in many cases and in places both a good foliation and lineation are present. For modes, see Table 7.

TABLE 7. *Modes of the Bethlehem gneiss*

	1	2	3	4	5	6	7
Quartz....	25	20	30	25	40	40	20
Microcline.	9	5	12	3	15	5	35
Andesine...	45	54	46	51	30	40	28
Myrmekite.	1	1	2	1	tr.	tr.	2
Muscovite.	1	tr.	2	2	5	1	1
Biotite.....	18	18	8	18	8	12	13
Chlorite...	.....	tr.	tr.	tr.	tr.	tr.	tr.
Epidote....	.....	tr.	....	tr.	....	.....	
Zircon.....	tr.	tr.	tr.	tr.	tr.	tr.	
Apatite....	tr.	tr.	tr.	tr.	tr.	tr.	
Magnetite..	tr.	tr.	....	tr.	....	.....	
Ilmenite...		....	....	....	....	tr.	
Sphene....		....	....	....	....	tr.	
Pyrite.....		tr.	tr.	....	....		
Rutile.....		tr.	....	....	....		
Allanite....		tr.	....	tr.	....		

1. Granodiorite from just east of the Height of Land School in Grafton.
2. Granodiorite from elevation 1120 feet in brook a mile north of Canaan village.
3. Granodiorite from knoll about half a mile west of the outlet of Grafton Pond.
4. Granodiorite from near side road north of Crystal Lake in Canaan.
5. Granodiorite from trail a mile southeast of Leavitt Pond in Grantham.
6. Granodiorite from top of hill east of Spectacle Pond in Enfield.
7 Quartz monzonite from top of knoll northeast of Grass Pond in Grantham.

The texture is inequigranular, and it is common to find the quartz segregated into lenses composed of many individual grains showing strain shadows. These lenses probably represent large crystals which have been slightly granulated and recrystallized. The plagioclase is sodic andesine (An_{30} to An_{40}). Microcline occurs in phenocrysts or as irregular grains in the groundmass, and is commonly replaced by myrmekite. Biotite is abundant in large, red-brown flakes up to 4 millimeters across. It characteristically contains numerous inclusions of zircon, allanite, and epidote, about which are strong pleochroic halos. Associated with biotite aggregates are flakes of muscovite.

Pegmatites.—Genetically related to the Bethlehem gneiss are pegmatites which occur within the igneous rock itself and the surrounding metamorphic rocks. Among those occurring in the igneous rock there are three types; segregation pegmatites, pegmatites associated with sheer zones, and vein pegmatites.

The segregation pegmatites are usually small, irregular masses a few inches across, but some are several feet wide. They are composed dominantly of microcline and quartz with minor amounts of muscovite. A little biotite and black tourmaline have been found.

Pegmatites associated with shear zones have been observed only in a few places. Perhaps the best examples are seen on the series of knobs which extends southward from Halfmile Pond, in Enfield Township. Here the shear zones are a few feet long and two or three inches wide. The relative displacement along these shears is revealed by the drag effect in the biotite layers of the gneiss. In many zones biotite is concentrated near the margins, and is in all cases scanty in the centers. The centers of these zones are filled with a mixture of quartz, microcline, and plagioclase, whose grain size is several times that of the surrounding Bethlehem gneiss. It may be assumed that during the consolidation of the igneous rock there was shearing which developed fractures in the semi-solid mass. During this shearing the biotite layers were dragged around into a new position, and pegmatitic juices, from the nearby wall-rock, filled the openings.

Vein pegmatites in the Bethlehem are numerous only in certain localities, one of which is on the hill just east of Spectacle Pond, in Grafton Township. Here pegmatite veins up to 10 or 20 feet wide strike east-west at right-angles to the gneissic structure of the enclosing rock. They are composed essentially of microcline, quartz, muscovite, and biotite. Minor amounts of black tourmaline, beryl, and garnet were seen. These vein pegmatites have never been worked commercially to any extent, perhaps, because of the abundance of larger bodies in the adjacent schists.

There is a broad zone of pegmatites several thousand feet wide in the high-grade Littleton schists near the contact with the Bethlehem. Along this belt, which extends for some distance northeast into the Cardigan quadrangle, are located some of the well-known pegmatite mines of New Hampshire. Several of these are still operating. In the Mascoma quadrangle, however, none of the pegmatites have been very productive. The individual bodies are elongate or irregular masses, usually a few tens of feet wide and a few hundred feet long. The largest of these, several hundred feet across, is on Aaron Ledge in Springfield Township. No detailed study of these pegmatites was made, but they consist predominantly of microcline-perthite and quartz (sometimes as graphic granite) with minor amounts of muscovite, biotite, plagioclase, black tourmaline, apatite, garnet, and beryl.

Age of intrusion.—The Bethlehem gneiss is younger than Lower Devonian because it is intrusive into Littleton schists of Lower Devonian age. From the lead-uranium ratio Shaub (1938, p. 339) has given the age for uraninite from a pegmatite in the Littleton schists two miles east of Spectacle Pond in Enfield Township, as 304 million years (late Devonian). Since this pegmatite is but one of the many genetically related to the Bethlehem gneiss, any data regarding its age is very helpful in determining the age of the gneiss itself. Considering the relatively short period between the intrusion of the gneiss and the subsequent formation of pegmatites, the writer believes that this age determination indicates that the Bethlehem gneiss was intruded during the late Devonian. The position of the intrusion in the sequence of tectonic events will be considered in the discussion of the Mt. Clough pluton.

WHITE MOUNTAIN MAGMA SERIES

Those igneous rocks younger than the New Hampshire magma series and possessing marked alkaline affinities belong to Billings' (1934, p. 56) "White Mountain magma series". In the Mascoma quadrangle, this alkaline suite is represented, for the most part, by numerous dikes which will be considered later. In Dorchester Township, however, there are two small intrusives, both of which belong to this magma series. One is a small stock of quartz syenite, and the other is probably a volcanic pipe.

Only one outcrop of the quartz syenite is seen along the road, southwest of the "P" in "Pollard Hill." The rock, in most places, has been highly disintegrated and the residual soil produced thereby is very distinct from any of the surrounding glacial drift. It is possible to get a general idea of the distribution of the parent rock by observing the distribution of this weathered material. In unweathered specimens this even-grained, quartz syenite has a greenish appearance, but most of the rock is highly stained with limonite. About 80 per cent of the rock is made up of perthite and antiperthite. The crystals are 2 or 3 millimeters long, and their interstices are filled with quartz, which constitutes about 12 per cent of the rock. The rock also carries about 5 per cent of biotite and small amounts of hastingsite, pyrite, zircon, fluorite, sphene, magnetite, and apatite.

The volcanic breccia, three-quarters of a mile south of the second "R" in "DORCHESTER," was probably formed in a small volcanic pipe, the diameter of which is not much more than one hundred feet. About 50 per cent of the rock is black, aphanitic groundmass composed chiefly of alkali feldspar, hastingsite, biotite, and magnetite. The rest of the rock consists of large phenocrysts of microcline, perthite, plagioclase, quartz, and basaltic hornblende and abundant inclusions of Ammonoosuc volcanics, quartz syenite, and quartz diorite from the Smarts Mountain dome. Many of these inclusions are a foot across. A similar but more extensive breccia is described by Modell (1936, p. 1910) from the Belknap Mountains, New Hampshire.

SILLS AND DIKES

Most of the pre-metamorphism sills are amphibolite. They are common in the Littleton formation, less common in the Clough formation, and rare in the Orfordville formation. They are a few feet wide, and are composed chiefly of amphibole and plagioclase. Their original composition was probably that of basalt.

Pre-metamorphism dikes are uncommon, and only one was studied in thin section. This dike cuts the Mascoma group northeast of North Canaan School, in Canaan Township. The rock is a light-green porphyry with phenocrysts of hornblende a centimeter long. These have been somewhat broken and recrystallized by metamorphism. The phenocrysts constitute about 25 per cent of the rock, but small crystals of the same mineral also make up about 35 per cent of the groundmass. Augite, in crystals 0.5 millimeter long, constitutes 25 per cent of the rock. Epidote is found in small crystals enclosed in the hornblende, or in slightly larger grains in the groundmass. Very minor amounts of microcline and andesine are present.

The post-metamorphism dikes include several distinct types, all of which are believed to belong to the White Mountain magma series. The following types are recognized: (1) olivine diabase, (2) troctolite, (3) camptonite, (4) bostonite, and (5) microgranite porphyry. Modes are given in Table 8.

STRUCTURE

GENERAL STATEMENT

The structure of the Mascoma quadrangle is a sample of the architecture of the belt of gneisses and schists which extends in a north-northeasterly direction through western New Hampshire (Fig. 3). The sedimentary and volcanic rocks, of middle Paleozoic age, have been folded, metamorphosed, and intruded, so that the structure is now exceedingly complicated. The various structural features of the area will be considered in chronological order. The oldest major features are the Oliverian domes, three of which are located along the axis of the Bronson Hill anticline. These will be considered first, and the Lebanon dome, to the west of the anticline, will be described separately. Although the Lebanon

TABLE 8.—*Modes of post-metamorphism dikes*

	1	2	3	4	5	6
Phenocrysts:						
Quartz	...	...	...	...	...	15
Perthite	...	...	...	...	25	10
Antiperthite	...	...	...	...	5	...
Oligoclase	...	...	...	...	...	15
Labradorite	...	3	7	...	...	...
Oxyhornblende	...	...	...	7	...	...
Apatite	...	...	...	tr.	...	...
Sphene	...	...	...	1	...	...
Groundmass:						
Quartz	...	...	...	...	5	20
Orthoclase	...	...	...	...	...	18
Albite	...	...	...	...	...	20
Albite-Oligoclase	...	...	...	...	59	...
Oligoclase	...	60	...	53	...	...
Andesine	65	...	...	...	...	...
Labradorite	...	...	58	...	...	...
Augite	10	10	...	...	...	...
Oxyhornblende	...	...	...	20	...	...
Hastingsite	...	...	...	...	tr.	...
Biotite	4	2	5	...	tr.	2
Chlorite	4	5	5	1	1	...
Serpentine	11	10	10	3	...	...
Magnetite	5	5	4	4	tr.	...
Hematite	...	...	...	...	1	...
Ilmenite	...	...	...	...	1	...
Pyrite	tr.	...	1	...	...	...
Sphene	1	3	7	4	...	tr.
Zircon	tr.	...	...	...	tr.	tr.
Apatite	...	tr.	...	tr.	...	tr.
Calcite	...	2	3	7	3	...
Fluorite	...	...	...	...	tr.	tr.
Texture	O	O	H	P	T	A
Size Phenocrysts in mm.	...	1.0–5.0	1.0–2.0	1.0–5.0	0.5–5.0	0.5–3.0
Size Groundmass in mm.	0.5–1.0	0.1–1.0	0.1–1.0	0.1–0.4	0.1–0.3	0.05–0.1

H = hypidiomorphic O = ophitic T = trachytic
A = allotriomorphic P = poikilitic

1. Medium-grained olivine diabase; average 3 thin sections.
2. Fine-grained olivine diabase; average 3 thin sections.
3. Troctolite; average 2 thin sections.
4. Camptonite; 1 thin section
5. Bostonite; 1 thin section.
6. Microgranite porphyry; 1 thin section.

dome is probably of about the same age as the other domes, there are many differences which justify its separate treatment here. After considering these domes, the Salmon Hole Brook syncline, in the western

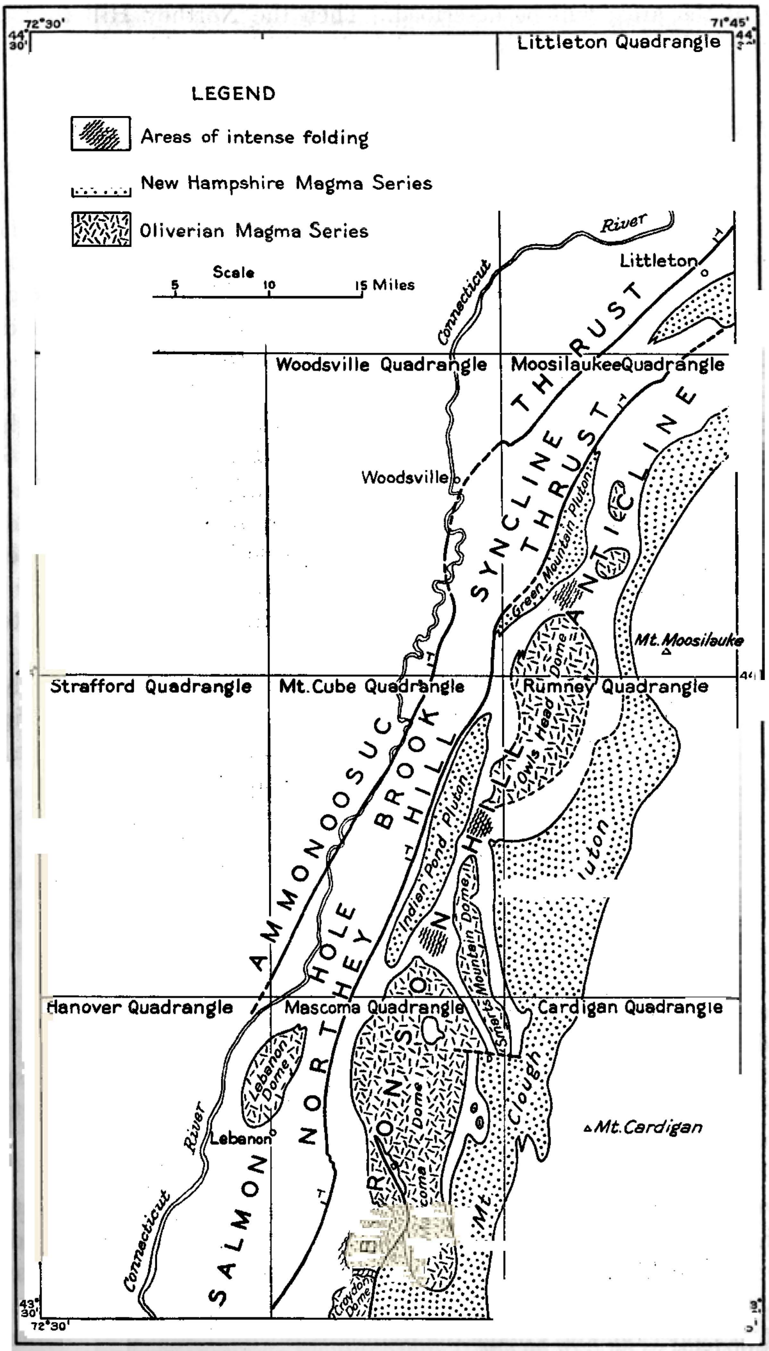


FIGURE 3.—*Structural units of western New Hampshire*

part of the area, will be described. Then the Northey Hill thrust, the Mt. Clough pluton, and the normal faults will be considered.

OLIVERIAN DOMES OF BRONSON HILL ANTICLINE

Mascoma dome.—The size and completeness of the Mascoma dome justify the emphasis given it here, and it may be taken as the type for the Mascoma quadrangle. It is located in the central part of the area, but extends north for a short distance into the Mt. Cube quadrangle. A central, domical, igneous core is surrounded by belts of metamorphic rocks, more or less concentrically arranged, in which the bedding and schistosity dip radially outward. The innermost belt consists predominantly of amphibolites, and constitutes the upper 600 feet of the Ammonoosuc volcanics. The next outer belt is the Clough formation, which is present mainly on the west side of the dome. Beyond the Clough is a wide belt of the Littleton schists. The foliation of the plutonic rocks near the contact also dips outward radially, and is parallel to the bedding and schistosity of the surrounding metamorphic rocks (see geological map). Well within the plutonic mass, however, the foliation pattern is much more complicated. This complex pattern is believed to have been produced from a simple concentric foliation which was later subjected to regional folding.

The bedding and schistosity of the metamorphic rocks dip north 20° to 25° at the north end of the dome, in the Mt. Cube quadrangle (Fig. 3). In the vicinity of North Peak in Hanover Township, the dip of the bedding and schistosity is 35° to 50° NW. This belt of metamorphic rocks has also been folded, and a small patch of Ammonoosuc volcanics has been brought up in the midst of the Clough formation, by an anticline, near the north end of Moose Mountain. Farther south the dips become steeper and steeper, so that west of Goss Neighborhood School, bedding and schistosity dip 75° to 85° W. Still farther south the bedding is vertical, and near the south end of Moose Mountain the bedding and schistosity have been overturned, to dip 80° to 85° E. It is probable that the narrow band of amphibolites continues southward under Mascoma Lake, but the resistant Clough formation is probably thin or absent. This may explain why the Mascoma and Knox Rivers were able to form the gap between Moose and Shaker Mountains.

The Clough and Ammonoosuc formations are readily followed from Lower Shaker Village to Butternut Pond. The bedding and schistosity of the rocks on the southwestern side of the dome have been crumpled into a series of folds which plunge at low angles to the south and southwest. The gentleness of this plunge explains the highly serrate contacts. Just west of Upper Shaker Village the folding is isoclinal, and the bedding and schistosity dip 70° east. Northwest of Smith Pond the folds are less tightly compressed, and dips in bedding and schistosity are between 35° and 70°. Just west of Montcalm Hill the bedding and schistosity in the Clough is nearly horizontal, and the folds are broad and open. The schistosity of the rocks from Montcalm Hill to Butternut Pond dips about 40° west.

A normal fault, which extends from Enfield Village to the south end of the quadrangle, has repeated the belt of metamorphic rocks along the southwestern side of the dome, forming a band of Ammonoosuc volcanics along the eastern shore of Mascoma Lake and a band of Ammonoosuc volcanics and the Clough formation around Cole Pond. The metamorphic rocks around the southern end of the dome have been cut out by the intrusion of Bethlehem gneiss.

The eastern flank of the Mascoma dome, south of the normal fault in Canaan Township (Pl. 6), is composed of Ammonoosuc volcanics which originally dipped east at moderate angles. Regional folding, however, has thrown this belt of volcanics into a series of anticlines and synclines with low plunges. The schistosity in this belt may dip, either east or west, at angles between 20° and 70°. The great breadth of Ammonoosuc volcanics near Canaan Village is due to the presence of a subsidiary dome, bringing to the surface a small patch of the Mascoma group (Pl. 6). South of East Hill the Clough formation is exposed for a short distance on the east flank of the dome and dips 60° E.

The Ammonoosuc volcanics extending northwest from the normal fault in Canaan Township form an overturned syncline between the Mascoma and Smarts Mountain domes. At the southeastern end of this belt the fold is nearly isoclinal with dips of about 75° NE. At the northwestern end of the belt, the southwestern limb dips 40° NE, whereas the opposite limb is about vertical. The Ammonoosuc volcanics near North Canaan School form part of the downfolded roof of the dome. These volcanics are in an open syncline trending about N 25° W. The foliation in the surrounding granodiorite dips under the volcanics at an angle of 40° on the west, is horizontal on the northeast, but dips away from the volcanics at about 10° or 20° on the hill a mile southeast of North Canaan School. The fact that the foliation dips away from the volcanics at a low angle on the south, may be explained by cross folds which trend NE-SW.

Croydon dome.—The Croydon dome, in the southwestern part of the quadrangle, originally must have been a comparatively simple dome, but it is now modified by later folding and faulting. Near the margins of the intrusive the foliation in the Croydon group is parallel to the bedding and schistosity of the surrounding metamorphic rocks as well as to the contact, and it dips outward at angles of 25° to 45° (Pl. 6). Nearer the center of the dome the foliation is weak and has been thrown into broad north-south folds.

The Clough formation on Croydon Mountain has been compressed into a series of north-south folds. Several of these folds extend northward for about two miles from the southern boundary of the quadrangle. Broad and open folds are characteristic of the eastern part of this belt, but farther westward, the folds are more tightly compressed, and near the contact with the Littleton formation they are almost isoclinal and overturned to the west. Just northeast of Stowell Hill is a small patch of Clough brought up in the midst of the Littleton formation, by an anticline. The metamorphic rocks around the northern end of the dome have been crumpled into a series of folds which plunge northward at moderate angles, giving somewhat sinuous contacts. The eastern part of the dome has been down-faulted by a normal fault, thus bringing the Bethlehem gneiss in contact with the Croydon group.

Smarts Mountain dome.—The Smarts Mountain dome, in the northeastern part of the Mascoma quadrangle, is asymmetrical. The axis of this highly elongated dome is located within a third of a mile of the southwestern contact of the Smarts Mountain group and the Ammonoosuc volcanics. Southwest of this axis the foliation of the Smarts Mountain group dips steeply to the southwest; northeast of the axis, the foliation dips 20° to 55° northeast. The bedding and schistosity in the metamorphic rocks along the southwestern flank of the domes is vertical in Dorchester Township, but it is slightly overturned farther south. The schistosity and bedding in the Ammonoosuc volcanics on Pollard Hill have been folded considerably, but in general, dip northeast at about 25°. The southern end of the Smarts Mountain dome is believed to have been displaced by an east-west fault.

Features in common to the domes.—There are eight important features common to all the domes. (a) The domes lie along the axis of the Bronson Hill anticline which trends north-northeast (Fig. 3). Its total length is at least 65 miles. (b) The long axes of the domes are at a small angle to the axis of the major anticline. (c) All the domes have a roof at about the same stratigraphic horizon, a few hundred feet below the base of the Clough formation. (d) The metamorphic rocks surrounding the igneous cores have a concentric schistosity which is, in general, parallel to the bedding. It is believed the bedding and schistosity originally dipped outward at low angles from the igneous cores, and that any marked variation from this relationship may be explained by later folding. (e) The foliation in the plutonic rocks near the contacts is parallel to the bedding and schistosity in the surrounding metamorphic rocks, but well within the domes, the foliation appears to be folded. (f) The north ends of the domes are relatively simple, and bedding and schistosity dip northward at low angles of 20° to 35°. The structure of the south ends of the domes is not so well known, but it, too, is perhaps relatively simple. The eastern and western flanks, on the other hand, have been folded and crumpled to a considerable extent. (g) The metamorphic rocks between adjacent domes have been intensely crumpled. (h) The igneous rocks of the domes have a similar petrography.

Mechanics of intrusion.—Five hypotheses as to the mode of intrusion of the Oliverian magma series may be considered.

(1) The Oliverian rocks could not have been derived from the Ammonoosuc volcanics through palingenesis or anatexis, because these rocks have never been deeply buried. The total thickness of the known stratigraphic column above the roofs of these intrusives is 7000 feet, and it is doubtful whether the thickness of the sediments overlying this known stratigraphic column could have exceeded one or two miles.

(2) If the Oliverian magma were injected to form a series of phacoliths, it is conceivable that dome shaped bodies would form. Whereas such a mode of intrusion might account for a foliation within and parallel to the walls of the igneous masses, and would explain why the domes had a similar petrography and a common roof, it would not explain why the schistosity of the overlying and adjacent metamorphic rocks was parallel to the contacts of the intrusion and also parallel to the foliation of the igneous rocks.

(3) Objections, similar to those given above, may be raised to the hypothesis that the various domes are part of a single, large sill which was later folded and partly eroded.

(4) It is also difficult to understand how these domes could represent a series of small batholiths and stocks, arranged in a narrow zone over 65 miles in length, which formed their roofs everywhere at the same stratigraphic horizon. It should be noted that the stratigraphic position of the roofs does not vary more than a few hundred feet.

(5) Finding all other theories untenable, the author considers laccolithic intrusion to be the best mechanism. Not only does it explain the foliation of the intrusion and the concentric schistosity of the surrounding metamorphic rocks but it also explains why the domes should have roofs at the same stratigraphic horizon.

Origin of schistosity and foliation.—Had the intrusion of these igneous cores been rapid, the roofs, undoubtedly, would have ruptured through tension, thus providing an easy escape for the magma. Doming must have proceeded slowly, allowing the overlying rocks to deform plastically under the vertical load of thousands of feet of sediments. It is believed that the upward push of the magma, combined with the downward force due to load, compressed and thinned the sediments. Elongation of the rock mass, which is essential to thinning, was permitted by an extension parallel to the bedding as the arches were being formed. Gilbert (1899, p. 81) calculates that the roof of the Lesser Holmes arch was elongated about two per cent when the laccolith formed. Brock (1934, p. 689) obtains the same value for one of the domes of the Shuswap terrain. In the Mascoma dome the elongation of the roof is calculated to have been at least 12 per cent of its original length. In describing the laccolith, Gilbert (1877, p. 82) says,

> "It was not *stretched* into the dome form; it was *compressed*. The efficient force did not act in the direction of the extension, but vertically. The sandstone was pushed, not pulled."

Following Brock (1934, p. 689), this type of deformation would require that, at any point on the laccolith, the strain ellipsoid be placed with its short axis normal to the bedding and its long axis parallel to the dip. The schistosity would develop parallel to the bedding. If a series of these ellipsoids were placed at intervals on the circumference of the dome, their long axis would radiate from some central point within the dome, and the intermediate axes would everywhere be parallel to the strike of the bedding. Thus a concentric schistosity would develop, and it would dip out radially from a central point within the dome. Although the perfectness of schistosity is, to a great extent, dependent upon the mineralogical composition of the rocks, this schistosity should be most pronounced in the lowest beds where thinning would be most intense. We would expect the schistosity to be less marked in the higher formations, and farther away horizontally from the igneous mass, as recrystallization is greatly enhanced by the heat and by solutions from the magma. It is then, a dynamo-contact metamorphism.

The foliation of the igneous rock is in part a flow structure, but it seems that this mechanism can be considered as important only in close contact with the walls. Perhaps still more important in the production of this foliation is the effect of doming. The upper parts of the laccoliths would start to crystallize early, and if crystallization were nearly complete before doming had ceased, the plates of biotite would become oriented in the crystal mesh in response to the same stress conditions as existed in the roof sediments.

Effect of regional folding and metamorphism.—After the foliation was produced, but perhaps before complete solidification of the magma, regional folding began. The linear distribution of the domes may have determined the position of the Bronson Hill anticline. During folding, the roofs of the domes were somewhat deformed. The development of a syncline, extending from Crystal Lake to past Halley School in Canaan

Township, separated a small part of the Mascoma dome, and formed the dome near Canaan Village. The Smarts Mountain dome appears to have been later pushed westward against the Mascoma dome, compressing the syncline on its western flank, and in places overturning the axial plane to the west.

The down-folding of the roof rocks of the Mascoma dome formed the syncline which brought down the Ammonoosuc volcanics near North Canaan School in the township of Canaan. This syncline trends northwest, about parallel to the syncline between the Mascoma and Smarts Mountain domes. The variation in direction and amount of dip of the foliation, particularly near the central part of the domes, suggests that the original, simple foliation pattern of the igneous rocks was folded during this period of regional compression (Pl. 6).

One of the best places to observe the effects of regional folding upon the roof rocks is along the southwestern flank of the Mascoma dome. Around Smith Pond the bedding and schistosity of much of the Clough are nearly flat, and the folds are broad and open. As one proceeds westward or northwestward from Smith Pond, the folds become more and more tightly compressed, until finally they are isoclinal, and the dome schistosity of the roof rocks appears parallel to the later regional schistosity. The igneous cores must have offered considerable resistance to this folding, and, undoubtedly, protected the overlapping rocks from considerable deformation. Thus we might expect decrease in intensity of folding of the roof toward the center of the dome.

The area of intense folding west and northwest of Smith Pond extends southward to Croydon dome, and is analogous to the intensely folded area between Owls Head and Smarts Mountain domes, in the Mt. Cube quadrangle. There is another similar area just north of the Owls Head dome in the Moosilauke quadrangle. These areas lie between domes (Fig. 3) and are probably the loci of most intense deformation, because they have not been protected by the buttressing effect of the igneous masses. In addition, any differential movement of two adjacent domes would help to intensify the degree of deformation in the intervening areas.

Minor structures.—There are inclusions of biotite gneiss within the Oliverian domes which are probably reworked fragments of the Ammonoosuc volcanics. In nearly all cases they are elongated parallel to the foliation of the igneous rock, and possess a schistosity parallel to their length.

As the magma was intruded into unmetamorphosed rocks, it is likely that many of the inclusions which sank into the liquid were more or less equidimensional. Small masses of femic volcanics might be quickly converted to a biotite rock, and, if doming continued after the surrounding magma had almost completely crystallized, the inclusions would be drawn out parallel to the foliation of the igneous rock, simultaneously developing a schistosity parallel to their length. Those inclusions which were originally disk-shaped were rotated early, parallel to the foliation surfaces in the crystallizing magma. They may later have been sheared out into still thinner discs, at the same time developing a schistosity parallel to their length.

The apparent streaking out of biotite flakes, in the plane of foliation is another minor structure in the plutonic rocks of the domes. (1) In some places flakes of biotite appear to have slipped parallel to the basal pinacoid, giving rise to elongated crystals. (2) More commonly, however, one finds biotite flakes arranged in parallel lines in the plane of foliation. The linear features produced in both cases are believed to indicate the direction of movement in the plane of foliation. The streaking of biotite, as found in the plutonic rocks of the domes, has a plunge which is, in most cases, down the dip. Any marked departure from this arrangement may be due to regional folding. The linear features, then, seem favorable to the theory that the foliation was produced by doming of a crystallizing magma, the biotite being streaked out in the planes of shearing.

LEBANON DOME

General structure of dome.—The general structure of the Lebanon dome is similar to that of the other domes. It consists of a plutonic core of Lebanon granite and border gneiss, which is intrusive into the upper part of the Post Pond volcanics. Small dikes and sills of the border gneiss intrude the volcanics on Lords Hill and near the road between Hayes and Signal Hills. The concentric foliation of the border gneiss, which is equally well developed throughout the mass, dips radially outward from the center (Pl. 6). In the Post Pond volcanics, which extend from just north of Hanover Reservoirs to Lords Hill, the schistosity dips 35° to 75° northwest and is parallel to the foliation of the adjacent gneiss. At the northeastern end of the dome on Lords Hill, the bedding and an old schistosity dip 55° north. These, however, are cut by a latter schistosity which is vertical and strikes north-northeast. From Lords Hill southward, along this belt of Post Pond volcanics, to Lebanon village, the schistosity dips east at 45° to 90°.

Mechanics of intrusion and origin of schistosity and foliation.—Merritt (1921, p. 16) considered the Lebanon dome to be a laccolith. Although the writer accepts this interpretation for the domes of the Bronson Hill anticline, he believes the Lebanon intrusive is more likely a stock which has domed its roof. Either the stock or laccolithic hypothesis will explain most of the features of the dome, but from his study of the eastern half of the dome, the writer is inclined to favor the former.

The composite character of the igneous core is, perhaps, more in favor of the stock hypothesis. The border gneiss was first intruded as a stock, and perhaps before it had completely crystallized, the upward push of the magma domed the overlying beds. As in the other domes, this doming mechanism could produce a foliation in the igneous rock, which was concentric and parallel to the schistosity formed contemporaneously in the surrounding Post Pond volcanics. After the border gneiss had solidified, the Lebanon granite was intruded, as shown by the abundance of inclusions of the border gneiss in the granite.

Effect of regional folding and metamorphism.—The fracturing and granulation of the microcline phenocrysts in the granite core was probably brought about by regional folding which followed intrusion. In general, this regional deformation was incapable of producing a new foliation in the igneous rock, but it was sufficiently intense to shatter the phenocrysts on microcline (Pl. 3, fig. 3). The effects of regional folding and metamorphism upon the rocks surrounding the igneous core are much more pronounced. Two distinct schistosities have been mentioned in the Post Pond volcanics on Lords Hill. The older schistosity which dips 55° north, parallel to the bedding, is believed to have been formed during the intrusion of the border gneiss, and it is equivalent to the concentric schistosity of the other domes. The later schistosity which is vertical and strikes north-northeast is considered as the regional schistosity superimposed upon the earlier dome schistosity. The fact that this old foliation is at right angles to the regional schistosity explains why the former still persists. Throughout the rest of the metamorphic rocks only one schistosity is recognized in any one outcrop. On the sides of this elongated dome, this is to be expected, as the strikes of the two foliations would be approximately the same, and the difference in dip might be small. Thus it would be difficult to recognize both features. Moreover, the older schistosity may have been folded isoclinally, and thus made parallel to the newer regional schistosity.

SALMON HOLE BROOK SYNCLINE

The area bounded on the west or northwest by the Ammonoosuc thrust, and on the east or southeast by the Northey Hill thrust is known as the Salmon Hole Brook syncline (Fig. 3). This major syncline was named and mapped by Billings (1935, p. 31) in the Littleton and Moosilauke quadrangles. Later field work, by Billings in the Woodsville quadrangle and by Hadley in the Mt. Cube quadrangle, showed that this same fold continued southwestward into the Mascoma quadrangle. Much of the eastern limb of this fold has been cut out, in the Mascoma quadrangle, by the Northey Hill thrust so that the axis of the syncline lies very close to the fault.

The Hardy Hill quartzite member of the Orfordville formation is one of the keys to the detailed structure of the Salmon Hole Brook syncline in the Mascoma quadrangle. Ten days of field work were devoted to a study of the quartzite by pace-and-compass methods, and detailed maps were then prepared on a scale of 800 feet to the inch. Directly beneath the quartzite is a thin bed of volcanics; in places, where the quartzite is absent, the volcanics serve as a good horizon marker. Although the most northerly outcrop of the quartzite in the Mascoma quadrangle is half a mile east of Hanover Center, the horizon itself may be traced for a mile farther north, by means of the bed of volcanics. From this point southward, the Hardy Hill quartzite may be traced almost continuously to East Plainfield.

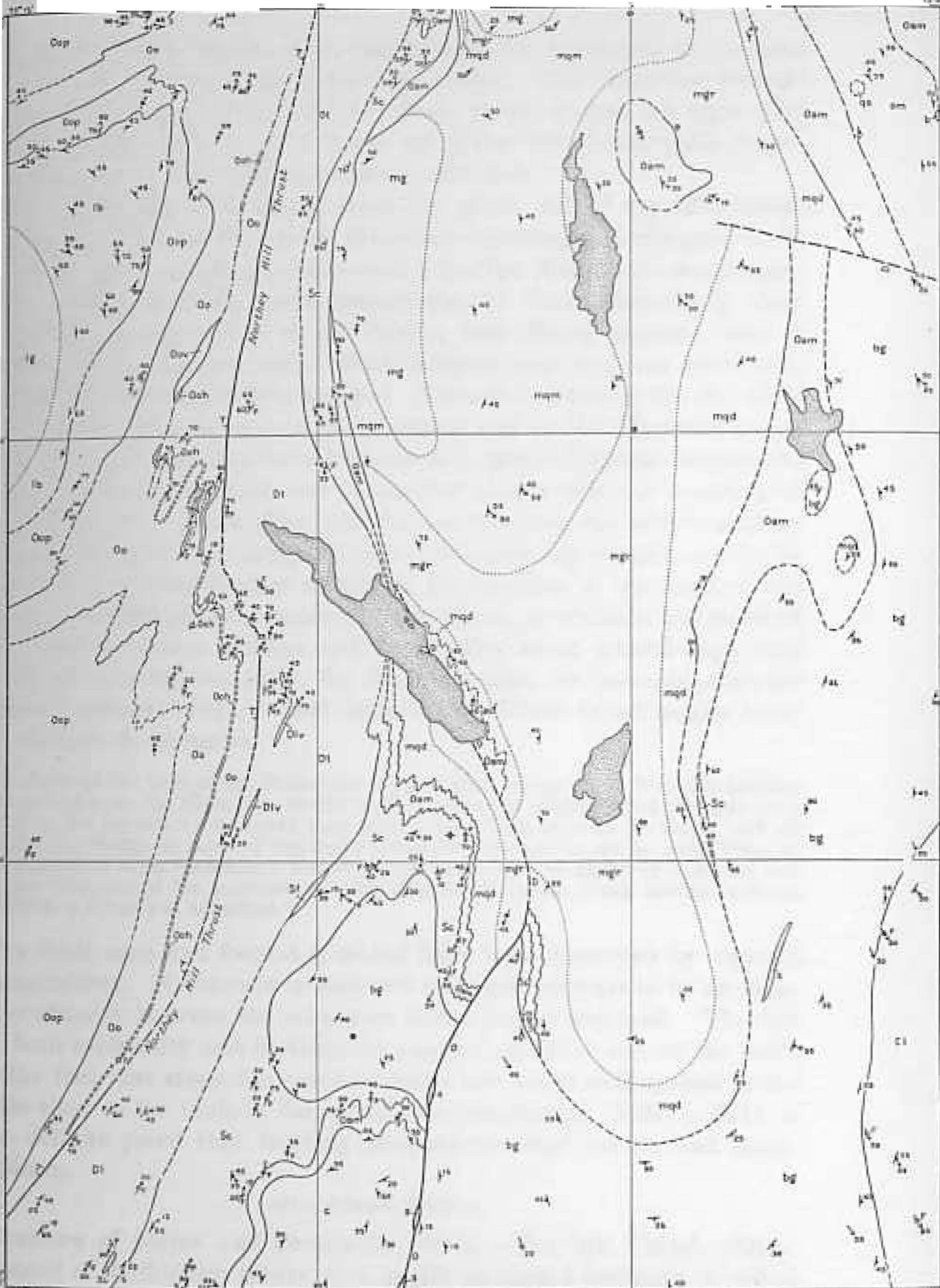
Detailed mapping shows that the quartzite has an intricate, zig-zag pattern; the belt as a whole trends about S 10° W, whereas the strike of the bedding at any locality is about S 25° W. This pattern suggests intense folding; numerous observations on single outcrops corroborate this. On an average the individual folds plunge 60° NE. Thus the Hardy Hill quartzite is on the west limb of a syncline plunging northeast.

Another good horizon marker in the Salmon Hole Brook syncline is the top of the Post Pond volcanics. From north of Huntington Hill in Hanover the horizon may be traced southwest, along the northwestern limb of a syncline, for an unknown distance into the Hanover quadrangle. It may be traced back again, on the southeastern limb of the syncline, as far as Lords Hill. From there it extends southwest to Lebanon Village. Reconnaissance work in the Hanover quadrangle shows that this contact continues for about four miles southwest of Lebanon, along the northwest limb of another syncline, and returns again on the southeast limb. For about three miles southeast of Lebanon Village the contact is highly folded; but from here southwestward, it is comparatively straight.

This contact has been folded more or less harmonically with the Hardy Hill quartzite as can be seen from the geological map. Furthermore, the fold pattern of both this contact and the quartzite indicates that the rocks in the western part of the quadrangle form the western limb of a syncline (Salmon Hole Brook syncline); the eastern limb is cut out by the Northey Hill thrust.

NORTHEY HILL THRUST

The Northey Hill thrust extends southward from North Neighborhood School in Hanover Township, to Arvin School, Mt. Tug, Potato Hill School, and Methodist Hill. From here it extends southwest to Cornish Township. A pace-and-compass traverse from near Mt. Tug to the highway south of Potato Hill School shows the contact between the Orfordville and Littleton formations to have a zig-zag pattern similar to that already described for the Hardy Hill quartzite. This indicates that



LEGEND

STRUCTURAL SYMBOLS

- Strike and dip of bedding
- Horizontal bedding
- Bedding and linear element
- Strike and dip of foliation or schistosity.
- Vertical foliation or schistosity.
- Horizontal foliation or schistosity.
- Foliation or schistosity and linear element.
- Foliation or schistosity with linear element directly down dip.
- Vertical foliation or schistosity and linear element.
- Horizontal foliation or schistosity with horizontal linear element.
- Strike and dip of axial plane of fold with direction and value of plunge of fold.
- Direction and value of plunge of fold with vertical axial plane.
- Fold with horizontal axis and vertical axial plane.
- Linear element alone.

FORMATIONS

qs	Quartz syenite	
vb	Volcanic breccia	
bg	Bethlehem gneiss	
mg	Granite	Mascoma group
mqm	Quartz monzonite	Mascoma group
mgr	Granodiorite	Mascoma group
mqd	Quartz diorite	Mascoma group
sm	Smarts Mountain group	
c	Croydon group	
lg	Granite	Lebanon group
lb	Border gneiss	Lebanon group
Dl	Mica schist, etc.	Littleton formation
Dlv	Volcanics	Littleton formation
Sf	Fitch formation	
Sc	Clough formation	
Oam	Ammonoosuc volcanics	
Oo	Black schist, etc.	Orfordville formation
Ooh	Hardy Hill quartzite	Orfordville formation
Oov	Volcanics	Orfordville formation
Oop	Post Pond volcanics	Orfordville formation
s	Silicified fault zone	

Scale in Miles

0 1 2 3

TECTONIC MAP OF MASCOMA QUADRANGLE

the surface of the thrust fault, which actually represents the contact between these two formations, has been folded. The thrust has brought the upper part of the Orfordville formation to rest against the upper part of the Littleton schists. The writer calculates the stratigraphic throw, along this part of the fault, to be about 9000 feet.

This thrust has been traced from the north end of the Moosilauke quadrangle to the south end of Mascoma quadrangle, a distance of 58 miles. As one proceeds southwestward from the Moosilauke quadrangle, to well within the Mt. Cube quadrangle, he finds successively older formations curving around in the Salmon Hole Brook syncline, only to end abruptly against the fault. With different rock types on either side, the fault has been accurately mapped. From the middle of the Mt. Cube quadrangle, southwestward to the southern end of the Mascoma quadrangle, Orfordville schists have been faulted against Littleton schists; the marked similarity of these two formations makes accurate mapping of the fault difficult. Upon close examination, however, the two formations may be told apart. By using the same distinguishing criteria as used by Billings and Hadley farther northeast, the location of the fault in the Mascoma quadrangle is accurate, in most places, to within a few hundred feet. Both Professor Billings and Dr. Hadley spent several days with the author tracing this fault, for the most part, by pace-and-compass methods. Barrow (1912, p. 284) describes the Moine thrust as also being very difficult to recognize.

"Similarly in the case of the Moine-thrust; a skilled stratigraphist, knowing nothing of the country or the literature, would at first cross the Moine-thrust without even suspecting its existence; it would take him a very long time to locate it, and an intimate knowledge of most of the rocks would be essential before he could trace it. How difficult it is to recognize a thrust of this nature can be gathered from the fact that the existence of the southern one was disputed for some years, indeed in Arran its existence is not yet admitted."

If a fault zone had formed it would have been destroyed by regional metamorphism. No breccia is observed and there appears to be an absolute continuity between the schists on either side of the fault. The fact that both schistosity and bedding are parallel on either side of the fault, and the fact that staurolite porphyroblasts are found undisturbed in the schists close to the fault in the Moosilauke quadrangle (1937, p. 531), is quite definite proof that faulting preceded isoclinal folding and metamorphism.

MT. CLOUGH PLUTON

Structure of pluton and surrounding rocks.—The Mt. Clough pluton, composed of Bethlehem gneiss, is a highly elongated intrusive, trending in a north-northeasterly direction, along the eastern limb of the Bronson Hill anticline. It is at least 65 miles long and extends from the Franconia quadrangle to the Sunapee quadrangle (Fig. 3). It may be seen from the geological map of the Mascoma quadrangle (Pl. 6) that there is a marked tendency for the foliation to be parallel to the contacts of the intrusion, and also parallel to the schistosity of the adjacent metamorphic rocks.

Northeast of Crystal Lake in Canaan Township, the foliation dips from 30° to 50° NE, but farther south, around Canaan Village, the dip is 40° to 60° E. A mile east of Halley School in Canaan Township, the foliation dips 25° SE. The small mass of Bethlehem gneiss which forms the Pinnacle in Canaan Township, however, has a foliation which dips at 35° W. From the road between Halley School and the Height of Land School in Grafton Township southward, almost to the Grafton county line, the foliation in the gneiss dips uniformly to the east, at angles of 35° or 40°. Just south of East Hill, where the Clough and Ammonoosuc volcanics dip 60° to 70° E, the foliation in the gneiss is also 60° to 70° E.

This structural conformability is brought out, perhaps most strikingly, around the southern end of the Mascoma dome. In the vicinity of Carter Brook in Springfield Township the foliation of the Bethlehem dips 20° to 35° E and SE. Near Washburn Corner it dips 30° to 50° S. From here northward to Cole Pond in Enfield Township it dips 45° to 60° W. West of the large normal fault which passes through Butternut Pond in Grantham Township there is a large oval-shaped area of Bethlehem gneiss. In general the foliation dips in toward the center of the oval at angles from 30° to 45°, although locally higher dips are observed. In the central part of this area the foliation is flat. Southwest of Eastman Pond in Grantham Township, the dip of the foliation is to the east and decreases from 40°, south of the "M" in "GRANTHAM," to about 10° at the fault farther west.

Along the eastern contact with the high-grade schists the foliation dips 45° east and is about parallel to the schistosity of the metamorphic rocks.

Mode of intrusion and origin of foliation.—The foliation of the Bethlehem gneiss is believed to be a primary flow structure. This is shown in part by the slab-like inclusions which are oriented parallel to the foliation. Originally some of these may have been disk-shaped and rotated into parallelism with the foliation. Others may have been sheared out into elongated masses, parallel with the flow structure. Even more compelling, however, are the shear zones in the gneiss filled with pegmatitic material. The foliation shows drag due to movement along these shear zones; the shearing must have occurred after the foliation was produced, but while some residual liquid was still left. The marked parallelism between the foliation of the gneiss and the strike of its contacts rules out the possibility that such a foliation could have been produced by horizontal compressive stresses. From these three lines of evidence one must conclude that the Bethlehem gneiss is a primary gneiss.

The flow structure can not be due solely to drag against the walls, for it is almost uniformly developed throughout the body. The foliation could be produced, however, if we assume a forceful intrusion of a partly crystalline magma so that flow layers would develop between crystal grains and the biotite become oriented into these flow layers. On this assumption we could explain the granoblastic texture of the gneiss as due to the mutual interference and granulation of crystals in a semi-solid magma.

The Bethlehem gneiss is believed to form a huge, sheet-like mass which, in the Mascoma quadrangle, forced its way up over the Mascoma dome and down the western side (cross-section C–C′, Pl. 6). There are four main lines of evidence which favor such an interpretation.

(1) The shape and structural position of the body as brought out by geological mapping. The body is an intrusive mass elongated parallel to the regional structure (Fig. 3). The Littleton formation is everywhere present on the eastern flank, whereas the Clough or Ammonoosuc usually form the western contact. Cross-cutting relations are insignificant when compared with the magnitude of the intrusive. This body, therefore, occupies essentially the same stratigraphic position throughout its extent.

(2) The pegmatites from the Bethlehem gneiss are confined almost wholly to the schists along the eastern contact. If the Bethlehem gneiss in the Mascoma quadrangle forms a thick sheet, the eastern contact of which dips 45° to the east, then we would expect to find the pegmatites most abundant on the eastern side, as it would be here, in the hanging wall of the intrusive sheet, that the escaping fluids from the crystallizing magma would concentrate. Conversely, we would expect to find few pegmatites along the western contact in the footwall. These expectations are borne out by field facts. A moderately dipping contact would also explain the extremely broad band of pegmatites in the schists, and why the outermost members of this belt appear to be so far removed from the igneous source.

(3) It is believed that the parallelism of the foliation in the gneiss and the bedding and schistosity of the metamorphic rocks indicate a low angle of dip for the contacts of the intrusive. The small patch of westerly dipping gneiss which holds up the Pinnacle in Canaan Township is probably a small outlier of the main intrusion. The concentric structure around the southern end of the Mascoma dome would indicate that the Bethlehem originally wrapped up over and down the western side of that dome. This sheet of gneiss extended as far west as Leavitt and Miller Ponds in Grantham Township. The nearly isolated mass of Bethlehem west of the fault in Grantham Township is interpreted as lying on top of the Clough formation, in a basin-like structure between the two domes. The inwardly dipping foliation, around the outer part of the mass, and

the horizontal structure in the center is in agreement with this interpretation. The dropping-down of the eastern block along the fault in Grantham Township has prevented erosion from removing the Bethlehem and underlying Clough and Ammonoosuc volcanics from the eastern half of the Croydon dome. The gneiss must have originally extended up over the Croydon dome, and must have been continuous with the basin-like mass around Leavitt Pond. This would explain why the foliation in the gneiss is nearly flat southwest of Eastman Pond; it must represent a flat-lying foliation in the Bethlehem which is wrapping up over the Croydon dome. In addition to the parallelism of structure in the Bethlehem and in the high-grade Littleton formation, the evidence of the pegmatites is in favor of a low angle dip for the eastern contact of the intrusive.

(4) It will be noticed from Figure 3 that the Bethlehem wraps around the southern end of the Owls Head dome as well as the Mascoma dome. It will also be noticed that the magma was able to intrude farthest to the west where there was a low divide in the Bronson Hill anticline. These two facts suggest that the magma was intruded along a definite horizon, and therefore has the characteristics of a concordant sheet.

Position of intrusion in tectonic sequence.—The high-grade Littleton east of the Bethlehem gneiss commonly exhibits a moderately or intensely folded schistosity. The foliation of the gneiss, however, is only locally wavy and is never observed to be even moderately folded. The fact that the foliation of the gneiss has been scarcely disturbed, even in the vicinity of its contact with the high-grade Littleton schists, the schistosity of which is conspicuously folded, would favor the belief that the Bethlehem was intruded after the major part of the folding but, perhaps, while regional stresses were still weakly active. The writer believes that the evidence in the Mascoma quadrangle favors placing the date of this intrusive only slightly later than that determined by Billings (1937, p. 537) in the Littleton and Moosilauke quadrangles. As has already been shown in the discussion of the New Hampshire magma series, the geological age of the Bethlehem gneiss is probably late Devonian.

NORMAL FAULTS

Extending southward from Mascoma Lake, for an unknown distance into the Sunapee quadrangle, is a normal fault, along which the eastern block has been dropped down. Along the southern part of the fault the Bethlehem gneiss comes in direct contact with the gneiss of the Croydon dome. Near North Grantham the belt of Clough and Ammonoosuc volcanics, encircling the Croydon intrusive, ends abruptly against the Bethlehem gneiss. The eastern part of the Croydon dome has been down-faulted. At Butternut Pond another belt of Clough and Ammonoosuc volcanics ends abruptly against the Bethlehem gneiss, but it is repeated farther east, near Cole Pond. Between these belts the Bethlehem gneiss comes in direct contact with the gneiss of the Mascoma dome. A structural break, therefore, is obvious; see section C–C′, Plate 6. The repetition of the belt of Ammonoosuc volcanics along the northeastern shore of Mascoma Lake is further evidence, confirming the existence of a normal fault farther south. If the roof of the Mascoma dome were projected northward from around Smith Pond, it would pass several thousand feet above Mascoma Lake. It seems logical, therefore, to explain this belt of volcanics by down-faulting of the roof.

Along much of its course the fault may be accurately located by the aid of silicified zones. Where the fault leaves the southern part of the quadrangle there is a large silicified zone which trends N 20° E, has a maximum width of 200 feet, and is several hundred yards long. On the east side it forms a steep cliff about 50 feet high. The dip of the zone appears to be 70° E. Brecciated Croydon gneiss is cemented by quartz, in the western part of the zones, but brecciation of the Bethlehem gneiss was not observed. Where the fault crosses the hill, a mile farther north, there is a smaller silicified zone. Here the brecciated Croydon gneiss is more abundant, but the Bethlehem seems scarcely disturbed. The individual fragments of Croydon gneiss are brittle, having been highly silicified. They also have been leached of biotite. The dip of this zone is very steep, judging from its straight course across the hill. Northwest of Anderson Pond in Grantham Township, is still a third silicified zone about 30 feet wide. This can be traced, somewhat interruptedly, for a distance of over a thousand feet. On the southeast side of the zone is a fault plane which strikes N 30° E and dips 65° SE. On this surface there are fault grooves which plunge S 30° E at 60°. The Bethlehem gneiss is exposed immediately to the east and west. The Mascoma gneiss northeast of Butternut Pond in Grantham Township, has much the same appearance as the Croydon gneiss already described along the fault. It is brittle, highly silicified, and contains little biotite. The gneissic structure is vague, and the whole mass appears to have been highly shattered. Near the lake-shore, east of the "O" in "MASCOMA LAKE," is a small silicified zone which may have formed along this fault.

The throw of the fault has been calculated at three different points; near Mascoma Lake, south of Prospect Hill in Enfield, and near the southern boundary of the map. All three values obtained were approximately 4000 feet.

The east-west fault in Canaan Township is hypothetical. No such fault has been observed, but it best explains the adjacent structures in both the Mascoma and Cardigan quadrangles (Fowler-Lunn and Kingsley, 1937, p. 1374). The silicified zone which holds up Banks Pinnacle in

Grafton Township may have been formed along a fault in the Bethlehem gneiss. Judging from the steep face exposed on the southeast side of the pinnacle, this zone probably dips at a steep angle to the southeast.

ORIGIN OF OLIVERIAN MAGMA SERIES

GENERAL STATEMENT

The author presents the following theory to explain the diversity of igneous rocks in the Oliverian domes of the Bronson Hill anticline. No consideration is given to the Lebanon dome. The theory is based primarily upon observations made in the field and laboratory, and deals only with the changes which took place in the domes, after the magma was intruded. More detailed consideration will be given to the Mascoma group, as this group has the greatest variety of rock types.

The igneous rocks of the Oliverian series range in composition from quartz diorite to granite, there being all gradational types. In the Croydon dome quartz diorite comprises most of the igneous core, save for a small amount of granodiorite and perhaps a little quartz monzonite, near the center of the body. The geological map shows the distribution of the various types in the Mascoma dome. The relative abundance, as seen at the surface, is as follows: granodiorite, quartz monzonite, quartz diorite, and granite. There is a slightly eccentric arrangement of the rock types, with the granite located near the western flank of the dome. In the Smarts Mountain dome in the Mascoma quadrangle, quartz diorite is more abundant than granodiorite; but in the Mt. Cube quadrangle Hadley has found the granodiorite to be the predominating type. The writer estimates the relative abundance of these rock types at the surface of all the domes to be as follows, in decreasing order: granodiorite, quartz diorite, quartz monzonite, and granite.

CONTACT EFFECTS OF MAGMA

In the Mascoma dome there is a zone, a few hundred feet wide, which is transitional between the intrusive rock and the surrounding Ammonoosuc volcanics. This transitional rock is a composite gneiss, produced by the intimate association of the Oliverian magma and the Ammonoosuc volcanics, which were converted to biotite gneiss. The magma was injected in thin, sill-like masses between the bedding of the volcanics. These small sills are so abundant that the intersill rock is now represented by a series of thin, sheet-like inclusions oriented parallel to the gneissic structure. The thickness of the sills and intersill rock varies from a fraction of an inch to several feet. The contacts of the sills are not sharp against the inclusions, but the light-colored grades into the darker colored inclusions. The bulk composition of the feldspars of several specimens of these transitional rock types is shown in Figure 5 (within the circle). These rocks contain andesine, whereas the strictly intrusive rocks seldom contain plagioclase more calcic than oligoclase.

GENERAL THEORY

The author's theory for the origin of the Oliverian magma series is composite, involving the processes of assimilation, pure melting, fractional crystallization, and replacement. It is assumed that a granodiorite magma was intruded to form the laccoliths, and non-uniform conditions of crystallization caused a slight heterogeneity. Assimilation of small amounts of Ammonoosuc volcanics would also help to explain some of this heterogeneity. Thus far, the theory explains all the plutonic rocks of the Smarts Mountain and Croydon domes; but to account for the more granitic rocks of the Mascoma dome, the process of replacement is here accepted.

After the laccolith had crystallized, and perhaps while it was still being deformed by regional stresses, solutions rich in potash rose from the solidifying magma reservoir below. Controlled somewhat by the gneissic structure in the laccolith, they were directed toward the western flank of the Mascoma dome, where they partially replaced the rock with potash feldspar. By this process, hereinafter referred to as replacement, the quartz diorites and granodiorites in the western half of the dome are believed to have been converted into rocks with compositions equivalent to quartz monzonites and granites. This process may not be considered one of gaseous transfer, as emphasized by Fenner (1926, p. 743), because it is not a process of differentiation. It is hydrothermal replacement by microcline, of a completely or nearly completely crystallized rock.

EVIDENCE OF REPLACEMENT

The several lines of evidence which favor the hypothesis of replacement are:

(1) The rock types are gradational and not cross-cutting. Thus, any theory involving a succession of intrusions from a chemically changing magma-source is incapable of explaining the rock types of the Mascoma dome.

(2) Near the contact along Moose Mountain it is common to find fine-grained igneous rocks with the characteristic appearance of quartz diorites, but with enough large crystals of microcline to give the bulk composition of a quartz monzonite or granite. In thin section the groundmass of these rocks looks like the typical quartz diorite, and in many specimens the plagioclase is An_{25} or An_{30}. These rocks appear to be the original quartz diorite replaced by metacrysts of microcline, so as to change the composition to a more granitic type. This same phenomenon is observed, somewhat less frequently, near the center of the dome.

(3) The presence of a band of microcline-rich quartzite on Moose Mountain, where the Clough formation comes in contact with the granite, is another line of evidence in favor of the replacement theory. The effects of replacement by microcline extend out for about 100 feet into the quartzite, and replacement is so complete that, in the field, it is difficult to find the true contact between the two rocks. In thin section, however, the quartzite may be distinguished by the absence of plagioclase and presence of muscovite. The microcline occurs in metacrysts of about the same size and shape as those in igneous rocks.

(4) The granoblastic texture of the dome rocks, the granulation of the large quartz phenocrysts, and the folding of the gneissic structure of the dome all indicate that the Oliverian domes suffered considerable shearing and deformation subsequent to crystallization. Even within the same thin section, highly granulated quartz phenocrysts are observed, but the large crystals of microcline are not granulated, nor even fractured. This strongly suggests that the large crystals of microcline are not phenocrysts, but are metacrysts, and were introduced after most of the deformation had ceased. It is probable that much of the microcline in the groundmass of these rocks is feldspar which was introduced while the rock was being sheared. Any large metacrysts which could have been formed would immediately have been granulated, and the microcline would have taken its place in the mosaic, along with the quartz and plagioclase.

(5) If these crystals of microcline were intratelluric phenocrysts, the magma must have been extremely rich in potash feldspar. It must have been so rich in potash feldspar that microcline was the first mineral to crystallize. The composition of such a magma would lie within the orthoclase field of the orthoclase-anorthite-albite diagram. We would expect, then, to find granite or quartz monzonite the predominating rock type derived from such a magma, and not a potash-poor granodiorite. Since the bulk composition of the plagioclase, in the Mascoma dome, is oligoclase (An_{23}), the microcline-oligoclase ratio would have to be at least 2:1 in order to lie within the orthoclase field of the ternary diagram given by Bowen (1928, p. 231). This ratio is represented by point X in Figure 4. It is nearly as high as that for the most potash-rich granites of the Mascoma dome. In no case is the microcline-oligoclase ratio of the dome known to exceed 5:2; and, furthermore, the ratio for the dome as a whole is estimated to be only 1:3. Starting at some point such as Y, orthoclase will crystallize until the boundary curve AB is reached. At this point, both orthoclase and plagioclase will crystallize, and the composition of the liquid will move along the boundary curve to A. At A the last drop of liquid will be gone. Every rock formed from such a liquid, however, will have a potash feldspar-plagioclase ratio greater than

3:2, and it will be impossible, on this theory, to explain the abundance of granodiorite and quartz diorite in the Mascoma dome.

(6) The uniformity of composition of the plagioclase in these rocks is also strongly in favor of replacement. In any particular magma series

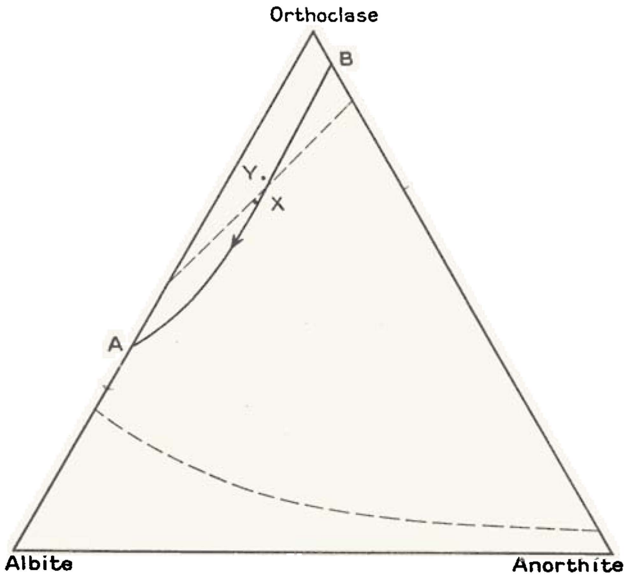


FIGURE 4.—*Ternary diagram of the system, orthoclase-anorthite-albite (after Bowen)*

of calc-alkaline rocks, the more granitic types contain the more sodic plagioclase as is well known. This is not the case, however, with the Oliverian magma series. The bulk composition of the feldspar, as obtained from the estimated modes of 49 thin sections of the Oliverian intrusives, is plotted in Figure 5. Of these, 39 are from the Mascoma dome, 5 from the Croydon dome, and 5 from the Smarts Mountain dome. These points lie near a straight line which passes through the potash-feldspar corner of the field. The plagioclase, therefore, has essentially the same composition in all the rock types. This may be explained by assuming partial, localized replacement of a slightly heterogeneous rock by microcline. Thereby, quartz diorites and granodiorites are changed to rocks with the composition of granite and quartz monzonite.

(7) In Figure 6 is plotted the mineral composition, as obtained from the estimated modes, of the same 39 specimens from the Mascoma dome as in Figure 5. As biotite is about equally abundant in all the rock types, it has been excluded from the plot. This plot shows a definite decrease in the amount of quartz, as well as plagioclase, as the amount of microcline

increases. The granites, therefore, have less quartz than the quartz diorites. The above relationship may be interpreted as evidence in favor of the hypothesis of replacement; but, at the same time, it may not be taken as conclusive proof thereof.

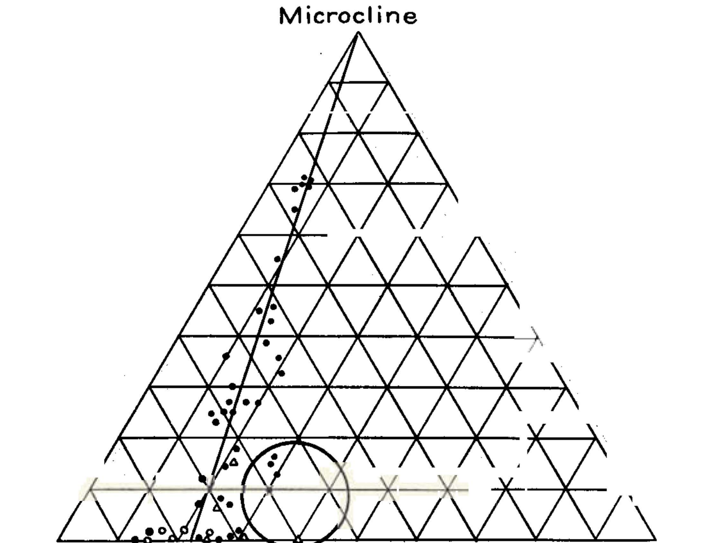


FIGURE 5.—*Plot of bulk composition of feldspars from estimated modes of Oliverian intrusives*

Dot = Mascoma group, triangle = Smarts Mountain group, circle = Croydon group.

The compositions within the circle are obtained from the transitional rocks formed by reaction between Ammonoosuc volcanics and the original magma.

METAMORPHISM

GENERAL STATEMENT

Many of the major problems, encountered in a detailed study of the metamorphism in western New Hampshire, have been considered by Billings (1937) for the Littleton-Moosilauke area. In the ensuing discussion, therefore, attention will be focused chiefly on new data or interpretation.

Only the middle and high-grade zones of metamorphism are present in the Mascoma quadrangle; the rocks belonging to the middle-grade zone lie west of the Bethlehem gneiss, and those of the high-grade zone lie east of the Bethlehem. In the middle-grade zone there is considerable variation in the intensity of metamorphism. According to Barrow's (1912) classification, these rocks would range in degree of metamorphism from the biotite zone to the staurolite zone. Barrow's position of the kyanite zone (between the staurolite and sillimanite zones) can not be considered correct, at least for the Mascoma quadrangle. The author believes that kyanite will form in lower zones of metamorphism than was recognized by Barrow.

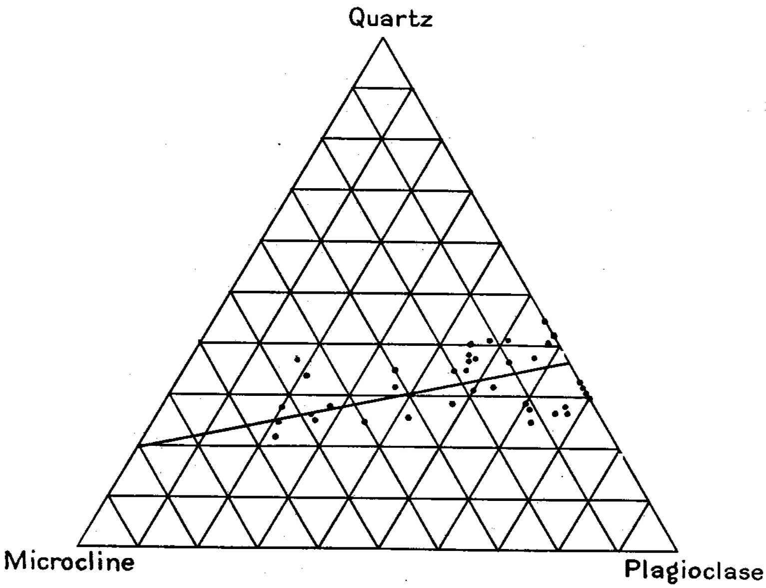


FIGURE 6.—*Plot of estimated modes of Mascoma group, biotite neglected*

MINERALOGICAL DATA

Amphibole.—Amphibole is present, in small amounts at least, in the metamorphic rocks throughout the area, and it remains stable up to the highest grades of metamorphism. Blue-green hornblende is the predominating type, and is most abundant in the femic rocks of the Ammonoosuc volcanics. The optics of several of these hornblendes are given in Table 3. There is a close resemblance between these hornblendes and an analyzed hornblende from the Littleton-Moosilauke area (see Lithology and Petrography of the Ammonoosuc Volcanics).

Chlorite.—Chlorite is apparently a stable mineral in the middle-grade zone, although most of it (penninite and ripidolite) has developed from other minerals through the process of retrograde metamorphism. Rocks of the Post Pond member, particularly those north of Gleason Cemetery in Plainfield Township, contain large quantities of chlorite and, in some cases, porphyroblasts of biotite. Muscovite is absent so these rocks must be low in potash. A little of the original chlorite combined with what muscovite was present to form the porphyroblasts of biotite, but the rest recrystallized into slightly larger and clearer-cut flakes. This chlorite, therefore, is stable in the biotite zone because there is no potash available to form biotite. In the black, garnet-mica schists of the Orfordville formation, probably of a little higher grade of metamorphism than those near Gleason Cemetery, part of the chlorite has been converted to garnet. Muscovite was absent so biotite could not form. This chlorite (thuringite) evidently is not stable in the upper part of the middle-grade zone. If biotite has not formed because of a lack of potash, chlorite will be transformed into garnet. Evidence in support of this statement will be given in the discussion on garnet.

Much of the chlorite (probably prochlorite) appears to be a late mineral, since it cuts across the schistosity, as can be seen in several thin sections of the Littleton and Orfordville schists. It occurs in sharply formed porphyroblasts and cuts flakes of biotite and muscovite. These chlorite porphyroblasts do not represent altered biotite crystals, because the rest of the biotite in the rock is fresh. It is apparently a higher temperature form of chlorite, and has developed like the porphyroblasts of any other mineral, or it may be a low-temperature chlorite which developed in large crystals during retrograde metamorphism.

The occurrence of chlorite (amesite) with muscovite in the kyanite schists in Plainfield Township would suggest that the reaction between muscovite and amesite to form phlogopite takes place at a higher temperature than does the reaction between muscovite and other chlorites to form biotite. Therefore, in the presence of muscovite, the magnesium-aluminum chlorite is more stable in higher zones of metamorphism than are the more common chlorites. Although these rocks contain kyanite, they do not represent the same grade of metamorphism as do the kyanite schists first described by Barrow (1912, p. 275).

Garnet.—Crystals of almandite occur up to an inch across and may be irregular or in well-formed dodecahedrons. Some are homogeneous, whereas others are inclusion-filled or highly skeletal. Inclusions consist mainly of quartz, feldspar, magnetite, and carbonaceous bands, and may be elongated parallel to the elongation of the garnet and the schistosity of the rock. Garnet seems to be a late mineral. It replaces bands of biotite, muscovite, and chlorite and may even replace well developed porphyroblasts of biotite. It is commonly seen replacing bands of biotite and muscovite in the high-grade zone. It occurs in staurolite crystals, but whether as an inclusion or as a replacing crystal is uncertain.

Masses of garnet a centimeter across appear to be homogeneous crystals in some of the Littleton and Orfordville schists, but microscopic study shows they are skeleton crystals enclosing quartz (see Pl. 4, fig. 2). The

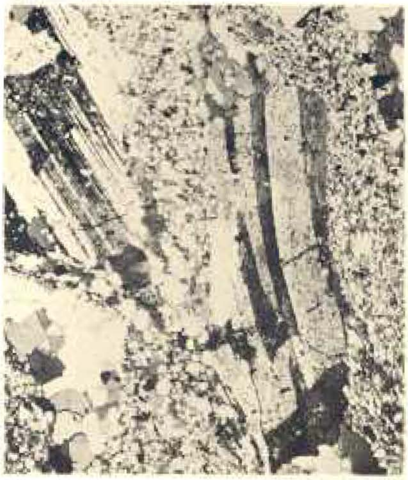


FIGURE 1. BENT CRYSTAL (INTRA-TELLURIC) OF OLIGOCLASE
In quartz-oligoclase-microcline gneiss (metamorphosed volcanic tuff) from Post Pond volcanic member. Nicols crossed (× 14).

FIGURE 2. CRYSTALS (INTRA-TELLURIC) OF QUARTZ AND OLIGOCLASE
In a quartz-oligoclase-muscovite schist (metamorphosed quartz latite tuff) from Post Pond volcanic member. Nicols crossed (× 14).

FIGURE 3. FEATHERY GROWTH OF KYANITE
In kyanite schist from Post Pond volcanic member. Large white grains are quartz. Groundmass is composed of quartz, muscovite, and chlorite (amesite). Nicols not crossed (× 14).

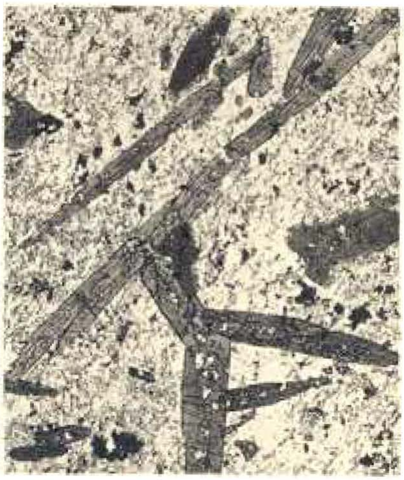


FIGURE 4. INCLUSIONS OF QUARTZ AND FELDSPAR IN CENTER OF HORNBLENDE NEEDLES
In a metamorphosed volcanic from the Post Pond volcanic member. Nicols not crossed (× 7).

PHOTOMICROGRAPHS OF ORFORDVILLE FORMATION

FIGURE 1. PORPHYROBLAST OF STAUROLITE
Surrounded by shell of chlorite and muscovite (alteration) in staurolite schist from Littleton formation. Dark band in staurolite is zone of inclusions (mostly quartz). Nicols crossed (× 14).

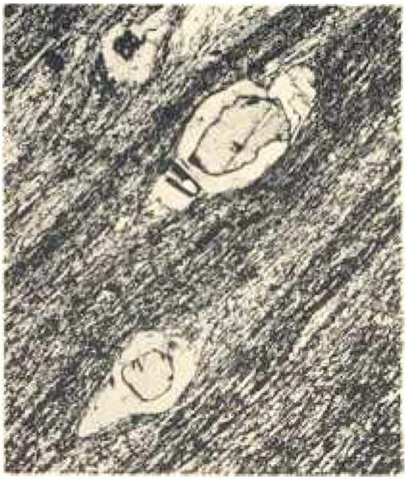


FIGURE 2. PORPHYROBLASTS OF GARNET
Surrounded by thick shells of chlorite (alteration) in mica schist from Littleton formation. Nicols not crossed (× 14).

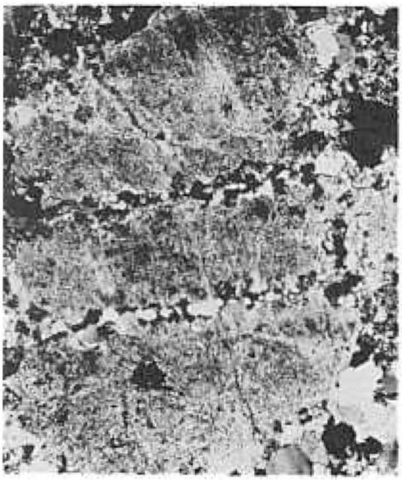


FIGURE 3. FRACTURED PHENOCRYST OF MICROCLINE
In Lebanon granite. Nicols crossed (× 14).

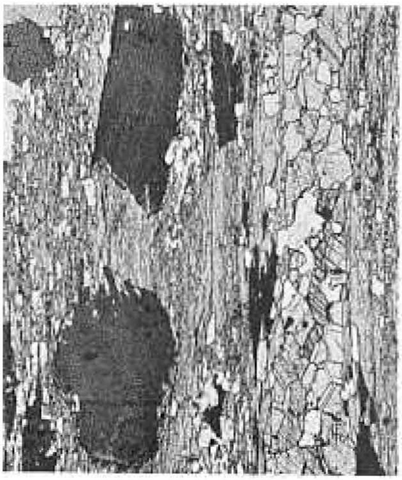


FIGURE 4. PORPHYROBLASTS OF BIOTITE
In layers containing fine-grained chlorite and muscovite in calcareous mica schist from Post Pond volcanic member. Nicols not crossed (× 19).

PHOTOMICROGRAPHS OF ORFORDVILLE AND LITTLETON FORMATIONS AND LEBANON GRANITE garnet seems to have grown at the expense of chlorite. As no white mica was present in the rock, biotite could not form, and the chlorite was transformed to garnet. The optics on the chlorite are $\beta = 1.653$, birefringence $= 0.006$, optically negative. According to Winchell (1936, p. 649), this indicates an iron-aluminum chlorite (thuringite) with very little magnesium. The index of the garnet is 1.806 and the specific gravity is 4.15. This, according to Winchell (1933, p. 176) is an iron-aluminum garnet (almandite) with a little magnesium and manganese. Such a similarity in composition suggests that the garnet could have formed from the chlorite.

Kyanite.—Kyanite is found in the upper part of the Post Pond member of the Orfordville formation. In the kyanite schists on Signal Hill in Lebanon Township, the kyanite is found only with quartz and muscovite. The rocks on either side of these schists, however, contain biotite, and in places a little garnet. This would indicate that the kyanite schists, here, are well within the middle-grade zone. Northeast of Gleason Cemetery in Plainfield Township, kyanite occurs with quartz, muscovite, and chlorite, but not biotite. It has already been shown how absence of biotite (or phlogopite) may be due, not to low temperature conditions, but to the composition of the chlorite. These rocks are in what is generally considered the biotite zone, but it takes a slightly higher temperature for this particular chlorite (amesite) to combine with the muscovite. The mineral kyanite, therefore, has formed in a much lower grade of metamorphism than first recognized by Barrow (1912, p. 275).

Sillimanite.—Sillimanite is found only in the Littleton formation in the highest grade of metamorphism. It occurs in rocks that are the high-grade equivalent of the staurolite schists. This mineral was one of the last to form as it replaces micas, quartz, feldspar, and garnet.

Staurolite.—Staurolite is restricted to the eastern half of the belt of the Littleton formation, between Mascoma Lake and Cornish. The crystals are usually in well-formed, stout prisms one-half to three inches long. There is a marked increase in size of the crystals as one proceeds from west to east across this belt. In many places the Littleton is composed of beds about a foot thick, some of which contain over a third staurolite whereas others contain little or none. This strongly suggests that staurolite was formed as a result of recrystallization of material already in the rock, and is not due to the introduction of material. Except for this mineral, the two types of beds closely resemble each other. Their chemical differences may lie mainly in the content of alumina. The presence or absence of staurolite cannot be explained as being due to differences in temperature or stress, because of this bedding relationship.

ROTATION OF PORPHYROBLASTS

Many porphyroblasts of biotite and garnet were rotated as a result of slight differential movement which continued after a schistosity had been produced. In some, rotation occurred contemporaneously with crystal growth, whereas in others it followed the formation of porphyroblasts. Evidence of rotation is most clearly seen where the minerals contain elongated inclusions or lines of inclusions, which were oriented parallel to the schistosity when they were enclosed and are now inclined to that schistosity. The fact that most porphyroblasts do not contain elongated inclusions or lines of inclusions and the fact that the plane of the thin section is not always parallel to the plane of rotation of the crystals leads one to believe that perhaps rotated porphyroblasts are much more common than is usually assumed.

The curved bands of inclusions indicate rotation during crystal growth for many of the biotite porphyroblasts, particularly in the Orfordville formation. The amount of this rotation has commonly been as much as 30°. In some specimens the basal cleavage of the biotite is at right angles to the lines of carbon inclusions. This would indicate that the porphyroblasts grew with their basal planes perpendicular to the bedding and schistosity. In the Orfordville schist, numerous porphyroblasts of biotite distort the schistosity, and give the rock a knotted appearance in hand specimen. In thin section the porphyroblasts are seen to be disk-shaped, with margins feathering-out into clear, recrystallized quartz. In spite of the fact that these porphyroblasts distort the schistosity, they originally must have replaced the rock in their entirety, because they contain wavy bands of carbon which represent crinkled bedding (Pl. 4, fig. 1). They may have been subjected to a later deformation which caused them to rotate slightly and distort the schistosity. Thus they might give the appearance of having originally displaced the schistosity. Most of these porphyroblasts show the effects of strain, which is further evidence of a late deformation. Indeed, many show a sharp bending of the cleavage. Several examples have been observed where biotite crystals have been ruptured, and one-half has been pushed far over the other so that the projecting ends distort the schistosity.

Rotated porphyroblasts of garnet are not so common as those of biotite, but they were observed in several thin sections. In one thin section garnets were seen, which contained curved lines of inclusions, indicating rotation during growth. The alignment of inclusions in the centers of these crystals, however, was parallel to the schistosity. It would seem, therefore, that the garnets had either been rotated back into place after formation, or else they had been rotated 180°.

ATTAINMENT OF EQUILIBRIUM

If during the course of progressive metamorphism, the reaction of lower temperature minerals to those of higher temperature is not complete, and equilibrium at a particular temperature and pressure is not attained, a progressive disequilibrium rock will be produced. Such a rock will contain minerals belonging to different zones of metamorphism, but this does not include those minerals formed by retrograde processes.

Some of the Orfordville schists, in which garnet has formed from chlorite, (thuringite) represent rocks of this type. These rocks were probably raised to a temperature above the range of stability for chlorite, and it was converted to garnet. For some reason, however, the reaction did not go to completion, and now both garnet and chlorite exist side by side in the same rock. One mile east of Lebanon Village, in a cut along a new road not shown on the accompanying map (Pl. 6), are schists in which large porphyroblasts of biotite are found imbedded in a fine-grained mixture of chlorite and muscovite. The biotite is scarcely altered, and it does not seem reasonable to suppose, therefore, that the chlorite could be retrograde (Pl. 3, fig. 4). These rocks were probably raised to the temperature where biotite started to form from the chlorite-muscovite mixture, but the conditions were not maintained long enough for all the muscovite and chlorite to react. Therefore, the reaction never went to completion, and a progressive disequilibrium rock was produced.

The two examples just cited are, perhaps, the most striking seen in the Mascoma quadrangle. It should be noted that progressive disequilibrium rocks may be much more common than is generally supposed. Our criteria for determining such rocks depend upon an accurate knowledge of the reactions which take place during metamorphism—a complicated subject in such multi-component systems.

In order to maintain equilibrium certain retrograde changes took place subsequent to the culmination of metamorphism. These changes were marked chiefly by the formation of lower temperature minerals from those of higher temperatures. Undoubtedly the most common effect of retrograde metamorphism is seen in the development of chlorite from biotite. Such a reaction necessitates the removal of potash, but, commonly, the titanium remains in the form of rutile needles enclosed in the chlorite. Chlorite, altered from fine-grained biotite, is common in the Littleton and Orfordville schists, and in some specimens this reaction has completely destroyed all the biotite, giving the rock the appearance of a low-grade type. Porphyroblasts of biotite are not so easily altered as are the finer flakes. The reason for this may be that the larger crystals offer a smaller surface for their size, than do innumerable smaller ones, and, therefore, are less subject to the attach of solutions essential to the process of chloritization. In the igneous rocks it is also common to find chlorite altered from biotite.

Somewhat less commonly garnet has altered to chlorite. This type of alteration has two particular modifications. The garnet may alter only along fractures within the crystal, or it may alter from the outside inward, thereby producing a protective chlorite shell (Pl. 3, fig. 2).

Crystals of staurolite are seen to be surrounded by a thick shell of muscovite in some specimens. In thin section this shell is clearly seen to have been derived from staurolite, and it is composed of large flakes of muscovite less than a millimeter across. Small amounts of chlorite are also present (Pl. 3, fig. 1). In extreme cases of retrograde metamorphism the whole crystal of staurolite has been converted to a mixture of muscovite and chlorite. Much of the kyanite in the belt of schists, extending north from Signal Hill, in Lebanon Township has been altered to muscovite. Although the kyanite may be completely muscovitized the outlines of the former crystals may still be seen in hand specimens. The transformations of both staurolite and kyanite to muscovite require the addition of potash, and are in a sense hydrothermal.

STAGES IN METAMORPHISM

It has already been shown how a definite schistose structure was developed in the sedimentary and volcanic rocks in the roofs of the Oliverian domes. This process of deformation is believed to have been accomplished by the aid of heat and solutions from the crystallizing magma, and the differential stresses set up by the particular mechanism of doming. It was contact metamorphism, in that heat and solutions from the Oliverian magma played a most important part; it was also dynamic, in that the roof rocks were compressed in a vertical direction and stretched radially in a horizontal direction.

At some time previous to the period of folding or during an early stage of folding, a schistose structure seems to have been developed on some of the rocks of the Orfordville formation. This structure was parallel to the bedding and may have formed merely by the recrystallization of micaceous material at low temperatures, under the weight of thousands of feet of sediments. Noll (1932) has shown that muscovite may crystallize from jell-like substances at temperatures as low as 225° C., and Barth (1936, p. 780) states

> ". . . as the rate of crystallization is slow and as no long runs were made by Noll, probably the low-temperature limit is even lower."

It is conceivable, therefore, that without any heat other than that given by the thermal gradient the micaceous material, in the presence of some connate water, would crystallize to form muscovite. Under the weight

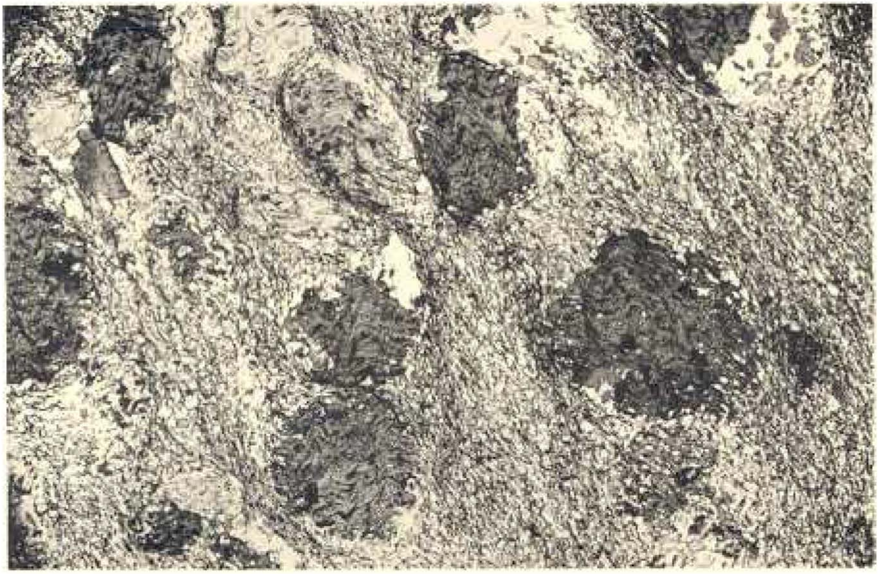


FIGURE 1. PORPHYROBLASTS OF BIOTITE
Enclosing wavy bands of carbonaceous material (probably original bedding) and distorting schistosity in mica-quartz schist from Orfordville formation. Nicols not crossed (× 19).

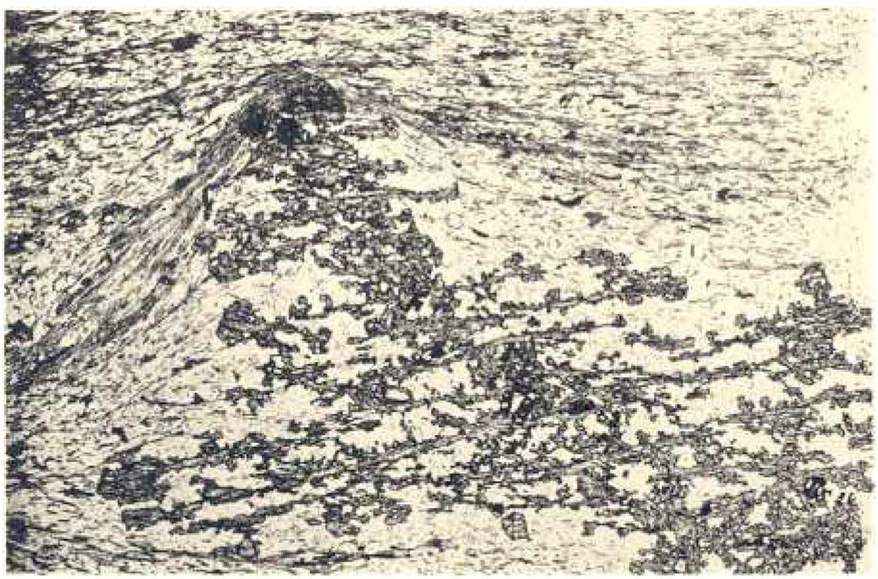


FIGURE 2. SKELETAL GROWTH OF GARNET AND DISTORTION OF MICA LAYERS
In mica-quartz schist from Orfordville formation. Nicols not crossed (× 19).

PHOTOMICROGRAPHS OF ORFORDVILLE FORMATION

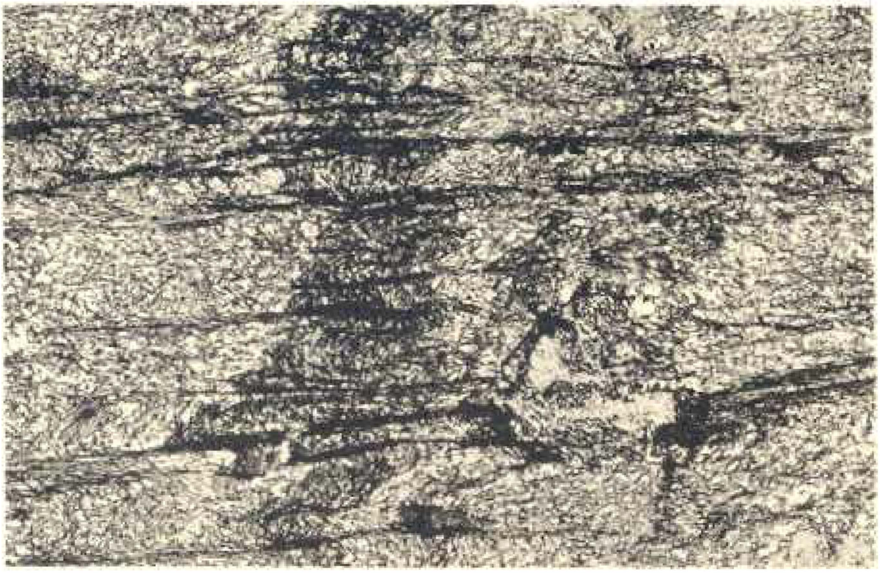


FIGURE 1. "SLIP CLEAVAGE" AT RIGHT ANGLES TO BEDDING
In mica-quartz schist from Orfordville formation. Traces of an older schistosity may be seen parallel to bedding (vertical). Micas of old schistosity have been bent and curved. Nicols not crossed (X 30).

FIGURE 2. "SLIP CLEAVAGE" AT RIGHT ANGLES TO BEDDING
In mica-quartz schist from Orfordville formation. Garnet crystal in center replaces rock. Where garnet replaces mica of shear zones, inclusions are absent but abundant elsewhere. Some traces of older schistosity may be seen parallel to bedding (horizontal). Nicols not crossed (X 12).

PHOTOMICROGRAPHS OF ORFORDVILLE FORMATION

of at least 11,000 feet of sediment, a schistose structure might be produced parallel to the bedding.

This original schistosity has been lost in most places, but it has been observed where the regional schistosity cuts across the bedding, as for example on the nose of a fold. Elsewhere the two schistosities are probably parallel. In one specimen, taken at the nose of a fold, the regional schistosity was actually a "slip-cleavage," developed at right angles to the bedding. Displacement along these cleavage planes caused a "slip folding" of the bedding and older schistosity (Pl. 5, fig. 1). The micas have been recrystallized along the new planes of shear, but elsewhere they have been somewhat rotated from their original position. The earlier schistosity and the bedding can still be traced across the thin section. Garnet crystals up to a millimeter across are abundant, and seem to have replaced only the mica (Pl. 5, fig. 2). That part of the garnet crystal in the shear zone is homogeneous, because this zone originally contained only mica. Those parts of the garnet crystal outside the shear zone, however, are filled with inclusions of quartz. Here the garnet replaced only the mica, and left the quartz as inclusions. By this process of selective replacement both early and late structures are preserved in the porphyroblasts.

As folding continued after the development of the Northey Hill thrust, a regional schistosity was developed upon the sedimentary and volcanic rocks of western New Hampshire. Billings (1937, p. 557) has shown that since the degree of folding and depth of burial of these rocks was nearly uniform throughout the region, one must explain the marked increase in metamorphism toward the southeast as due to the proximity of large igneous bodies which were intruded in the late stages of folding. These plutonic bodies belong to the New Hampshire magma series and are represented chiefly by the Bethlehem gneiss and Kinsman quartz monzonite (Billings, 1937, p. 506). The main rôle of these intrusives was to furnish heat and solutions, and aided by differential stresses, a progressive increase in the intensity of metamorphism toward the southeast was accomplished. There is no indication that much magmatic material was introduced, and it seems correct to assume that only water and heat were necessary for the rearrangement of material already present in the rocks.

This will explain the middle-grade and high-grade rocks in the Mascoma quadrangle. The most intense metamorphism occurred in the Littleton schists in the southeastern part of the quadrangle where the rocks lay between the two plutonic masses of the New Hampshire magma series.

TECTONIC SUMMARY AND CONCLUSIONS

Sometime after the deposition of the Littleton formation, the Oliverian magma series was intruded to form laccoliths in the upper part of the

Ammonoosuc volcanics, along what is now known as the Bronson Hill anticline. With the formation of these intrusive bodies, a schistosity developed in the roof sediments, parallel to the bedding, and contemporaneously, in the igneous rocks, a foliation was produced. The schistosity and foliation were parallel and concentric. Perhaps at the same time a stock-like mass, composed of the Lebanon group, was intruded into the Post Pond volcanics. The upward push of the magma, as in the case of the laccoliths, domed and metamorphosed the roof sediments, and produced a concentric foliation in the igneous rock itself. A later intrusion formed the central core of Lebanon granite. This granite is less gneissic, but shows effects of granulation.

During the late Devonian folding began and the Salmon Hole Brook syncline was formed. Eventually the eastern limb of the syncline broke and the Northey Hill thrust developed. The whole western block was relatively overthrust to the east and came to rest high upon the flank of the Bronson Hill anticline. The fault plane itself became crumpled as folding continued after thrusting, and the intensely contorted sediments were dynamically metamorphosed. During the early stages of folding the roofs of the Oliverian domes were crumpled. These igneous bodies must have protected the immediately surrounding rocks from crumpling to a considerable extent, but the effects of regional folding penetrated, for at least a short distance, down into the domes. The folded Clough formation and the Ammonoosuc volcanics on the Croydon dome are illustrative of the effect of a later folding on the roof rocks. Where folding was most intense, as on the southwestern flank of the Mascoma dome, the rocks were isoclinally folded. The superposition of a regional schistosity on the rocks surrounding the Lebanon intrusive destroyed most signs of any previous structure, and to a certain extent, the effects of this dynamic metamorphism extended down into the border gneiss.

Potash-rich solutions are believed to have risen from below the Mascoma dome, and to have replaced much of the original quartz diorite and granodiorite with metacrysts of microcline. Thus, these igneous rocks are believed to have been converted into rocks with compositions equivalent to quartz monzonite and granite. The solutions penetrated, for a few hundred feet, out into the Clough formation on Moose Mountain, converting the quartzite to a rock with the composition of granite.

Near the close of the period of folding, the Bethlehem gneiss (New Hampshire magma series) was intruded, as a huge sheet, at the base of the Littleton formation. Developing a foliation more or less parallel to its walls, it forced its way up over the northern end of the Croydon dome and the southern end of the Mascoma dome, and down the western flank of the Bronson Hill anticline. While some shearing stresses still persisted, the heat and solutions (chiefly water) from this crystallizing mass and others farther east in New Hampshire are supposed to have raised the temperature of the rocks in the Mascoma quadrangle, and produced rocks characteristic of the middle grade zone of metamorphism. The rocks of the Littleton formation, which lay between the Bethlehem gneiss on the west and the slightly younger mass of Kinsman quartz monzonite on the east, were raised to the temperature conditions characteristic of high-grade metamorphism. As a result, the alumina-rich beds were converted to sillimanite schists and the rocks as a whole developed a much coarser texture.

Perhaps in Carboniferous time numerous dikes and two small bodies of the White Mountain magma series were intruded. It was not possible to determine the period of formation of the normal fault extending from Enfield Village to past North Grantham. The fault is probably younger than late Devonian as it displaces the Bethlehem gneiss which is believed to be of that age.

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