METAMORPHOSED MAFIC DIKES OF THE WOODSVILLE QUADRANGLE, VERMONT AND NEW HAMPSHIRE

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ABSTRACT

Metamorphosed mafic dikes in the Woodsville quadrangle, Vermont and New Hampshire, intrude metasedimentary and metavolcanic rocks ranging from Middle Ordovician to Early Devonian. The mafic dikes are probably Late Devonian. The grade of metamorphism in the metasedimentary and metavolcanic rocks ranges from low-grade (chlorite zone) to high-grade (sillimanite zone). The metamorphosed mafic dikes, many of which were presumably diabases before metamorphism, now show seven principal mineral assemblages as well as several transitional types.

In the chlorite zone the metamorphosed mafic dikes are now characterized by five significant mineralogical assemblages. One of these assemblages, the metadiabases, represent rocks that preserve relics of the original igneous minerals; these rocks did not attain equilibrium in the chlorite zone. A second group, the albite-actinolite-epidote-chlorite rocks, represent a stable assemblage to which no carbon dioxide was added during metamorphism. A third assemblage, the albite-chlorite-epidote-calcite-actinolite schists, represent rocks to which some carbon dioxide was added during metamorphism. A fourth group, the albite-chlorite-calcite schists are rocks to which so much carbon dioxide was introduced that all the lime was utilized to make calcite except for the small amount of lime that went into albite. A fifth assemblage, the albite-chlorite-ankerite schists are rocks into which so much carbon dioxide was introduced that some iron and magnesia as well as all the lime, except that present in the albite, went into carbonate.

Albite-epidote amphibolites formed in a belt lying in the higher grade part of the chlorite zone and in the biotite zone; but there are also many green schists in this same belt. Amphibolites developed in the higher grade part of the garnet zone and in the staurolite and sillimanite zones.

INTRODUCTION

Metamorphosed mafic dikes and sills are common throughout eastern Vermont and western New Hampshire. These rocks, as well as the metasedimentary and metavolcanic rocks into which they are intruded, show a great range in the grade of metamorphism. Consequently, an excellent opportunity is available to investigate the mineral assemblages in equilibrium in metamorphosed mafic rocks under a wide range of physical conditions.

The Woodsville quadrangle covers an area of about 210 square miles in east-central Vermont and west-central New Hampshire between north latitudes 44°00′ and 44°15′ and west longitudes 72°00′ and 72°15′. The structure, stratigraphy, and metamorphism of this area has been described elsewhere (White and Billings, 1950). It will suffice here to say that the metasedimentary and metavolcanic rocks range from Middle Ordovician to Early Devonian and are approximately 35,000 to 40,000

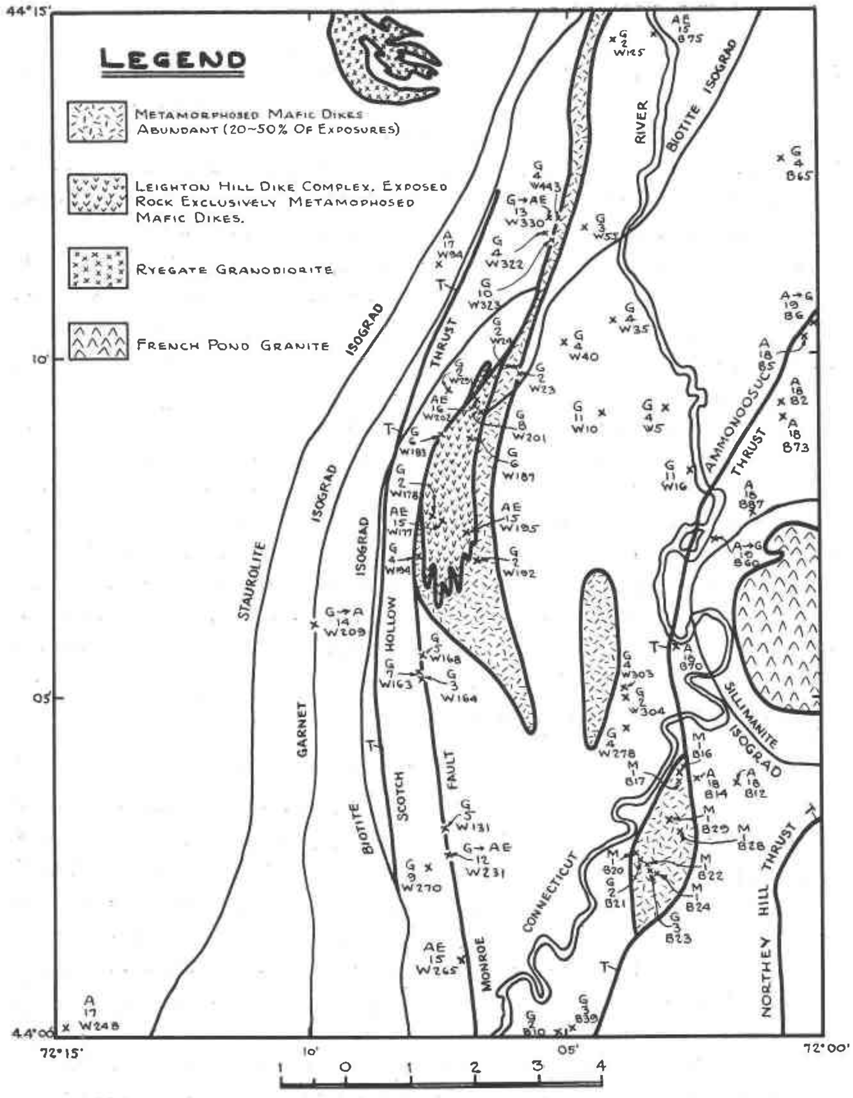

FIG. 1.—*Location of Metamorphosed Mafic Dikes Studied Microscopically in the Woodsville Quadrangle.* Principal faults and isograds are labelled. In the eastern part of quadrangle the biotite, garnet, and staurolite isograds coincide with the Ammonoosuc thrust because the chlorite and staurolite zones have been brought together. Location of each metamorphosed mafic dike studied in thin section is shown by a cross. Each cross is accompanied by letters and numerals. The upper capital letter indicates the grade of metamorphism: *M*=metadiabase, *G*=green schist facies, *AE*=albite-epidote amphibolite facies, *A* =amphibolite facies; transitional types are shown by horizontal arrow. The intermediate numeral indicates the mineral assemblage in the dike and corresponds to columns in Table 1. The lowest letter and number indicates specimen number; those preceded by *W* were collected by White, those preceded by *B* were collected by Billings.

feet thick. Plutonic rocks, which are not abundant, have been mapped as the French Pond granite and the Ryegate granodiorite (Fig. 1). Three major faults divide the area into four tectonic units; these faults from east to west are the Northey Hill, Ammonoosuc, and Monroe (Fig. 1). The rocks in the various blocks are intensely folded. The orogeny and the metamorphosed mafic dikes are probably late Devonian.

A belt of low-grade metamorphism (chlorite zone of the British classification, green-schist facies of Eskola's classification) extends northeasterly from the south-central margin of the quadrangle to the northeast corner. The grade of metamorphism increases both to the east and west; along the west and east margins of the quadrangle the rocks show middle-grade and high-grade metamorphism (staurolite and sillimanite zones of the British classification, amphibolite facies of Eskola's classification.)

West of the belt of metasedimentary rocks in the chlorite zone there is a progressive increase in the grade of metamorphism. The biotite, garnet, and staurolite isograde appear in orderly succession (Fig. 1). East of the belt of rocks in the chlorite zone some of the metamorphic zones have been eliminated along the Ammonoosuc thrust because rocks in the chlorite zone on the west have been thrust over rocks in the staurolite zone on the east. The metasedimentary rocks around the French Pond granite lie in the sillimanite zone.

PETROGRAPHY OF THE MAFIC ROCKS

General Statement.—Metamorphosed mafic dikes are present throughout the Woodsville quadrangle, but are far more abundant in some places than in others. East of the Ammonoosuc thrust they nowhere constitute more than a few per cent of the bedrock. West of this thrust they make up 15 per cent or more of the bedrock in much of the area between the Ammonoosuc and Monroe faults. Areas where they are even more abundant, making up 20 to 50 per cent of the bedrock, are shown in Fig. 1 by a special symbol.

An area of extraordinary dike intrusion in the center of the quadrangle has been distinguished on Fig. 1 as the Leighton Hill dike complex. In this area all the outcrops are metamorphosed mafic rocks, and no exposures of metasediments were encountered. Outcrops a few tens of feet apart generally contain rocks of different structure and texture. Locally contacts between different types may be observed. For this reason the rocks in this area are believed to represent a dike complex rather than a single massive body of metamorphosed igneous rock. The eastern and southern boundaries of the area as mapped are gradational, but the western boundary is abrupt.

The metamorphosed mafic dikes are uncommon west of the Monroe fault. A few were observed within a mile of the fault, but farther west they are rare.

The dikes range in width from a fraction of an inch up to as much as 50 feet. Most of them are parallel to the schistosity of the adjacent country rock. They characteristically crosscut the bedding. Although a few appear to be folded, many of them truncate the fold axes. Some that are parallel to the bedding are technically sills, but to conserve space all the intrusives will hereafter be referred to as dikes.

General lithologic features.—The metamorphosed mafic dikes show an extraordinary diversity in color, structure, texture and mineralogy. They are gray, dark-green, or black. In general, dikes over 10 feet thick are massive, whereas the thinner dikes are schistose. Some thick dikes have massive interiors bordered by schistose margins. In many of the massive dikes relic phenocrysts are preserved; originally plagioclase, augite, or hornblende, these phenocrysts are now plagioclase, hornblende, epidote, or some other secondary mineral. A coarse texture in some rocks, especially in the Leighton Hill dike complex, is considered to be a relic from the original igneous rock. Although the texture of many of the rocks is lepidoblastic or granoblastic, some are ophitic or hypidiomorphic granular.

The mineralogy is also very varied. This is due primarily to differences in the grade of metamorphism and to changes in chemical composition during metamorphism, chiefly variations in the amount of introduced carbon dioxide. Theoretically in an area such as this, where the metasedimentary rocks show progressive metamorphism from the chlorite zone to the sillimanite zone, the metamorphosed mafic rocks should similarly range from green schists through albite-epidote amphibolites to amphibolites (Turner, 1948,p. 76–98). In general, this expectation is fulfilled. Although chemical changes and structural differences introduce numerous complications, the classification of the metamorphosed mafic rocks adopted here is primarily mineralogical. Nevertheless, the detailed classification used in this paper has a genetic basis that is presented in the section dealing with metamorphism. Although many hundreds of dikes were observed in the field, hand specimens were collected for only about 100. From these, 57 thin sections were prepared and studied to form the basis of the paper. The location and lithology of those dikes studied in thin section are shown on Fig. 1. The reader should not be misled into thinking that the dikes are more abundant near the faults. The distribution merely indicates that the dikes were more intensively studied in these areas in order to compare them on opposite sides of the faults.

The metamorphosed mafic rocks may be grouped into four main cate-

TABLE 1. ESTIMATED MODES OF METAMORPHOSED MAFIC DIKES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Number of sections	7	9	4	9	2	2	1	1	1	1	2	1	1	1	4	1	2	6	2
Quartz	6	1	10	5	13		5	25	20	35	40		20	30		5	23	2	3
Plagioclase	33	26	28	35	30	11	5	5		25	x	30	25	30	35	25	28	38	45
Actinolite	30†	32	3			79	45	10	33										
Hornblende												30	10	10	42	65	40	48	
Epidote*	15	23	15	1	1	8	x	60		10	3	5	5		14	1	x	4	4
Chlorite	8	15	32	43	27		40		5	10	40	25	25	20	2		1	3	30
Calcite	1	t	10	14		1			17		13		10	10			3	1	12
Ankerite					23														
Biotite	1	1	t	1					23	20			5		1	2	4	t	
Muscovite				1	6				2						t				
Sphene	t	1	t	t	x		x	x	x				x		1		x	1	1
Leucoxene	1	1	2	t	x	1	2	x			2	10			1			t	2
Apatite	x	t	t					x	x			x	x	x		x	x		
Rutile	t			t															
Magnetite		t	t	t	x			x		x			x	x	3	2	x	1	
Ilmenite	3	x	t	t	x		3	x							1		x	1	1
Pyrite	1	t		t			x				x	x		x	t			1	
Garnet																		1	
Allanite									x										
Sericite	1																		2
Per cent of anorthite in plagioclase	27 (12–35)	9 (5–12)	7 (0–10)	3 (0–10)	5 (0–10)	2 (0–3)	2	10	0	0	?	0	0	16	4 (0–10)	0	33 (15–52)	35 (30–65)	10

* Includes clinozoisite.
† Includes some hornblende.
x—Present in 50 per cent or more of thin sections.
t—Present in less than 50 per cent of thin sections.
Blank—Not seen in any of thin sections.

1. Metadiabase.
2. Albite-actinolite-epidote-chlorite rock.
3. Albite-chlorite-epidote-calcite-actinolite schist.
4. Albite-chlorite-calcite schist.
5. Albite-chlorite-ankerite schist.
6. Actinolite schist.
7. Actinolite-chlorite schist.
8. Epidote-quartz rock.
9. Actinolite-biotite-calcite schist.
10. Quartz-albite-biotite schist.
11. Quartz-chlorite-calcite schist.
12. Albite-chlorite-hornblende schist; transition from green schist facies to albite-epidote amphibolite facies.
13. Chlorite-quartz-albite-hornblende schist; transition from green schist facies to albite-epidote amphibolite facies.
14. Quartz-andesine-chlorite-calcite-hornblende schist; transition from green schist facies to amphibolite facies.
15. Albite-epidote amphibolite.
16. Albite amphibolite.
17. Quartz amphibolite in western part of quadrangle.
18. Amphibolite in eastern part of quadrangle.
19. Albite-chlorite-calcite rock, retrogressed from amphibolite, directly east of Ammonoosuc thrust.

gories, although various transitional types occur: (1) metadiabases; (2) green schist facies; (3) albite-epidote amphibolite facies; and (4) amphibolite facies.

Metadiabase.—The metadiabase might equally well be called metadolerite or metagabbro. These rocks are confined to a small area in the southeast corner of the quadrangle between the Ammonoosuc thrust and the Connecticut River, although elsewhere, notably in the Leighton Hill dike complex, some of the rocks locally retain textural relics suggestive of metadiabase. The metadiabases are gray, dark-green, or yellowish green. Although the texture of some is ophitic, more commonly it is hypidiomorphic granular. The grains generally range from 0.5 to 2 mm. in maximum dimension, but plagioclase phenocrysts 4 mm. long are common and some are 10 mm. long. In the hypidiomorphic rocks the dark minerals tend to be euhedral to subhedral whereas the plagioclase tends to be anhedral, molding around the dark minerals. Such rocks are difficult to distinguish in the field from the massive amphibolites and massive albite-epidote amphibolites. In fact, the general mineralogy of the metadiabases is not unlike that of the amphibolites and albite-epidote amphibolites; only microscopic study distinguishes the metadiabases from the albite-epidote amphibolites.

An average mode of seven thin sections of metadiabase is given in Table 1, column 1. The essential minerals are calcic oligoclase or sodic andesine, amphibole, epidote or clinozoisite, and chlorite. The various minerals are intergrown and overlap in a complex way. Although in most specimens the plagioclase is unzoned, in some it shows normal zoning with the cores more calcic than the peripheral shell.

Two kinds of amphibole are present. One has the following optical properties: biaxial negative, $2V=65^\circ \pm 5^\circ$; $Y=b$, $Z \wedge c=18^\circ$; $X=$light-yellow, $Y=$ light-yellowish-green, $Z=$blue-green; $X<Y<Z$; $\alpha=1.660$ (1.655–1.666), $\beta=1.672$ (1.667–1.679), $\gamma=1.680$ (1.673–1.686). The optical properties are so similar to an analyzed common hornblende from an intrusive amphibolite in the Littleton-Moosilauke area (Billings, 1937, p. 513) that this amphibole is considered to be common hornblende with an average alumina content of about 10 per cent. In other specimens the amphibole is colorless or only slightly colored in thin section; it is fibrous in some specimens but massive in others. The optical properties are: biaxial negative, $2V=60^\circ$, $Y=b$, $Z \wedge c=18^\circ$; $X=$colorless, $Y=$very light yellowish-green, $Z=$light-blue; $X<Y<Z$; $\alpha=1.634$ (1.632–1.636), $\beta=1.647$ (1.646–1.648), and $\gamma=1.656$ (1.655–1.657). These data suggest an amphibole that is essentially actinolite, but containing several per cent of alumina. Perhaps it should be called actinolitic hornblende. But for brevity it will be called actinolite in accordance with the usage

followed by Turner (1948, p. 94). Some geologists, such as Wiseman (1934), prefer to call it hornblende. The curves prepared by Foslie (1945) suggest that the ratio $MgO/2Fe_2O_3+FeO+MnO+MgO$ (in molecular per cents) averages 0.67, but ranges from 0.70 to 0.64. The same ratio in an amphibole with similar indices and analyzed by Wiseman (1934, p. 368) is 0.57; the alumina content is 2.35.

Green schist facies.—Rocks with mineralogical assemblages characteristic of the green schist facies occupy a belt three to six miles wide between the Ammonoosuc thrust and a line half a mile west of the Monroe fault. The western mile of this belt, however, also contains some dikes with mineral assemblages indicative of the albite-epidote amphibolite facies, which is discussed on a later page.

The principal rocks in the green schist facies have been assigned to four categories: (1) albite-actinolite-epidote-chlorite rocks, (2) albite-chlorite-epidote-calcite-actinolite schists, (3) albite-chlorite-calcite schists, and (4) albite-chlorite-ankerite schists. Average modes are given in Table 1, columns 2, 3, 4, and 5. It will be shown later that this is a single isophysical series of rocks of differing chemical composition. Initially all the rocks had essentially the same chemical composition, but it was subsequently changed by the introduction of varying amounts of carbon dioxide.

The albite-actinolite-epidote-chlorite rocks are gray, dark-gray, or dark-green rocks. They are commonly massive, rarely schistose; of the nine specimens listed in Table 1, column 1, 7 are massive, 1 is slightly schistose, and 1 is schistose. The plagioclase is albite-oligoclase. The amphibole has the following optical properties: X = colorless, Y = colorless or very light green, and Z = colorless or very light blue-green; $\alpha = 1.629$ (1.619–1.635) $\beta = 1.642$ (1.632–1.648), and $\gamma = 1.654$ (1.645–1.661). It is considered to be actinolite with a small amount of alumina. The curves prepared by Foslie (1945) suggest that the ratio $MgO/Fe_2O_3+FeO+MnO+MgO$ in molecular per cents averages 0.67, but ranges from 0.80 to 0.60.

A problem in nomenclature is introduced by these rocks. They are identical with the actinolitic greenstones of Vogt (Barth, Correns, and Eskola, 1939, p. 356) and assemblage #7 of Turner (1948, p. 94). As shown by the average mode the most abundant mineral is amphibole and in this sense they are amphibolites. However, in all other respects they are unlike true amphibolites, inasmuch as they have considerable epidote and chlorite, the plagioclase is highly sodic, and the amphibole is actinolite. Moreover, because of the facies classification, the term amphibolite is generally restricted to rocks composed chiefly of intermediate plagioclase and common hornblende, relatively rich in alumina.

The albite-chlorite-epidote-calcite-actinolite and albite-chlorite-calcite schists are greenish-gray or dark-green. Of 13 specimens listed in Table 1, columns 3 and 4, all but one are schistose.

The albite-chlorite-ankerite schists are green to dark-green schistose rocks with ankerite porphyroblasts, 0.5 to 1.5 mm. in diameter, which are pink to light-brown where fresh but weather to chocolate-brown limonite. They are extensively developed in the Littleton-Moosilauke area (Billings, 1937, p. 512).

Modes of some uncommon rocks found in the green schist facies of the Woodsville quadrangle are given in Table 1, columns 6, 7, 8, 9, 10, and 11.

Albite-epidote amphibolite facies.—These rocks are confined to a belt one to two miles wide in the vicinity of the Monroe fault (Fig. 1). They are dark-yellow-green, dark-gray, and black; some are massive, some are schistose, and some even preserve a relic ophitic texture. The essential minerals are albite, amphibole, and epidote; the average mode of 4 speci- is given in Table 1, column 15. The optical data for the amphibole in one of these specimens are: biaxial negative, $2V=65°$; X=light-yellow, Y=brownish-green, Z=blue-green; $X<Y<Z$; $\alpha=1.651$, $\beta=1.664$, and $\gamma=1.673$; $Z\wedge c=19°$. These data suggest a common hornblende similar to that analyzed in the Littleton-Moosilauke area (Billings, 1937, p. 513), in which the ratio $MgO/2Fe_2O_3+FeO+MnO+MgO$ (in molecular proportions) is 0.55. This is also in close agreement with the curve given by Foslie (1945) for hornblende in the albite-epidote amphibolite facies. Foslie believes that in these hornblendes the alumina substitutes in part for silica and in part for the magnesium-iron-manganese group in the space lattice.

A few specimens, from the vicinty of the Monroe fault, apparently represent a transition from the green schist facies to albite-epidote amphibolite. Representative modes are given in Table 1, columns 12 and 13. Like the rocks in the green schist facies, they have considerable chlorite and albite. But the amphibole is apparently common hornblende, because the optical properties are: X=light-yellow, Y=light-yellow-green, and Z=bright blue-green; $\alpha=1.663$, $\beta=1.674$, and $\gamma=1.684$.

Amphibolite facies.—The amphibolites have been most extensively studied in the area east of the Ammonoosuc thrust. Here they are massive or weakly schistose, speckled black and white rocks which in some outcrops have plagioclase phenocrysts 1 to 5 mm. long. In some specimens the groundmass is so dense that the individual minerals can be recognized only by the aid of a hand lens, in others the hornblende occurs as black needles 1 to 7 mm. long, surrounded by small white grains of feldspar 1 to 4 mm. in diameter.

Microscopic study shows that essential minerals are intermediate plagioclase (andesine or labradorite) and common hornblende; an average mode is given in Table 1, column 18. In the non-porphyritic specimens the plagioclase is uniform within a single hand specimen, but ranges from An_{30} to An_{42} in different specimens. The hornblende is in needles flattened parallel to the front pinacoid, encloses other minerals poikilitically, and has the following optical properties: biaxial negative, $2V=60°$; X = light-yellow, Y = brownish-green, and Z = blue-green; $X<Y<Z$; $\alpha=1.655$ (1.649–1.660), $\beta=1.666$ (1.659–1.671), and $\gamma=1.675$ (1.669–1.680); dispersion, low; $Z\wedge c=20°$. These data are very similar to those obtained from common hornblende in the Littleton-Moosilauke area (Billings, 1937, p. 513 and 556).

West of the Ammonoosuc thrust the amphibolites are confined to that part of the quadrangle west of the garnet isograd (Fig. 1). An average mode is given in Table 1, column 17. The amphibole is apparently common hornblende, as the indices are $\alpha=1.655$, $\beta=1.665$, and $\gamma=1.675$.

One specimen (Table 1, column 14) is considered to be a transitional variety from the green schist facies to the amphibolite facies. It is rich in chlorite, indicative of the green schist facies, but the plagioclase is fairly calcic and the amphibole is common hornblende; the indices are: $\alpha=1.654$, $\beta=1.666$, $\gamma=1.676$. The hornblende is younger than the chlorite, for the former cuts across the schistosity defined by the latter.

Metamorphism of Mafic Dikes

General Statement.—In the description of the mafic dikes it was pointed out that many rocks, now mineralogically and chemically different, were originally diabase. The diabase is now represented by at least 7 different mineralogical assemblages; moreover, these rocks possess numerous textural and structural differences. It is the purpose of this section of the paper to inquire into the processes whereby originally similar rocks became so diversified. The three principal factors causing this diversification were: (1) differences in physical conditions during metamorphism, indicated by the progressive metamorphism; (2) changes in chemical composition, chiefly due to the introduction of carbon dioxide; and (3) differences in structural behavior and history.

Metadiabases.—The average mode of the metadiabases of the Woodsville quadrangle is repeated in Table 2, column 1. The essential minerals are calcic oligoclase, amphibole, epidote, and chlorite. The amphibole is both hornblende and actinolite. For comparison, the average mode of 24 metadiabases from the White Mountain magma series in the Mt. Washington quadrangle (Fowler-Billings, 1944, p. 1263) is given in Table 2, column 2; the essential minerals are labradorite and hornblende. The hornblende is secondary after pyroxene, probably due to late magmatic

TABLE 2. MODES OF METAMORPHOSED DIABASE

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Quartz	6	1		1	3	11	10	16	5	16	13				2
Plagioclase	33	55	32	26	35	31	28	30	35	29	30	32	35	39	38
Actinolite	30†		28	32	27	10	3								
Hornblende		20										58	42	61	48
Chlorite	8	6	18	15	12	30	32	37	43	33	27		2		3
Epidote*	15		22	23	14	9	15		1		1	10	14		4
Calcite	1	4			3	9	10	16	14						1
Ankerite										18	23				
Biotite	1	3		1	2				1				1		
Muscovite								1	1	4	6				
Pyroxene		3													
Leucoxene	1	1					2						1		
Magnetite		2											3		1
Ilmenite	3	4			1								1		1
Pyrite	1	1													1
Sphene				1	1								1		1
Sericite	1				2										
Per cent of anorthite in plagioclase	27	57	10	9	5	10	7	10	3	10	5	10	4	26	35

* Includes clinozoisite.

† Includes some hornblende.

1. Average mode of 7 metadiabases, Woodsville quadrangle.
2. Average mode of 24 metadiabases of White Mountain magma series, Mt. Washington quadrangle (K. Fowler-Billings, 1944, p. 1263).
3. Calculated mode of Daly's average diabase metamorphosed to green schist facies without introduction of carbon dioxide.
4. Average mode of 9 albite-actinolite-epidote-chlorite rocks, Woodsville quadrangle.
5. Average mode of Moulton diorite, Littleton-Moosilauke area (Billings, 1937, p. 503).
6. Calculated mode of Daly's average diabase metamorphosed to green schist facies with introduction of 4.4 weight per cent of carbon dioxide, mode recalculated to 100 per cent.
7. Average mode of 4 albite-chlorite-epidote-calcite-actinolite schists, Woodsville quadrangle.
8. Calculated mode of Daly's average diabase metamorphosed to green schist facies with addition of 7.25 weight per cent of carbon dioxide; mode recalculated to 100 per cent.
9. Average mode of 9 albite-chlorite-calcite schists, Woodsville quadrangle.
10. Calculated mode of Daly's average diabase metamorphosed to green schist facies with introduction of 8.8 weight per cent of carbon dioxide; mode recalculated to 100 per cent.
11. Average mode of 2 albite-chlorite-ankerite schists, Woodsville quadrangle.

hydrothermal alterations (Fowler-Billings, 1944, p. 1271). The metadiabases of the Woodsville quadrangle are more extensively altered. The original plagioclase, presumably labradorite, has gone to calcic oligoclase, thus releasing considerable anorthite to form epidote. Much of the hornblende has gone to actinolite. The metadiabases of the Woodsville quadrangle are well on the way to a mineralogical assemblage characteristic of the green schist facies, but have not fully acquired the mineralogical characteristics of that facies. These changes must have taken place during the regional metamorphism.

The restriction of the metadiabases to a relatively small area demands explanation. The adjacent metasedimentary rocks in this area are hornfelses, apparently due to the abundance of the mafic dikes. The resulting rigid block resisted deformation more than the sedimentary rocks in other parts of the quadrangle. Possibly the temperatures were also lower here during the metamorphism than elsewhere in the area. If rigidity of the rocks were the sole explanation, one might expect the metadiabases to be even more abundant in the Leighton Hill dike complex. Some of the mafic dikes in that complex do preserve relics of ophitic and hypidiomorphic granular textures. But the isograds suggest that the temperature during metamorphism was somewhat higher in the region occupied by the Leighton Hill dike complex and thus conditions were favorable for more complete metamorphism.

Green schist facies.—The writers have calculated the expected mineralogy of an average diabase (Daly, 1933, p. 18) when metamorphosed under various conditions. The results are given in Table 2, columns 3, 6, 8, 10, 12, and 14. For these calculations TiO_2 and H_2O were neglected and Fe_2O_3 was converted to FeO. Water was also neglected, on the assumption that it was always available in sufficient quantity to form whatever minerals were demanded by the physical conditions. No attempt was made to calculate the amount of such minor minerals such as sphene, ilmenite, magnetite, or pyrite. It is obvious that the calculated modes will not agree rigorously with the actual modes found in the rocks in the Woodsville quadrangle. The chemical composition of the original mafic rocks of this area must have differed somewhat from Daly's average diabase. Moreover, the chemical composition of the actual minerals must differ to some extent from those used in the calculations. The best that

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12. Calculated mode of Daly's average diabase metamorphosed to albite-epidote amphibolite.
13. Average mode of 4 albite-epidote amphibolites, Woodsville quadrangle.
14. Calculated mode of Daly's average diabase metamorphosed to amphibolite.
15. Average mode of 6 amphibolites from eastern part of Woodsville quadrangle.

can be expected is that there will be a general similarity between the calculated modes and the actual modes.

Table 2, column 3 gives the calculated mineralogical composition of Daly's average diabase metamorphosed in the green schist facies without introduction of carbon dioxide. Table 2, column 4 lists the average mode of 9 albite-actinolite-epidote-chlorite rocks from the Woodsville quadrangle. The calculated and actual modes compare very favorably. Table 2, column 5 lists the average mode of the Moulton diorite of the Littleton-Moosilauke area (Billings, 1937, p. 503); this rock has been metamorphosed so that it now consists of a mineralogical assemblage typical of green schists. It likewise compares favorably with the calculated mode in column 3.

When carbon dioxide is introduced into the rocks, the lime is used to form calcite. With a progressive increase in the amount of carbon dioxide introduced there will be a corresponding decrease in epidote and actinolite accompanied by an increase in chlorite, calcite, and quartz. Table 2, column 6 gives the calculated mode if 100 molecular proportions (4.4 weight per cent) of carbon dioxide are added to Daly's average diabase and the resulting mode recalculated to 100 per cent. Table 2, column 7 lists the average mode of 4 albite-chlorite-epidote-calcite-actinolite schists from the Woodsville quadrangle. The similarity between the actual and calculated modes is striking.

So much carbon dioxide may be introduced that all the lime—except that necessary to form albite-oligoclase—is used up to form calcite. In this case the mode would be that given in Table 2, column 8; 165 molecular proportions (7.25 weight per cent) of carbon dioxide were added. Epidote and actinolite are no longer present, but chlorite, calcite, and quartz have increased. Table 2 column 9 lists the average mode of 9 albite-chlorite-calcite schists from the Woodsville quadrangle. The calculated and actual modes compare favorably, except perhaps for quartz.

If even a greater quantity of carbon dioxide is introduced, it combines with some of the ferrous oxide and magnesium oxide as well as lime to form ankeritic calcite or ankerite. Table 2, column 10 gives the calculated mode if 200 molecular proportions (8.8 weight per cent) of carbon dioxide are added to Daly's average diabase. Table 2, column 11, gives the average mode of 2 albite-chlorite-ankerite schists from the Woodsville quadrangle. The calculated and actual modes compare favorably.

The assumption has been made in the preceding paragraph that ferrous and magnesium oxides would not combine with carbon dioxide until all the available lime—except that necessary for albite-oligoclase—has been used. Actually, of course, the relations may be more complex and carbon dioxide may begin to combine with ferrous and magnesium oxide at an earlier stage.

We conclude that under physical conditions characteristic of the green schist facies 4 different mineralogical assemblages have been produced from original diabases due to variations in the amount of carbon dioxide introduced. The mineralogical and chemical changes, however, are not the only factors involved. The metamorphosed mafic dikes in the green schist facies range from massive to schistose. The massive dikes locally preserve relics of the original igneous textures. In general, the massive dikes are albite-actinolite-epidote-chlorite rocks without carbonate, whereas the schistose dikes are rich in chlorite and carbonate. Considerable carbon dioxide was added to the schistose dikes. Moreover, several dikes carefully studied in the field have a massive interior with little or no carbonate but a schistose border rich in carbonate. There is clearly a problem to determine which was cause and which was effect. Did the presence of schistosity permit the introduction of carbon dioxide or did the introduction of the carbon dioxide and the consequent formation of carbonate and chlorite permit the development of schistosity?

In general, therefore, small dikes were metamorphosed into albite-chlorite-calcite schists. Large dikes, on the other hand, developed into rocks devoid of carbonates, although the margins may have become an albite-chlorite-carbonate schist. Size, however, is not the only factor. In some areas dikes of equal size have suffered very different fates, one forming massive albite-actinolite-epidote-chlorite rocks, the other developing into an albite-chlorite-calcite rock. Possibly the orientation of the dike relative to tectonic forces may have played a role; one dike would be sheared whereas its neighbor would not. This phase of the problem needs further investigation in the field.

The 31 modes averaged to give columns 1, 2, 3, 4, and 5, Table 1, represent diabase dikes that are essentially the same in chemical composition as the original igneous rock, except for the addition of water and in some instances carbon dioxide. On the other hand, the 8 modes given in Table 1, columns 6, 7, 8, 9, 10, and 11 cannot have been diabase originally, unless even more extensive changes in chemical composition took place. The rock represented by the mode given in column 10 was presumably originally a quartz diabase. Columns 6 and 7 may represent highly mafic portions of an original diabase dike. But the four modes given in columns 8, 9, and 11 are rich in quartz and mafic minerals, whereas they have little or no plagioclase; soda is very low in these rocks. If they were diabase prior to metamorphism, extensive changes in chemical composition have taken place and most of the soda was removed.

Some of them may have been sedimentary rocks that were misinterpreted to be dikes in the field. Unfortunately, the writers have not had an opportunity to restudy these problems in the field, but future investigators in this and similar areas should appreciate the several possibilities.

Albite-epidote amphibolite facies.—The calculated mineralogical composition of Daly's average diabase metamorphosed to albite-epidote amphibolite is given in Table 2, column 12; the average mode of 4 albite-epidote amphibolites from the Woodsville quadrangle is given in Table 2, column 13.

In addition to the four dikes that were studied microscopically and classified as albite-epidote amphibolite, three additional dikes (Table 1, columns 12 and 13) are considered to be transitional from the green schist facies to the albite-epidote amphibolite facies. As shown on Fig. 1, all seven of these rocks lie within a narrow belt about one mile wide near the Monroe fault. The proximity to the fault is believed to be a coincidence and to have no genetic significance. Rocks characteristic of the green schist facies lie within this same belt (Fig. 1). In the southern part of the quadrangle this belt lies east of the biotite isograd, but in the northern part it lies to the west. According to Turner (1948, p. 88) the albite-epidote amphibolites coincide approximately with the garnet (almandite) zone, that is they lie between the garnet and staurolite isograds. In the Woodsville quadrangle they lie in the higher grade part of the chlorite zone and in the biotite zone.

Amphibolite facies.—The calculated mineralogical composition of Daly's average diabase metamorphosed to amphibolite is given in Table 2, column 14, and may be compared with the average mode of 6 amphibolites from the eastern part of the quadrangle given in Table 2, column 15.

Unfortunately, the precise data are lacking in this area on the spatial relations of amphibolites to the isograds defined by the argillaceous sedimentary rocks. In the eastern part of the quadrangle the displacement along the Ammonoosuc thrust has brought the green schist facies into direct contact with the amphibolite facies. In the western part of the quadrangle not enough thin sections were studied to define precisely the eastern limit of the amphibolites. The scanty data available are merely suggestive. At the garnet isograd (Fig. 1) a rock belonging to the green schist facies is partially transformed into an amphibolite (Table 1, column 14). An amphibolite—actually a quartz amphibolite with garnet—lies one-third of a mile east of the staurolite isograd. These data suggest that the amphibolites may develop within the garnet zone, but the data are admittedly inconclusive. Turner (1948, p. 76), however, likewise places the first appearance of amphibolites within the garnet zone.

Retrograde effects.—Rather striking retrograde effects are found in the metasedimentary rocks in a belt 500 to 1000 feet wide directly east of the Ammonoosuc thrust (White and Billings, 1950). Amphibolite dikes in this zone have retrogressed to albite-chlorite-calcite schists. Two such dikes, specimens B 6 and B 60, are indicated in Fig. 1. An average mode is given in Table 1, column 19.

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