Petrology and Geochemistry of Selected Talc-bearing Ultramafic Rocks and Adjacent Country Rocks in North-Central Vermont

GEOLOGICAL SURVEY PROFESSIONAL PAPER 345

Petrology and Geochemistry of Selected Talc-bearing Ultramafic Rocks and Adjacent Country Rocks in North-Central Vermont

By ALFRED H. CHIDESTER

GEOLOGICAL SURVEY PROFESSIONAL PAPER 345

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1962

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library has cataloged this publication as follows :

Chidester, Alfred Herman, 1914—

Petrology and geochemistry of selected talc bearing ultramafic rocks and adjacent country rocks in north-central Vermont. Washington, U.S. Govt. Print. Off., 1961.

vii, 207 p. illus., maps (7 fold. col. in pocket) diagrs., tables. 29 cm.
(U.S. Geological Survey. Professional paper 345)

Bibliography : p. 205-207.

1. Petrology—Vermont. 2. Talc—Vermont. 3. Mines and mineral resources—Vermont. 4. Geochemistry—Vermont. 5. Rocks, Igneous—Vermont. I. Title. (Series)

CONTENTS

Abstract.....	Page 1	Geology of the Barnes Hill, Waterbury mine, and Mad River localities—Continued	
Introduction.....	3	Petrography—Continued	
Location and history.....	3	Schist—Continued	
Barnes Hill locality.....	3	Mineralogy, etc.—Continued	Page
Waterbury mine locality.....	4	Ilmenite, rutile, and sphene.....	52
Mad River locality.....	4	Garnet.....	52
Previous investigations.....	5	Apatite.....	53
Fieldwork and acknowledgments.....	5	Epidote and allanite.....	53
Geologic setting.....	6	Other minerals.....	53
Regional setting.....	6	Petrogenesis.....	53
Waterbury-Waitsfield area.....	7	Quartzite.....	55
Metamorphosed sedimentary and volcanic rocks.....	8	Mineralogy, textural features, and para-	
Intrusive igneous rocks.....	9	genesis.....	55
Ultramafic rocks.....	9	Petrogenesis.....	55
Mafic hypabyssal and granitic rocks.....	9	Greenstone.....	55
Metamorphism.....	10	General features.....	55
Structure.....	10	Mineralogy, textural features, and para-	
Geology of the Barnes Hill, Waterbury mine, and Mad River localities.....	10	genesis.....	57
General geology.....	10	Albite.....	57
Barnes Hill locality.....	11	Chlorite.....	57
Waterbury mine locality.....	12	Amphibole.....	57
Mad River locality.....	14	Epidote and allanite.....	58
Structure.....	16	Biotite.....	58
Major features.....	16	Carbonate.....	58
Structural details.....	16	Ilmenite, rutile, and sphene.....	59
Bedding.....	17	Other minerals.....	59
Layering in ultramafic rocks.....	17	Petrogenesis.....	59
Folds.....	17	Carbonate rock.....	60
Schistosity.....	22	General features.....	60
Slip cleavage.....	23	Barnes Hill.....	60
Fracture cleavage.....	23	Waterbury mine.....	61
Other cleavage.....	24	Mad River.....	61
Lineation.....	24	Mineralogy, textural features, and para-	
Shear polyhedrons.....	24	genesis.....	61
Joints.....	24	Carbonate.....	61
Faults.....	24	Amphibole.....	62
Structural features of the Sterling Pond area.....	24	Chlorite.....	62
Origin and relations of structural features.....	25	Other minerals.....	62
Petrography.....	27	Petrogenesis.....	63
Methods and procedures.....	27	Albite porphyroblast rock.....	64
Determination of mineral compositions.....	41	Mineralogy, textural features, and para-	
Chlorite.....	44	genesis.....	64
Serpentine.....	46	Albite.....	64
Talc.....	48	Chlorite.....	64
General features.....	48	Accessory minerals.....	64
Schist.....	49	Petrogenesis.....	64
Mineralogy, textural features, and para-		Rocks of the blackwall zone.....	65
genesis.....	49	General features.....	65
Quartz.....	49	Blackwall chlorite rock.....	65
Albite.....	50	Tremolite rock.....	65
Sericite.....	50	Talcose carbonate rock.....	66
Chlorite.....	51	Mineralogy, textural features, and para-	
Biotite.....	51	genesis.....	66
Graphite.....	52	Chlorite.....	66
		Ilmenite, rutile, and sphene.....	69
		Magnetite.....	69

Geology of the Barnes Hill, Waterbury mine, and Mad River localities—Continued	Petrology and geochemistry—Continued	
Petrography—Continued	Steatitization—Continued	Page
Rocks of the blackwall zone—Continued	Relation of steatitization to structure and regional metamorphism.....	92
Mineralogy, textural features and paragenesis—Continued	Volume relations in steatitization.....	93
	Temperature relations during steatitization.....	94

TABLES

TABLE 1. Modes of rocks from the Barnes Hill, Waterbury mine, and Mad River localities.....	Page
2. Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities.....	29
3. Chemical and spectrographic analyses of rocks and minerals.....	34
4. Formula compositions and optical properties of blackwall chlorite.....	42
5. Formula compositions of antigorite.....	68
6. Formula representations of the average composition of intermixed magnetite and chromite in serpentinite.....	74
7. Formula compositions of carbonate in serpentinite.....	75
8. Formula compositions of talc.....	76
9. Formula compositions of carbonate in talc-carbonate rock and talc-carbonate veins.....	80
10. Modes of suites of specimens across the contacts of ultramafic bodies.....	81
11. Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality.....	96
12. Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the contact of the main ultramafic body at the Waterbury mine locality.....	97
13. Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality.....	109
14. Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the contact of the main ultramafic body at the Waterbury mine locality.....	110
15. Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the west contact of the ultramafic body at the Barnes Hill locality.....	112
16. Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the west contact of the ultramafic body at the Barnes Hill locality.....	113
17. Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the east contact of the ultramafic body at the Barnes Hill locality.....	114
18. Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the east contact of the ultramafic body at the Barnes Hill locality.....	115
19. Calculated modes, rock formulas, and gains and losses during steatitization, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist.....	116
20. Gains and losses during steatitization per zone, for selected elements and radicals, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist.....	117
21. Percentage gains and losses per modified standard cell of the principal constituents during steatitization.....	119
22. Formulas and symbols of equivalent mineral units, densities, equivalent weights, equivalent volumes, equivalent mineral units per modified standard cell, and cell factors of some common minerals.....	120
23. Calculations for determining the volume of 100 equivalent mineral units of Leith and Mead's average shale.....	131
24. Sample calculation of the modified standard cell, the mode, and the formula of a mineral in the rock.....	133
25. Calculations upon analysis of carbonate in talc-carbonate rock, Waterbury mine.....	134
26. Calculations upon analysis of carbonate in talc-carbonate rock, Johnson mine.....	138
27. Calculations upon analysis of carbonate in talc-carbonate rock, Barnes Hill.....	140
28. Calculations upon analysis of carbonate in talc-carbonate rock, Rousseau prospect.....	141
29. Calculations upon analysis of carbonate in veins in serpentinite, Waterbury mine.....	142
30. Calculations upon analysis of carbonate in veinlets in serpentinite, Barnes Hill.....	143
31. Calculations upon analysis of carbonate in talc-carbonate vein, Waterbury mine.....	144
32. Calculations upon analysis of carbonate in talc-carbonate vein, Johnson mine.....	145
33. Calculations upon analysis of talc in talc-carbonate vein, Waterbury mine.....	145
34. Calculations upon analysis of talc in veinlike mass in steatite, Johnson mine.....	147
35. Calculations upon analysis of magnetic concentrate from serpentinite, Waterbury mine.....	147
36. Calculations upon analysis of magnetic concentrate from serpentinite, Barnes Hill.....	148
37. Calculations upon analysis of magnetic concentrate from serpentinite, Barnes Hill.....	149
38. Calculations upon analysis of high-grade chrysotile asbestos, Ontario, Canada.....	149
39. Calculations upon analysis of schistose serpentinite, Mad River.....	151
40. Calculations upon analysis of massive serpentinite, Waterbury mine.....	152
41. Calculations upon analysis of massive serpentinite, Barnes Hill.....	154
42. Calculations upon analysis of massive serpentinite, Mad River.....	156
43. Calculations upon analysis of steatite, Waterbury mine.....	158
44. Calculations upon analysis of steatite, Rousseau prospect.....	162
45. Calculations upon analysis of talc-carbonate rock, with coarse carbonate, Johnson mine.....	164
	166

	Page
TABLE 46. Calculations upon analysis of talc-carbonate rock, very low in carbonate, Waterbury mine.....	168
47. Calculations upon analysis of talc-carbonate rock, with coarse carbonate, Rousseau prospect.....	170
48. Calculations upon analysis of blackwall chlorite rock, Waterbury mine.....	172
49. Calculations upon analysis of blackwall chlorite rock, Waterbury mine.....	174
50. Calculations upon analysis of blackwall chlorite rock, Barnes Hill.....	176
51. Calculations upon analysis of blackwall chlorite rock, Barnes Hill.....	178
52. Calculations upon analysis of blackwall chlorite rock, Mad River.....	180
53. Calculations upon analysis of bedded carbonate rock, Mad River.....	182
54. Calculations upon analysis of schist, Waterbury mine.....	184
55. Calculations upon analysis of albite porphyroblast rock, Waterbury mine.....	186
56. Calculations upon analysis of schist, Barnes Hill.....	188
57. Calculations upon analysis of schist, Barnes Hill.....	190
58. Calculated analysis of nonalbitic schist.....	192
59. Calculated analysis of talc-carbonate rock.....	194
60. Calculated analysis of steatite.....	195
61. Calculated analysis of talc-carbonate rock.....	196
62. Calculated analysis of graphitic albitic schist.....	197
63. Calculated analysis of albite porphyroblast rock.....	199
64. Calculated analysis of blackwall chlorite rock.....	201
65. Calculated analysis of steatite.....	202
66. Calculated analysis of talc-carbonate rock.....	203
67. Calculated analysis of serpentinite.....	204

PETROLOGY AND GEOCHEMISTRY OF SELECTED TALC-BEARING ULTRAMAFIC ROCKS AND ADJACENT COUNTRY ROCKS IN NORTH-CENTRAL VERMONT

By ALFRED H. CHIDESTER

ABSTRACT

The ultramafic rocks in the Barnes Hill, Waterbury mine, and Mad River localities are representative, in their total range of variation in petrographic features and structural setting, of the ultramafic rocks in the Waterbury-Waitsfield area in north-central Vermont. This area contains many bodies of ultramafic rock that have been almost entirely serpentinized and extensively steatitized.

The Paleozoic metamorphosed sedimentary and volcanic rocks in Vermont may be divided into a western and an eastern facies, separated in the southern half of the State by a relatively narrow, northward-trending belt of Precambrian rocks. The rocks of the western belt consist of marble, quartzite, slate, and phyllite, of Cambrian and Ordovician age, and are commonly fossiliferous. The rocks of the eastern belt comprise chiefly schist, gneiss, phyllite, slate, metamorphosed volcanic rocks, and argillaceous limestone, that range in age from Cambrian to Devonian, inclusive, and that are rarely fossiliferous.

The rocks of the western belt are folded into a series of anticlines and synclines, and are broken in many places by thrust faults and normal faults. The rocks of the eastern belt are arched, near their western border, into the Green Mountain anticlinorium. East of the anticlinorial axis the rocks are predominantly homoclinal, with only minor subsidiary anticlines and synclines. Few faults of appreciable extent and displacement are known within the eastern belt.

Granitic rocks are abundant in northeastern Vermont, in the eastern part of the eastern belt. Dikes and sills of mafic rock, both metamorphosed and unmetamorphosed, are common throughout the whole State. Ultramafic rocks are confined to rocks of Cambrian and Ordovician age in the western part of the eastern belt, and, except for a few deposits in the northern part of the State, are east of the axis of the Green Mountain anticlinorium.

The rocks of the Waterbury-Waitsfield area are in the eastern belt and comprise metamorphosed sedimentary and volcanic rocks, numerous small bodies of ultramafic rock, a few small bodies of granitic rock, metamorphosed mafic dikes and sills, and a few unmetamorphosed mafic dikes. The metamorphosed sedimentary and volcanic rocks, which range in age from Cambrian through Silurian (?) and Devonian (?), crop out in bands that trend predominantly N. 10°-20° E.

Ultramafic rocks occur throughout a zone that extends diagonally north-northeastward across the area. The ultramafic bodies consist of a central core of serpentinite surrounded, successively, by shells of talc-carbonate rock and steatite. A thin zone of blackwall—a generally schistose rock composed essentially of chlorite—separates the steatite from the country rock everywhere except where carbonate rock adjoins the ultramafic body—there tremolite commonly is developed. Where the schist bordering the blackwall is albitic, albite porphyroblasts

form conspicuously heavy concentrations (albite porphyroblast rock) a few inches wide at the transition from blackwall to schist.

Most of the rocks in the Waterbury-Waitsfield area are in the chlorite zone (greenschist facies) of metamorphism, but much of the rock in the Worcester and Northfield Mountains is in the garnet zone (epidote-amphibolite facies).

The rocks in the Waterbury-Waitsfield area form a homocline in the east limb of the Green Mountain anticlinorium, but subsidiary anticlinal axes in the Worcester and Northfield Mountains mark relatively minor complications of the structure.

The Barnes Hill, Waterbury mine, and Mad River localities are each about 6 to 8 miles east of the axis of the Green Mountain anticlinorium. In each locality the schistosity is about vertical and strikes a little east of north, and folding is minor or nearly absent. Quartz-sericite-chlorite schist predominates at all three localities, but greenstone forms two prominent units at the Mad River locality and a prominent unit at Barnes Hill; carbonate rocks are exposed at the Barnes Hill and Mad River localities and in the underground workings of the Waterbury mine. Unmetamorphosed mafic dikes are exposed at the Waterbury mine and Mad River localities.

The Barnes Hill locality contains a single large ultramafic body, which consists of a thin sheath of steatite surrounding a mass of talc-carbonate rock throughout which are distributed several large masses of serpentinite. The Waterbury mine locality contains a large main ultramafic body and one or more smaller ones, a little east of the main body. All contain a central core of serpentinite surrounded by successive shells of talc-carbonate rock and steatite. The Mad River locality contains a large main ultramafic body and several small, podlike bodies a short distance east of the main body. All of these, except the very small pods, contain a core of serpentinite, surrounded by shells of talc-carbonate rock and steatite.

All the ultramafic bodies at the three localities are surrounded—immediately outside the steatite zone—by a thin shell of blackwall chlorite rock generally less than half a foot thick. Locally the blackwall chlorite is faulted out; elsewhere it is missing only where carbonate rock adjoins the ultramafic body. At the contact with carbonate rock, tremolite rock is developed rather than blackwall chlorite. Albite porphyroblast rock occurs at the outer margin of the blackwall where the adjacent schist is albitic.

Not all the structural features and their relationships are clearly understood, but they can be related generally to structural features in areas near the crest of the Green Mountain anticlinorium, where the relationships are clearer. Northward-trending folds with gentle plunge are related to the Green Mountain system of folds, and most or all of the slip cleavage is parallel to the axial planes of, and genetically related to, these folds. Steeply plunging folds probably correlate mainly with the eastward-trending folds exposed near the Green Mountain

anticlinorial axis, which are older than the Green Mountain folding; some of the steeply plunging folds may be of the same age or even younger than the Green Mountain folding. If younger, there may also be a younger generation of slip cleavage. Continuous schistosity is believed to be the oldest secondary structural feature in the rocks. Spaced schistosity is of complex origin; it is probably contemporaneous, in part, with the earlier steeply plunging folds, but in many or most places it has been recurrently renewed during later orogenic episodes. The spaced schistosity is interpreted to be genetically equivalent to slip cleavage. Fracture cleavage is of diverse origin, but most is late and related to minor orogenic movements. Crinkle lineations are probably mostly related to Green Mountain folds, but the possible relations are as complex as those for the steeply plunging folds. Most of the quartz rodding is related to the earlier steeply plunging folds, but some may be later than the Green Mountain folding. Shear polyhedrons are believed to have formed by shearing and brecciation of the ultramafic rocks during tectonic transport of the crystalline mass. Layering in serpentinite and talc-carbonate rock is possibly an inherited feature of the primary ultramafic rock.

The schist ranges widely in composition, but it does not differ greatly among localities. The essential constituents are quartz, sericite, and chlorite. Graphite is commonly a conspicuous component, and numerous accessory minerals occur with varying persistence and in varying proportions. Quartzite commonly contains 98 percent or more quartz, and only sericite and graphite as persistent accessory minerals. The actinolitic greenstone at Barnes Hill and the chloritic greenstone at Mad River are both rather uniform in composition and abruptly gradational. Both approach basalt in composition, the chloritic greenstone less closely than the actinolitic greenstone. The chief differences in chemical composition between the two are in the lower content of Al_2O_3 and H_2O , and the higher content of SiO_2 and CaO , for the actinolitic greenstone. Carbonate rock at the three localities ranges widely in composition and includes magnesite marble, dolomite marble, and calcite marble. All contain variable proportions of quartz, chlorite, sericite, and, commonly, amphibole as impurities; and all grade rather sharply into schist and greenstone. Blackwall chlorite rock is very uniform in composition, and abruptly gradational. The sole essential constituent is chlorite, and sphene and ilmenite are persistent accessory minerals. The tremolite rock and talcose carbonate rock of the blackwall zone are highly variable in character and rather sporadic in distribution; the one is associated with dolomite and calcite marble, the other with magnesite marble. Albite porphyroblast rock contains features of mineralogic composition and texture common to both schist and blackwall, but the dominant feature is the densely porphyroblastic texture.

The serpentinite is remarkably uniform in composition. Antigorite is the sole essential constituent of the serpentinite, but magnetite and talc are common accessories, and chromite is a relatively rare accessory mineral. Veinlets of chrysotile asbestos are not uncommon but are negligible in quantity.

The steatite is uniform in composition, the talc-carbonate rock grossly uniform but variable on a small scale. Each intergrades irregularly with the other; the steatite also grades sharply into blackwall, talc-carbonate rock irregularly into serpentinite. Talc is the sole essential constituent of steatite, and magnetite is the only common accessory mineral. Talc and carbonate in roughly equal proportions are the essential constituents of the talc-carbonate rock; magnetite and rare chromite are the chief accessories. Talc-carbonate veins contain variable proportions of coarse dolomite and foliate talc.

Unmetamorphosed mafic dikes at the Mad River and Water-

bury mine localities are similar in appearance and composition; they correspond to spessartite or camptonite.

The plagioclase in all the rocks is nearly pure albite. The total range in composition of chlorite is very wide; most of the chlorite in the schist and actinolitic greenstone has a composition of about $(\text{Mg}_{2.1}\text{Fe}^{+2}_{2.6})\text{Al}_{1.3}(\text{Al}_{1.3}\text{Si}_{2.7})\text{O}_{10}(\text{OH})_8$; that in the chloritic greenstone ranges from $(\text{Mg}_{3.0}\text{Fe}^{+2}_{1.8})\text{Al}_{1.2}(\text{Al}_{1.2}\text{Si}_{2.8})\text{O}_{10}(\text{OH})_8$ to $(\text{Mg}_{1.6}\text{Fe}^{+2}_{3.0})\text{Al}_{1.4}(\text{Al}_{1.4}\text{Si}_{2.6})\text{O}_{10}(\text{OH})_8$; most of the chlorite in the blackwall has a composition of about $(\text{Mg}_{3.5}\text{Fe}^{+2}_{1.2})\text{Al}_{1.3}(\text{Al}_{1.3}\text{Si}_{2.7})\text{O}_{10}(\text{OH})_8$, but the $\text{Mg}:\text{Fe}^{+2}$ ratio increases sharply next to the steatite and decreases next to the schist; the composition of chlorite in the carbonate rocks varies with the composition of the carbonate rock. Actinolitic hornblende in all the greenstone is uniformly near the composition $\text{Na}_{0.2}\text{Ca}_{2.0}[\text{Mg}_{3.7}\text{Fe}^{+2}_{1.1}(\text{Al},\text{Fe}^{+3})_{0.2}](\text{Al}_0.4\text{Si}_{7.6})\text{O}_{22}(\text{OH})_2$. Biotite varies rather widely, from varieties with approximately equal proportions of Fe^{+2} and Mg , to nearly pure annite. Most of the epidote is pistacite, but tiny inclusions in albite appear generally to have a lower iron content and are probably clinozoisite. Carbonate in the talc-carbonate rock and serpentinite is chiefly ferroan magnesite, but some dolomite occurs. Sparse carbonate in the steatite is nearly pure calcite; the carbonate in the talc-carbonate veins is dolomite. The composition of the talc at each locality is uniform as determined from optical properties, but that at Barnes Hill is inferred from optical properties to have probably a slightly higher $(\text{Mg}:\text{Fe}^{+2})$ ratio; an analyzed sample of steatite from the Waterbury mine gave a calculated composition for the talc of $(\text{Mg}_{2.78}\text{Fe}^{+2}_{0.25}\text{Al}_{0.06})\text{Si}_{3.97}\text{O}_{10}(\text{OH})_{2.16}$; talc in the talc-carbonate veins has a slightly higher ratio of Mg to Fe than the talc in the steatite and talc-carbonate rock. Antigorite appears to differ slightly among the three localities, probably in content of Fe^{+2} chiefly; calculations based upon rock analyses indicate an average composition near $(\text{Mg}_{2.8}\text{Fe}^{+2}_{0.15}\text{Al}_{0.05})\text{Si}_2\text{O}_5(\text{OH})_4$. Analyses of magnetic concentrates from serpentinite indicate appreciable proportions of Al and Cr .

Most of the minerals are of metamorphic origin, but a few minerals in the country rock, particularly quartz, much of the albite—though originally, in part at least, a more calcic plagioclase—and some accessory minerals, such as zircon, are stable relicts inherited from the parent sedimentary rocks; chromite is a stable relict in the serpentinite inherited from the parent igneous rock. Metamorphism of the schist was essentially isochemical, except only for loss of volatile constituents and local redistribution of Si . Serpentinization and steatitization were accompanied by marked metasomatism, particularly with movement of H_2O , CO_2 , MgO , and SiO_2 .

Although retrograde metamorphic effects complicate the picture somewhat at the three localities, the effects probably are slight enough to be negligible at each locality. The mineral assemblages, and the pattern of variation in composition of biotite, chlorite, and plagioclase in critical associations, indicate that all the rocks at each locality belong to the same metamorphic facies, and that the grade of metamorphism at all the localities is very nearly the same, but that the grade at the Waterbury mine is slightly higher than that at the other localities. All three are in the greenschist facies near the boundary with the epidote-amphibolite facies.

Relations at the contacts of the ultramafic bodies indicate that when they were emplaced the ultramafic rocks were not appreciably hotter than the enclosing schists, so that crystallization from a magma of ultramafic composition, at their present sites, appears to be ruled out. Serpentinization was accomplished prior to steatitization. Rather extensive tectonic transport, probably with simultaneous serpentinization, is indicated by

contact relations and by the shear polyhedrons in the serpentinite. These conclusions, the association of mafic volcanic rocks with the belt of ultramafic rocks, and the experimental evidence on systems approaching the composition of serpentinite, suggest that the parent ultramafic rocks were formed by fractionation of a complex magma. Alternatively, it may be postulated that they were derived by remelting of a peridotite shell of the earth. In either alternative, serpentinitization appears to have been accomplished largely during tectonic transport of the solid crystal mass by water from the enclosing rocks. There is no evidence that solutions from granitic magmas were necessary to the serpentinitization.

The geologic evidence indicates that steatitization was later than serpentinitization, and the over-all interpretation of serpentinitization and steatitization suggests that the two processes were unrelated. Talc-carbonate rock and steatite are of the same age and of related mode of origin, but were formed by distinctly different reactions. The alteration of serpentinite to talc-carbonate rock was accomplished solely by carbon dioxide metasomatism. Steatite, derived principally from serpentinite but also to a small extent from schist, was formed, simultaneously with the genetically related blackwall, by metamorphic differentiation through interaction between the ultramafic rocks and the bordering schists of markedly different composition.

The alteration to talc-carbonate rock, steatite, and blackwall was accomplished very nearly on a volume-for-volume basis. Comparison of equal volumes of the several kinds of rock by means of a modified standard cell (designed to contain approximately 100 cations) discloses that almost the only chemical changes involved in the alteration of serpentinite to talc-carbonate rock was the gain of CO_2 and loss of H_2O . In the formation of steatite and blackwall, Mg migrated from the serpentinite into the blackwall zone, and Si from the schist into the steatite zone. Other chemical changes were, for the most part, minor or negligible, but the alkalis and carbon were "flushed out" of the blackwall zone during chloritization to form locally conspicuous concentrations of albite and graphite at the outer margins of the blackwall zone. Mineralogic changes in the formation of talc-carbonate rock were simply the alteration of serpentine to talc and magnesite, probably accompanied generally by a diminution in content of finely disseminated magnetite. In the steatite-blackwall reaction all minerals tended to alter to talc (in the steatite zone) and to chlorite (in the blackwall zone). Where carbonate rock borders the ultramafic rocks, the formation of steatite was inhibited by lack of SiO_2 , and as a result tremolite or talc formed in the blackwall zone.

Steatitization is considered to be the same age as and genetically related to regional metamorphism. Retrograde effects probably are negligible. Some paragenetic relations may record falling-temperature effects, but most that have been so interpreted result from metasomatic changes during growth and enlargement of the zones during metamorphic differentiation. There is no evidence that solutions from granitic magmas were necessary for steatitization. The solutions may well have been mobilized from the country rock during the process of regional metamorphism.

INTRODUCTION

The ultramafic rocks of Vermont are part of a great belt that extends along the eastern border of North America from Alabama to Newfoundland. The belt lies entirely within the crystalline rocks of the Appalachian Mountain system. The precise stratigraphic relations of the rocks that enclose the ultramafic bodies

are uncertain in many places, but with a few doubtful exceptions the enclosing rocks are very probably of Cambrian and Ordovician age.

In Vermont the ultramafic rocks are confined to a rather narrow belt that extends northward through the central part of the State from Massachusetts to Canada.¹ Within this belt the distribution of ultramafic rocks is uneven. At the scale of plate 1, a geologic sketch map of Vermont upon which the distribution of the ultramafic rocks is shown, the ultramafic bodies form several for the most part well-defined groups whose patterns are predominantly elongate northward, though some are rather haphazardly distributed and belong to no distinct group. A few of the symbols for ultramafic bodies on plate 1, particularly the small oval symbols near Roxbury and Rochester, represent clusters of several small ultramafic bodies that, both individually and as groups, also have a pattern that is elongate northward. Unexposed and undiscovered bodies probably would not greatly change the pattern of distribution shown.

Three localities in which large bodies of ultramafic rock occur and which are favorably exposed for detailed study are described in this report: the Barnes Hill, Waterbury mine, and Mad River localities, shown on figure 1. They are part of an irregular group of ultramafic bodies that extends from near Waitsfield village to northeastern Waterbury township. (See pl. 1.) The three localities are widely separated in the group. They embrace the extent of structural and petrographic variations within the group, and are representative of the type of ultramafic body that consists typically of a core of serpentinite, most of which is thoroughly sheared, surrounded by envelopes of talc-carbonate rocks and steatite (talc rock).

LOCATION AND HISTORY

BARNES HILL LOCALITY

The Barnes Hill ultramafic body is in northeastern Waterbury township, Washington County, Vt., 2.2 miles N. 35° E. of the road triangle at Waterbury Center. The deposit crops out between altitudes of 1,150 and 1,190 feet above sea level on the crest of a broad low ridge about 1,000 feet east of the main gravelled road.

Small pits and trenches have been dug at several places in the ultramafic body, reportedly in search for asbestos many years ago. About 1920 a prospect shaft for talc was sunk to a depth of about 15 feet near the eastern border of the deposit. In 1947 Eastern Magnesia Talc Co. diamond-drilled, along the east side of the deposit, six holes that total about

¹ Reported ultramafic rocks elsewhere in Vermont (Hitchcock, 1861, p. 539, 543; see Chidester, Billings, and Cady, 1951, p. 12) appear to have been misidentified (Lyons, 1955, p. 118).

FIGURE 1.—Index map of northern Vermont showing areas of this report.

1,300 feet (numbered 1 to 6 on pl. 3). In 1950 the Geological Survey drilled seven additional holes that total about 1,900 feet (Nos. 7, 7A, 8, 9B₁, 9B₂, 11, and 12 on pl. 3).

WATERBURY MINE LOCALITY

The Waterbury talc mine, the second largest in Vermont, is in a large ultramafic body in northwestern Moretown township, Washington County, Vt., 2 miles southeast of the junction in Waterbury village of State Route 100 and U.S. Route 2. The deposits crop out between the altitudes of 450 feet at the north end and about 1,300 feet at the south end. Maximum relief within a mile of the mine is about 1,200 feet.

There are four levels in the Waterbury mine: the Tramway level, the 1st (or adit) level, the 2d level, and the 420-foot level. Only the 1st level, which is

entered by an adit, and the 420-foot level, which is entered by an inclined shaft, are accessible and being actively worked (1955). Parts of the Tramway and 2d levels were accessible during part of the mapping (1945). Combined workings of all levels total about 8,000 feet. Twelve diamond-drill holes that total about 3,000 feet were drilled by Eastern Magnesia Talc Co. in 1948 and 1950; these are indicated by appropriate numbers on plate 4.² Plate 5 is a geologic map of the underground workings.

MAD RIVER LOCALITY

The Mad River ultramafic body, so designated after the name of a talc mine that was operated in it for

² Drill holes 1-6 are earlier short holes drilled from the underground workings. Drill hole 14 was abandoned after only a few feet because of difficulties encountered in drilling.

several years, is in the southeastern part of Duxbury and the northeastern part of Fayston townships, Washington County, Vt. The talc mine, a little south of the inferred center of the body and at the south end of the large mass of serpentinite that forms most of the body, is 2 miles S. 63° W. of the center of the village of Moretown. The deposit crops out between the altitudes of 900 and 1,200 feet throughout the extent of a well-defined ridge on the southeast slope of a hill that attains an altitude of 2,100 feet about 2.5 miles west of Moretown.

Several small prospects, apparently for talc, have been opened along the east side of the main body of ultramafic rock and in the string of small lenses of ultramafic rock east of the main body, probably in the early 1900's. Two quarries for verde antique "marble" were opened in the north end of the main body, probably in the early 1930's. Considerable quarrying for test purposes was carried out at these two sites, but commercial production was never attained. Several diamond drill holes were put down in the vicinity of the quarries as part of the exploration program carried out along with the quarry operations.

The talc mine in the main body of ultramafic rock has been operated by different owners at several times over a period of many years. It has been idle since 1946, and most of the equipment at the mine and mill has been dismantled. There are five so-called levels or groups of workings at the mine, designated for convenience as the 890-, 900-, 907-, 930-, and 968-foot levels; the numbers refer to the altitudes of the floors of the levels above sea level. Access to the workings is provided by an adit on the 968-foot level, from which a winze opens into the 930-foot level, and by an inclined shaft to the 890- and 900-foot levels, and a vertical shaft to the 907-foot level. The total length of the underground workings is about 1,000 feet. Parts of all levels were accessible at the time of mapping (1945) but all are now flooded or caved, and inaccessible. The locations of the several pits, trenches, quarries, shafts, and drill holes are shown on plate 6. Plate 7 contains a detailed map of the underground workings.

PREVIOUS INVESTIGATIONS

The ultramafic rocks of Vermont have long attracted the attention of geologists, and have been the subject of rather extensive investigation by several, notably Wigglesworth (1916), Gillson (1927), Bain (1932; 1936), Keith and Bain (1932), Hess (1933b), and Phillips and Hess (1936), but no detailed investigations of individual deposits have been published. The three bodies of ultramafic rock considered in this report have not previously been studied and described

in detail, but each has received varying attention in one or more reports on some aspect of the ultramafic rocks of Vermont. The following entries in "References cited" contain brief geologic descriptions of the ultramafic bodies indicated:

Barnes Hill: Wigglesworth, 1916.

Waterbury mine: Hitchcock and others, 1861; Jacobs, 1914, 1916; Gillson, 1927.

Mad River: Hitchcock and others, 1861; Gillson, 1927; Bain, 1932, 1936; U.S. Bureau of Mines, 1944.

The U.S. Geological Survey has published maps relating to the Barnes Hill, Waterbury mine, and Mad River ultramafic bodies in the course of the investigations described in the following section. They are listed under the following entries in "References cited":

Barnes Hill: Billings and Chidester, 1948a; Chidester and others, 1952.

Waterbury: Billings and Chidester, 1948b.

Mad River: Billings and Chidester, 1949.

General: Chidester and others, 1951; Cady, 1956; Albee, 1957.

FIELDWORK AND ACKNOWLEDGMENTS

The fieldwork upon which this report is based was carried out during part of the period August 1944 to October 1945, within the Geological Survey's program of strategic minerals investigations under the immediate direction of M. P. Billings; and during part of the period 1948-52, within the program of the Vermont talc project of the Geological Survey under the direction of W. M. Cady. Billings and Chidester made detailed geologic maps of the surface areas of the Barnes Hill talc prospect, the Waterbury talc mine, and the Mad River talc mine, at scales of 1 inch : 50 feet to 1 inch : 80 feet, and mapped the underground workings of the Waterbury and Mad River mines at scales of 1 inch : 20 feet to 1 inch : 40 feet. Since 1948, Chidester has from time to time brought the underground mapping of the Waterbury mine up to date (October 1953), assembled records of diamond drilling at the Waterbury mine and the Barnes Hill prospect, and extended the surface mapping, at a field scale of 1:2,000, of the Mad River talc mine area to cover the entire Mad River ultramafic body.

Surface geology was mapped by planetable, telescopic alidade, and stadia rod. Underground geology at the Waterbury mine was mapped, on base maps furnished by the mining company, at 1 inch : 20 feet and 1 inch : 40 feet. Underground geology of the Mad River was mapped on a base prepared by Ben Levin, of the U.S. Bureau of Mines, scale of 1 inch : 20 feet, and by compass and tape survey. Locations were

established by inspection, by pacing, or by taping as the situation required. Several stopes were surveyed with brunton compass and tape.

Local magnetic anomalies are common in areas of serpentinite and may lead to large errors in measurements of attitudes of structural features unless care is taken. Throughout the surface mapping within the limits of the ultramafic bodies the magnetic declination was continually checked against a true north direction on the map, maintained by backsight-foresight orientation, and when an appreciable variation in declination was detected, bearings were established by turning the angle between the strike of the structural feature and the line of sight to the planetable board. In underground workings within the ultramafic body, practically all bearings were established by estimating or measuring the divergence between the trend of the feature to be measured and that of some readily identifiable feature depicted on the mine survey, such as the walls of the levels. For these reasons the attitudes of structural features plotted on the several maps are probably not consistently accurate to closer than about 10° , and a few may be off as much as 20° .

Many people have contributed to the fieldwork on which this report is based, to an understanding of the general problems of ultramafic rocks, and to the writing of this report. To all, I wish to acknowledge my sincere appreciation. Marland P. Billings established the general methods of mapping that have been followed throughout the work. His insight into the geologic problems, and his patient unobtrusive guidance and direction throughout the work done under his supervision were invaluable to the writer at the critical period of his early experience in systematic field studies. My colleagues on the Vermont talc project—W. M. Cady, chief of the project, and Arden L. Albee—have been constant sources of help and ideas throughout the work. Each has contributed materially in the fieldwork: Cady in part of the surface mapping of the Mad River ultramafic body, and both Cady and Albee in part of the underground mapping at the Waterbury mine. Many of the ideas developed in this report are the outgrowth of continual discussions with Cady and Albee on the many aspects of the problems of ultramafic rocks.

Cady's mapping of the Montpelier quadrangle (1956), Cady, Albee, and Murphy's mapping of the Lincoln Mountain quadrangle (manuscript map, 1956), and Jahns' mapping of the Barre quadrangle (manuscript map, 1956) are the basis for the description of the geology of the Waterbury-Waitsfield area, which furnishes the geologic setting for the descriptions of the ultramafic bodies.

E. G. Ehlers, in the summer of 1949, and G. W.

Stewart and D. Morris, in the summer of 1950, assisted in the fieldwork. The author is indebted to them for their efficient assistance, for their pleasant companionship, and for their stimulating discussion of many field problems.

Several members of the Geological Survey with wide experience in the problems of ultramafic rocks have visited the Vermont talc project and have contributed unreservedly of their time and ideas. Among them are T. P. Thayer and G. T. Faust. To each, the author is considerably indebted, especially for enlightening comment enhanced by experience in other areas of ultramafic rocks in many places throughout the world.

Other geologists working in Vermont have supplied factual information and have contributed ideas through discussion of mutual problems during several visits in the field. Among them are Professors J. B. Thompson, of Harvard University; J. L. Rosenfeld of the University of California at Los Angeles; P. H. Osberg, of the University of Maine; Rama Murthy, of the California Institute of Technology; and James Skehan, S. J., of the Seismological Observatory at Weston College.

The Geological Survey is indebted to the officers of Eastern Magnesia Talc Co., Burlington, Vt.—particularly E. W. Magnus, president; Victor N. Backles, general superintendent; and the late Heming Franz, formerly superintendent—for their courteous and wholehearted cooperation and material help throughout the investigations at Barnes Hill and the Waterbury mine; to the Mad River Talc Corp. for permission and cooperation during mapping of the underground workings of the Mad River mine; and to the Vermont Marble Co. for information regarding exploratory work carried out on the Mad River ultramafic body.

GEOLOGIC SETTING

REGIONAL SETTING

Bedrock in Vermont includes Precambrian rocks probably of both sedimentary and plutonic igneous origin, Paleozoic igneous and metamorphosed sedimentary and volcanic rocks, and mafic dike rocks probably of Permian or Triassic age. Plate 1 is a generalized geologic map of Vermont showing the distribution of rocks by systems, and the pattern of major structural features. Precambrian sedimentary and igneous rocks are undifferentiated. Paleozoic metamorphosed sedimentary and volcanic rocks, granitic rocks, and ultramafic rocks are distinguished. Mafic dikes and sills are too small to be shown.

The Paleozoic metamorphosed sedimentary and volcanic rocks may be divided, in a general way, into a western facies chiefly of quartzites and marbles

and an eastern facies made up predominantly of argillaceous and arenaceous rocks. These two facies are separated by the area of Precambrian rocks in the central and southern part of the State, and adjoin about along the easternmost line of thrust faults shown on plate 1 in the northwestern part of the State. This simple picture is complicated in the area of the Taconic Mountains in southwestern Vermont, and in the vicinity of Milton and St. Albans in northwestern Vermont, by the predominance to the west of argillaceous and arenaceous rocks. The rocks in the Taconic area are generally regarded as a klippe—corresponding generally, on plate 1, to the area of Cambrian (?) or Ordovician (?) in southwestern Vermont—whose root is far to the east (Keith, 1932, p. 404; Prindle and Knopf, 1932), thus accounting for their anomalous lithologic character. Some geologists currently active in the area, however, appear to have reservations about the reality of the Taconic thrust (Thompson, 1952, p. 16–17; Weaver, 1953, p. 1489; Herz, 1955, p. 1714; MacFadyen, 1956, p. 58–64). The scarcity of marble and quartzite in northwestern Vermont may be due to a localized northerly trend of the trough of deposition relative to northerly structural trends. Whatever the explanation of the anomalies, the western and eastern facies, except for the anomalous features noted, may be characterized as follows:

The rocks of the western belt consist of marble, quartzite, slate, and phyllite, of Cambrian and Ordovician age. In many places they contain abundant fossils, and generally show the effects of only low-grade metamorphism. This belt is the northern extension of the folded belt of the Appalachian Mountains, whose anticlines and synclines here trend about north. Several major thrust faults that dip eastward and trend about northward can be traced for many miles. Several sets of normal faults are extensively developed. (See Cady, 1945, p. 570–572.) These lithologic and tectonic features are typical of rocks deposited on mobile shelves (miogeosynclines) at the margins of stable continental blocks.

The rocks of the eastern belt comprise chiefly schist, gneiss, phyllite, slate, metamorphosed volcanic rocks, and argillaceous limestone, that range in age from Cambrian to Devonian, inclusive. They contain very few fossils, and show the effects of low- and middle-grade metamorphism. Near the western border of this belt the rocks are arched in the Green Mountain anticlinorium, whose axis is shown on plate 1. Rocks of Precambrian age are exposed in the southern part of the State at the core of the anticlinorium. East of the anticlinorial axis the rocks are, for the most part, homoclinal and dip steeply eastward; locally, the homo-

cline is complicated by minor anticlines and synclines, domes, and broad, shelf-like warps. The locations of some of the domes are marked on plate 1 by oval and crescentic map patterns for the metamorphosed sedimentary rocks in Windham, Windsor, and Orange Counties. The eastern limit of the homocline is not certainly known, but it has generally been considered to be about along the Connecticut River at the western limit of the area shown on plate 1 as Ordovician, Silurian, and Devonian undifferentiated. However, tentative correlations based on recent work suggest that there may be a major synclinorial axis trending northward within the Waits River or Gile Mountain formations, corresponding approximately to the rocks shown by "SI" and "Dsp" on plate 1 (J. B. Thompson, oral communication, 1953; see Boucot and others, 1953, p. 1397–1398). Such an interpretation would considerably restrict the eastern extent of the homocline. In any case, the rocks of the eastern belt, and the tectonic features characteristic of them, are the kind generally considered to be indicative of the deeply subsided parts of geosynclines (eugeosynclines) beyond the margins of stable continental blocks.

The distribution of ultramafic rocks in Vermont with relation to major geologic features is similar to that for the Appalachian Mountains as a whole; they are confined to the crystalline rocks east of the Folded Appalachians. Furthermore, the ultramafic rocks in Vermont occur near the western border of, but within, the eastern (eugeosynclinal) belt of rocks. Throughout most of Vermont the ultramafic rocks are east of the Green Mountain anticlinorial axis, but northward from about the latitude of central Lamoille County several bodies of ultramafic rock occur west of this anticlinorial axis.

WATERBURY-WAITSFIELD AREA

The Waterbury-Waitsfield area, embracing the group of ultramafic bodies that includes those at the Barnes Hill, Waterbury Mine, and Mad River localities, is almost entirely in the homocline on the east limb of the Green Mountain anticlinorium; the anticlinorial axis barely intersects the northwest corner of the area. Geologic maps of the Montpelier and Hyde Park quadrangles, embracing much of the Waterbury-Waitsfield and nearby areas, have recently been published (Cady, 1956; Albee, 1957). Plate 2, a sketch map of the area based upon those publications and upon U.S. Geological Survey studies in progress, shows the distribution of formations, metamorphic zones, and chief structural features. The studies by Cady and Albee should be consulted for details of the geology. Here the geology will be summarized only in sufficient detail to interrelate the geology of the three localities and to establish their immediate geologic setting.

METAMORPHOSED SEDIMENTARY AND VOLCANIC ROCKS

The metamorphosed sedimentary and volcanic rocks in most of the Waterbury-Waitsfield area dip steeply east, and the formations make a rather simple pattern of somewhat irregular bands, from $\frac{1}{2}$ to more than 5 miles wide, that trend generally N. 10° – 20° E. This simple pattern is complicated in the northwest corner of the area by the arching of the rocks over the axis of the Green Mountain anticlinorium, and in a few other places by subsidiary anticlines and synclines. Within some of the formations mappable units such as greenstone beds and graphitic varieties of schist range in size from lenticular beds a few hundred feet wide and less than a mile long to irregular zones more than a mile wide and as much as 20 miles long. The formations include Cambrian, Ordovician, Silurian(?) and Devonian(?) strata. The Cambrian rocks include the Camels Hump group and the Ottawaquechee formation; the Ordovician rocks include the Stowe and Moretown formations; the Silurian(?) and Devonian(?) rocks, for the purposes of this report, are undifferentiated, but include the Shaw Mountain, Northfield, and Waits River formations. (See Cady, 1956.) The formations of the Cambrian and Ordovician systems are intergradational; the zones of transition from one formation to another range from a few tens of feet to nearly a thousand feet in thickness. The boundary between Ordovician and Silurian(?) rocks is an unconformity, marked in many places by conglomerate of the Shaw Mountain formation at the base of the Silurian.

The Camels Hump group is composed chiefly of schist, quartzite, and gneiss. Schist predominates, and light-gray quartz-sericite³ schist is the most common type. Light-gray quartzite beds with sericitic partings occur in poorly defined stratigraphic zones. Dark-gray to black schist and quartzite and black phyllite occur locally where graphite as well as sericite is relatively abundant. Greenstone is rare.

The Ottawaquechee formation intergrades with the underlying Camels Hump group, and comprises chiefly interbedded phyllite and quartzite, both of which are carbonaceous. The quartzite occurs in sharply defined beds from a few inches to 10 feet in thickness, interstratified with phyllite which makes up the major part of the formation. Greenstone is interbedded with these rocks chiefly in the upper part of the formation.

The Stowe formation consists of schist with thick interbeds of greenstone or amphibolite. Two principal types of rock are quartz-sericite-chlorite schist, which

in zones of greater metamorphism grades into quartz-muscovite-garnet-kyanite schist, and greenstone, which under similar circumstances grades into amphibolite. The schists and the greenstone (or amphibolite) grade into one another chiefly parallel to the bedding, and into miscellaneous types of rocks that occur locally. The more intensely metamorphosed rocks are in and near the Worcester and the Northfield Mountains. On plate 2 they are enclosed by the garnet isograd.

The quartz-sericite-chlorite schist is typically marked by columnar masses, lenticular in cross-section, of granular white quartz. The rock enclosing the granular quartz masses is a green-gray quartz-chlorite-sericite schist. It is locally garnetiferous, but contains few other accessory minerals. In zones of greater metamorphic intensity the rock is coarser grained, and almandite, kyanite, and rare biotite occur. An albitic facies of the quartz-sericite-chlorite schist occurs principally in a poorly defined belt along the west slopes and foothills of the Worcester and Northfield Mountains; there the albite is commonly porphyroblastic.

Greenstone and amphibolite show distinct compositional layering although they are rather massive granular rocks that, except locally, lack well-defined schistosity. Calcareous zones, as well as part of the quartz in layers, are probably sedimentary materials intermixed with the volcanic detritus. Structures suggestive of pillow lava occur in a few places. Buff-weathering white-to-gray crystalline limestone commonly forms lenses a few feet thick next to greenstone, with which the limestone intergrades; the contacts with schist are commonly abrupt.

The Moretown formation is composed chiefly of granulite, quartzite, phyllite, and slate, and is transitional with the underlying Stowe formation. The granulite is most characteristic of the Moretown—a finely laminated quartz-albite-sericite-chlorite rock with a fine stripe, this granulite is commonly called the pinstripe. Carbonaceous slate and phyllite form thick units of the Moretown and grade into granulite, chiefly parallel to the bedding. The granulite grades locally into gray to buff quartzite. Coarse facies of the carbonaceous slate and phyllite also grade into quartzite, commonly by fine interlamination. The carbonaceous rocks also grade by interlamination into the granulite and into the quartz-chlorite slate and phyllite.

The rocks that succeed the Moretown formation are undifferentiated on plate 2 because none is a host for ultramafic rocks, and they therefore have no direct bearing upon the problems of this report. Included within the area of undifferentiated rocks are the Shaw Mountain formation—which includes conglomerate, albite-chlorite-calcite schist, and crystalline limestone—the Northfield slate, and the Waits River formation—

³ The term "sericite" is applied in this report to various white micas that are too fine for individual flakes to be readily visible megascopically and that cannot be reliably distinguished by optical means alone. Muscovite doubtless predominates greatly over other white micas in most of the rocks concerned with here, but one or more of paragonite, pyrophyllite, margarite, and talc may be present, and rarely may predominate over muscovite.

which includes, chiefly, interbedded phyllite and crystalline limestone. (See particularly Cady, 1956.)

INTRUSIVE IGNEOUS ROCKS

Intrusive igneous rocks in the Waterbury-Waitsfield area include ultramafic rock and metamorphosed mafic dikes and sills, probably of Ordovician age, granite of Devonian age, and unmetamorphosed mafic dikes and sills, probably of Permian or Triassic age. The ultramafic rocks are confined essentially to the western half of the area. Metamorphosed mafic dikes and sills occur abundantly in the eastern half of the belt underlain by the Moretown formation. Granitic rocks occur sparsely and in small bodies confined to the southeastern corner of the area. Unmetamorphosed mafic dikes and sills are known at scattered localities throughout the area and are probably numerous.

ULTRAMAFIC ROCKS

Known occurrences of ultramafic rock within the Waterbury-Waitsfield area are shown on plate 2. The bodies are lenticular and range in size from a few tens of feet long and several feet wide to more than a mile long and almost a thousand feet wide. None is known to contain unaltered dunite or peridotite. All consist of a core of serpentinite, or irregularly distributed masses of serpentinite, within a mass of talc-carbonate rock that is locally called "grit" by miners. Where the serpentinite forms a regular core the talc-carbonate rock forms a fairly regular sheath from a few feet to a few tens of feet thick. Where the serpentinite masses are irregularly distributed, the talc-carbonate rock mass is correspondingly irregular. Steatite⁴ forms a thin envelope, from a few inches to a few feet thick, around the talc-carbonate rock. This type of ultramafic body, sometimes called the "verde antique type," contrasts with the type that contains considerable fresh dunite and peridotite or serpentinitized dunite and peridotite in which the primary textures are preserved.⁵

⁴ The term "steatite" is used to designate a rock that consists almost entirely of talc. Various meanings have been attached to the word in geologic literature. Priority and general geologic usage favor the definition given here, but in some geologic literature, and especially in writings on high-quality ceramic talcs, a different usage has evolved. "Steatite" is used in the ceramic industry to denote a massive, compact, and comparatively pure variety of talc-rock which must meet certain chemical and physical requirements for the manufacture of ceramics. Specifications vary with the manufacturer and intended use. In our opinion, it is best to define "steatite" in the broad sense in general geologic usage, and to apply such terms as "ceramic-grade steatite" or "electrical-grade steatite" when it is desired to indicate a specific grade or type of steatite. (After Chidester, Billings, and Cady, 1951, p. 3, footnote 7.)

⁵ The distinction between the two types of bodies is less clear-cut than was earlier believed (Chidester, Billings, and Cady, 1951, p. 4-5). Examples of the verde antique type of body are common, but most of the dunite type contains features intermediate between the two extremes and probably all gradations exist. Furthermore, the characteristic rock types exhibit similarities or overlap in petrographic features formerly thought to be distinctive: Although chrysotile is fairly common and locally abundant in the matrix of some serpentinite in the dunite type of body and rarely occurs in the verde antique type of serpentinite, antigorite is by far the more abundant in both. The verde antique type of serpentinite consistently weathers white or pale green, and dunite typically weathers buff, brown, or reddish brown; but some dunite and much serpentinitized dunite weather white, pale green, or very pale buff green.

At the outer border of the steatite zone all varieties of country rock except carbonate rock are separated from the steatite by a thin zone of chlorite rock a few inches to, locally, a little more than a foot thick. Carbonate rock is separated from the steatite either by an irregular zone a foot or less thick and composed entirely of tremolite, or by a narrow zone of talcose carbonate rock a few inches thick. Where the country rock is albitic, the transition from chlorite rock to "normal" country rock is marked by a heavy concentration of albite porphyroblasts. All rocks of the several zones are transitional into one another, generally within a few inches.

The volumes occupied by the serpentinite mass, or masses; the talc-carbonate rock; the steatite; the chlorite rock, or tremolite rock or talcose carbonate rock where the country rock next to the steatite is carbonate rock; and the albite porphyroblast rock will be referred to throughout this report as the serpentinite, talc-carbonate rock, steatite, blackwall, and albite zones (or shells), respectively. The term "blackwall", originally a miner's term, but now well entrenched in the geologic literature, is applied to the chlorite rock adjacent to the steatite zone; tremolite rock and talcose carbonate rock in that position have received no special designation. In this report, all will be considered as occupying the blackwall zone, but the term "blackwall" will be applied only to the chlorite rock.

MAFIC HYPABYSSAL AND GRANITIC ROCKS

Metamorphosed mafic sill-like dikes are numerous in the eastern half of the Moretown formation and cut the bedding at very slight angles. The thicker bodies tend to be massive, the thinner ones schistose. The color of the rock is gray green, and some of the massive rock is sufficiently coarse grained to show a mottling of green specks against a gray background. Relics of ophitic texture are locally preserved in massive greenstone, and suggest that the rock was originally diabase.

Thick sills and subsidiary thin sill-like dikes of granite occur in the Waits River formation—included within the undifferentiated phyllite, limestone, slate, schist, and conglomerate on plate 2—and the Moretown formation. The granite is mottled gray and ranges in texture from medium grained to coarse grained; smaller masses are commonly porphyritic.

Unmetamorphosed mafic dikes are sparsely exposed and are commonly less than 5 feet thick; they dip vertically and most are intruded in transverse joints about at right angles to the schistosity of the enclosing rocks. Some show columnar jointing. The freshly broken rock is black and generally is too fine grained for either the individual mineral grains or the texture to be distinguished in hand specimens.

METAMORPHISM

The pattern of regional metamorphism is shown by the garnet isograds that enclose areas of middle-grade metamorphism in the Worcester Mountains and a little west of the Northfield Mountains. (See pl. 2.) These areas are all within the Stowe formation. Kyanite and hornblende, as well as almandite, occur within the areas enclosed by the garnet isograds, and the distribution of hornblende closely approximates that of almandite; kyanite is distributed erratically. Actinolitic hornblende occurs in the low-grade zone. Retrograde metamorphic effects, chiefly replacement of garnet by chlorite and kyanite by sericite, are common in the middle-grade zone. Contact metamorphism is shown principally by the occurrence of cordierite and diopside in the Waits River formation in the vicinity of granite; scattered biotite in eastern exposures of the Moretown formation is ascribed to contact metamorphism.

Intrusive igneous rocks, other than small bodies of serpentinite, have not been discovered in the area of the Worcester Mountains enclosed by the garnet isograd, or anywhere in the vicinity, and they are very likely absent at depth. The area within the garnet isograd in the Worcester Mountains coincides with the Worcester Mountain anticline, which suggests that the increase in metamorphism is due either to greater frictional heat produced by slightly greater deformation of the anticline relative to other folds in the area, or more likely to differential uplift of once nearly horizontal isothermal surfaces. (After Cady, 1956.)

STRUCTURE

The dominant structural feature within the Waterbury-Waitsfield area is a homocline in the east limb of the Green Mountain anticlinorium. Throughout most of the area the beds in the homoclinal succession are vertical or dip steeply east, but near the eastern side of the area the beds are nearly all overturned to the east. Several subordinate anticlines and synclines disrupt the homocline locally. The largest of these is the Worcester Mountain anticline. South of the Waterbury mine there is another anticlinal axis that appears to die out northward a little south of the Winooski River. These synclines and anticlines are apparently of the same age as, and have a pattern consistent with, the Green Mountain anticlinorium.

Faults of regional extent have not been recognized in the area, but two northward-trending steeply dipping faults of not more than a few hundred feet displacement have been recognized in the underground workings of the Waterbury mine and the Mad River mine. Both appear to have an appreciable horizontal component of displacement.

The rocks exhibit a variety of minor structural features; they include folds, schistosity, slip cleavage, and lineation. There appear to be more than one generation of some of these structural features, as well as differences in the ages of different features. Some are related to and of the same age as the Green Mountain anticlinorium; others appear to be unrelated to it and of different age.

Detailed consideration of the minor structural features and of their genetic relations will be deferred until the discussion of the individual localities (p. 16-27).

GEOLOGY OF THE BARNES HILL, WATERBURY MINE, AND MAD RIVER LOCALITIES

The Barnes Hill, Waterbury mine, and Mad River ultramafic bodies are so similar in many respects that they can conveniently and profitably be discussed as a unit. At the same time they show enough diversity to be supplementary to one another, and as a group they provide much more complete information than could be gained from the study of any single one of the bodies. The deposits are generally similar in structural, stratigraphic, and metamorphic setting, in gross shape of the bodies, and in such features of serpentization and steatitization as the completeness of serpentization and the distribution with relation to each other of the products of steatitization. On the other hand, they differ in detail in the abundance and variety of minor structural features, precise stratigraphic position, precise grade of metamorphism, composition and variability of the country rock—with resulting differences in features of the alteration zones at the outer borders of the ultramafic body—presence of mappable horizons in the country rock, and regularity and thickness of rock units of the ultramafic bodies. Furthermore, different features are exposed to particular advantage, both at the surface and in underground workings and in diamond-drill holes, at each of the localities.

GENERAL GEOLOGY

The rocks within the map areas at the three localities do not reflect accurately the lithologic features of the formations of which they are a part, because each map area represents an inadequately small sample of the formation. The Barnes Hill and Waterbury mine localities are within the Stowe formation, and the Mad River locality is within the Ottauquechee, but the schist at the three localities does not differ strikingly, and the differences are not typical for the formations.

Several excellent key horizons characterize the country rock of the Mad River locality; several map units occur in the country rock at Barnes Hill, but conditions of exposure do not permit entirely satisfactory delineation.

tion; the schist at the Waterbury mine locality contains no mappable variations. Mafic dikes occur in the Mad River and Waterbury mines, but none is exposed at Barnes Hill. Faults are prominent features in the underground workings at Mad River and Waterbury mines; none has been detected at Barnes Hill, possibly only because of lack of suitable exposure.

The Mad River and Waterbury mine localities each contain a large main ultramafic body and small lenticular bodies in a narrow belt a few hundred feet east of this main body. Barnes Hill contains only a single body. The serpentinite core at Mad River and Waterbury mine has a simple regular distribution, centrally located in the mass, and is absent only where the body is narrowly constricted. The serpentinite at Barnes Hill is irregularly distributed in masses that range widely in size. Talc-carbonate rock and steatite make up about half of the Barnes Hill body and are irregularly distributed; they are a relatively small proportion of the Waterbury mine and Mad River bodies. The zone of talc-carbonate rock and steatite combined is of minable thickness at most places in the main ultramafic body in the Waterbury mine locality, but commonly is somewhat thicker at the keel of the lens of ultramafic rock; the combined zone is of appreciable thickness in the main body at the Mad River locality only at the north and south ends of the deposit. The blackwall zone is typically developed at all places where exposure permits observation except at the Mad River locality, where in a few places the bordering country rock is observed or inferred to be carbonate rock. No systematic variation in thickness of the blackwall with respect to position in the ultramafic body is observable, though in places the blackwall appears to be somewhat thicker where the steatite is thicker. The steatite and blackwall zones are so thin and so erratically exposed that they are not mapped separately. Albite porphyroblast rock at the outer border of the blackwall is a prominent feature at many places in the Waterbury mine locality, where much of the country rock is highly albitic; the porphyroblast rock occurs only sporadically at the Barnes Hill and Mad River localities, where the albite content of the country rock is predominantly low.

BARNES HILL LOCALITY

The Barnes Hill ultramafic body is about 8 miles east of the axis of the Green Mountain anticlinorium. A subsidiary anticline about half a mile west and the Worcester Mountain anticline about 2 miles east of Barnes Hill are notable deviations of the strata from a simple homocline with tops of beds facing eastward. The ultramafic body is intruded into rocks of the

Stowe formation of Ordovician age. The Stowe at the latitude of Barnes Hill includes varied schist, amphibolite, greenstone, and carbonate rocks.

The detailed geology of the Barnes Hill locality is shown on plate 3. Rocks within the area include schist, actinolitic greenstone (see p. 55), quartzose and chloritic carbonate rock, serpentinite, talc-carbonate rock, and steatite. (See footnote 6; for a discussion of other terms peculiar to ultramafic rocks see Chidester, Billings, and Cady, 1951, p. 3.)

The greenstone is moderately well exposed along the southwestern border of the ultramafic body, and several outcrops on the northeastern side, near the collar of diamond-drill hole 7, contain thin layers of greenstone.⁶ Elsewhere, outside the ultramafic body, there are only scattered exposures, all of locally graphitic quartz-sericite-chlorite schist. The schist is variable in composition, but the several types are integrational, their boundaries are indefinite, and surface exposures are very few, so that it is not feasible to attempt to map the several types as different units. All are represented by a single pattern on plate 3.

Considerable greenstone was encountered in the diamond-drill holes. The drill-hole data indicate that east of the ultramafic body there is a zone, of unknown thickness, composed predominantly of greenstone and separated from the body by a zone of schist of variable thickness that ranges from 10 to as much as 100 feet. At the western contact near the north end of the ultramafic body, drill holes encountered at depth a zone predominantly of greenstone as much as 70 feet thick, bordered on the west by schist. This greenstone does not extend to the surface along most of the western contact. It may, however, connect with the greenstone exposed at the surface at the southwestern border of the ultramafic body; if so, the greenstone is probably a lens the upper edge of which plunges northward beneath the schist. The contact between the ultramafic body and the greenstone exposed at the surface is generally concordant; consequently, the lenticular form of the greenstone is probably an original feature—rather than, say, the effect of faulting—modified slightly by folding and possibly by minor shearing along the limb of a fold.

The zones of greenstone encountered in drill holes are variable, particularly in the distribution, number, thickness, and lithologic character of schist interbeds. The

⁶ The greenstone exposed northeast of the ultramafic body, and similar rock encountered in drill holes, was previously described as "chlorite-albite schist" (Chidester, Stewart, and Morris, 1952) on the basis of megascopic examination. This rock differs in appearance from the greenstone at the southwest side of the ultramafic body: it has a very regular bedding schistosity which imparts to it a slabby appearance, the amphibole (actinolitic hornblende) is so fine that it can seldom be recognized megascopically, and the albite occurs in prominent porphyroblasts. However, actinolitic hornblende is the predominant ferromagnesian mineral and chlorite is a relatively minor constituent; hence the rock is an actinolitic greenstone, like that at the southwest side.

evidence suggests that the lateral distribution of the greenstone is variable and that it forms several lenses. Because of the uncertainties of correlation and the scarcity of surface outcrops, the greenstone encountered only in drill holes has been distinguished in cross section only along the drill holes, and has not been extrapolated to the surface map.

The general trend of schistosity and bedding of the country rock in the area is about N. 20° E. and the dip steeply east. The principal departures from this regional trend are caused by distortion near the contact of the ultramafic body, chiefly of the greenstone at the southwestern border. In the greenstone the departure from regional trends is accented locally by broad folds and warps as much as 150 feet across.

The ultramafic body is crudely elliptical in plan and tabular to wedge shaped in cross section. It is about 1,600 feet long, a maximum of 360 feet wide, and probably more than 500 feet in vertical extent. The body trends about N. 20° E. and dips steeply eastward in general conformity with the schistosity of the country rock.

Serpentinite forms several irregular lenses surrounded by talc-carbonate rock and steatite, rather than a single central core such as is typical of most ultramafic bodies that are extensively altered to talc. (See Chidester, Billings, and Cady, 1951, p. 4-5.) The lenses range from a few feet in length to as much as 350 feet by 150 feet at the surface, and probably as much as 500 feet in vertical extent. Serpentinite is most abundant in the southwestern part of the ultramafic body, and makes up a little less than one-half of the ultramafic body as a whole. Serpentinite and talc-carbonate rock are intergradational over a few inches or a few feet. The distinction between the two on plate 3 is primarily economic, and is based on inspection of color and hardness.

Talc-carbonate rock is irregularly distributed throughout the deposit, but is much more abundant than serpentinite in the northeastern part of the body. It constitutes a little more than half of the whole ultramafic body. Steatite occurs as a thin irregular envelope at the borders of the ultramafic body. At the contact with the steatite, the country rock has been altered for a few inches to blackwall chlorite rock. The contact line between "steatite or talc-carbonate rock" and "schist" on plate 3 represents approximately the combined steatite and blackwall zones. The pattern of the blackwall is inferred from a few surface outcrops, from drill-hole data, and from analogy with similar deposits where the blackwall is extensively exposed by underground mining. At a few places in drill cores where the country-rock schist is albitic, the transition from blackwall to unaltered

schist is marked by a concentration of albite porphyroblasts.

Several tabular or lenticular septa of quartzose and chloritic carbonate rock and of schist occur within the ultramafic body, and are oriented parallel to it. The septa of schist are altered at the borders to blackwall chlorite, and a thin zone of steatite occurs between the blackwall and the talc-carbonate rock. Thin masses of carbonate rock of undetermined shape and extent were encountered near the borders of the ultramafic body in several drill holes.

The contacts of the ultramafic body are generally concordant with the schistosity of the schist and the bedding of the greenstone, although there are local discordances of small magnitude. The effect of these minor discordances on the overall pattern probably is small. One cause of small local discordance is irregular steatitization of the country rock at the borders of the ultramafic body.

WATERBURY MINE LOCALITY

The Waterbury mine locality is about 7 miles east of the axis of the Green Mountain anticlinorium. The only significant departure from a homocline near the locality is marked by beds of greenstone that plunge steeply northward in the crest of an anticline about 2 miles south-southwest of the mine. (See pl. 2.) The anticline cannot be traced into the mine area, but the projection northward of the axis passes through the vicinity of the mine, and folds in the contact of the main ultramafic body may mark the subdued northern extension of the anticline. The ultramafic rocks intrude rocks of the Stowe formation, which at the latitude of the mine includes schist and greenstone.

The detailed geology of the Waterbury mine area is shown on plate 4. Plate 5 is a geologic map of the underground workings. Rocks within the area include schist, serpentinite, talc-carbonate rock, and steatite.

Surface exposure constitutes about 15 or 20 percent of the area and is rather uniformly distributed; hence an adequate sample of the schist and serpentinite is exposed. The talc deposit is poorly exposed at the surface, but is well exposed in the extensive underground workings. The country rock is quartz-sericite-chlorite schist. There are no significant lithologic variations in the schist on a scale large enough to map, but there are numerous local variations in mineral content. Most evident is the sporadic occurrence of graphite; the relative proportions of quartz, albite, sericite, and chlorite also vary widely. The different types of rock grade into each other both laterally and along the strike. Massive greenstone

crops out a few hundred feet west of the area, but within the area only a few thin beds, from a few inches to 1 or 2 feet in thickness, have been observed in drill cores and the the underground workings.

The general trend of schistosity and bedding of the country rock is about N. 20° E., and the strata are predominantly vertical or dip steeply east. No marked deviations of the schistosity from this general trend occur in surface outcrop, but the surface of the ultramafic body and exposures on the 2d level of the mine workings disclose a fold with maximum amplitude of about 300 feet.

The ultramafic body is an irregular elongate lens whose minimum length is about 4,500 feet. The body pinches and swells along the strike, both on the surface and in the underground workings, from a maximum width of 550 feet at the surface and 150 feet underground to a minimum width of 30 or 40 feet at the surface and less than a foot underground. The body ranges from crudely tabular to wedge shaped or Y-shaped in vertical cross section. The south end of the deposit is complicated by folding of the eastern contact. The average attitude of the deposit is vertical or steep to the east. Both walls, on the average, dip steeply inward, although there are numerous local reversals of this attitude. Several septa or isolated tabular inclusions of schist occur within the ultramafic body, some as large as 700 feet in maximum known dimension and 30 feet or more thick. At most places where exposed, the septa are altered for a few inches at the outer border to blackwall chlorite schist and are bordered by a thin zone of steatite from a few inches to a foot or more thick. The few exceptions probably represent fault contacts. Numerous long thin slablike projections of schist from the walls into the ultramafic body are exposed in the underground workings. They uniformly show offset to the right in plan and present the appearance of having "peeled-off" from the schist wall. (See geologic map of the adit (1st) level, pl. 5.)

About 300 to 600 feet east of the main ultramafic body, serpentinite, talc-carbonate rock, and steatite crop out at the surface or are exposed in underground workings and drill holes intermittently throughout a north-south distance of about 3,200 feet. The outcrops probably are on several small lenticular or tabular bodies, as depicted on the maps and cross sections of plate 4, but it is possible that some of the lenses are connected to form a single body as much as 2,500 feet long. The widest body in this eastern belt is about 80 feet at the surface. The general attitude is about the same as that of the main body, and the geologic relations are similar.

Serpentinite forms the central core of the ultramafic body at the Waterbury mine. The core of serpentinite

makes up the greater part of the body throughout, except that where the body is narrow the core is commonly absent. Serpentinite and talc-carbonate rock are gradational over a few inches or a few feet; the gradation from talc-carbonate rock with little or no serpentine into serpentinite with little or no talc commonly takes place over about a foot. The distinction between the two on plates 4 and 5 is primarily economic, and is based on color and hardness; the contact line marks the outer limit of the zone in which serpentine predominates markedly over talc.

Talc-carbonate rock surrounds the core of serpentinite in a shell that ranges from less than a foot to 20 feet thick. Where the ultramafic body is very thin—less than 3 feet or so, as in the southernmost tabular body east of the main ultramafic body—both the talc-carbonate and the serpentinite zones are inconspicuous or absent, and steatite alone occurs. For the most part, the peripheral arrangement of talc-carbonate rock with reference to serpentinite is fairly regular, but locally talc-carbonate rock irregularly embays the serpentinite, or cuts across it in fairly regular, tabular zones a foot or less thick and hundreds of square feet in extent. The carbonate content of the talc-carbonate rock is variable. The talc-carbonate rock grades imperceptibly into steatite, commonly within a foot, but in many places the gradation is irregular and occurs over several feet.

Veins composed of anhedral masses of carbonate formed of crystals as much as 2 inches across and of sheaves of talc formed of leaves as much as 1 inch across are exposed in the serpentinite and talc-carbonate rock at several places in the underground workings of the Waterbury mine; they are comparatively rare, and form only a negligible proportion of the total talc-carbonate rock or serpentinite. The veins range in thickness from about an inch to as much as a foot, and the talc and carbonate are irregularly intermixed in the veins. The vein borders are irregular in detail, but in general their gross form is rather regularly tabular. Individual veins can be traced for several tens of feet, and in some places for as much as 100 feet. No veins were observed to extend into the steatite, blackwall, or schist, but conditions of exposure do not permit exclusion of such a possibility in some instances.

Steatite makes up the outer portion of the ultramafic bodies throughout the extent of the underground workings and wherever the contact is suitably exposed on the surface. Bordering the steatite, and separating it from the unaltered schist, is a narrow zone of blackwall chlorite rock. It is inferred that the steatite and blackwall zones form continuous, concentric shells at the borders of the ultramafic bodies. The steatite zone commonly is 2 or 3 feet thick, but locally it is as thin as 1 foot

or as thick as 6 or 7 feet. Where the gradation into talc-carbonate rock is irregular and broad, an exact thickness cannot be assigned. The variations in thickness of the steatite zone are local in extent and bear no relation to position with respect to the ultramafic body; rather they appear to be controlled by local structural features such as flexures and fracturing, and possibly by the lithologic character of the schist. The steatite and blackwall chlorite rock are intergradational, but the transition is abrupt, commonly taking place in a fraction of an inch to two inches; in a few places the transition is irregular and is as much as a foot wide. The blackwall zone is fairly uniform in thickness throughout the exposed length of the body and through a vertical exposure of more than 600 feet; it averages about one-half foot. In a few places, especially at irregularities where the contact of the ultramafic body is slightly cross-cutting and the transition from steatite to blackwall is apt to be somewhat irregular, the blackwall zone is as much as 1 or 2 feet wide. Such thicknesses are purely local in extent and show no relation to depth below the top of the lens. These observations on thickness of the blackwall and steatite zones contrast markedly with the relations at Roxbury, Vt., depicted by Hess (1933*b*, p. 639-640; figs. 3 and 5), who describes a marked thickening of the blackwall zone upward and at the top of the lens of ultramafic rock, and of the steatite zone downward and at the keel of the lens. This matter is discussed further on page 92, below.

The country rock adjacent to the ultramafic body is albitic in many places. In such places, the transition zone from the blackwall to unaltered schist is invariably marked by a heavy concentration of albite porphyroblasts in a zone a few inches thick. The amount of albite in the zone varies generally in proportion to the amount of albite in the schist several inches outside the zone of concentration.

The contacts of the ultramafic bodies in the Waterbury mine locality are generally concordant with the schistosity of the schist. Along the main drift of the adit (1st) level, small departures from concordance occur at intervals of several hundred feet. The discordance in each place is small, and consistently offsets the contact a few feet to the right in plan, away from the observer. Most of these places are marked by long, thin septa of schist, previously described (p. 13), which project from the wall into the talc body. In one or two places the offset to the right appears to be due to folding rather than discordance. Small local discordances of a few inches are caused by irregular steatitization of the country rock at the borders of the ultramafic bodies.

Near the southern end of the main ultramafic body, in the vicinity of the large fold in the eastern contact

about under the powerline (see pl. 4), the contact and the schistosity in the schist appear to diverge markedly. Outcrops of schist, especially near the contact, are few, and the relation of schistosity and contact are obscure. However, all observations of schistosity indicate that it does not wrap around the folds, but retains its general regional trend with only slight to moderate local deflection. The schistosity appears to be about parallel to the axial plane of the fold in the contact. In the second level of the underground workings the same fold is exposed. Relations are obscured by chloritization of the schist at the contact with the steatite and by much fracturing resulting from mining; inconclusive evidence suggests that bedding is parallel to the contact of the ultramafic rock and that schistosity, though variable, is approximately parallel to the axial plane of the fold.

A mafic dike that cuts the steatite and schist at a large angle is exposed in the adit (1st) level about 1,000 feet north of the southern end of the workings. The segment of the dike in the east wall is offset to the north about 135 feet from that in the west wall, along a fault that parallels the ultramafic body. The dike strikes about N. 70° E. and dips 80° to 85° N. The fault dips steeply eastward. The apparent offset is therefore very nearly equal to the horizontal displacement on the fault.

MAD RIVER LOCALITY

The Mad River locality is about 6 miles east of the axis of the Green Mountain anticlinorium. The rocks in the vicinity are rather uniformly steep, with tops of beds facing east. The only significant departures from the homocline at the latitude of the mine occur 2 to 2½ miles east of the mine, where the pattern of greenstone beds marks an anticline. (See pl. 2.) The ultramafic rocks intrude schist, carbonate rock, and greenstone at and immediately above the zone of transition between the Camels Hump group and the Ottauquechee formation.

The geology of the Mad River ultramafic body is shown on plate 6. The detailed geology of the surface of the talc deposit and of the underground workings is shown on plate 7. Rocks within the area include locally graphitic quartz-sericite-chlorite schist, quartzite, greenstone, carbonate rock, serpentinite, talc-carbonate rock, steatite, and diabase.

Bedrock is exposed over about 15 to 20 percent of the area, and is enough to show fairly accurately the outlines of the ultramafic bodies and the distribution of the various lithologic units of the adjoining country rock throughout most of the area. Exposures of talc-carbonate rock, steatite, and blackwall—confined to a thin zone along the contact of the ultramafic body—are rare, however. The country rock comprises schist,

greenstone, and quartzite. These rocks are intergradational, but the transitions between them are nearly everywhere abrupt, and markedly so between quartzite and schist. The composition of the schist is somewhat variable, notably the content of graphite. Schist predominates and constitutes 80 to 85 percent of the country rock. Greenstone constitutes about 15 to 20 percent of the country rock and forms two prominent units, which are 15 to 100 feet wide, bordering much of the east side of the main ultramafic body. Smaller units occur along the southwest side of the main body, and several beds too small to map occur elsewhere in the schist. A bed of quartzite from 5 to 10 feet thick is exposed intermittently near the eastern border of the map area. Thin beds of carbonate rock and carbonate-chlorite rock are exposed at several places along the east side of the main ultramafic body, and form small septa within the body at a few places near the eastern border.

The general trend of schistosity and bedding of the country rock is about N. 20° E., and the dip ranges from vertical to steeply east or west. Deviations from the general trend are few, and most of the variations in attitude appear to reflect variations in the attitude of the contact of the ultramafic body. In only a few places are folds noticeable, and their maximum amplitude and wave length are 2 or 3 feet.

The main ultramafic body is irregularly elliptical in plan, and is inferred to be lenticular. It is 4,700 feet in known length, and may be at least 6,500 feet long if the outcrop of talc-carbonate rock in Shepard Brook at the south end of the map area is continuous with the main ultramafic body. The ultramafic body half a mile north of the Mad River locality (pl. 2) is probably not continuous with Mad River body. The maximum width of the main body is about 700 feet. The general trend of its long axis is about N. 25° E., and the principal plane of the lens is inferred to dip steeply eastward. Both walls dip steeply inward, the west wall somewhat less steeply than the east wall.

A few large inclusions of greenstone, schist, and carbonate-chlorite rock occur within the ultramafic body, and several inclusions of schist too small to map are exposed in the easternmost quarry near the north end of the ultramafic body. The contacts of the large inclusions are not exposed, but the smaller, fully exposed inclusions in the quarry are completely chloritized and are bordered by thin zones of steatite. The outlines of the two large inclusions near the western contact (pl. 6) are uncertain because of poor exposure, but their schistosity and inferred pattern, and the observed pattern of the small inclusions in the quarry are parallel to the principal plane of the ultramafic body.

A series of small lenses of serpentinite, talc-carbonate rock, and steatite crops out a few hundred feet east of the main ultramafic body, within and at the western contact of the easternmost of the two greenstone units—hereinafter called western and eastern greenstones—shown east of the main ultramafic body (pl. 6). The outcrops of serpentinite, talc-carbonate rock, and steatite extend for about 3,000 feet in a northerly direction, but they are separated for the most part by intervening areas of greenstone. Probably at least nine separate bodies occur, though it is possible that some or all join at depth. They are elongate northward, generally lenticular but locally irregular, and their general geologic relations are similar to those of the main ultramafic body.

Serpentinite forms the central core and much the greater part, probably more than 90 percent, of the main ultramafic body. It also forms the center of the larger ultramafic bodies in the eastern greenstone. Where the main body is narrowly restricted—as at the site of the inclined shaft, in the smaller bodies in the eastern greenstone, and in the tongue-like projections at the north and south ends of the main ultramafic body—the core of the serpentinite is absent. The serpentinite grades rather abruptly into talc-carbonate rock, or into steatite where the talc-carbonate zone is absent. A few dike-like masses of serpentinite were observed in the central mass of serpentinite within the main ultramafic body. These dikes are as much as 6 inches thick and were traced for as much as 15 feet along the strike and 6 feet down the dip. They are about vertical and strike about east.

Talc-carbonate rock forms a relatively thin discontinuous zone outside the core of serpentinite, and is not as fully developed as in most similarly extensively steatitized bodies of ultramafic rock in Vermont. Even at the south end of the main ultramafic body, near the mine, where steatitization has been most extensive, the talc-carbonate rock zone commonly is less than 10 feet thick. Farther north it is commonly less than 2 or 3 feet thick, and in a few places it is entirely absent. The proportion of talc-carbonate rock in the talc deposit at the extreme north end of the main ultramafic body is not known. In and near the mine, much of the talc-carbonate rock appears to be contaminated by masses of tremolite-carbonate rock. It is difficult to determine the exact relations of these masses, because of poor exposure, but they probably are altered inclusions of impure carbonate rock. The talc-carbonate rock grades into steatite, generally abruptly, but rather erratically.

No late talc-carbonate veins were noted at the Mad River locality, probably because of lack of suitable exposure rather than because of real absence of such veins.

Steatite and blackwall occur at the outer margin of the ultramafic body at all places at which the contact is exposed; hence they are inferred to form continuous shells. The thickness of the steatite probably averages about 2 or 3 feet, but in one place—near drill hole 85 (pl. 6)—is only about 0.5 foot thick, and in many places where the carbonate content of the grit is variable and the gradation irregular precise thicknesses cannot be assigned. Throughout most of the ultramafic bodies, where the adjacent country rock is schist, the steatite is bordered by a narrow zone of blackwall chlorite rock about half a foot wide. At the one place where the schist exposed at the contact of the main ultramafic body is albitic (near diamond-drill hole 85, pl. 6), a narrow zone (0.1–0.2 foot thick) at the outer border of the blackwall zone—here only about 0.1 foot thick—contains porphyroblasts of albite more abundantly than the adjacent schist. For about 2,000 feet north from the mine workings along the eastern contact of the main ultramafic body, the steatite zone is bordered in many places by talcose tremolite-chlorite-carbonate rock rather than by the usual blackwall chlorite schist. In a few places this grades into impure carbonate rock; elsewhere it grades into quartz-sericite-chlorite schist. Exposure of the blackwall is poor, and is limited to a vertical range of 300 feet, but throughout that range no consistent variation in thickness of blackwall dependent upon position with respect to the ultramafic body was observed. The only systematic variation noted appeared to be related to the thickness of the steatite zone.

The contacts of the ultramafic bodies at the Mad River locality are generally conformable with the schistosity and with greenstone beds in the schist. Divergence from strict parallelism is apparent along the eastern contact, but the pattern of the different rock units suggests that this is due, in part at least, to tectonic thinning adjacent to the thickest part of the ultramafic body. Local discordances of a few inches, produced by irregular steatitization of the country rock, occur in many places, especially at the borders of the small bodies within the eastern greenstone. Inclusions and septa several feet thick within the serpentinite and the occurrences of different rock types at different places along the eastern contact show that the original contact of the intrusive body is locally crosscutting.

A mafic dike 3 to 6 feet thick and two dikelets a few inches thick are exposed at the surface and in the underground workings of the talc mine. The dikes strike east or slightly north of east and dip about 75° N. They are offset at several places by small faults or shears. The larger of the shears, in the eastern part of the 968-ft level, strike about N. 20°–30°

E. and dip steeply east, but many minor shears whose attitudes vary branch off from the larger ones. Near the margins of the body these shears dip parallel to the adjacent contact of the ultramafic body. Fragments of dike rock tail out northward from the dike in the fault that cuts off the dike in the west wall of the east branch of the 968-ft level; the east side has therefore moved northward with respect to the west side. The dikes are not exposed in the wallrock east of the ultramafic body, and total offset cannot be determined; exposure in the east adit of the 968-ft level indicates that total offset exceeds 100 feet.

STRUCTURE

MAJOR FEATURES

No large-scale departures from a homocline in the east limb of the Green Mountain anticlinorium occur at any of the three localities. Throughout most of the area at each locality, and throughout the entire area of the Mad River locality, the schistosity is characteristically steep and trends a little east of north in the attitude typical of rocks in the east limb of the Green Mountain anticlinorium. Deviations from this regional attitude reflect chiefly the lenticular form of the ultramafic bodies and haphazard irregularities in their form, but locally at the Barnes Hill and Waterbury mine localities broad folds more than a hundred feet in wave length affect the contacts of the ultramafic bodies. At the Waterbury mine locality the gross bedding pattern is not discernible. At the Barnes Hill locality the greenstone at the southwest margin of the ultramafic body is folded in conformity with the contact of the ultramafic body. At the Mad River locality, units of greenstone as much as 100 feet thick bend approximately in conformity with the outlines of the ultramafic body, but they delineate, in general, a simple steep homocline throughout the area.

STRUCTURAL DETAILS

The terminology of structural features, particularly that of planar features of secondary origin, is unsatisfactory in many ways. Terms such as foliation, schistosity, slaty cleavage, flow cleavage, axial-plane cleavage, axial-plane foliation, shear cleavage, shear schistosity, slip cleavage, and fracture cleavage have been variously employed by different writers. Each term has been interpreted variously and has acquired by connotation contrasting genetic implications. Consequently each of the terms may mean a different thing to different people and may, as well, convey different genetic implications.

In view of this, it is necessary to define terms; even so, it is difficult not to convey unwarranted and un-

desirable connotations. Throughout this paper the following definitions will be followed:

Foliation is a family name for planar structures marked by parallelism of fabric elements, which commonly imparts the ability to break along approximately parallel surfaces; it is a visible *s*-surface (see Turner, 1948a; Fairbairn, 1949, p. 235).

Slip cleavage is a secondary planar feature consisting of discretely spaced surfaces of parting or incipient parting subparallel to limbs of small folds, and generally parallel to the axial planes of the folds. Excellent descriptions and discussions of slip cleavage closely similar in all aspects to that described in this report have recently been published (White, 1949, p. 587–594; Brace, 1953, p. 84–91; Osberg, 1952, p. 84–87).

Fracture cleavage is defined as a secondary planar feature consisting of spaced surfaces of parting without significant alinement of platy minerals along the cleavage surfaces. It is essentially a form of close-spaced jointing.

Schistosity will be used to denote all other types of secondary foliation. Schistosity formed by discrete spaced surfaces of discontinuity or closely spaced shear zones in which the lepidoblastic minerals are alined, and not apparently related to folds or crinkles, is called a *spaced schistosity*; it occurs both in lepidoblastic layers and in layers with appreciable granoblastic minerals. Spaced schistosity is here considered to be genetically equivalent to slip cleavage. (See p. 26.) Schistosity in which all the platy minerals are conspicuously parallel in entirely or predominantly lepidoblastic layers—that is, where the dimensional parallelism in favorable bands is continuous—will be referred to as *continuous schistosity*. In outcrop, continuous schistosity commonly cannot be distinguished from spaced schistosity unless the spaced schistosity is unusually coarse. Field identification nearly always requires corroboration under the microscope.

Figures 2 to 12 illustrate several kinds of secondary foliation in different types of rock.

BEDDING

Individual beds of quartzite and greenstone, marked by differences in color, texture, and mineralogic character, can commonly be traced for tens of feet and are parallel to the boundaries of larger units within limits of observation. Beds in the schist can generally be traced only a few feet and rarely as much as a few tens of feet; they appear generally to be parallel to the regional pattern and to nearby beds of quartzite and greenstone, and only locally in small folds does the bedding trend sharply across the regional pattern. Throughout each locality most measurements of the attitude of bedding in outcrop are approximately

parallel to the regional pattern except near the contacts of ultramafic bodies, where individual measurements of bedding attitude conform approximately with the attitude of the nearby contact. The average bedding attitude at each locality is about N. 10°–20° E., and the dip is steep either side of vertical.

LAYERING IN ULTRAMAFIC ROCKS

Layering in serpentinite at Barnes Hill is nearly planar, and uniform in attitude throughout the extent of unsheared masses (shear polyhedrons) of serpentinite, which range from a foot or less to 10 feet or more across. The attitude of the layering varies markedly and abruptly among shear polyhedrons. The pattern shows no discernible relation to the contacts of the ultramafic body, nor does it form a regular pattern of folds. Dips range from 45° to 90°, through a wide range in direction.

FOLDS

In this report, folds and lineations are described as “gently plunging,” “moderately plunging,” and “steeply plunging.” The terminology—a natural and convenient outgrowth of field mapping in rocks that are steep or vertical—is not strictly applicable in rocks with gentle dips. But such areas of gentle dip are few and small, and no confusion will result if it is realized that the essential distinction is based upon pitch (measured in the plane of bedding or schistosity), and that such terms as “gently plunging” and “steeply plunging” are a kind of shorthand to denote, respectively, a linear feature about parallel to the strike of bedding or schistosity, and one about down the dip. It seems better to use these shorthand terms than to introduce into the general discussion the seldom-measured “pitch,” with the resulting necessary wordiness, or to classify features in terms of trend of the linear element, which is dependent upon the attitude of bedding or schistosity, and is, therefore, greatly influenced by local variations. “Gently plunging” is applied to folds or linear features with a pitch of 0° to 30°; “moderately plunging” to features with a pitch of 30° to 60°; and “steeply plunging” to features with a pitch of 60° to 90°.

Folds in the areas are of two general types: gently plunging folds consistent with the pattern of the Green Mountain anticlinorium, and steeply plunging folds with no apparent such relationship. Gently plunging folds visible in outcrop are confined to the greenstone at the southwest border of the ultramafic body at the Barnes Hill locality, and to a few small exposures along the east side of the main ultramafic body at the Mad River locality. The axial planes of the gently plunging folds are somewhat variable in attitude, but strike generally about N. 20° E. and dip steeply either side of vertical. Most axes plunge 5° to 35° northward,

FIGURE 3

FIGURE 5

FIGURE 2

FIGURE 4

FIGURE 7

FIGURES 2-7.—PHOTOMICROGRAPHS SHOWING CONTINUOUS AND SPACED SCHISTOSITY.

FIGURE 6

2. Quartz-sericite schist, showing details of continuous schistosity in a layer composed entirely of sericite. Nearly all the individual flakes of mica are uniformly parallel to the layering in the schist so that within such a layer the potential number of breakage surfaces is very large, being determined only by the limit to which the sericite can be cleaved. X700. Crossed nicols.
3. Steatite, showing spaced schistosity. Most of the flakes of talc are oriented diversely, but the rock is traversed rather uniformly by parallel zones 0.01-0.05 mm apart and about 0.001 mm wide in which the flakes are arranged parallel to the zones. In the photograph the surfaces of spaced schistosity are marked by dark lines or narrow bands that dip steeply left. In contrast with continuous schistosity (see fig. 2), the spaced schistosity imparts to a rock the tendency to break along only a limited number of surfaces. X90. Crossed nicols.
4. Blackwall chlorite rock, showing spaced schistosity. The thin section in the areas of the photographs is entirely of chlorite. Spaced schistosity shows up as dark, narrow, vertical bands, irregular in detail but with a uniform and regular general pattern. In the layers (vertical bands in the photographs) that form the spaced schistosity, the flakes of chlorite are uniformly parallel to the boundaries of the layers. Between schistosity surfaces, the flakes are diversely oriented. The rectangle outlines the area of figure 5. X90. Crossed nicols.
5. Detail of figure 4, illustrating details of the uniform orientation, parallel to the boundaries of the bands of spaced schistosity, of the flakes of chlorite within the bands and the diverse arrangement of flakes between bands. X700. Crossed nicols.
6. Serpentinite, showing spaced schistosity. Narrow, dark, vertical bands in photograph are formed by the spaced schistosity. The pattern is most regular and closed-spaced near the center of the photograph. Flakes of serpentine in the schistosity bands are predominantly closely parallel to the boundaries of the bands, but a few scattered flakes are only subparallel or are diversely oriented. Between the schistosity, nearly all the flakes of serpentine are diversely oriented. Rectangle outlines area of figure 7. X135. Crossed nicols.
7. Detail of figure 6, illustrating details of the oriented flakes of serpentine in the schistosity and the diverse arrangement of flakes between. X700. Crossed nicols.

FIGURE 9

FIGURE 11

FIGURE 8

FIGURE 10

FIGURES 8-11.—PHOTOMICROGRAPHS SHOWING SPACED AND CONTINUOUS SCHISTOSITY.

8. Granitic quartz-sericite schist, showing spaced schistosity traversing not only those lepidoblastic layers in which the minerals are oriented diversely but also those which exhibit a marked continuous schistosity. In the bands marked "d, s," flakes of sericite between surfaces of spaced schistosity are oriented diversely. In the band marked "c, s," the sericite flakes between surfaces of spaced schistosity have a continuous schistosity parallel to the spaced schistosity. Photomicrograph emphasizes the spaced schistosity, which shows as nearly vertical black bands. $\times 90$. Crossed nicols.
9. Quartz-sericite schist, showing spaced schistosity in a rock with both granoblastic and lepidoblastic layers. The granoblastic layers (marked "g") show almost no parallel arrangement of minerals and only widely spaced and irregularly spaced schistosity. The lepidoblastic layers show both diverse arrangement of flakes of sericite between surfaces of spaced schistosity (bands marked "d, s"), and continuous schistosity parallel to the spaced schistosity (bands marked "c, s"). The photomicrograph emphasizes the spaced schistosity and shows the textural pattern of granoblastic layers. $\times 45$. Crossed nicols.
10. Quartz-sericite schist as in figure 9. Photomicrograph emphasizes the diverse arrangement of most of the sericite in some layers and the continuous schistosity in others. The black lines and bands dipping steeply to the right mark concentrations of graphite along surfaces of spaced schistosity. $\times 46$. Plane-polarized light, analyzer out.
11. Quartz-sericite schist with porphyroblasts of albite. An irregular slip cleavage dips steeply left. The lepidoblastic layers show a generally good continuous schistosity nearly perpendicular to the slip cleavage; in places the sericite between slip-cleavage surfaces is diversely oriented, possibly as a result of extreme distortion locally. Graphite occurs in layers parallel to the continuous schistosity, in concentrations along surfaces of slip cleavage, and in concentric zones—throughout which the pattern inherited from the schist is evident—in the subhedral crystal of albite. A portion of a glomeroporphyroblast of albite shows at the top left of the photograph. $\times 55$. Plane-polarized light, analyzer out.

but some plunge southward. At Barnes Hill, folds with wavelengths of as much as 150 feet can be traced in the bedding pattern of closely spaced outcrops. The folds are left handed or sinistral (White and Jahns, 1950, p. 197), and are consistent in pattern with their position (Billings, 1942, p. 77) on the Green Mountain anticlinorial structure (see pl. 3.) At the Waterbury locality, near the southern border of the map area, a fold as much as 400 feet in wavelength is a conspicuous feature of the map pattern of the eastern contact of the main ultramafic body. Exposures of the same feature in the underground workings (see text, p. 14; also pls. 4 and 5) indicate an average plunge northward of a little less than 30° . The pattern of the fold is right handed or dextral, but the gross pattern of bedding in rocks of the area is undeterminable, so that it is not possible to relate the fold in the contact to any large-scale fold pattern in the rocks.

Schist from drill cores at the Barnes Hill and Waterbury mine localities commonly shows minor folding, and in a few places the angular relations of the schistosity suggest folds at least several feet across. The attitudes of the folds could not, of course, be determined, but in many instances the folds have an associated slip cleavage parallel to the axial planes. If the slip cleavage is the same as that conspicuous in the Sterling Pond area (see p. 24-25), the folds are probably gently plunging and are genetically related to the Green Mountain anticlinorium.

Steeply plunging folds are widespread in the schist but are nowhere conspicuous or abundant at any of the localities. The axial planes of measurable folds differ considerably in attitude, and the plan of the fold pattern (whether right or left handed) varies markedly, even within relatively small areas, but the fold axes are consistently about downdip. In many places the schist is crumpled irregularly, and no decipherable pattern exists. In many of the steep folds the schistosity butts into the bedding at the noses of the folds. (See also p. 65, where such a fold in a thin section of the blackwall is described.) Elsewhere, the schistosity appears to wrap around the noses of the folds, parallel to the bedding, in the manner of the Green Mountain folding.

SCHISTOSITY

All the rocks are schistose to some degree, at least locally, but the conspicuousness and perfection of the schistosity varies considerably among rock types, and also from place to place in some of the rocks. Spaced schistosity (figs. 3-10) generally predominates strongly over continuous schistosity, but continuous schistosity (figs. 2, 11, 12) is present locally in most rocks, and is the principal schistosity in some.

The schist everywhere has a conspicuous and well-formed but wavy-spaced schistosity. Continuous schistosity is prominent locally. The greenstone commonly, but not everywhere, shows a poor to good continuous schistosity; in a few places, it has a very obscure and irregular spaced schistosity. Nearly all the blackwall has a moderately good to very good spaced

A

FIGURE 12.—Photomicrographs of sericite-chlorite-quartz schist, showing the relationships between bedding and secondary foliations.

A. Bedding forms a series of thin layers that have a sinuous pattern of rather sharp folds. Most of the layers—such as those labeled *c*—exhibit an excellent continuous schistosity, but lenses and beds rich in silt-size quartz grains—such as the one labeled *s*—contain only diversely oriented lepidoblastic minerals. A minor but appreciable proportion of thin layers (such as the one labeled *r*) are composed entirely of sericite and chlorite. A slip cleavage parallel to the axial planes of the folds forms the most prominent breakage surface of the rock. The slip cleavage is closely spaced and prominent in layers that also exhibit a good continuous schistosity—those labeled *c*—and is widely spaced and irregular or entirely absent in silty layers (*s*) and in layers of diversely oriented lepidoblastic minerals (*r*). The arrow locates the approximate position of B. $\times 7$. Plane-polarized light, analyzer out.

B. Detail of area indicated in A, showing the pattern of spaced schistosity. Rectangle outlines C. $\times 150$. Crossed nicols.

C. Detail of area outlined in B, showing the relationship of slip cleavage (dark, vertical bands) and the pattern, in the layers between the slip cleavages, of the sericite flakes. The dimensional orientation of the flakes produces continuous schistosity, only slightly disarranged by the development of the slip cleavage. $\times 700$. Crossed nicols.

schistosity that is commonly fine and of uniform quality (figs. 4-5). Continuous schistosity is present in a few places in the blackwall, particularly at Barnes Hill. Steatite at the outer margin of the steatite zone commonly has a good spaced schistosity, whereas that at the center and inner margin of the zone generally has a less perfect schistosity or none. Only rarely does the

steatite show an approach to continuous schistosity. Talc-carbonate rock shows only a coarse spaced schistosity that is generally erratic in distribution and of rude quality. Serpentine is for the most part nonschistose, but a rude and irregular spaced schistosity is not uncommon locally; and in a few places it is very regular and perfect.

Detailed discussion of petrographic and mineralogic manifestations of schistosity is deferred to the section on "Petrography."

Spaced schistosity outside the ultramafic bodies regularly strikes about N. 10° - 20° E. and is uniformly steep at all three localities, except locally near irregularities in the contacts of the ultramafic bodies. Within the ultramafic bodies the attitude of the spaced schistosity averages about the same as the regional trend, but variations are more widespread and erratic. Continuous schistosity also most commonly strikes about N. 10° - 20° E. and is nearly vertical, but where folds are present the attitude is variable. The most notable departure is shown by the greenstone at Barnes Hill, in which throughout much of its extent the continuous schistosity strikes northwest and dips moderately northeast.

SLIP CLEAVAGE

Slip cleavage is not commonly exposed at any of the three localities, and is confined to the metamorphosed sedimentary and volcanic rocks. It is most prevalent in the schist, and is rarely observed in the greenstone. The slip cleavage is wavy, irregularly spaced, and discontinuous, and is associated almost invariably with crinkles in the schistosity. Generally, no distinct shear surfaces have formed on the limbs of the crinkles. The irregular shape of the crinkles and the abruptness with which they die out is responsible for the irregularity and discontinuity of the slip cleavage. The slip cleavage is about parallel to the limbs and axial planes of the small folds and crinkles. The overall spatial relations are not adequately known, but the average attitude of the slip cleavage appears to be about parallel to the general attitude of the schistosity. The inferred genetic equivalence of slip cleavage and spaced schistosity is discussed on page 126. Figures 11 and 12 illustrate two slip cleavages of contrasting regularity and perfection.

FRACTURE CLEAVAGE

At several places in the underground workings of the Waterbury mine the steatite is marked by a pronounced fracture cleavage—that is, a system of close-spaced joints. The attitude is variable, both from place to place and at a given exposure. Particularly striking is the way that the fracture cleavage is warped near irregularities in the contact between the steatite

B

C

and the adjacent, more competent rock—schist, serpentinite, or talc-carbonate rock. Very rarely, the fracture cleavage is associated with folds in the steatite and is on the average about parallel to the axial planes. In such instances the cleavage fans so that in anticlinal folds it converges downward. In most places the fracture cleavage appears to be unrelated to folds and its relationships to other features are erratic.

OTHER CLEAVAGE

A coarse cleavage that diverges from the predominant schistosity is conspicuous at a few places in the steatite, particularly in some of the small talc bodies east of the main ultramafic body at the Mad River locality. This cleavage is formed by somewhat irregular but generally parallel thin zones from 0.1 to 1.0 mm wide and 1.0 to 10.0 mm apart. In places the shear zones appear to be attenuated monoclinical flexures. The shear zones clearly are later than the general fabric of the steatite, but in places the fine-spaced schistosity appears to feather into and bend them slightly, but the pattern of the spaced schistosity in the thin shear zones is much less prominent and irregular than elsewhere in the steatite.

LINATION

Lineation is not a prominent structural feature at any of the three localities. Nearly all lineations observed were formed by crinkles on surfaces of schistosity; in a few places a slip cleavage is associated with the crinkle, and the lineation also may be regarded as marking the intersection of slip cleavage and schistosity. Rodding, formed by thickening of quartz lenses in noses of folds, is relatively rare and poorly formed. Most of the lineations are steep, but that associated with slip cleavage in some places plunges gently. Poor exposures and aberrant attitudes of many minor folds—probably attributable, in part at least, to proximity to the ultramafic bodies—make it generally impossible in most places to relate a given lineation to a particular type of fold.

SHEAR POLYHEDRONS

In addition to schistose zones of considerable linear extent, most of the serpentinite is traversed by thin irregular sheared zones that enclose close-packed polyhedral masses of relatively unsheared serpentinite termed "shear polyhedrons" (Chidester, Billings, and Cady, 1951, p. 7). The sheared zones do not conform to any apparent system. A detailed description of the feature is given on page 71.

JOINTS

Regularly patterned joints are relatively uncommon in the area, but in a few places joints as much as several tens of feet in extent and of constant attitude are con-

spicuous features of the serpentinite and talc-carbonate rock. At one place in the Waterbury mine (stope 15, pl. 5) a system of three mutually perpendicular sets of joints is exposed: one about east and vertical, the others about north and dipping, respectively, 30° E. and 60° W.

FAULTS

Small faults exposed in the underground working of the Waterbury and Mad River mines have been traced not more than a few feet beyond the limits of the ultramafic bodies, and it is likely that the faults are confined essentially to the immediate vicinity of the ultramafic rocks. The faults are irregular, and in places anastomose into systems of small shears. The attitudes of individual fault planes are highly variable, but the average is about parallel to the regional trend of schistosity and to the long dimension of the ultramafic bodies—striking a little east of north and dipping rather steeply either side of vertical. The horizontal offset, indicated by displacement of almost vertical mafic dikes and contacts of the ultramafic bodies, ranges from a few feet along small faults to as much as 135 feet at the Waterbury mine, and consistently shows that the east side moved north relative to the west side. The total horizontal offset at the Mad River mine for the entire system of faults may be several hundred feet. There is no reliable evidence of the true direction of movement on the faults, but numerous slickensides and gouges, though highly variable, all plunge moderately to steeply and suggest a moderately large vertical component of movement along the faults.

STRUCTURAL FEATURES OF THE STERLING POND AREA

Evidence within the area of this report is insufficient to determine satisfactorily the genetic relations and mode of origin of all the structural features. Studies now in progress by the Geological Survey throughout north-central Vermont furnish a basis for better understanding, though some features and relationships are still incompletely known. Various structural features are particularly well shown in the Sterling Pond area (Chidester, 1953), about 15 miles north-northwest of Waterbury village (see fig. 1). A brief summary of the structural features there will provide a framework upon which to relate the structural features of the localities with which this report is concerned.

In the Sterling Pond area the predominant schistosity has been shown to be parallel to bedding in most places and probably genetically related to eastward-trending isoclinal folds, which are predominantly a few inches in amplitude, but in a few places are as much as several feet. The schistosity diverges from bedding only near the noses of eastward-trending folds. Northward-trending gently-plunging folds conform to the pattern

of the Green Mountain anticlinorium and are genetically related to it; they range in size from tiny crinkles to folds several hundred feet across. The schistosity and the eastward-trending folds are so warped by the northward-trending folds that the attitudes of both schistosity and axial planes of the eastward-trending folds range from nearly horizontal to moderate east or west dips. Clearly, then, the eastward-trending folds and the schistosity are older than the northward-trending folds, though the evidence does not preclude the northward-trending folds being a later-stage effect of the orogenic episode that earlier produced the eastward-trending folds and the schistosity.

Associated with the northward-trending folds and trending about at right angles to them are broad, shallow culminations and depressions that mark reversals in plunge of the northward-trending folds. The culminations and depressions are genetically related to and essentially contemporaneous with the northward-trending folds.

Slip cleavage is conspicuous throughout the Sterling Pond area and bears a constant parallel relation to the axial planes of the northward-trending folds. The slip cleavage was formed contemporaneously with and is genetically related to the northward-trending folds.

Three types of lineation are prominent in the Sterling Pond area: "rodding" formed by thickening of quartz lenses in the noses of the eastward-trending isoclinal folds, crinkles in the schistosity, and striations on surfaces of schistosity. The rodding is older than the other lineations, and its orientation about at right angles to the axes of northward-trending folds is considered to be fortuitous in the sense that the two are of different age and are not genetically related. A crinkle lineation parallel to the axes of northward-trending folds—marking the intersection of schistosity and slip cleavage—and fine striations about normal to the axes of northward-trending folds are contemporaneous with and genetically related to the northward-trending folds. Tiny crinkles about normal to the axes of the northward-trending folds are considered to be contemporaneous with and genetically related to culminations and depressions in the system of northward-trending folds.

Similar features with similar relationships have been noted near the crest of the Green Mountain anticlinorium in the Hyde Park quadrangle (Albee, 1957). The eastward-trending folds and related rodding are not as well developed in areas to the south of the Hyde Park quadrangle along the crest of the Green Mountain anticlinorium (Cady and Albee, oral communications, 1954).

ORIGIN AND RELATIONS OF STRUCTURAL FEATURES

Schistosity and bedding in the rocks at the Barnes Hill, Waterbury mine, and Mad River localities are

mostly about vertical, in contrast with the Sterling Pond area and elsewhere near the axis of the Green Mountain anticlinorium. It is not possible, at the present stage of regional investigations, to interrelate precisely all features in the areas of vertical rocks with features better displayed in the flatter rocks near the crest of the anticlinorium, but a generally satisfactory interrelationship can be deduced for most features. The relatively rare minor folds with gentle plunge in the vertical rocks probably belong to the Green Mountain system of folds represented in the Sterling Pond area by northward-trending folds with gentle plunge. Steeply-plunging folds in the vertical rocks are thought to correlate, in part at least, with the eastward-trending, older folds of the Sterling Pond area; but some of the steeply-plunging folds, particularly those with which is associated an axial-plane slip cleavage, are possibly of the same age or even younger than the Green Mountain folds. If the same age as the Green Mountain folds, their steep plunge is a puzzling feature for which no entirely satisfactory explanation has been found; if younger, they were probably produced by shear couples in a nearly horizontal plane, after the strata were steeply tilted.

Slip cleavage at the three localities probably correlates in most cases with that at the Sterling Pond area—that is, it formed at the same time as the Green Mountain folds—though minor folds similar in pattern to the Green Mountain folds cannot generally be observed so that the correlation can be verified. Some slip cleavage, such as that associated with a steep-crinkle lineation and that associated with and parallel to the axial planes of steeply plunging folds may, however, be of different age. Several possible relationships suggest themselves:

- (1) All the steeply plunging folds are of the same age and correlate with the eastward-trending folds of the Sterling Pond area, in which case two interpretations of the associated slip cleavage are possible: (a) all the slip cleavage correlates with that which is parallel to the axial planes of northward-trending folds at Sterling Pond, in which case the parallelism with the axial planes of the steeply plunging folds in the Waterbury-Waitsfield area is fortuitous. (b) The slip cleavage parallel to the axial planes of steep folds, though indistinguishable from slip cleavage associated with a gently plunging crinkle, is actually older and is genetically equivalent to the schistosity of the Sterling Pond area.
- (2) The steeply plunging folds with slip cleavage parallel to their axial planes are younger than the eastward-trending folds of the Sterling Pond area but older than the Green Mountain folds.

In this case the slip cleavage parallel to the axial planes of the steeply plunging folds would be older than a second slip cleavage associated with the Green Mountain folds, but would not be genetically equivalent to the schistosity of the Sterling Pond area, at least not entirely.

- (3) The steeply plunging folds with a slip cleavage parallel to their axial planes are the same age as the Green Mountain folds; therefore, there is only one generation of slip cleavage in the Waterbury-Waitsfield area, and all the slip cleavage correlates with that at Sterling Pond.
- (4) The steeply plunging folds with a slip cleavage parallel to their axial planes are younger than the Green Mountain folds—formed after the strata were steeply tilted—and there are two generations of slip cleavage in the Waterbury-Waitsfield area. One, associated with gently-plunging crinkles, is of the same age as the slip cleavage at Sterling Pond and is related to Green Mountain folds. The other, parallel to the axial planes of steeply plunging folds, is younger than the Green Mountain folds and probably formed as the result of the horizontal shear mentioned in connection with the steeply plunging folds, above.

Continuous schistosity probably is the oldest secondary structural feature of the rocks. It is everywhere parallel to bedding; the orientation of the platy minerals parallel to bedding is believed to be largely the result of mimetic crystallization, and the later growth of the minerals and perfecting of the schistosity during the early states of orogeny to have been effectively controlled by the early mimetic crystallization and by the structural effect of the thinly laminated beds.

Spaced schistosity in the Waterbury-Waitsfield area is probably of complex origin, in contrast with that at Sterling Pond,⁷ which appears to be genetically related to and contemporaneous with the eastward-trending folds. Probably all the spaced schistosity in the vertical rocks of the Waterbury-Waitsfield area is in part contemporaneous with and genetically related to folds that correlate with the eastward-trending folds of the Sterling Pond area, but in many or most places the spaced schistosity has been recurrently renewed, so to speak, during later orogenic episodes. Probably the most important of these later episodes was the Green Mountain folding. During the Green Mountain folding, rocks in the Waterbury-Waitsfield area were tilted

about vertical. On the steep limbs approximately parallel to the axial planes of the northward-trending folds the secondary foliation generated by the folding took the form of spaced schistosity essentially parallel to the earlier spaced schistosity, whereas in the relatively flat rocks near the crest of the anticlinorium and in the noses of minor northward-trending folds in the steep rocks on the limbs, the secondary foliation was a slip cleavage. Similar renewals of the spaced schistosity may have occurred according to the alternative sequences of events outlined above in the discussion of slip cleavage.

The above interpretation of spaced schistosity makes it genetically equivalent to slip cleavage. Such an interpretation is in keeping with the nearly continuous series between the two observable in thin section (see fig. 12 A), and is supported by observations in the Hyde Park, Vt., quadrangle (Albee, 1957), where, locally, slip cleavage parallel to the axial planes of steeply plunging folds in micaceous quartzite beds grades into schistosity of identical attitude in the immediately adjacent beds of graphitic phyllite. The interpretation is also in harmony with the conclusions of White (1949, p. 591) on the equivalence of slip cleavage and schistosity in east-central Vermont.

Fracture cleavage appears not to be all of one age and mode of origin. That associated with folds in steatite may correlate with similar fracture cleavage in steatite and blackwall at Sterling Pond, which is thought to have formed in the closing stages of the Green Mountain folding (Chidester, 1953). The rest of the fracture cleavage appears to be of several ages and diverse origin. Some may have formed during faulting; other may be attributable to local adjustments in the incompetent steatite at irregularities in adjacent competent rocks during subsequent minor orogenic movements.

Other cleavage in the steatite, consisting of widely-spaced narrow shears divergent from the spaced schistosity, is a late-stage phenomenon, locally somewhat offset by minor amounts of renewed movement along dislocation surfaces in the spaced schistosity. This cleavage is of such limited occurrence that its mode of origin is doubtful.

Lineations in the Waterbury-Waitsfield area probably do not correlate entirely with lineations in the Sterling Pond area. Gently plunging crinkles probably are of the same age as the Green Mountain folds. Some of the steeply-plunging crinkles may also be the same age but have anomalously steep plunges because of aberrant structural attitudes near the ultramafic bodies. On the other hand, the steep crinkles offer the same alternative interpretations of genetic relations and mode of origin as those outlined

⁷ Continuous and spaced schistosity were not distinguished in the report on the Sterling Pond area (Chidester, 1953), but reexamination of some of the material from there shows that both exist, though continuous schistosity is probably much more widespread in the Sterling Pond area. The age assigned to the "schistosity" of the Sterling Pond area—contemporaneous with the early (eastward-trending) folds—would be actually the age of the spaced schistosity of the area; the spaced schistosity appears to grade into a microscopic (early) slip cleavage in the noses of early folds.

above for steep folds and slip cleavage. Rodding formed by quartz lenses presumably correlates, in part at least, with that at Sterling Pond associated with early eastward-trending folds, but some may have formed later by segregation of quartz in the noses of small flexures formed by nearly horizontal shear in approximately vertical strata.

Some joints are about parallel to or conjugate with a set of eastward-trending nearly vertical joints that are widespread throughout much of northern Vermont and which appear to control many of the postmetamorphic diabase dikes. Other joints in serpentinite and talc-carbonate rock may have formed as the result of stresses localized within the ultramafic rocks because of their relative incompetency.

Faults are the youngest structural features in the area. The inferred movement in all cases indicates that the faults formed as the result of a couple with a relatively strong horizontal component, and that the east side move northward and downward with respect to the west side. It may be that faults are abnormally prominent in the ultramafic bodies because the ultramafic rocks, by virtue of their incompetency, formed zones of weakness in which stresses throughout a wide zone were relieved.

Layering in serpentinite is older than the development of the shear polyhedrons because the attitude of the layering is fairly constant in a given polyhedron, but is markedly variable from unit to unit. Diagnostic textural and mineralogic criteria have been almost completely destroyed during serpentinization so that the mode of origin of the layering is largely conjectural. The early age of the layering suggests that it may be primary, and the most likely immediate cause of primary layering in ultramafic rocks would probably be variation in pyroxene content, caused, perhaps, by rhythmic variation in the relative rate of precipitation of pyroxene. No direct evidence has been found to substantiate this conjecture, but the concentration locally of carbonate and magnetite in the layers suggests original variation in composition among layers.

Layering in talc-carbonate rock is identical with that in serpentinite and is an inherited feature that has survived the alteration of the serpentinite.

The schistose zones surrounding the unsheared units that form shear polyhedrons conform to no discernible system. The structure is peculiar to serpentinite, and is considered to be due to and indicative of the mode of intrusion of the serpentinite, discussed on pages 88–89. Transport of the ultramafic rocks under conditions of regional compression caused extensive shearing and brecciation of the serpentinite at the borders of the massive units (shear polyhedrons), which were the largest structural units to maintain

coherence during transport and emplacement. The rotation and jostling of the units as they moved past one another explains the diverse orientation of the shear zones and the approach to equidimensional form of the polyhedrons.

Other possible interpretations include formation in place under the effect of regional stresses, and formation as the result of expansion within the serpentinite body during serpentinization. (See Chidester, Billings, and Cady, 1951, p. 7.) Formation in place under the effect of regional stresses is rejected because the diverse orientation of the shear zones bounding the shear polyhedrons is in marked contrast with the regular pattern of the regional schistosity. Expansion during serpentinization may have been a minor contributing factor in producing the polyhedrons, but the pattern of shearing must have preceded serpentinization, and was probably imposed upon the body by stresses from without.

PETROGRAPHY

The effects of progressive regional metamorphism and of orogeny, modified locally and slightly by those of retrograde metamorphism, dominate the petrographic features of the country rock. Within and at the borders of the ultramafic bodies are recorded the effects of intensive metasomatism through introduction of material from distant sources and through metamorphic differentiation that was restricted to a range of only a few inches or a few feet. Primary features of the country rock and of the ultramafic rocks are largely obscured by metamorphic recrystallization, but relict features, textural relations, and compositional variations provide clues to the nature and origin of the primary rocks. The nature of the processes by which rocks were altered to the present state must be deduced from the relationships between the inferred features of the original rock and the observed features of the present rock. In the following discussion, interpretation will be limited principally to an attempt to determine the parentage of each rock type, and to a brief enumeration and classification of the changes in mineralogic character deduced from paragenetic relations. (See "Petrogenesis" under description of each rock type. Detailed consideration of the mode of origin and of the processes involved is included under the major heading "Petrology and geochemistry.")

METHODS AND PROCEDURES

Megascopic features of the petrography, such as gross mineralogic character and the general pattern of distribution of minerals, were determined by a total of several hundred field observations at all outcrops and in the mines and quarries at each locality. Diamond-drill

cores from the Barnes Hill and Waterbury mine were carefully logged—from Barnes Hill, holes 1–6, by W. M. Cady and holes 7–12, by Duane Morris; at Waterbury mine, several holes, by John Murphy—and provided continuous sections of as much as 600 feet through the country rock and the ultramafic bodies; drill cores at each locality total about 3,000 feet. Field observations were supplemented by laboratory examination of about 400 selected hand specimens, more than half of which were also studied in thin section, to improve correlation of microscopic study and field observations.

Two hundred and twenty-five thin sections from the three localities were studied microscopically. Modes of 81 thin sections were determined by point-counter analysis. About a dozen thin sections each of steatite and blackwall were of such simple mineralogic character and so nearly pure talc or chlorite that estimates were obviously of suitable accuracy, probably in error less than 1 percent. The remaining estimated modes are of thin sections not suitable for point-counter analysis and may be in error by as much as 20 percent, though probably generally less. For the remainder of the thin sections it was either not feasible or was considered unnecessary to obtain a mode. All the modes of rocks from Barnes Hill, Waterbury mine, and Mad River localities are tabulated in table 1.

Point-counter analyses were made by means of a mechanical stage adapted for point counting as described by Chayes (1949). Traverses about perpendicular to the direction of schistosity were spaced 1 mm apart, and points within each traverse were spaced at 0.3-mm intervals. As many points were determined as

the area of the thin section permitted; for most sections this allowed determination of from 1,000 to 1,600 points, but for some as few as 600 points were possible. Visual estimates of modes were made by means of several random samples measured by intercept along the scale of a micrometer ocular.

Microscopic features of the fabric of the rock were determined by study of thin sections, and most mineral identifications were made by means of optical properties determined in thin section. For precise identification of some minerals, such optical data were supplemented by determinations of optical indices by means of oil-immersion media, using white light; many more optical indices, particularly of serpentine and talc, were determined principally to provide optical data to be correlated with chemical data, and to indicate the variability of certain minerals. In all, approximately 280 determinations of optical indices were made on specimens of chlorite, amphibole, carbonate, biotite, epidote, serpentine, talc (see table 2), muscovite, plagioclase, apatite, and tourmaline. Determinations of indices probably are generally accurate to within about ± 0.002 . This estimate is supported by agreement, within those limits, of routine measurements made in the present study and of precise determinations in sodium light made by E-an Zen (1956, p. 54) on three specimens of carbonate.

X-ray powder photographs of several specimens of both serpentinite and blackwall were made to confirm the optical identification of serpentine and chlorite. Preliminary results of X-ray and differential thermal analysis of serpentines are reported under "Serpentinite" (p. 73). (See table 2.)

TABLE 1.—Modes of rocks from the Barnes Hill, Waterbury mine, and Mad River localities

[Abbreviations: Est., estimated; Tr., less than 0.1 percent]

A. SCHIST AND QUARTZITE

Specimen	Source	Points counted	Quartz	Albite	Serpentine	Chlorite	Biotite	Graphite	Garnet	Apatite	Rutile	Ilmenite	Sphene	Epidote	Allanite	Tourmaline	Carbonate	Zircon	Pyrite
<i>Barnes Hill</i>																			
B-1	Distance from an ultramafic body, in feet:	799	32.6	12.3	52.8	33.3	13.4	12.2		Tr		1.3	11.1	1.3		Tr	Tr		1.1
B-11	20	908	21.0	12.3	47.3	33.7	13.4	4.3		6.3		1.8	1.3				1.3		
B-15	3	1,100	12.9		47.3	33.7	13.4	4.3				1.8	1.3						
B-18	50	1,200	33.3		47.3	33.7	13.4	4.3				1.8	1.3						
B-DDH-1-45	50	1,041	20.8	21.1	37.6	14.2	1.6	9.4	Tr			0.9	1.6	Tr					6
B-DDH-1-47	22	1,780	48.9	12.1	26.8	3.0	6.7	1.6	1.0			1.2	1.1	Tr					Tr
B-DDH-8-95	4	1,497	22.1	12.8	51.0	10.4	6.7	1.6				1.2	1.1	Tr			1.5	Tr	2
B-DDH-8-372	5	1,000	22.2	21.4	32.0	13.0	Tr		Tr			1.5	1.2	Tr					7
B-DDH-11-78	2	1,134	15.5	26.3	28.1	26.5			.6			.5	1.0	Tr			.5		
<i>Waterbury mine</i>																			
W-1	15	Est.	15	4	27	40			10	Tr		4	Tr			Tr			
W-2	1.5	957	27.6	27.6	50.7	14.6	5.1			Tr		2.0	Tr			Tr			
W-21	1.5	935	2.5	2.5	60.3	1.9	26.3		1.0	Tr		1.5	Tr			Tr			Tr
W-31	3.5	934	22.1	22.1	57.0	12.4				Tr		3.9	Tr						Tr
W-32	Adjacent; fault contact	Est.	15.4		57.0	20.4		Tr	Tr	Tr		2	Tr				1.9		1.1
W-56	23	1,083	17.0	26.8	46.4	5.4		6.8	1.6	Tr		2	Tr						
W-57	36	620	49.0	25.3	50.3	9.0		8.0	Tr	Tr		2	Tr						
W-75	10	944	19.1	22.5	40.4	7.7	11.6	.1	Tr	Tr		2	Tr						
W-76	6	1,254	17.1	22.5	40.4	7.7	11.6	.1	Tr	Tr		2	Tr						
W-77a	1	1,213	12.6	17.3	57.4	5.0	5.2	2.0	Tr	Tr		2	Tr						
W-90	20	1,475	34.8	8.4	44.3	5.0				Tr		1	Tr			0.1	2.8		1.3
W-93	3	Est.	25		90	3				Tr		1	Tr						Tr
W-94	2.5	Est.	1	3	17	9			.1	Tr		2	Tr						Tr
W-95	5	Est.	70	3	75.6	4.0		4.5		Tr		.2	8.0	.8		.1	14.0		5.7
W-DDH-4-225	1	848	7.5	35.6		37.6													
W-DDH-13-210	46	1,000	4.0																
<i>Mad River</i>																			
MR-15	25	1,148	34.9	7.6	17.1	26.6				Tr			3.1	.3			10.4		
MR-70	25	1,301	23.2		6.1	66.8	.6						2.9		Tr				
MR-79	25	Est.	60	Tr	30	7		3				Tr	Tr						
MR-90	25	Est.	40	15	37	37				Tr		Tr	Tr				5		
MR-105	25	Est.	98		.5	13	5	1.5		1			2	3	Tr		Tr		
MR-108	25	Est.	17	60											Tr			Tr	

B. ACTINOLITIC GREENSTONE

Specimen	Source	Points counted	Amphibole	Albite	Chlorite	Epidote	Carbonate	Biotite	Sphene	Magnetite
<i>Barnes Hill</i>										
B-2	SW. of ultramafic body	1,000	47.3	31.3	9.3	11.1		Tr	1.0	
B-3	do	1,072	58.6	21.5	3.4	12.9			3.6	
B-4	do	1,312	62.0	24.1	.5	11.5			1.9	
B-10	Inclusion in serpentinite	Est.	90			3	1		5	Tr
B-12	SW. of ultramafic body	1,076	49.6	20.1	2.6	26.9		5.0	.8	
B-DDH-8-42	E. of ultramafic body	744	26.7	23.3	7.9	35.6			1.3	
B-DDH-12-209	W. of ultramafic body	Est.	65	20	5	8			2	Tr

TABLE 1.—Modes of rocks from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

C. CHLORITIC GREENSTONE

Specimen	Source	Points counted	Quartz	Amphibole	Albite	Chlorite	Epidote	Allanite	Carbonate	Sericite	Biotite	Ilmenite	Sphene	Rutile	Garnet	Tourmaline	Apatite	Pyrite	Magnetite
<i>Mad River</i>																			
MR-63	Center of eastern greenstone	Est. 1,527	7	1	60	30	<1	Tr	2		0.2		Tr				4.3		0.7
MR-64	do	1,147	10.7		21.3	56.5							17.0	2.4			1		
MR-81	W. border of eastern greenstone	597		23.1	1.9	19.4	23.6			0.1			3.2						Tr
MR-85	Center of eastern greenstone	600			12.4	58.3	25.5			3.8			1						
MR-88	E. side of eastern greenstone	1,621			46.6	2.3	7.7		0.4	42.6							4		
MR-89	Schist layer in eastern greenstone	1,184			68.6	18.1				2.8			2.3				Tr		Tr
MR-91-4	do	Est. 955	Tr	15.6	47.1	7.2	<1	Tr	14.5	25	5.7	0.1	1				Tr	0.2	Tr
MR-95	Center of eastern greenstone	1,000			28.7	33.7				.2	17.7		12.5				8		Tr
MR-112	do	1,061	8.9		20.8	45.9			16.0				8.1				1		Tr
MR-119	Quartzose bed in eastern greenstone																		

D. CARBONATE ROCK

Specimen	Source	Points counted	Carbonate	Quartz	Albite	Chlorite	Amphibole	Apatite	Rutile	Sphene	Pyrite	Magnetite	Talc	Sericite	Zircon
<i>Barnes Hill</i>															
B-17	Contact of septum in talc-carbonate rock	1,187		25.8								1.6	14.1	Tr	
B-22	Center of septum in talc-carbonate rock	1,612		14	Tr	7.3			5.5					Tr	
B-DDH-3-67	Center of 8-ft thick septum in talc-carbonate rock	Est. 40				45	17		1						
B-DDH-12-188	At contact with serpentine	Est.				2									
<i>Mad River</i>															
MR-3	Septum in talc-carbonate rock	1,100		4				1.5			0.9		Tr		
MR-11	Distance from an ultramafic body in feet:														
MR-17	1	Est. 58				1	40				1				
MR-54	8	Est. 70				Tr	30					Tr			
MR-58	10	Est. 73				15	25					2			
MR-59	13	Est. 50				3	33				Tr	1			
MR-61	Septum in serpentine	Est. 96				3	9					1			
MR-91-2	do	Est. 85				2.7	2.4					1.4			
MR-98	do	1,192													
<i>Waterbury mine</i>															
W-11	Septum in talc-carbonate rock	Est. 65					35								

E. MAFIC DIKE

Specimen	Source	Points counted	Augite	Plagioclase	Green biotite and chlorite	Brown biotite	Hornblende	Glass	Magnetite	Carbonate	Quartz
<i>Waterbury mine</i>											
W-60	Chilled border of 5-ft dike	Est. 1,180	15	25	20			35	5		
W-62	Center of 5-ft dike		13.1	55.2	14.9	3.3			10.1	3.4	Tr
<i>Mad River</i>											
MR-12	Center of 4-ft dike	435	23.7	1.4	6.9		18.2	38.6	10.6	.5	0.2

Explanation:

Green biotite and chlorite: Identification not positive; chiefly an alteration product of pyroxene; consists of an aggregate of very fine shreds whose optical properties cannot be determined satisfactorily.
 Glass: A dirty appearing, confused aggregate of very fine grained material, probably consisting principally of plagioclase, hornblende, chlorite, and magnetite dust. Locally, tiny indistinct laths of plagioclase and grains of hornblende can be identified, and in places the groundmass contains abundant tiny needles of rutile(?) in a latticework arrangement.

[illegible]

[In specimen W-34, 38 percent of the chlorite is pseudomorphic after albite, 58 percent is "matrix chlorite"]

[illegible]

TABLE 1.—Modes of rocks from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

H. TREMOLITE ROCK

[Tremolite rock from the blackwall zone]

Specimen	Source	Points counted	Tremolite-Actinolite	Chlorite	Carbonate	Pyrite	Sphene	Ilmenite	Apatite
<i>Mad River</i>									
MR-2	At contact between main ultramafic body and sedimentary carbonate rock.	Est. 50	50	40	10	Tr			
MR-4		Est. 100	100	100					
MR-8		Est. 40	40	60					
MR-9		Est. 100	100	30					
MR-16		Est. 70	70						
MR-12a									
<i>Waterbury mine</i>									
W-8	At outer border of steatite	Est. 87	87	55			5	3	Tr
W-13	do	Est. 95	95	5					
W-16	do	Est. 100	100						

I. STEATITE

Specimen	Source	Points counted	Talc	Chlorite	Magnetite	Pyrite	Biomite	Apatite	Zircon	Quartz	Ilmenite	Amphibole	Sphene	Rutile	Carbonate	Chromite
<i>Barnes Hill</i>																
B-13b	Adjacent to chloritized actinolitic greenstone	Est. 65	65	32	1		2					Tr				
<i>Waterbury mine</i>																
W-6	2 ft from blackwall	Est. 100	100		Tr							4			Tr	
W-7	1½ ft from blackwall	Est. 100	100													
W-10	At gradational contact with tremolite rock	Est. 98	98		Tr											
W-23	½ ft from blackwall	Est. 100	100									15				
W-35	From center of 1½ ft thick "finger" in schist	Est. 85	85		Tr	Tr										
W-40	5 ft from blackwall	Est. 100	100			Tr										
W-49	From thin zone in talc-carbonate rock	Est. 98	98	5												
W-51	From fault zone in talc-carbonate rock	Est. 95	95	3												
W-59	5 ft from blackwall	Est. 97	97	20						Tr						
W-69	Pencil stock at blackwall contact	Est. 80	80	2												
W-73	do	Est. 98	98	2												
W-78	At blackwall contact	Est. 70	70	29									1			
W-81	1½ ft from blackwall	Est. 98	98	4.1		Tr								0.2		
W-89	2 ft from blackwall	Est. 900	900									13	1			0.7
W-DH-15-223	Tongue of steatite in schist	Est. 85	85													
<i>Mad River</i>																
MR-6	5 ft from contact	Est. 100	100													
MR-14	Gradation between tremolite and chlorite rock	Est. 65	65			Tr						35				
MR-60	In small body in eastern greenstone	Est. 80	80	20	Tr								Tr			
MR-71	do	Est. 985	985	5.5					Tr						2	
MR-78	do	Est. 75	75	23	Tr	Tr					1.2		Tr			
MR-84	do	Est. 100	100	Tr												
MR-106	do	Est. 100	100	1	Tr										Tr	
MR-118	do	Est. 99	99							Tr					Tr	
MR-125	do	Est. 95	95	Tr	Tr							5			Tr	

J. TALC-CARBONATE ROCK

Specimen	Source	Points counted	Talc	Carbonate	Magnetite	Serpentine	Chlorite	Pyrite	Quartz	Chromite
<i>Barnes Hill</i>										
B-9	50 ft from serpentinite	900	54.9	41.1	4.0					
B-14	8 ft from amphibolite	Est.	65	35	Tr					
B-20	35 ft from serpentinite	Est.	60	35	2	3				
B-DDH-1-218	Adjacent to serpentinite	Est.	75	25	Tr					
B-DDH-2-170	do	Est.	80	20						
B-DDH-6-76	1 ft from serpentinite	833	62.8	34.1	3					
B-DDH-9B-325	Adjacent to serpentinite	1,000	42.7	53.1	2.2					
<i>Waterbury mine</i>										
W-15	1 1/4 ft from blackwall	Est.	64	35			Tr	1		
W-28	Adjacent to serpentinite	Est.	75	15	Tr	10		Tr		
W-44	Thin zone of talc-carbonate rock in serpentinite	Est.	55	53	Tr	40		Tr		
W-55	do	Est.	55	53	Tr	2		Tr		
W-65	Center of 3 ft seam in schist	Est.	45	40				Tr	6	
W-71	Center of small irregular mass	Est.	97	1			2	Tr		
W-92	Adjacent to serpentinite	Est.	55	45	Tr	Tr		Tr		Tr
<i>Mad River</i>										
MR-113	Small talc body in eastern greenstone	Est.	90	5	2		Tr			3

K. SERPENTINITE

Specimen	Source	Points counted	Anthophyllite	Chrysotile (disseminated)	Chrysotile (asbestos)	Carbonate	Talc	Actinolite	Magnetite	Chromite	Pyrite
<i>Barnes Hill</i>											
B-5	Distance from talc-carbonate rock, in feet:	1,600	80.2			17.5	0.8		1.5		
B-6	6	1,133	95.1			.4	.4		4.1		
B-8	3	1,321	96.8			Tr	6		2.3		
B-19	10	Est.	90			Tr	.7		4		
B-DDH-4-200	10	1,544	98.0	0.3		11.2			.8	.1	
B-DDH-9B-432	45	2,100	82.1	Tr					6.7		
<i>Waterbury mine</i>											
W-12	Adjacent	Est.	74			1	25		Tr		
W-45	10	Est.	82			3	15		Tr		
W-47	Adjacent	Est.	70			2	30		Tr		
W-50	7	Est.	90			15	8		Tr		
W-88	6	Est.	60			5	25		Tr		
W-91	Adjacent	Est.	60				35		Tr		
<i>Mad River</i>											
MR-10	10	Est.	80			5	15		Tr		
MR-13	60	1,201	67.3			23.2	9.1		.2	.1	
MR-18	Adjacent	Est.	94			1	5		Tr		
MR-19	Adjacent	1,522	86.7			3.5			8.6	.5	
MR-20	Adjacent	1,116	71.2	16.9	1.5	1.6			6.4	2.4	
MR-21	50	755	87.0			4.3			8.6	.1	
MR-26	200	888	98.4				Tr		1.2	.4	
MR-103	40	1,639	93.1			1.4	.2		6.1	.2	
MR-107	7	Est.	80			Tr	20		Tr		
MR-127	1	Est.	70			10	25		Tr		
MR-128	40	1,500	94.6			Tr	Tr		1	.1	
MR-129	20	Est.	87			Tr	Tr		6.3	2	
		Est.	99			Tr	Tr		1	Tr	

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities

[Quantitative color designations follow the Munsell system (Goddard and others, 1948)]

A. CHLORITE

Specimen	2V (deg.)	Optic sign	Sign of elongation	Indices			Birefringence	Abnormal interference colors	Pleochroism	Parent rock
				α	β	γ				
In tremolite rock										
Waterbury mine										
W-8	5	+	—	$\approx \beta$	1.593	1.601	0.008	None	Nonpleochroic	
W-13	0	+	—	$\approx \beta$	1.602	1.606	.004	None	do	
Mad River										
MR-2			+		1.584		.000	Blue	do	
MR-9	0	+	—	$\approx \beta$	1.584		.000	Brown	do	
MR-126	Small	+	—	$\approx \beta$	1.594	1.600	.006	None	do	
				$\approx \beta$	1.599	1.606	.007	None	Slight: <i>n</i> , pale green; <i>N</i> , pale buff	
In steatite and talc-carbonate rock										
Waterbury mine										
W-15			+		1.60			Grayish blue (5 PB 4/2)	Moderate: <i>n</i> , grayish orange (10 YR 7/4); <i>N</i> , light bluish gray (5 B 7/1)	
W-46	25	+	—		1.60			Brown	Nonpleochroic	
W-51	Moderate	+	—	$\approx \beta$	1.598	1.601	0.003	Brownish gray	do	
W-77	25	+	—	$\approx \beta$	1.598	1.604	.006	None	do	
W-79			—	$\approx \beta$	1.596	1.602	.006	None	do	
W-81			—	$\approx \beta$	1.595	1.599	.004	Brownish gray	do	
Mad River										
MR-60			—	$\approx \beta$	1.604	1.608	.004	None	do	
MR-68			—	$\approx \beta$	1.602	1.608	.006	Brownish gray	Faint: <i>n</i> , pale green; <i>N</i> , colorless	
MR-71			—					None	do	
MR-78			—		1.605			Brownish gray	Very faint in pale greens	
MR-113			—					Grayish brown	Weak: <i>n</i> , pale yellowish green (10 GY 7/2); <i>N</i> , yellowish gray (5 Y 7/2)	
MR-116			+		1.586			Blue violet	Faint, in pale greens	
MR-118			—		1.586			Grayish brown	do	
MR-125			—		1.603			None	Nonpleochroic	
			—		1.603			Grayish brown	do	
In carbonate rocks										
Barnes Hill										
B-DDH-3-67	5	+	—	$\approx \beta$	1.594	1.599	0.005	None	Nonpleochroic	
B-DDH-12-188	40	+	—		1.603			Brown	Faint in pale greens	
Mad River										
MR-17			+		1.607			Blue	Moderate: <i>n</i> , colorless; <i>N</i> , pale green	
MR-54a			+		1.607			Brown	Moderate: <i>n</i> , pale green; <i>N</i> , colorless	
MR-55			+		1.627	$\approx \beta$		Deep blue to pale blue		
MR-91-1			+					Rich blue to reddish purple	Strong: <i>n</i> , pale yellowish orange (10 YR 8/6); <i>N</i> , moderate yellowish green (10 GY 6/4)	
MR-91-2			—					Blue	Moderate: <i>n</i> , pale buff; <i>N</i> , pale green	
MR-98			—					Deep brown	Moderate: <i>n</i> , pale green; <i>N</i> , pale buff	
			—					Olive brown	Faint in pale greens	
			—					Brownish gray	Colorless	
In albite porphyroblast rock										
[W-DDH-13-164B ₁ and W-DDH-13-164B ₂ are from points in the sample near to the schist and to the blackwall, respectively]										
Waterbury mine										
W-3	25	—	+		1.627	$\approx \beta$		Grayish blue (5 PB 3/2)	Strong: <i>n</i> , moderate grayish yellow green (5 GY 7/3); <i>N</i> , dark yellowish green (5 GY 4/4)	
W-9	5-35	+	—	$\approx \beta$	1.604	1.608		Brownish gray	Faint in pale yellowish greens	
W-14			+	$\approx \beta$	1.628	$\approx \beta$	0.000	Brown	Strong: <i>n</i> , pale olive (10 Y 6/2); <i>N</i> , moderate yellow green (5 GY 6/2)	
			—	$\approx \beta$	1.628	$\approx \beta$	.000	Blue violet	do	
W-17			+		1.63			Grayish blue (5 PB 4/2)	Moderate: <i>n</i> , very pale green (10 G 8/2); <i>N</i> , light green (5 G 7/4)	
W-29a	25	+	—	$\approx \beta$	1.604	1.608		None	Nonpleochroic	
W-84	Moderate	+	—	$\approx \beta$	1.624			Brown (10 YR 5/4)	Moderate: <i>n</i> , pale green; <i>N</i> , nearly colorless	
W-85	Small	+	+		1.629	1.633	$\approx \beta$	Blue gray	Strong: <i>n</i> , nearly colorless; <i>N</i> , moderate green	
W-86	10	+	—	$\approx \beta$	1.613	1.617	.004	Brownish gray	Faint: <i>n</i> , very pale green; <i>N</i> , colorless	
W-DDH-117C	5-35	+	—	$\approx \beta$	1.624	1.628	.004	Dark yellowish brown (10 YR 3/2)	Strong: <i>n</i> , dusky yellowish green (5 GY 4/2); <i>N</i> , grayish yellow green (5 GY 7/2)	
W-DDH-13-164B ₁	5	+	—	$\approx \beta$	1.623			Moderate yellowish brown (10 YR 5/2)	Moderate: <i>n</i> , moderate yellow green (5 GY 6/2); <i>N</i> , grayish yellow green (5 GY 7.5/2)	
W-DDH-13-164B ₂			—	$\approx \beta$	1.615			Pale brownish gray	Faint in pale greens	
Mad River										
MR-73	20	+	—		1.610			Brownish gray	Slight: <i>n</i> , pale green; <i>N</i> , colorless	

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

[Quantitative color designations follow the Munsell system (Goddard and others, 1948)]

A. CHLORITE—Continued

Specimen	2V (deg.)	Optic sign	Sign of elongation	Indices			Birefringence	Abnormal interference colors	Pleochroism	Parent rock
				α	β	γ				
In blackwall										
Barnes Hill										
B-10a.....	Small	+	—	$\approx \beta$	1.610	1.616	0.006	Pale brownish gray.....	Moderate: <i>n</i> , light bluish green; <i>N</i> , pale yellow green.	Amphibolite.
B-13.....	0	+	—	—	1.629	—	Low	None.....	Nonpleochroic.....	Do.
B-DDH-1-93.....	—	—	—	—	1.610	—	Low	None.....	do.....	Schist.
B-DDH-1-123.....	20	+	—	—	1.591	—	.006	None.....	Slight: pale green to yellowish green.....	Blackwall.
B-DDH-5-131.....	10	+	—	$\approx \beta$	1.605	1.612	.007	None.....	Faint: <i>N</i> , colorless; <i>n</i> , pale yellow green.....	Schist.
B-DDH-8-99.....	Small	+	—	—	1.599	—	—	None.....	Nonpleochroic.....	Do.
B-DDH-11-76.....	Small	+	—	$\approx \beta$	1.599	1.605	.006	None.....	do.....	Do.
Waterbury mine										
W-4.....	20	+	—	$\approx \beta$	1.601	1.608	.007	None.....	do.....	Do.
W-20.....	20	+	—	$\approx \beta$	1.598	1.607	.009	None.....	do.....	Do.
W-24.....	20	+	—	$\approx \beta$	1.598	1.607	.009	None.....	do.....	Do.
W-29.....	10	+	—	—	—	—	—	None.....	do.....	Do.
W-30.....	15	+	—	$\approx \beta$	1.597	1.604	.007	None.....	do.....	Do.
W-32.....	Var. 0-30	+	—	$\approx \beta$	1.614	1.620	.006	None.....	Faint, in shades of pale green.....	Do.
W-33.....	35	+	—	$\approx \beta$	1.596	1.602	.006	None.....	Nonpleochroic.....	Do.
W-34.....	40	+	—	$\approx \beta$	1.595	1.601	.006	None.....	do.....	Do.
W-37.....	15	+	—	$\approx \beta$	1.595	1.601	.006	None.....	do.....	Do.
W-38.....	15	+	—	$\approx \beta$	1.615	1.619	.004	Yellowish brown.....	<i>n</i> , moderate yellow green (5 GY 6/2); <i>N</i> , pale yellow green (5 GY 8/2).	Do.
W-70.....	10	+	—	$\approx \beta$	1.593	1.599	.006	None.....	Nonpleochroic.....	Do.
W-74.....	5	+	—	$\approx \beta$	1.604	1.610	.006	None.....	do.....	Do.
W-80.....	5	+	—	$\approx \beta$	1.597	1.603	.006	None.....	do.....	Do.
W-82.....	0	+	—	$\approx \beta$	1.590	1.598	.008	None.....	do.....	Do.
W-DDH-4-22.....	0	+	—	$\approx \beta$	1.601	1.610	.009	None.....	Faint in shades of pale green.....	Do.
W-DDH-11-117A.....	20	+	—	$\approx \beta$	1.609	1.614	.005	Pale brownish gray.....	Slight: <i>n</i> , pale green (5 GY 8/2); <i>N</i> , very pale yellow green (10 GY 8/2).	Do.
W-DDH-11-117B.....	10	+	—	$\approx \beta$	1.615	1.620	.005	Brownish gray.....	Moderate: <i>n</i> , dusky yellow green (5 GY 5/2); <i>N</i> , grayish yellow green (5 GY 7/2).	Do.
W-DDH-13-164A.....	0	+	—	$\approx \beta$	1.610	1.614	.004	None.....	Faint in pale greens.....	Do.
Mad River										
MR-22.....	—	—	—	$\approx \beta$	1.577	1.582	.005	None.....	Nonpleochroic.....	Blackwall.
MR-23.....	—	—	—	$\approx \beta$	1.591	1.598	.007	None.....	do.....	Do.
MR-74.....	—	—	—	$\approx \beta$	1.606	1.610	.004	Pale brownish gray.....	Very faint in pale greens.....	Greenstone.
MR-102.....	—	—	—	$\approx \beta$	1.584	1.588	.004	None.....	Nonpleochroic.....	Do.
MR-120.....	20	+	—	$\approx \beta$	1.599	1.603	.005	None.....	do.....	Do.
MR-122.....	—	—	—	$\approx \beta$	1.605	1.610	.005	None.....	Faint in pale greens.....	Do.
MR-123.....	—	—	—	$\approx \beta$	1.605	1.610	.005	None.....	Nonpleochroic.....	Do.
In amphibolite, greenstone and variants										
Barnes Hill										
B-2.....	—	—	—	—	1.628	—	—	Brown.....	Moderate: <i>n</i> , light blue-green; <i>N</i> , pale yellow green.	
B-3.....	—	—	—	—	1.628	—	—	Brown.....	do.....	
B-12.....	—	—	—	—	—	—	—	Brownish gray.....	Slight in pale greens.....	
B-DDH-8-42.....	Small	+	—	—	1.624	—	—	Brown.....	Moderate: <i>n</i> , dusky green; <i>N</i> , pale yellow green.	
B-DDH-12-209.....	5	+	—	—	1.612	—	—	Brownish gray.....	Slight in pale greens.....	
Mad River										
MR-63.....	—	—	—	$\approx \beta$	1.618	—	—	Dusky yellowish brown.....	Moderate: <i>n</i> , mod. yellowish green; <i>N</i> , pale buff.	
MR-64.....	25	—	+	—	1.634	$\approx \beta$	—	Rich blue to reddish purple.	Moderate: <i>n</i> , nearly colorless; <i>N</i> , pale yellowish green.	
MR-81.....	—	—	—	$\approx \beta$	1.615	1.618	—	Pale brownish gray.....	Faint: <i>n</i> , very pale green; <i>N</i> , colorless.....	
MR-85.....	20	+	—	—	1.620	—	—	Pinkish tan (<i>n</i>) to yellowish brown (<i>N</i>).	Strong: <i>n</i> , mod. yellowish green (10 GY 6/4); <i>N</i> , pale yellowish buff.	
MR-88.....	—	—	—	$\approx \beta$	1.612	1.616	0.004	Pale brownish gray.....	Slight; colorless to pale green.....	
MR-89.....	—	—	+	—	1.630	—	—	Reddish purple to reddish brown.	Strong; <i>n</i> , pale buff; <i>N</i> , grass green.....	
MR-91-4.....	—	—	+	1.633	1.636	$\approx \beta$	.003	Blue.....	Strong: <i>n</i> , pale yellow-buff; <i>N</i> , mod. green.....	
MR-95.....	—	—	—	$\approx \beta$	1.615	1.618	.003	Brownish gray.....	Strong: <i>n</i> , yellowish green; <i>N</i> , pale buff.....	
MR-97.....	Small	+	—	$\approx \beta$	1.618	1.627	.009	Brown.....	Strong: <i>n</i> , mod. green; <i>N</i> , pale buff.....	
MR-109.....	45	—	+	—	1.627	$\approx \beta$	—	Dusky reddish purple.....	Strong: <i>n</i> , pale buff; <i>N</i> , mod. yellowish green.....	
MR-112.....	—	—	+	—	1.638	$\approx \beta$	—	Pale lavender.....	Strong: <i>n</i> , pale yellowish buff; <i>N</i> , mod. green.....	
MR-119.....	0	+	—	$\approx \beta$	1.613	1.618	.005	Pale brownish gray.....	Nonpleochroic.....	

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

[Quantitative color designations follow the Munsell system (Goddard and others, 1948)]

A. CHLORITE—Continued

Specimen	2V (deg.)	Optic sign	Sign of elongation	Indices			Birefringence	Abnormal interference colors	Pleochroism	Parent rock
				α	β	γ				
In schist										
Barnes Hill										
B-11.....	10	+	—		1.628			Brown.....	Strong: <i>n</i> , dark yellowish green (5 GY 4/4); N, dark greenish yellow (10 Y 6/6).	
B-15.....	Var. 5-15	+	—		1.58			Brownish gray.....	Nonpleochroic.....	
B-18.....					1.628					
B-DDH-1-45.....			±		1.622			Bluish gray to brownish gray.....	Strong: blue green to pale yellow green.....	
B-DDH-1-67.....			+					Blue-gray.....	Moderate: <i>n</i> , pale yellow green; N, bluish green.	
B-DDH-8-95.....			+		1.629			Purplish blue.....	Moderate: <i>n</i> , greenish yellow; N, pale green.	
B-DDH-11-78.....	10	—	+		1.631			Purplish blue.....	Moderate: <i>n</i> , colorless; N, pale green.	
Waterbury mine										
W-1.....	25	—	+		1.627	$\approx \beta$		Grayish blue (5 PB 3/2).....	Strong: <i>n</i> , moderate grayish yellow green (5 GY 7/3); N, dark yellowish green (5 GY 4/4).	
W-2.....	Small	—	+		1.627	$\approx \beta$		Grayish blue (5 PB 3/2).....	Strong: <i>n</i> , moderate grayish yellow green (5 GY 7/3); N, dark yellowish green (5 GY 4/4).	
W-21.....			+					Dusky blue.....	Slight in pale greens.....	
W-31.....	20	+	—		1.628			Brown with violet tinge.....	Moderate: pale yellowish green to moderate yellow green.	
W-52.....			—	$\approx \beta$	1.611	1.615	.004	Brown.....	Slight, colorless to pale green.....	
W-56.....	Large	—	+		1.618	$\approx \beta$		Dusky blue (5 PB 3/2).....	Moderate in pale greens.....	
W-57.....			+		1.637	$\approx \beta$		Purplish blue.....	do.....	
W-75.....	0	—	+		1.643	$\approx \beta$		Bluish gray.....	Moderate: <i>n</i> , grayish yellow green (5 GY 7/2); N, dusky yellow green (5 GY 5/2).	
W-77a.....	0	—	+		1.643	$\approx \beta$		Bluish gray.....	do.....	
W-90.....	Small	—	+		1.625	$\approx \beta$		Bluish gray.....	Moderate: <i>n</i> , colorless; N, pale green.	
W-95.....	Small	—	+		1.630	$\approx \beta$		Grayish dusky blue (5 PB 4/2).....	Moderate: <i>n</i> , grayish yellow green (5 GY 7/3); N, dusky yellow green (5 GY 5/2).	
W 97.....	40	—	+					Grayish blue (5 PB 5/2).....	Strong: <i>n</i> , grayish yellow green (5 GY 7/2); N, dusky yellow green (5 GY 5/2).	
W-DDH-4-23.....			+		1.632	$\approx \beta$		Grayish blue (5 PB 5/2).....	Strong: <i>n</i> , grayish yellow green (5 GY 7/2); N, dusky yellow green (5 GY 5/2).	
W-DDH-13-210.....	10	+	—	$\approx \beta$	1.627			Dusky yellowish brown (10 YR 2/2).....	Slight, in grayish yellow greens.....	
Mad River										
MR-15.....	40	+	—		1.625			Brownish gray.....	Slight: <i>n</i> , pale yellowish green; N, nearly colorless.	
MR-70.....			—		1.610			Pale brownish gray.....	Moderate: <i>n</i> , pale green; N, nearly colorless.	
MR-79.....	Small	—	+					Pale bluish gray.....	Nonpleochroic.....	
MR-99.....			—	$\approx \beta$	1.625	1.632	.007	Grayish brown.....	Slight: <i>n</i> , greenish buff; N, pale buff.....	
MR-108.....	0	—	+		1.632			Reddish purple.....	Strong: <i>n</i> , pale buff; N, mod. yellow green.....	

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

B. AMPHIBOLE

Specimen	2V (deg.)	Optic sign	Sign of elon- ga- tion	Indices			Ex- tinc- tion ($\gamma/\wedge c$, in deg.)	Pleochroism
				α	β	γ		
In greenstone								
Barnes Hill								
B-2.....	75	—	+	1.63	1.642	1.658	19	α , moderate greenish yellow (10 Y 7/4); β , yellow green (5 GY 7/3); γ , light blue green (5 BG 6/2).
B-3.....	75	—	+	1.63	1.643	1.658	19	Do.
B-4.....	75	—	+	-----	-----	1.658	19	Do.
B-10.....	75	—	+	1.628	1.642	1.660	19	α , grayish yellow green (5 GY 7/2); β , moderate green (5 G 5/6); γ , blue green (5 BG 5/6).
B-12.....	75	—	+	-----	-----	1.658	16	α , moderate greenish yellow; β , yellow green; γ , light blue green.
B-DDH-8-42.....	75	—	+	1.63	1.641	1.650	19	α , grayish yellow green; β , moderate green; γ , blue green.
B-DDH-12-209.....	80	—	+	1.629	1.64	1.655	20	α , moderate greenish yellow; β , yellow green; γ , light blue green.
Mad River								
MR-85.....	-----	-----	-----	1.627	-----	1.652	-----	α , moderate greenish yellow; β , yellowish green; γ , light blue green.
MR-97.....	-----	-----	-----	-----	-----	1.652	20	Do.
In carbonate rock								
Waterbury mine								
W-11.....	80	—	+	1.610	-----	1.643	21	Nonpleochroic.
Mad River								
MR-11.....	-----	-----	-----	-----	-----	1.628	19	Do.
MR-17.....	-----	-----	-----	-----	-----	1.628	19	Do.
MR-54a.....	80	—	+	-----	-----	1.632	18	Do.
MR-55.....	-----	-----	-----	-----	-----	1.659	-----	Do.
MR-91-1.....	-----	-----	-----	-----	-----	-----	19	Do.
MR-91-2.....	-----	-----	-----	-----	-----	1.634	19	Do.
In tremolite-chlorite rock								
Waterbury mine								
W-8.....	85	—	+	1.609	1.625	1.640	19	Nonpleochroic.
W-13.....	80	—	+	1.61	-----	-----	19	Do.
Mad River								
MR-2.....	85	—	+	-----	-----	1.629	20	Do.
MR-4.....	75	—	+	-----	-----	1.628	19	Do.
MR-9.....	80	—	+	-----	-----	1.640	16	Do.
MR-16.....	85	—	+	-----	-----	1.632	19	Do.
MR-126.....	-----	-----	-----	-----	-----	1.64	-----	Do.
In steatite								
Waterbury mine								
W-10.....	Large	—	+	1.609	1.625	1.640	19	Nonpleochroic.
W-DDH-15-223.....	-----	-----	-----	-----	-----	1.642	19	Do.
Barnes Hill								
B-DDH-12-188.....	Large	—	-----	1.611	1.628	1.638	-----	Do.
Mad River								
MR-14.....	80	—	+	-----	-----	1.636	15	Do.
MR-84.....	-----	-----	-----	-----	-----	1.64	-----	Do.
MR-125.....	-----	-----	-----	-----	-----	1.643	-----	Do.
In serpentinite								
Mad River								
MR-128.....	-----	-----	-----	-----	-----	1.64	-----	Nonpleochroic.
In mafic dike								
Mad River								
MR-12.....	-----	-----	-----	-----	-----	-----	14	α , grayish orange; β , dusky yellow; γ , moderate yellowish brown.

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

C. CARBONATE

Specimen	ω index	Cation ratio from optics	Description	Specimen	ω index	Cation ratio from optics	Description
In steatite				In schist			
<i>Waterbury mine</i>				<i>Barnes Hill</i>			
W-58.....	1.728	$Mg_{94}Fe^{+2}_{16}$	Disseminated anhedral crystals.	B-DDH-8-95.....			Small veinlets and disseminated anhedral grains.
W-18.....	1.691	$Ca_{50}Mg_{44}Fe^{+2}_5$	Large mosaic aggregates.	<i>Waterbury mine</i>			
<i>Mad River</i>				W-90.....	1.668	$Ca_{93}(Mg, Fe^{+2}, Mn)_7$	Irregular granular aggregates.
MR-78.....	1.66	$Ca_{93}Mg_7$	Irregular mosaic aggregates.	W-DDH-13-210..	1.662	$Ca_{93}Mg_7$	Disseminated grains and aggregates.
MR-118.....	1.662	$Ca_{93}Mg_7$	Very sparse grains.	In mafic dike			
In blackwall				<i>Waterbury mine</i>			
<i>Barnes Hill</i>				W-62.....	1.668	$Ca_{93}(Mg, Fe^{+2}, Mn)_7$	Pseudomorphic after pyroxene.
B-DDH-1-93.....	1.703	$Mg_{99}Fe^{+2}_1$	Rhombs and irregular grains.	In serpentinite			
B-DDH-1-123.....	1.737	$Mg_{79}Fe^{+2}_{21}$	Veinlets and disseminated grains.	[Optical data on W-DDH-13-146 by E-an Zen: index obtained on clear grains; a few cloudy grains have slightly higher index]			
B-DDH-5-131.....	1.660	$Ca_{95}Mg_5$	Irregular grains.	<i>Barnes Hill</i>			
<i>Waterbury mine</i>				B-5.....	1.705	$Mg_{97}Fe^{+2}_3$	In small veinlets and isolated anhedral grains.
W-18.....	1.691	$Ca_{50}Mg_{44}Fe^{+2}_5$	Large mosaic aggregates.	B-19.....	1.703	$Mg_{98}Fe^{+2}_2$	Replacement of chrysotile asbestos and as scattered grains.
<i>Mad River</i>				B-DDH-4-200.....	1.706	$Mg_{96}Fe^{+2}_4$	Do.
MR-115.....	1.661	$Ca_{94}Mg_6$	Disseminated rosettes.	B-DDH-9B1-380..	1.702	$Mg_{98}Fe^{+2}_2Mn_1$	Abundant irregular veins in slightly sheared serpentinite.
MR-122.....	1.661	$Ca_{94}Mg_6$	Elongate grains and layered aggregates.	B-DDH-9B1-432..	1.704	$Mg_{97}Fe^{+2}_3$	Replacement of chrysotile asbestos and as scattered grains.
In veins				<i>Waterbury mine</i>			
<i>Waterbury mine</i>				W-12.....	1.691	$Ca_{50}Mg_{44}Fe^{+2}_5$	Very sparsely scattered rhombic crystals.
W-39.....	1.688	$Ca_{50}Mg_{44}Fe^{+2}_5$	Late talc-carbonate vein in serpentinite.	W-88.....	1.718	$Mg_{90}Fe^{+2}_{10}$	In small veins.
W-43.....	1.688	$Ca_{50}Mg_{44}Fe^{+2}_5$	Late talc-carbonate vein in serpentinite and talc-carbonate rock.		1.688	$Ca_{50}Mg_{45}Fe^{+2}_5$	Sparsely scattered rhombic crystals.
W-83.....	1.687	$Ca_{50}Mg_{44}Fe^{+2}_5$	Do.	W-91.....	1.718	$Mg_{90}Fe^{+2}_{10}$	In veins and disseminated crystals.
W-78.....	1.693	$Ca_{50}Mg_{45}Fe^{+2}_7$	Rhombs in quartz-chlorite-carbonate vein.	W-DDH-13-146..	1.713	$Mg_{92}Fe^{+2}_8$	In veins and disseminated anhedral grains.
	1.705	$Mg_{97}Fe^{+2}_3$	Veinlets in quartz-chlorite-carbonate vein.	<i>Mad River</i>			
In carbonate rock				MR-10.....	1.689	$Ca_{50}Mg_{44}Fe^{+2}_5$	Anhedral grains.
<i>Barnes Hill</i>				MR-13.....	1.689	$Ca_{50}Mg_{44}Fe^{+2}_5$	Do.
B-17.....	1.718	$Mg_{99}Fe^{+2}_{10}$	Septum in talc-carbonate rock.	MR-18.....	1.688	$Ca_{50}Mg_{44}Fe^{+2}_5$	Do.
B-22.....	1.700	Mg_{100}	Do.	MR-19.....	1.68	$Ca_{50}Mg_{50}$	Do.
B-DDH-3-67.....	1.679	$Ca_{50}Mg_{50}$	Do.	MR-21.....	1.702	$Mg_{93}Fe^{+2}_7$	Do.
B-DDH-12-188.....	1.691	$Ca_{50}Mg_{44}Fe^{+2}_5$	Mosaic aggregate grains.	MR-107.....	1.684	$Ca_{50}Mg_{47}Fe^{+2}_3$	Irregular patches.
	1.680	$Ca_{50}Mg_{50}$	Veinlets in chlorite.	MR-128.....	1.703	$Mg_{93}Fe^{+2}_7$	Oval spots, and tiny veinlets.
<i>Waterbury mine</i>				MR-129.....	1.681	$Ca_{50}Mg_{50}$	Very sparse tiny grains.
W-11.....	1.689	$Ca_{50}Mg_{45}Fe^{+2}_5$	Mosaic aggregates, replace tremolite.	In talc-carbonate rock			
<i>Mad River</i>				<i>Barnes Hill</i>			
MR-3.....	1.687	$Ca_{50}Mg_{45}Fe^{+2}_5$	Mosaic of inequigranular grains.	B-9.....	1.710	$Mg_{94}Fe^{+2}_6$	Rosettes and anhedral grains.
MR-17.....	1.683	$Ca_{50}Mg_{47}Fe^{+2}_3$	Mosaic of equigranular grains.	B-14.....	1.670	$Ca_{93}(Mn, Mg, Fe^{+2})_5$	Small veinlets and irregular masses.
MR-54a.....	1.682	$Ca_{50}Mg_{47}Fe^{+2}_3$	Do.	B-20.....	1.703	$Mg_{96}Fe^{+2}_4$	In veins and isolated grains.
MR-55.....	1.660	$Ca_{90}Mg_{10}$	Carbonate layers interbedded with chloritic layers.	B-DDH-1-218.....	1.705	$Mg_{97}Fe^{+2}_3$	Rosettes, anhedral grains, and (few) rhombs.
MR-91-1.....	1.682	$Ca_{50}Mg_{47}Fe^{+2}_3$	Mosaic of equigranular grains.	B-DDH-3-170.....	1.684	$Ca_{50}Mg_{47}Fe^{+2}_3$	Augen-shaped grains.
MR-91-2.....	1.684	$Ca_{50}Mg_{47}Fe^{+2}_3$	Do.	B-DDH-6-76.....	1.705	$Mg_{97}Fe^{+2}_3$	Disseminated grains and aggregates.
In tremolite-carbonate rock at blackwall position				B-DDH-6-84.....	1.704	$Mg_{97}Fe^{+2}_3$	Mosaic aggregate of grains distributed in layers.
<i>Mad River</i>				B-DDH-6-125.....	1.704	$Mg_{97}Fe^{+2}_3$	Large anhedral crystals.
MR-2.....	1.686	$Ca_{50}Mg_{45}Fe^{+2}_5$	Anhedral to subhedral grains and mosaic aggregates of grains.	B-DDH-9B1-325..	1.684	$Ca_{50}Mg_{47}Fe^{+2}_3$	Irregular grains and elongate mosaic aggregates.
MR-11.....	1.663	$Ca_{93}Mg_7$	Interlayered with tremolite.	<i>Waterbury mine</i>			
In greenstone				W-15.....	1.691	$Ca_{50}Mg_{44}Fe^{+2}_5$	Mosaic aggregates and disseminated subhedral crystals.
<i>Mad River</i>				W-44.....	1.688	$Ca_{50}Mg_{45}Fe^{+2}_5$	Sparse mosaic aggregates and disseminated subhedral crystals.
MR-63.....			Disseminated anhedral grains.	W-55.....	1.723	$Mg_{94}Fe^{+2}_{14}$	Mosaic aggregates and anhedral crystals.
MR-97.....	1.66	$Ca_{95-100}Mg_{5-0}$	Disseminated grains concentrated in quartzose layers.	W-65.....	1.690	$Ca_{50}Mg_{44}Fe^{+2}_5$	Subhedral crystals.
MR-119.....	1.663	$Ca_{93}Mg_7$	Do.	W-71.....	1.732	$Mg_{93}Fe^{+2}_{10}Mn_2$	Disseminated rhombs.
					1.690	$Ca_{50}Mg_{44}Fe^{+2}_5$	Few tiny, late veins.
				W-92.....	1.718	$Mg_{90}Fe^{+2}_{10}$	Elongate mosaic aggregates and disseminated grains.

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

D. BIOTITE

Specimen	2V (deg.)	Optic sign	Sign of elonga- tion	Index ($\beta \approx \gamma$)	Pleochroism	Rock
<i>Barnes Hill</i>						
B-11	0-10	—	+	1.651	<i>n</i> , pale yellow brown; <i>N</i> , dark olive brown	Schist.
B-DDH-1-45	0	—	+	1.651	do.	Do.
B-DDH-1-67	0	—	+	1.651	do.	Do.
B-DDH-8-42	Small	—	+	1.635	<i>n</i> , pale yellow brown; <i>N</i> , mod. brown	Greenstone.
<i>Waterbury mine</i>						
W-2	0	—	+	1.635	<i>n</i> , mod. yellowish green; <i>N</i> , grayish olive green	Schist.
W-17	0	—	+	1.647	<i>n</i> , yellowish gray; <i>N</i> , olive brown	Albite porphyroblast rock.
W-21	0	—	+	1.651	<i>n</i> , mod. yellowish green; <i>N</i> , grayish olive green	Schist.
W-75					<i>n</i> , grayish orange; <i>N</i> , dark yellowish brown	Do.
W-76					do.	Do.
W-77a					do.	Do.
W-84	0	—	+	1.623	<i>n</i> , pale yellow brown; <i>N</i> , mod. brown	Albite porphyroblast rock.
W-DDH-13-164B	0	—	+	1.623	<i>n</i> , yellowish gray; <i>N</i> , mod. yellow brown	Do.
<i>Mad River</i>						
MR-64					<i>n</i> , yellow brown; <i>N</i> , olive brown	Greenstone.
MR-66					<i>n</i> , pale brown; <i>N</i> , dark brown	Do.
MR-74					<i>n</i> , pale yellow brown; <i>N</i> , brownish black	Blackwall.
MR-97				1.66	<i>n</i> , pale buff; <i>N</i> , dark olive brown	Greenstone.
MR-108				1.689	<i>n</i> , pale yellow brown; <i>N</i> , brownish black	Schist.

E. EPIDOTE

Specimen	2V (deg.)	Optic sign	Indices			Interference colors	Rock
			α	β	γ		
<i>Barnes Hill</i>							
B-2						Abnormal blue and lemon yellow	Greenstone.
B-3						do.	Do.
B-10	Large	—	1.722	1.744	1.767	Third-order green	Do.
B-11						Abnormal lemon yellow and bluish gray	Schist.
B-12	85	+			1.748	Abnormal bluish gray and lemon yellow	Greenstone.
B-16	80	—	1.718	1.744	1.766	Third-order green	Vein.
B-DDH-8-42	85	—		1.75		do.	Greenstone.
B-DDH-12-209	85	+				Abnormal lemon yellow and bluish gray	Do.
<i>Waterbury mine</i>							
W-32						Mostly abnormal lemon yellow and bluish gray; maximum first-order red.	Blackwall.
W-86	70	—				Third-order green	Albite porphyroblast rock.
W-DDH-3-167						Mostly abnormal lemon yellow and bluish gray; maximum first-order red.	Blackwall.
W-DD-H11-117B	85	—				do.	Do.
W-DD-H11-117C	85	—				do.	Albite porphyroblast rock.
W-DD-H13-210						Mostly abnormal lemon yellow and bluish gray; maximum second-order blue.	Schist.
<i>Mad River</i>							
MR-15						First-order red	Do.
MR-85				1.75		Third-order green	Greenstone.
MR-88	80	—		1.738	1.764	do.	Do.
MR-89	75	—		1.753		do.	Do.
MR-97	80	—		1.74		do.	Do.
MR-108				1.75		do.	Schist.
MR-112	70	—		1.750		do.	Greenstone.

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

F. SERPENTINE

Specimen	2V (deg.)	Optic sign	Sign of elon- gation	Indices		Abnormal interference colors	Rock	Variety of serpentine and habit
				γ	$\beta \approx \gamma$			
<i>Barnes Hill</i>								
B-5	0-35	—	+	1.568	1.571	Light bluish gray (5 B 7/1)	Serpentinite	Antigorite, flaky.
B-6	Small	—	+	1.568	1.571	do	do	Do.
B-8	Mod.	—	+	1.566	1.570	Bluish gray (5 B 6/1)	do	Do.
B-19	Small	—	+	1.568	1.568	do	do	Do.
B-DDH-4-200	20	—	+	1.563	1.567	Light bluish gray (5 B 7/1)	do	Antigorite, columnar.
			+	1.562	1.571	Bluish gray (5 B 6/1)	do	Antigorite, flaky.
B-DDH-9B1-432	Small	—	+	1.548	1.560	Normal straw yellow	do	Chrysotile asbestos vein.
			+	1.565	1.565	Bluish gray (5 B 6/1)	do	Antigorite, flaky.
			+	1.546	1.557	Normal straw yellow	do	Chrysotile asbestos vein.
<i>Waterbury mine</i>								
W-5			+		1.578	Bluish gray (5 B 6/1)	do	Antigorite, columnar.
W-12	35	—	+		1.571	do	do	Antigorite, flaky.
W-19	Small	—	+		1.577	do	Talc-carbonate rock	Do.
W-28	30	—	+	1.570	1.574	Light bluish gray (5 B 7/1)	do	Do.
W-44	15	—	+	1.565	1.572	Bluish gray (5 B 6/1)	do	Do.
W-55			+	1.571	1.576	Mod. dusky blue (5 PB 4/2)	do	Do.
W-45	Small	—	+	1.566	1.574	Bluish gray (5 B 6/1)	Serpentinite	Do.
W-47			+		1.576	Medium bluish gray (5 B 5/1)	do	Do.
W-50	Small	—	+		1.575	do	do	Do.
			+	1.573	1.577	Bluish gray (5 B 6/1)	do	Antigorite, columnar.
W-88	Small	—	+		1.572	Light bluish gray (5 B 7/1)	do	Antigorite, flaky.
W-91			+	1.567	1.573	Bluish gray (5 B 6/1)	do	Do.
W-DDH-13-65	Small	—	+	1.565	1.572	Light bluish gray (5 B 7/1)	do	Do.
<i>Mad River</i>								
MR-10			+		1.578	do	do	Do.
MR-13	15	—	+		1.574	do	do	Do.
MR-18	10	—	+		1.573	do	do	Do.
MR-19	25	—	+		1.565	Bluish gray (5 B 6/1)	do	Do.
			+		1.552	Normal straw yellow	do	Chrysotile asbestos vein.
MR-20	Small	—	+		1.565	Bluish gray (5 B 6/1)	do	Antigorite, flaky.
			+		1.55	Normal straw yellow	do	Chrysotile asbestos vein.
			+		1.55	do	do	Chrysotile, small elliptical aggregates of fibers in groundmass.
MR-21			+		1.565	Light bluish gray (5 B 7/1)	do	Antigorite, flaky.
MR-26	20	—	+		1.570	Bluish gray (5 B 6/1)	do	Do.
MR-103	Small	—	+	1.564	1.569	do	do	Do.
MR-107			+		1.572	Medium bluish gray (5 B 5/1)	do	Do.
			+	1.568	1.576	Light bluish gray (5 B 7/1)	do	Antigorite, columnar.
MR-117	0	—	+		1.574	do	do	Antigorite, flaky.
MR-127	Small	—	+	1.564	1.571	do	do	Do.
MR-128			+	1.563	1.570	do	do	Do.
MR-129			+	1.565	1.572	do	do	Do.

TABLE 2.—Optical data on minerals from the Barnes Hill, Waterbury mine, and Mad River localities—Continued

G. TALC

Specimen	2V (deg.)	Optic sign	Sign of elon- gation	Indices		Occurrence
				α	$\beta \approx \gamma$	
<i>Barnes Hill</i>						
B-9	10	—	+	1.541	1.585	Talc-carbonate rock.
B-13	10	—	+		1.585	Steatite altered from greenstone.
B-14	15	—	+		1.585	Talc-carbonate rock.
B-DDH-1-123					1.585	Streaks and patches of talc in blackwall.
B-DDH-1-218					1.584	Talc-carbonate rock.
B-DDH-3-170	0	—	+		1.587	Do.
B-DDH-4-200	10	—	+		1.585	Talc pseudomorphous after chrysotile asbestos in serpentinite.
B-DDH-6-76	25	—	+		1.585	Talc-carbonate rock.
B-DDH-6-125	10	—	+		1.583	Do.
B-DDH-9B1-325	10	—	+		1.585	Do.
<i>Waterbury mine</i>						
W-5				1.545	1.591	Serpentinite, talcose; talc replaces columnar serpentine.
W-6				1.544	1.592	Steatite 2 ft from blackwall.
W-10					1.592	Steatite, tremolitic.
W-12			+		1.592	Serpentinite, talcose; talc replaces columnar serpentine.
W-15	5	—	+		1.592	Talc-carbonate rock.
W-18					1.590	Small schist inclusion altered to chlorite-talc rock.
W-19					1.589	Steatite, serpentinous.
W-22					1.592	Do.
W-23					1.593	Do.
W-35					1.591	Steatite, tremolitic.
W-39	0	—	+		1.586	Vein of coarse dolomite and flamboyant talc.
W-40	0	—	+		1.592	Steatite, 5 ft from blackwall.
W-41	0	—	+		1.592	Talc-carbonate rock, serpentinous, low-carbonate phase.
W-43	0	—	+		1.590	Vein of coarse dolomite and flamboyant talc.
W-44					1.590	Talc-carbonate rock, serpentinous, low-carbonate phase.
W-46	0-5	—	+		1.590	Steatite, grey talc of groundmass.
W-49	0	—	+		1.590	Steatite.
W-50					1.589	Serpentinite, talc pseudomorphous after chrysotile asbestos.
W-51	Small	—	+		1.591	Steatite.
W-55					1.590	Talc-carbonate rock, serpentinous, low-carbonate phase.
W-59	0	—	+		1.591	Steatite, chloritic.
W-65	20	—	+		1.591	Talc-carbonate rock, quartzose.
W-71	0	—	+		1.592	Talc-carbonate rock, chloritic, low-carbonate phase.
W-73					1.592	Steatite.
W-83	0	—	+		1.589	Vein of coarse dolomite and flamboyant talc.
W-88	0	—	+		1.590	Serpentinite, talc pseudomorphous after chrysotile asbestos.
W-89	5	—	+		1.592	Steatite.
W-DDH-15-223					1.592	Steatite, actinolitic.
<i>Mad River</i>						
MR-3	5	—	+		1.590	Carbonate rock, slightly talcose; septum in talc-carbonate zone.
MR-7	5	—	+		1.591	Steatite.
MR-14	10	—	+		1.590	Steatite, tremolitic.
MR-78					1.594	Steatite, probably derived from greenstone.
MR-84	0	—	+		1.592	Steatite.
MR-106	0	—	+		1.590	Do.
MR-113					1.591	Talc-carbonate rock, low-carbonate phase.
MR-116					1.591	Steatite, serpentinous.
MR-118					1.591	Steatite.
MR-125					1.589	Do.

The chemical compositions of several of the rocks and minerals were determined from 31 chemical analyses. Of these, 13 are partial mineral analyses made by standard methods, 6 are standard rock analyses, and 12 are are rapid analyses made by colorimetric methods (Shapiro and Brannock, 1952). These analyses, supplemented by two from the geologic literature, are given in table 3. Where satisfactory representative samples could not be obtained for analysis, as in talc-carbonate rock, an estimated composition was calculated on the basis of information available from other sources, from rock analyses, and from analyses of component minerals.

Material submitted for chemical analysis was selected, insofar as possible, only after microscopic study of thin sections of the material. In a few cases, however, it was necessary to select specimens before thin section studies were made. With one exception no serious

shortcomings resulted from this necessity; the specimen of amphibolite from a drill core at Barnes Hill, which contained the only suite that appeared suitable for the purpose, turned out to contain a relatively large amount of admixed arenaceous and argillaceous material. Thus satisfactory analyzed suites across the contact between ultramafic rock and amphibolite are lacking.

DETERMINATION OF MINERAL COMPOSITIONS

The formula compositions of most of the minerals that vary significantly in composition were determined from optical data by means of published charts and graphs, chiefly those in Winchell and Winchell (1951). Carbonate formulas were determined from optical data by means of a chart constructed from data given by Winchell. Formula compositions of some minerals—talc, serpentine, some chlorite, carbonate, chromite, and magnetite—were calculated from analyses of min-

Analyses 1-31 were made in the laboratories of the U.S. Geological Survey. Analyses 32 and 33 are from the geologic literature: 32, from Phillips and Hess (1936, p. 340), A. H. Phillips, analyst; 33, from Cooke (1937, p. 101), R. J. C. Fabry, analyst]

Mineral samples										Rock samples									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Laboratory No. and Field No.	50-1989 CDMSW W-71	50-1990 CDMSW J-106	50-1991 CDMSW DDH-9B1-325	50-1992 CDMSW DDH-8-146	50-1993 CDMSW DDH-13-146	50-1994 CDMSW DDH-9B1-380	50-1995 CDMSW W-83	50-1996 CDMSW J-108	50-1997 CDMSW W-43	50-1998 CDMSW J-50	51-1072 MCSW DDH-13-35-50	51-1073a MCSW DDH-9B1-432	51-1073b MCSW DDH-9B1-407	50-1999 CDMSW DDH-11-60	50-2001 CDMSW MR-103	50-2002 CDMSW DDH-13-65	50-2003 CDMSW DDH-9B1-432	50-2007 CDMSW W-23	50-2009 CDMSW W-38
Density: Bulk Powder							2.76	2.83	2.82	2.84					2.68 2.66	2.65 2.71	2.65 2.71	2.84 2.83	2.94 2.94
Standard chemical analyses																			
[Analysts: 1-10, Wilbur J. Blake; 11-13, Joseph I. Dimin; 14, Lucille M. Kehl; 15-19, Robert N. Eeher]																			
SiO ₂							62.44	62.24			0.4	0.4	0.7	65.60	41.59	43.10	38.30	25.59	
Al ₂ O ₃							1.07	1.09			0.4	0.4	0.6	1.77	8.58	1.06	1.44	18.83	
FeO	0.88	10.27	0.36	1.25	0.34	0.16	2.19	4.22	0.64	0.58	28	61	56	1.83	3.58	1.07	1.08	10.64	
MgO	32.87	38.00	22.34	38.23	39.04	46.33	30.01	28.57	18.10	18.76	24	24	29	2.58	4.41	5.22	4.95	20.14	
CaO									29.98	30.10	1.0			2.58	37.36	37.14	38.27	18.45	
Na ₂ O														1.51	0.09	0.09	0.09	2.01	
K ₂ O														0.01	0.01	0.01	0.01	0.01	
Fe ₂ O ₃							0.04	0.00						3.69	0.09	0.08	0.09	0.02	
SiO ₂ + FeO							4.63	4.47						2.47	11.32	11.71	10.73	10.89	
FeO + Fe ₂ O ₃														0.82	0.01	0.01	0.01	3.87	
CaO + MgO							0.04	0.04	46.73	47.10	3.0	1.5	2.2	0.07	0.64	0.08	2.46	0.05	
SiO ₂ + FeO + CaO + MgO							77	0.00			1.1	2.2	4	0.09	0.01	0.01	0.02	0.01	
SiO ₂ + FeO + CaO															0.01	0.06	0.01	0.01	
SiO ₂ + FeO							13	18			36.1	11.0	9.6	31	12	31	30	26	
SiO ₂ + FeO + CaO + MgO							0.00	0.00	81	69	7	1.2	7	43	28	22	20	20	
SiO ₂ + FeO + CaO + MgO + Na ₂ O							0.00	0.00	0.00	0.00					0.07	11	09	09	
SiO ₂ + FeO + CaO + MgO + Na ₂ O + K ₂ O							0.003	0.003	0.003	0.003					0.01	0.01	0.01	0.01	
SiO ₂ + FeO + CaO + MgO + Na ₂ O + K ₂ O + Fe ₂ O ₃							0.003	0.003	0.003	0.003					3.0009	4.006	6.0023	7.0003	
Sum	97.90	97.55	94.65	98.72	94.00	99.00	99.76	99.91	99.91	100.32				99.90	100.32	100.32	100.14	100.15	
Less O for S							0.00	0.00							0.00	0.03	0.01	0.00	
Total	97.90	97.55	94.65	98.72	94.00	99.00	99.76	99.91	99.91	100.32	97.7	100.7	100.4	99.90	100.32	100.29	100.13	100.10	100.15
Spectrographic analyses—quantitative																			
For Mg and Ca, plate W-830(2); Janet D. Fletcher, analyst. For other elements, plates W-292(2) and W-293(2); Elizabeth Hufschmidt, analyst. Looked for but not found (Nos. 1-10 and 14): Ag, Au, Pt, Mo, W, Sn, As, Sb, Bi, Zn, Cd, Tl, Y, Nb, Ta, and U]																			
Be	8 nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	0.0002					
Cu	0.0009	0.0004	nf	0.0006	0.0008	0.0003	0.001	0.0003	nf	0.0002	nf	nf	nf	0.002					
Zn	2.1 nf	4 nf	2 nf	1.0 nf	8 nf	8 nf	0.01	0.03	nf	4 nf	nf	nf	nf	0.003					
Mn	0.002	0.001	0.001	0.002	0.003	0.006	0.006	0.006	0.008	nf	nf	nf	nf	0.008					
Co	0.02	0.02	0.02	0.01	0.03	0.01	0.01	0.01	0.001	0.0008	nf	nf	nf	0.005					
Ni	0.03	0.02	0.03	0.01	0.01	0.002	0.002	0.005	0.001	nf	nf	nf	nf	0.005					
Sr	0.02	0.02	0.03	0.01	0.01	0.002	0.002	0.002	0.001	nf	nf	nf	nf	0.02					
Zr	0.001	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.007	nf	nf	nf	nf	0.006					
La	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	0.01					
Ce	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	High					
Pr	0.007	nf	nf	nf	nf	nf	0.002	0.002	nf	nf	nf	nf	nf	0.06					
Zr	nf	nf	nf	nf	nf	nf	nf	nf	0.09	2 nf	nf	nf	nf	0.02					
Ba	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	nf	0.08					
B	nf	nf	nf	nf	nf	nf	0.005	0.004	nf	nf	nf	nf	nf	0.03					
Mg	nf	nf	nf	nf	nf	nf			nf	nf	2	0.4	0.8						
Ca	nf	nf	nf	nf	nf	nf			nf	nf	0.4	0.4	0.05						

[Nos. 11-13. Plate W-830(2); Janet D. Fletcher, analyst. Looked for but not found: Ag, Au, Hg, Ir, Pt, Mo, W, Ge, Sn, Pb, As, Sb, Bi, Zn, Cd, Tl, In, Ga, Se, Y, Yb, La, Zr, Th, Nb, Ta, Be, Sr, P, and B: the presence of Cr interferes with the determination of Zn]

See footnotes on p. 44.

Footnotes for table 3 on p. 42-43.

¹ Determined by quantitative spectrographic analysis. Elizabeth L. Hufschmidt, analyst.

² The analyst states in a footnote to the report of analysis: "With this unfavorable ratio of calcium to magnesium, it is possible that as much as 0.1 percent of CaO may be missed."

³⁻⁷ Redeterminations of As_2O_3 after NaOH fusion of the samples. Hy Almond, analyst.

3. Average of 0.0011 and 0.0007.

4. Average of 0.005 and 0.007.

5. Average of 0.05 and 0.08.

6. Average of 0.0020 and 0.0026.

7. Average of 0.0005 and 0.0001.

⁸ "nf" means "not found."

⁹ See table 42 and descriptive text in appendix G for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

¹⁰ See table 45 and descriptive text in appendix H for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

¹¹ See table 46 and descriptive text in appendix H for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

¹² See table 47 and descriptive text in appendix H for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

¹³ Carbonate assumed to be absent. See tables 49, 50, 51, in appendix I, and tables 55 and 57, in appendix K.

¹⁴ Based on carbonate content of 0.5 percent, by volume. See table 56, in appendix K.

¹⁵ See table 53 and descriptive text in appendix J for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

¹⁶ See table 44 and descriptive text in appendix H for method of estimating $\text{H}_2\text{O}+$ and CO_2 .

Description of samples:

1. Carbonate in talc-carbonate rock.
2. Carbonate in talc-carbonate rock.
3. Carbonate in talc-carbonate rock.
4. Carbonate in talc-carbonate rock.
5. Carbonate in veined serpentinite.
6. Carbonate in massive serpentinite.
7. Talc in talc-carbonate vein.
8. Pale green talc in steatite.
9. Carbonate in talc-carbonate vein.
10. Carbonate in talc-carbonate vein.
11. Magnetic concentrate from serpentinite.
12. Magnetic concentrate from serpentinite.
13. Magnetic concentrate from serpentinite.
14. Biotitic quartz-sericite-albite-chlorite schist.
15. Schistose serpentinite.
16. Massive serpentinite.
17. Massive serpentinite.
18. Schistose steatite.
19. Blackwall near outer edge of zone.
20. Massive serpentinite.
21. Talc-carbonate rock with coarse carbonate.
22. Talc-carbonate rock low in carbonate.
23. Talc-carbonate rock with coarse carbonate.
24. Albite porphyroblast rock.
25. Blackwall.
26. Blackwall.
27. Albite porphyroblast rock.
28. Blackwall.
29. Quartz-sericite-albite-chlorite schist.
30. Bedded carbonate rock septum in talc-carbonate rock.
31. Pale green steatite derived from schist.
32. Completely chloritized blackwall.
33. Chrysotile asbestos, high grade, Deloro Township, Ontario.

erals and of almost monomineralic rocks. Most operations in the various determinations and calculations require no explanation other than that given in the discussion of the mineralogic composition of each type of rock. Problems in computation introduced by limitations of the analyses are described in the appendix where the calculations are tabulated. Special problems concerned with the determination of the formula compositions of chlorite, serpentine, and talc are discussed in the following paragraphs.

CHLORITE

Minerals of the chlorite group have the ideal general formula $(\text{Mg}, \text{Fe}^{+2})_{6-p}(\text{Al}, \text{Fe}^{+3})_p(\text{Si}_{4-p}\text{Al}_p)\text{O}_{10}(\text{OH})_8$. The generally accepted structural formula, $[(\text{Mg}, \text{Fe}^{+2})_2\text{Al}(\text{OH})_6][(\text{Mg}, \text{Fe}^{+2})_{3-x}\text{Al}_x(\text{Al}_{1+x}\text{Si}_{3-x})\text{O}_{10}(\text{OH})_2]$, indicates a minimum value of 1 for the quantity p in the general formula. (See Brindley and Robinson, 1951, p. 179-180.) For most chlorites, the value of p is equal

to or appreciably greater than 1, but a few have a value slightly less than 1; none of those listed by Berman (1937, p. 378-382), however, has a value of p appreciably less than 0.8. Current usage and nomenclature vary considerably, and no completely satisfactory classification or correlation between composition and optical properties exists. Winchell's charts (1951, p. 385, fig. 267) are based upon the assumption of isomorphism for several structurally distinct species (see Brindley and Robinson, 1951, p. 173-177; Hey, 1954, p. 277-278), and his assignment of species names is arbitrary and commonly at variance with prior usage. Furthermore, his choice of end-member "molecules" for his diagram makes it very clumsy to translate a given point on the diagram into simple terms of mineral composition. Some of the optical data, particularly that on birefringence, appear to be inadequate. For these reasons, precise correlation of optical properties with chemical composition is not possible. The difficulty is increased by the fact that determination of birefringence by routine methods commonly is not sufficiently precise for the requirements of the diagrams, and by the fact that compositional variations more complex than can be represented on the diagram may be responsible for variations in the optical properties.

In spite of these difficulties, Winchell's diagram serves with reasonably sufficient accuracy to determine from optical properties the compositions of chlorites within the range commonly encountered, particularly if an orderly variation in content of Al for the range of chlorites under consideration can be assumed, so that allowance can be made for individual errors in determination of birefringence. The diagram is least reliable in the region of chlorite of very low index (the area of penninite and clinochlore), where the curves assume continuous variation between chlorite and antigorite, and near the amesite corner. For chlorites that fall in these areas it may be necessary to disregard the optic sign or to make allowances for the birefringence curves, and to rely in part on other evidence. The fact that chlorites have a p -value equal to or greater than about 0.8 (see above) is helpful in fixing the composition of chlorites of low index.

If birefringence values are not available or are unreliable, and if, on the basis of geological inference or comparison with analyses of chlorites from similar geologic environments, it is possible to estimate reliably the formula value of Al, such inference may be coupled with information on the index of refraction to determine a formula composition from the diagram. If such a basis for estimating Al is especially reliable, it may preferably be used in place of birefringence data.

Isomorphous substitution within the chlorite series appears to be rather uniform, and no natural division

FIGURE 13.—Chart for correlation of optical properties with formula composition of chlorite (after Winchell and Winchell, 1951, fig. 267, p. 385, incorporating suggestions made by Arden L. Albee).

into species is evident. The nomenclature of the chlorites is cumbersome and to some extent confusing. Varietal names are useful and meaningful only if they readily signify to the interested reader a certain composition, or range in composition, of chlorite; it is extremely doubtful that many of the varietal names do so: thus, many nonspecialists may not recognize as members of the chlorite series such varieties as klemetitite, kochubeite, and virdite. Because of these considerations, the chlorite minerals will be discussed in this report in terms of formula composition, rather than by varietal names. For this purpose Winchell's diagram cannot be used conveniently, and a diagram has been devised, based on the optical data of Winchell, upon which formula compositions can be determined directly, on the basis of optical properties. The diagram is shown in figure 13. Note that the shapes of the curves in figure 13 differ somewhat from those in Winchell's diagram. This is because in figure 13 the corners of the diagram represent equivalent molecular amounts of chlorite, whereas in Winchell's diagram the right side of the diagram represents a different amount from the left side. As a consequence of this difference between the two diagrams, in figure 13 the formula numbers of FM, Si, and Al plot arithmetically along the horizontal scale and the plot of FM : Al is geometric, whereas on Winchell's diagram the plot of FM : Al is arithmetic along the horizontal scale and the formula numbers are on a geometric scale.

To determine the formula composition, locate the point on the chart that is determined by the β index of refraction and the birefringence and optic sign. At the bottom of the chart read the values for Si, Al, and FM, vertically below this point. In the general formula, $(\text{Mg Fe}^{+2})_{FM-v} \text{Al}_{\frac{v}{2}} (\text{Al}_{\frac{v}{2}} \text{Si}_v) \text{O}_{10} (\text{OH})_8$, where each subscript "v" represents the value for that element obtained from the graph, insert the Si value as a subscript to Si, $\frac{1}{2}$ the Al value as a subscript to each Al, and the FM value after FM. Along the left margin, opposite the point located by the optical properties, read the Mg factor and the Fe^{+2} factor. Multiply each factor by the FM value and insert the appropriate products as subscripts to Mg and Fe^{+2} in the formula.

After determination of the mineral compositions of all the chlorites based upon optical identification had been completed on the basis of figure 13, and the results incorporated into the numerous calculations tabulated in the appendix and into the major portion of the text, Hey (1954) published a new classification of the chlorites and a new chart for the determination of the orthochlorites from optical properties (1954, fig. 4, p. 284). The chart is simpler and appears to improve in some respects upon Winchell's diagram. The birefringence curves especially differ, but, at least in the region centered about $\text{Fe}' \approx 2.5$, $\text{Al} \approx 2.6$, do not appear to fit our experience as well as those of Winchell's diagram, particularly in the position of the transition from optically negative to optically positive chlorite. A check upon several specimens of chlorite indicates that, for the range of chlorites concerned in this report, the differences between formula compositions determined from Winchell's data and those based upon Hey's data are usually negligible, and always small; all are probably less than the margin of error inherent in either diagram plus that involved in the optical data of the chlorites being determined. Furthermore, where there is the greatest discrepancy, it is questionable whether the formulas based upon Hey's chart are as good as those based upon Winchell's. Consequently, it was deemed unnecessary and inadvisable to recalculate the chlorites on the basis of Hey's charts. For the sake of comparison by those interested, a chart based upon that of Hey, but retaining the features incorporated in figure 13 that are designed to simplify determination of formula compositions, is presented in figure 14.

To determine the formula composition of a chlorite from optical data, locate the point on the chart that is determined by the β index of refraction and the birefringence and optic sign. At the bottom of the chart read the values for Si, Al, and FM, vertically below this point. In the general formula, $(\text{Mg Fe}^{+2})_{FM-v} \text{Al}_{\frac{v}{2}} \text{Si}_v \text{O}_{10} (\text{OH})_8$

FIGURE 14.—Chart for correlation of optical properties with formula composition of chlorite (after Hey, 1954, fig. 4). Data are for the orthochlorites; for oxidized chlorites, B and D are higher and $(\gamma-\alpha)$ lower, in proportion to the percentage of Fe_2O_3 .

$(\text{Al}_{v/2}\text{Si}_v)\text{O}_{10}(\text{OH})_8$, where each subscript “ v ” represents the value for that element obtained from the graph, insert the Si value as a subscript to Si, $\frac{1}{2}$ the Al value as a subscript to each Al, and the FM value after $\text{FM} =$. Along the left margin, opposite the point located by the optical properties, read the value of Fe^{+2} , designated Fe^t . The value for Mg is obtained by subtracting Fe^t from FM.

SERPENTINE

Many varieties of serpentine—distinguished on the basis of supposed differences in chemical composition, slight differences in optical properties, and differences in textural features—have been described in the geologic literature. Recent studies—particularly those of Selfridge (1936), Gruner (1937), Bates and Mink (1950), Nagy and Bates (1952, 1952a), Nagy (1953), Nagy and Faust (1956), and Faust (written communication)—

have shown that most of the supposed differences are not fundamental but are relict structures superimposed by environmental conditions (Selfridge, 1936, p. 500). Selfridge (1936, p. 468–469) divided the minerals of the serpentine group into two fundamentally distinct species and assigned the name “serpentine” to one species, “antigorite” to the other; “chrysotile” was reserved for fibrous varieties of the species “serpentine.” This double usage of the word “serpentine” as both a group name and a species name is awkward and confusing, and most recent workers use “serpentine” as a designation for the mineral group where it is not desirable or feasible to distinguish between species; the two species of serpentine are distinguished as “antigorite” and “chrysotile.” Where desirable, chrysotile of asbestiform habit is designated as “chrysotile asbestos.”

The crystal structure and chemical relations of chrysotile and antigorite are as yet incompletely known. The following relations, however, seem to be fairly well established (Brindley, 1951, p. 59–61; Gruner, 1937; Bates and Mink, 1950; Nagy and Bates, 1952; Nagy, 1953; Roy and Roy, 1952, 1953; Nagy and Faust, 1956):

Chrysotile and antigorite have the same general formula, usually idealized as $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$. Some Fe^{+2} substitutes for Mg, and Al has generally been considered also to substitute directly for Mg (in the ratio of 2Al for 3Mg). A formula taking into account these substitutions is

$$[(\text{Mg}, \text{Fe}^{+2})_{(3-\frac{3x}{2})}\text{Al}_x]_{(3-\frac{x}{2})}\text{Si}_2\text{O}_5(\text{OH})_4. \quad (1)$$

Roy and Roy (1955, p. 153) have concluded that coupled substitution of Al for Si and Mg is of paramount importance in serpentine. If so, the general formula becomes

$$[(\text{Mg}, \text{Fe}^{+2})_{(3-y)}\text{Al}_y]_{-3}(\text{Si}_{2-y}\text{Al}_y)\text{O}_5(\text{OH})_4. \quad (2)$$

If both direct and coupled substitution of Al occur significantly, the formula should be expressed by

$$[(\text{Mg}, \text{Fe}^{+2})_{(3-\frac{3x}{2}-y)}(\text{Al}, \text{Fe}^{+3})_{x+y}]_{-(3-\frac{x}{2})}(\text{Si}_{2-y}\text{Al}_y)\text{O}_5(\text{OH})_4. \quad (3)$$

Hess, Smith, and Dengo (1952), on the basis of a chemical analysis, deduced a different formula for a specimen of antigorite from Caracas, Venezuela, but Brindley

⁸ More recently, Whittaker and Zussman (1956, p. 107–126) have distinguished three principal species of serpentine: chrysotile, antigorite, and lizardite. Since then, other investigators have reported lizardite and chrysotile to be the principal or only serpentine minerals in some widely separated bodies of serpentinite. (See, for instance, Nenecz, 1958, p. 424–434.) These investigations suggest that much or all the material identified as antigorite in this report may also contain appreciable—or be composed entirely of—lizardite.

(1954) recalculated the chemical data and concluded that the results fit the conventional formula acceptably.

The differences in composition implicit in the different formulas are, in general, too subtle for present-day sampling techniques and methods of chemical analysis; so formula (3) has no present practical value, and the choice between (1) and (2) is rather arbitrary. In the present investigation, formula (1) has been used because it fits the analytical results somewhat better than formula (2) does.

Both chrysotile and antigorite have a fundamentally ribbonlike form. In chrysotile the ribbons are curled about the a -axis (parallel to the 5.3A cell dimension), which is parallel to the long dimension of the ribbons, to form hollow tubes.⁹ These hollow tubes, singly or in bundles, impart a fibrous habit. The curling of the chrysotile ribbons is attributed to difference in size between the octahedral (brucite) layers and the tetrahedral (silicon-oxygen) layers. In antigorite the ribbons do not curl; therefore it has a lamellar or platy habit. The lack of curling in antigorite is attributed to a better fit between the octahedral and tetrahedral sheets because of the partial substitution of $2(\text{Al}, \text{Fe}^{+3})$ for 3Mg in the octahedral layers.

The difference between chrysotile and antigorite appears, therefore, to be based fundamentally upon compositional differences—in particular, upon the $(\text{Al}, \text{Fe}^{+3})$ content—rather than upon structure. There are not sufficient satisfactory chemical analyses, particularly of antigorite, to establish unequivocally the inferred relationship.

Recent investigators have used X-ray techniques, differential thermal analysis, electron microscopy, and optical methods in the study of serpentine minerals, and it seems to be the consensus that several or all methods are generally necessary to distinguish the species. Brindley (1951, p. 59) states that the optical properties are very similar and that "X-rays alone will distinguish them." However, our experience with ultramafic rocks in Vermont, supplemented by a few observations of serpentine occurrences elsewhere, both in ultramafic bodies and in carbonate rocks, leads us to believe that, in a given occurrence, it is generally possible to distinguish between antigorite and chrysotile by microscopic methods. The indices of chrysotile are lower than those of antigorite from the same locality, and the birefringence is markedly higher.¹⁰ The habit of chrysotile is always fibrous, though it may not be apparent except under very high magnification. No platy serpentine

has been observed to have low indices and high birefringence comparable to those of chrysotile. Antigorite generally is of lamellar or platy habit, but fibrous habit occurs, though relatively uncommonly. The indices and birefringence of fibrous antigorite are about the same as those of lamellar antigorite. Moreover, the fibrous antigorite is in nearly all instances coarser and of less regular habit than the chrysotile. In all specimens in which the fibers were sufficiently large to be tested, chrysotile for the most part could be separated readily into flexible fibers; the fibrous serpentine identified as antigorite breaks into brittle columnar fragments. These characteristics are inferred to extend to fine chrysotile and fibrous antigorite of the matrix of the rock, though confirmation by megascopic examination was not possible. These conclusions have not as yet been sufficiently substantiated by other methods of investigation, but the few checks available on specimens of antigorite corroborate identification (see p. 73).

It should be emphasized that the distinctions in optical properties apply only to serpentine from the same locality, because chrysotile and antigorite from different localities show a considerable overlap in indices and even reversals in relations. For instance, antigorite and chrysotile from the Apache Mine, Fort Apache Indian Reservation, Gila County, Ariz., and from the Barnes Hill locality in Vermont, have the following optical properties:

	Index	Apache mine	Barnes Hill locality
Antigorite-----	α	1. 544	1. 562—1. 568
	$\beta \approx \gamma$	1. 547	1. 568—1. 571
Chrysotile-----	α	1. 507	1. 546—1. 548
	γ	1. 524	1. 557—1. 560

The γ -index of antigorite from the Apache Mine is lower than the α -index of some of the chrysotile from the Barnes Hill locality. Obviously, then, in comparing serpentine from one locality to that from another of different geologic environment, relative indices alone cannot be relied upon for species identification of the serpentine.

The fact that the fundamental difference between chrysotile and antigorite appears to rest upon the reported difference in content of $(\text{Al}, \text{Fe}^{+3})$, coupled with the observation that fibrous antigorite is brittle and not separable into fine fibers, suggests that a relatively high content of $(\text{Al}, \text{Fe}^{+3})$ may at least be one cause of harshness and brittleness in chrysotile asbestos. This possibility is supported by a few observations on harsh fiber asbestos from Vermont, Quebec, and Arizona, which showed the harsh fibers to be intermediate in index between associated soft silky chrysotile and antigorite.

⁹ Some chrysotile appears to show negative elongation, which may possibly result from curling about the b -axis.

¹⁰ True maximum and minimum indices probably are never measured because even very small particles of antigorite and chrysotile consist, respectively, of aggregates of plates and bundles of fibers variously disoriented, so that optical compensation lowers the apparent birefringence. Compensation is probably more pronounced generally in the platy antigorite than in the fibrous chrysotile.

It is not possible at present to correlate even roughly the optical properties of serpentine with chemical composition. Undoubtedly, indices increase both with increase of Fe^{+2} and of $(\text{Al}, \text{Fe}^{+3})$. Within each species, higher indices probably reflect chiefly higher content of Fe^{+2} .

TALC

Talc is generally considered to show no significant variations in composition, and the formula is generally written $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$. Most talc contains small amounts of Fe^{+2} (generally not more than about 0.X formula number) and lesser amounts of Al (not more than about 0.0X formula number). The mode of occurrence of the Al is not definitely known, but a coupled substitution for Mg and Si appears likely. The Fe^{+2} substitutes directly for Mg; a few other elements occur in talc in very small amounts (generally less than 0.00X formula number) and probably also substitute directly for Mg. The general formula, taking into account the principal substitutions discussed, becomes $(\text{Mg}, \text{Fe}^{+2})_{3-x}\text{Al}_x(\text{Al}_x\text{Si}_{4-x})\text{O}_{10}(\text{OH})_2$. There may possibly also be some direct substitution of 2Al for 3Mg.

To the best of the writer's knowledge there is no information upon which to correlate optical data and chemical composition of talc. Variation of indices may reflect either variation in the ratio of $\text{Mg}:\text{Fe}^{+2}$ or of the content of $(\text{Al}, \text{Fe}^{+3})$, or both. Other elements are present in such small amounts that they probably have no significant effect upon the optical properties.

GENERAL FEATURES

Both the ultramafic rocks and the country rocks at the three localities are variable in composition and gradational in character. Each locality differs in detail from the others in the characteristics of the several rock types, and the different rock types differ markedly from one another in their range of variation and manner of intergradation. Schist shows the greatest range of composition and the most complete gradation between types. Gradual transitions between extreme types can be traced in outcrops and in drill cores. The transitions are by rather uniform and gradual changes in the relative abundance of minerals in the component layers and by small-scale interlamination of layers of markedly different composition; gradation by gradual change is perhaps predominant. Greenstone is less variable and more abruptly gradational; but typical specimens do show a considerable range in proportions of minerals, and types transitional into schist, through relatively minor in quantity, do exist. The gradation from greenstone into schist is predominantly by fine-scale interlamination of greenstone and quartz-sericite-chlorite laminae; some gradation by gradual and rather

uniform increase in quartz and sericite content occurs, but it is relatively minor. Carbonate rock and tremolite-carbonate rock vary widely in composition. They intergrade, but transitions into schist or greenstone appear everywhere to be very abrupt. The quartzite is uniform in composition and the contacts with schist are sharp.

Primary features in the country rock are obscured by the metamorphic and tectonic effects, but bedding can be detected, at least locally, in all the quartzite and schist and in most of the greenstone, although it differs greatly in characteristics among rock types. The most conspicuous indications of bedding are afforded by the contrast in lithologic character between schist, quartzite, and greenstone. Greenstone commonly furnishes the better clues as to large-scale bedding pattern, because it forms units that can be correlated between outcrops for hundreds or even thousands of feet. Quartzite layers can commonly be traced for the extent of an outcrop, and in places can be correlated between outcrops for several hundred feet. Elsewhere in schist, bedding can rarely be traced for more than a few tens of feet. In detail, bedding in all the rocks is marked by contrasts in mineralogic composition, texture, and color between adjacent layers, but the degree of contrast and the extent to which one or another contrasting feature predominates differs markedly between rocks. So, also, does the uniformity and continuity of individual beds. Details of bedding are described below in the petrography of each rock type. Particularly well preserved bedding in a fine-grained sericite-chlorite-quartz schist is illustrated in figure 12, A.

Secondary foliation is the most striking petrographic feature in most of the schist, and is present in varying degree in all the rocks. Included under secondary foliation are schistosity (both spaced and continuous), slip cleavage, and fracture cleavage. Figures 2 to 12 illustrate continuous and spaced schistosity in several kinds of rock.

The various ultramafic rocks are mineralogically simple and generally not conspicuously variable, though locally the talc-carbonate rock and serpentinite vary appreciably in color and content of carbonate at all three deposits. At Barnes Hill, the degree to which the serpentinite and talc-carbonate rock are layered varies considerably throughout the deposit, whereas at the Waterbury mine and Mad River localities they show no layering. Also, there appear to be slight overall differences among the three localities in composition of the ultramafic rocks. Gradation between types of ultramafic rock is by gradual increase of one or more minerals at the expense of another, but it is commonly irregular in detail. The transition commonly takes place in a relatively short distance. Thus talc-carbon-

ate rock and serpentinite commonly intergrade over a distance of a few inches, but locally over as much as 2 or 3 feet. Talc-carbonate rock and steatite intergrade typically over a distance of a few inches, but the transition is vague and irregular where the carbonate content of the talc-carbonate rock is abnormally low or variable.

The composition of the blackwall is remarkably uniform except in zones where it is transitional into schist and steatite. The principal variation is in the content of minor constituents. The transition into steatite is by very abrupt and generally uniform increase in talc content, commonly within less than an inch. The transition into schist where no pronounced albite porphyroblast zone intervenes is almost equally abrupt, and takes place by uniform, sharp decrease in chlorite content. The albite porphyroblast rock at the outer border of the blackwall zone varies considerably in albite content. The transition from the albite porphyroblast rock into the blackwall is commonly an inch or two wide; it is marked by sharp decrease in the abundance of albite porphyroblasts and sharp increase in chlorite content, with a concomitant change in the composition of the chlorite. The boundary surface that marks the first appearance of albite does not generally coincide with the boundary surface that marks the farthest advance of chloritization, but the two are generally not more than an inch or so apart. Transition from albite porphyroblast rock into unaltered schist is generally not so well defined, but the change occurs in most places within a distance of 2 or 3 inches.

SCHIST

The schist at the three localities is composed essentially of varying proportions of quartz, sericite, and chlorite and is commonly slightly albitic; that at Mad River contains consistently less sericite and more chlorite than that at Barnes Hill and Waterbury mine localities. Biotite is locally a major constituent. Much of the schist, particularly that rich in sericite and low in chlorite, is conspicuously graphitic; none of the graphitic schist was observed to contain magnetite. The total range in composition of the schist is wide, as is evident in the tabulation of modes in table 1A. Analyses of schist are shown in table 3 (analyses 14 and 29), and calculated analyses are given in tables 58 and 62. In general terms, the range in composition embraces about the range from shale to sandstone.

On fresh surfaces the schist ranges from medium greenish gray with lustrous cleavage surfaces in the more sericitic varieties to grayish olive green in the highly chloritic and biotitic varieties. Graphitic types range from dark gray to almost black. Albite por-

phyroblasts impart a lighter overall color and a mottled or speckled appearance. Where pyritiferous, the schist weathers dark buff to rusty brown.

All the schist shows layered distribution of granoblastic minerals (largely quartz and albite) and lepidoblastic minerals (mostly chlorite and sericite). The layers are about 0.3 to 3 mm thick, and commonly are combined in larger groups in which either lepidoblastic or granoblastic layers are more prominent. Individual granoblastic layers can rarely be traced more than a few centimeters or tens of centimeters, but the larger groups can in many places be traced for tens of feet. Larger scale compositional variations are gradational, but their boundaries appear to be generally parallel to the fine layering. The fine layering probably is parallel to bedding, and in most places probably represents bedding modified and enhanced by metamorphic differentiation. Locally, in the sheared noses of folds, quartz lentils may have formed entirely by metamorphic differentiation. The prevailing attitude of the layering observed in outcrop may differ greatly from the overall bedding trend where the pattern of tight folds has been obscured by shearing out of the shorter limbs of the folds.

Schistosity, the most prominent feature of the schist, is expressed in two conspicuously different ways. Continuous schistosity (see p. 17) is shown by uniform orientation parallel to the layering of the minerals in the lepidoblastic layers. Spaced schistosity (p. 17) is marked by tiny shear zones 0.005–0.2 mm wide and 0.02–0.5 mm apart, sensibly parallel to the boundaries of the layers; in a few places the shear zones, marked by shreds of sericite, project into or even extend across granoblastic layers at a slight angle to the layering. Within the shear zones the micaceous minerals are parallel to the surfaces of the shears. Between shear zones the micaceous minerals commonly are diversely oriented, either individually or in small clusters. In a few thin sections of rocks with a spaced schistosity, the micaceous minerals between shear zones are uniformly parallel to the spaced schistosity.

Tiny crinkles of both the continuous and the spaced schistosity are a conspicuous feature in thin section. The crinkles range from 0.1 to 1 mm in wavelength and from about 0.1 to 0.2 mm in amplitude. Associated with the crinkles is a slip cleavage formed by the alinement of stretched and thinned limbs of crinkles or by microfaults along the stretched limbs. Commonly the slip cleavage is about parallel to the axial planes of the crinkles.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

QUARTZ

Quartz is a major granular constituent of the schist and occurs predominantly in granoblastic layers in

which quartz or quartz and albite form an interlocking mosaic. Grains commonly are from 0.02 to 0.5 mm in diameter, but are as large as 1 or 2 mm in the larger quartz lenticles. In the granular layers quartz and albite each commonly contains irregular inclusions of the other mineral. Small clusters and isolated grains of quartz are scattered sparsely throughout the lepidoblastic layers. At either end of elongate porphyroblasts of albite, quartz commonly forms wedge-shaped mosaic clusters of tiny grains that tail off between converging folia of sericite.

Uniform extinction in the quartz is common, but much of the quartz shows slightly undulose extinction and, abnormally, biaxial interference figures. Pronounced strain shadows are relatively rare.

ALBITE

Albite is a common constituent of the schist, and at the Waterbury mine locality is moderately to very abundant. The pattern and distribution of much of the albite is identical with that of the quartz, though albite is never the sole constituent of a granular layer. Albite also forms anhedral to subhedral porphyroblasts from 0.5 to 3 mm in diameter, both of single crystals and of aggregates of sutured grains (glomeroporphyroblasts). Single-crystal porphyroblasts and larger glomeroporphyroblasts composed of only a few grains commonly have inclusion-crowded cores and relatively clear narrow rims, though in many there is no clear rim. Most of the smaller glomeroporphyroblasts and some of the single-crystal porphyroblasts contain no discernible core, and are nearly free of inclusions throughout. Grains with tails of fine-grained quartz appear augenlike.

Most of the other minerals in the schist form inclusions in the porphyroblasts. The pattern of some, especially of graphite and to some extent ilmenite, commonly reflects the direction of the layering in the rock; the rest generally have a random pattern, but locally retain the pattern of continuous schistosity, spaced schistosity, and slip cleavage. Helicitic structures range from nearly planar to broadly S-shaped; a few preserve the pattern of crinkles in the schistosity. Planar patterns of inclusions commonly are at a marked angle with the schistosity and layering of the schist. Some of the inclusions, particularly garnet, have been protected by the albite from retrogradation.

Most of the porphyroblasts of albite both bulge out the folia of the micaceous minerals and cut across them slightly. Bulging of the folia predominates in some, crosscutting in others. The porphyroblasts also butt against and interrupt surfaces of slip cleavage. Figure 11 shows a subhedral porphyroblast and a glomeroporphyroblast of albite, and illustrates the patterns of

inclusions in them and their relations to textural and structural features of the rock.

Optical data indicate that the plagioclase is nearly pure albite, $\text{NaAlSi}_3\text{O}_8$. Optical properties are consistently as follows: $\beta=1.532$, $2V$ is about 75° , and the optic sign is positive. Many grains show simple twinning. Rarely, some of the clear rims of the albite porphyroblasts show polysynthetic twinning. Much of the albite shows slightly undulose extinction.

SERICITE

Sericite (see footnote 3, p. 8) is generally a major constituent of the schist, and generally predominates over chlorite except at the Mad River locality. The sericite occurs as shreds and flakes, which in thin section are generally less than 0.3 by 0.1 mm, commonly interleaved with chlorite or biotite or both. Layers wholly of sericite commonly show parallel orientation, whereas in all layers that contain abundant interleaved chlorite and biotite, particularly biotite, the sericite, as well as the biotite and chlorite, is diversely oriented. The sericite in the granoblastic layers occurs principally as lathlike flakes. In the shear zones of spaced schistosity and slip cleavage, flakes of sericite are parallel. Figures 2 and 8 to 12 illustrate several habits and structural patterns of sericite in schist.

The optical properties of the sericite, except for the optic axial angle, are fairly uniform. Indices of refraction range from $\beta=1.600$ to $\beta=1.609$; in most specimens β is about 1.603. The optic angle varies considerably in different specimens and even in the same specimen or the same flake, but in general is conspicuously small for muscovite, ranging chiefly between 10° and 25° . Axelrod and Grimaldi (1949, p. 563) attribute the small, variable $2V$ of muscovite studied by them to the superposition of layers rotated with respect to each other about $c[001]$ in multiples of 60° . An appreciable content of $(\text{Fe}^{+2}, \text{Mg})$ also results in a decrease in the optic axial angle.

Muscovite cannot be distinguished optically from paragonite, but X-ray study of two specimens of the sericite, one each from schist of the Waterbury mine and Barnes Hill localities, indicates that no paragonite is present (H. P. Eugster, written communication to A. L. Albee, Nov. 17, 1953). Consequently, the sericite is inferred to have generally the composition of muscovite. The optical properties indicate a relatively high content of $(\text{Fe}^{+2}, \text{Mg})$ and appreciable Fe^{+3} (Winchell, 1951, p. 368, fig. 254). Information available from chemical analyses of schist suggests that substitution of Na for K in the muscovite is slight at most. This conclusion is supported by the observation that in the nearby Hyde Park quadrangle rocks of suitable composition—that is, with Na in excess of that

required for albite—and of similar metamorphic grade contain both paragonite and muscovite (A. L. Albee, oral communication, June 1956). No more precise determination of composition can be made with the data available.

CHLORITE

Chlorite is a major constituent of nearly all the schist, though a few thin zones contain little or none. The chlorite is varied in habit. Most occurs in the lepidoblastic layers intermixed with sericite or biotite, or both. The habit of the chlorite in these layers is similar to that of the sericite, but it seldom shows as pronounced dimensional parallelism. Not uncommonly, part of the chlorite is subparallel and part diversely oriented. In layers predominantly of chlorite, most of the chlorite shows a distinct but imperfect dimensional and optical parallelism; a small proportion commonly is diversely oriented. Like sericite, chlorite flakes in thin shear zones that mark spaced schistosity and slip cleavage are parallel to the shear zones. Chlorite in the granoblastic layers is nearly everywhere diversely oriented. It occurs as irregular flakes and aggregates interstitial to grains of quartz and albite, and as inclusions within the grains. Chlorite also occurs as complete or partial pseudomorphs of garnet; though distinctive, this is a volumetrically minor occurrence. Such pseudomorphs of garnet are most conspicuous in porphyroblasts of albite that do not completely enclose the crystals of garnet. Relatively few were observed among the micaceous minerals, probably because those with no remnant garnet are difficult to distinguish from ground-mass chlorite. Pleochroic halos that surround minute grains of allanite, epidote, sphene, rutile, and zircon are a common feature of the chlorite.

Optical data on chlorite in the schist are summarized in table 2A. The chlorite is variable, and the total range in optical properties at each locality is fairly wide, but there are no significant differences between localities. All the chlorite in a given specimen, both in lepidoblastic layers and in pseudomorphs after garnet, is uniform, except for the special cases of that in pleochroic halos and chlorite in the transition between optically positive and negative. That in pleochroic halos invariably has negative sign, positive elongation, abnormal blue interference colors, and higher indices than the host chlorite. Chlorite in the transition between optically positive and negative exhibits flakes of either optic sign in the same thin section, commonly side by side, presumably because of very slight differences in composition between flakes. The optical properties of most of the chlorite are near to the following: $2V=0^\circ-20^\circ$; optic sign (—); elongation (+); $\beta=1.628$; birefringence very low, with pronounced abnormal blue interference colors; pleochroism moderate to strong, ranging from pale yellow

low green to bluish green. Chlorite of higher index than $\beta=1.628$ has similar optical properties, but the pleochroism is generally stronger and the intensity of the abnormal birefringence colors greater. Chlorite of lower index is commonly optically positive, though change in optic sign relative to index of refraction varies a little; pleochroism is generally less pronounced; the interference colors of optically positive chlorite in the schist are abnormal brown, but the brown tinge is generally faint in chlorite of index of $\beta=1.610$ and less.

The chlorite throughout most of the schist ($\beta=1.628$) is inferred on the basis of optical properties (see fig. 13) to approximate the composition $(\text{Mg}_{2.1}\text{Fe}^{+2}_{2.6})\text{Al}_{1.3}(\text{Al}_{1.3}\text{Si}_{2.7})\text{O}_{10}(\text{OH})_8$. The range in composition is approximately from $(\text{Mg}_{4.6}\text{Fe}^{+2}_{2.4})\text{Al}(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$ for $\beta=1.58$, or $(\text{Mg}_{3.0}\text{Fe}^{+2}_{1.8})\text{Al}_{1.2}(\text{Al}_{1.2}\text{Si}_{2.8})\text{O}_{10}(\text{OH})_8$ for $\beta=1.611$, to $(\text{Mg}_{1.4}\text{Fe}^{+2}_{3.0})\text{Al}_{1.6}(\text{Al}_{1.6}\text{Si}_{2.4})\text{O}_{10}(\text{OH})_8$ for $\beta=1.643$. It should be emphasized that the compositions shown are only approximate and are intended only to give a general idea of the composition of the chlorite. The relative constancy of birefringence for chlorite of a given index would seem to indicate that the Al content of chlorite of given index does not vary appreciably; however, the range of index throughout which chlorite near $\beta=1.628$ passes from optically positive to negative implies some variation in Al content for chlorite of the same index. The chlorite in sample B-DDH-1-45 with index $\beta=1.622$ is interpreted as an extreme example of how a low Al content depresses, with respect to the optic index, the transition from optically negative to positive chlorite. No analyses of chlorite from the schist are available, and calculation of the mineral composition from rock analyses of schist is unsatisfactory.

BIOTITE

Biotite is a minor constituent of a relatively small proportion of the schist at each locality, and can seldom be detected megascopically. Biotite is a major constituent which is conspicuous in hand specimen in a few places. The biotite is confined almost entirely to the micaceous layers, where it is commonly interlayered with the chlorite and sericite, but also occurs as inclusions in albite. It is commonly lathlike, as much as 0.4 mm long and ranging from a thin film to 0.2 mm thick. It almost everywhere shows diverse orientation. In places, irregular, branching patterns of a brown material resemble iron rust along shears or interconnected surfaces of sericite flakes, but appear pleochroic; and locally, under highest magnification, the stain can be resolved into tiny, discrete flakes of a micaceous mineral that is decidedly pleochroic in shades and tints of yellowish brown. The mineral may be biotite, but may in some places possibly be stilpnomelane or an oxidized chlorite.

Optical data on biotite from schist are included in table 2D. The total range in variation of indices and pleochroism is considerable. Material from Barnes Hill and Waterbury is similar in range and value of optical properties; material from Mad River has much higher indices and markedly stronger pleochroism. Various colors are represented, including greenish brown, yellowish brown, and brownish black. Various shades and tints of yellowish brown are predominant. Correlation between optical properties and chemical composition of biotite is possible only in a very general way, because variation in optical properties depends upon variations of several components, some of whose effects cannot be distinguished from one another. On the basis of Winchell's diagram (1951, fig. 257, p. 374), biotite of the schist at Barnes Hill and Waterbury mine would be intermediate between the phlogopite-eastonite and the annite-siderophyllite series, averaging about 60 molecular percent of the iron members. The content of Al, Fe^{+3} , and Ti, designated in the formula below as R, cannot be estimated from the optical data available. However, analogy with analyzed biotite from rocks of comparable metamorphic grade (see, for instance, Barth, 1936, p. 782) suggests that the average biotite from Barnes Hill and Waterbury mine has a composition approximately as follows: $\text{K}[(\text{Fe}^{+2}, \text{Mn})_{1.6}\text{Mg}_{1.1}]\text{R}_{.3}[\text{R}_{1.3}\text{Si}_{2.7}]\text{O}_{10}(\text{OH})_2$, which would place it in the field of siderophyllite near the center of Winchell's diagram. The biotite from the schist at Mad River, on the basis of Winchell's diagram (1951, fig. 257) has a composition near pure annite, $\text{KFe}^{+2}_3\text{RSi}_3\text{O}_{10}(\text{OH})_2$.

GRAPHITE

Much of the carbonaceous material in all the rocks may be cryptocrystalline or even amorphous, but for convenience all free carbon will be designated "graphite" throughout this report. Graphite is present in various amounts in much of the schist. Generally it constitutes only a few tenths of a percent of the rock, but in a few places it forms as much as 12 percent by volume of layers an inch or more thick. The graphite is associated predominantly with the sericitic layers of the schist, but occurs also with the chlorite and disseminated sparsely as tiny specks in the quartz and albite of the granoblastic layers. The graphite associated with the sericite and chlorite occurs at the interfaces of micaceous flakes as films and small clots. Heavy concentrations of graphite commonly mark narrow zones within the lepidoblastic layers. Where spaced schistosity and slip cleavage are prominent in graphitic schist, the foliation surfaces commonly contain marked concentrations of graphite. Porphyroblasts of albite very commonly contain included graphite which generally retains the

pattern of original layering. Figures 8 to 11 illustrate the distribution of graphite in three specimens of schist.

ILMENITE, RUTILE, AND SPHENE

Ilmenite is a common accessory of the schist and makes up as much as 2 percent of the rock. It occurs principally in chloritic layers and sparsely in sericitic and granoblastic layers. The distribution of ilmenite is generally rather uniform throughout a given layer, but varies considerably between layers; however, it is not uncommon for ilmenite to be concentrated heavily in a thin zone within a lepidoblastic layer. The mineral grains are commonly lathlike, or platy, and as large as 0.05 by 0.2 mm. Some are irregular, and in two thin sections the ilmenite forms tiny hexagonal plates. Some of the plates are translucent (yellowish brown) on thin edges, which suggests the presence of appreciable manganese.

Most, but not all, ilmenite is coated with an extremely fine grained substance, white in reflected light, identified as leucoxene. In some instances the coating is thick enough to form a distinct rim around the laths of ilmenite. There appear to be all gradations between such rims in which the material is submicroscopic and those made up of tiny but recognizable grains of sphene or, rarely, rutile. Such a gradation suggests that the leucoxene may be either very fine grained sphene or rutile.

Rutile was found only in one specimen of schist, from the Mad River locality. It occurs as tiny yellowish-brown needles and anhedral grains confined entirely to layers rich in chlorite.

Sphene is a persistent accessory of the schist, and locally constitutes as much as 11 percent of the rock, though generally only a few percent or a few tenths of a percent. The sphene has two principal habits: as anhedral to euhedral (diamond-shaped) single-crystal grains from 0.01 mm to as much as 0.5 mm in length, and as aggregates of fine grains pseudomorphic after laths of ilmenite, commonly with a core of ilmenite; the single-crystal grains predominate. The pattern of distribution is similar to that of ilmenite.

GARNET

Although garnet is not uncommon in the schist at Barnes Hill and Waterbury, it is rarely detected in hand specimen because the grains are small and few in number. Garnet rarely constitutes more than 1 percent of the rock, but in one specimen, from Waterbury, it is 10 percent. No garnet has been observed in the rocks at Mad River. The garnet occurs as dodecahedral crystals as large as 0.1 mm across. It is most abundant in the lepidoblastic layers but is not uncommon in the granoblastic layers. Garnet

included in porphyroblasts of albite is commonly concentrated near the cores of the porphyroblasts, though not as characteristically so as inclusions of graphite and ilmenite.

Practically all the garnet in the lepidoblastic layers and most of that in the granoblastic layers, where not embedded in porphyroblasts of albite, is partly or entirely altered to chlorite. Commonly at the Waterbury mine locality a core remains ranging in size from a tiny grain to a crystal that is only slightly embayed and rimmed; garnet in the granoblastic layers is generally less completely altered, but most has a rim of chlorite. At the Barnes Hill locality all or nearly all the garnet not armored by albite is completely altered to chlorite. Garnet included in the albite porphyroblasts at both places is almost entirely fresh, commonly with no trace of alteration to chlorite; a very thin rim of albite, as little as 0.005 mm, appears to have effectively prevented chloritization. Garnets not completely surrounded by porphyroblasts, even though only slightly exposed, generally are extensively or completely chloritized.

No optical data were obtained on the garnet other than that they are a reddish variety. They are presumed to be near almandite in composition.

APATITE

Apatite is a persistent accessory mineral in the schist. It generally makes up less than 1 percent of the rock and averages about 0.2 to 0.3 percent, but locally it constitutes as much as 6 percent. It occurs predominantly as oval grains 0.05 to 0.2 mm in mean diameter and somewhat irregular in outline, but it also forms small irregular inclusions in quartz and albite. The apatite occurs erratically throughout the rock; in a few thin sections examined it is associated predominantly with granoblastic layers, and in some others principally with highly chloritic (and biotitic) layers. There are no persistent differences in size and shape of the apatite in the different associations.

All the apatite has very low birefringence; for this reason interference figures are mostly diffuse and unsatisfactory, but favorably oriented grains gave a nearly uniaxial optically negative figure. Indices of refraction are $\omega=1.633$, $\epsilon=1.630$. These optical data indicate a composition of approximately $\text{Ca}_5\text{P}_3\text{O}_{12}\text{F}$, fluorapatite (Winchell and Winchell, 1951, figs. 112, 113, p. 199–200).

EPIDOTE AND ALLANITE

Epidote occurs in only a few specimens of schist from each locality, either in isolated mafic layers or in transitional zones near greenstone or amphibolite. The epidote is invariably associated with layers rich

in chlorite, and occurs both in subequant grains as large as 0.1 mm and as tiny grains in the center of pleochroic halos in chlorite. Allanite, noted only at Mad River, occurs chiefly as small cores in grains of epidote. A few grains large enough to be identified occur at the center of pleochroic halos in chlorite.

Optical data on epidote in schist, included in table 2E, are meager, but indicate a composition about that of pistacite (common epidote), according to Winchell (1951, p. 449, fig. 343), or approximately $\text{Ca}_2\text{Al}_{2.4}\text{Fe}_{0.6}^{+3}\text{Si}_3\text{O}_{12}(\text{OH})$. No information is available on the composition of the allanite, which is yellowish to reddish brown and moderately pleochroic.

OTHER MINERALS

Zircon is very rare and occurs chiefly as scattered well-rounded oval grains. Some tiny grains at the center of pleochroic halos in chlorite appear to be zircon, though most are too small to be positively identified.

Tourmaline commonly occurs very sparsely as subhedral to euhedral prismatic crystals, chiefly as inclusions in quartz and albite. The tourmaline is strongly pleochroic, varying from: ω , olive green to purplish blue; ϵ , pale bluish green to colorless. Some is zoned, with a core of pale blue green and a border of light olive brown.

Carbonate is seldom abundant, but in a few places it constitutes as much as 10 to 15 percent of thin layers of schist. The carbonate is disseminated in irregular grains and small aggregates of grains, and forms tiny discontinuous veinlets. Where carbonate is a major constituent it is concentrated chiefly in layers with a low content of granoblastic quartz and albite. Much of the carbonate shows glide twinning. Indices range from $\omega=1.662$ to 1.668, indicating calcite with only minor amounts of iron, magnesium, and manganese.

Pyrite is a common accessory, but rarely forms more than 1 or 2 percent of the schist. It occurs as tiny irregular grains and blebs, commonly but not always elongate parallel to the schistosity; less commonly, small cubic crystals of pyrite transect the schistosity.

Magnetite occurs rarely in the schist. None was distinguished at Barnes Hill and Waterbury mine, and it was identified in only one specimen from Mad River, though it is possible that some magnetite is associated with ilmenite in sections in which no magnetite was identified. The magnetite forms subequant grains and ranges from dustlike particles to as large as 0.2 mm across.

PETROGENESIS

Metamorphic features predominate in the schist, but sedimentary features are clearly recognizable and influence the metamorphic fabric. Most of the minerals are metamorphic, but some have only been re-

crystallized or slightly redistributed, and are stable relicts (Barth, 1952, p. 327) of the protolith; a very few stable relicts appear to have been entirely unchanged during metamorphism, and retain their detrital outlines.

Most of the quartz and granular albite appears to have recrystallized from detrital grains, but some has probably formed by metamorphic reaction, particularly of sodic clay minerals to form albite. Many of the quartz lentils probably have accumulated entirely by metamorphic differentiation with concretionary growth (see Eskola, 1932, p. 71-73; Ramberg, 1952, p. 91-92). The present distribution of these minerals probably reflects that of detrital quartz and plagioclase and of sodic clay minerals in the sedimentary rock. Tails of fine-grained quartz on albite porphyroblasts appear to have formed by diffusion of SiO_2 into "potential voids" induced by rotation of the porphyroblasts.

The albite porphyroblasts have formed almost entirely by concretionary growth, replacing and pushing apart the host minerals. The porphyroblasts are younger than the schistosity and slip cleavage, which they cut. The pattern of helicitic structures indicates that the porphyroblasts were only little rotated during growth, and were slightly rotated after. The inclusion-filled cores and clear rims of the porphyroblasts suggest that growth during the early stages was very rapid, and resistant minerals were uncut; growth during later stages was slower and resistant minerals were pushed out. The occurrence of some entirely clear porphyroblasts and of some inclusion-filled ones without clear rims indicates that growth neither began nor ceased simultaneously everywhere.

The distribution of sericite, chlorite, and biotite probably reflects the original distribution of fine clay minerals, and variation in composition within clay layers. Sericite and chlorite formed early during metamorphism and remained stable throughout the metamorphic history in most places; in layers of favorable composition chlorite reacted, at the peak of metamorphism, to form biotite, garnet, and a more magnesian chlorite. After the peak of metamorphic intensity, during retrograde metamorphism, much of the garnet and perhaps some of the biotite altered to chlorite. The late development of some chlorite is reflected in the diverse orientation of that chlorite, though an additional factor may be that chlorite does not assume dimensional parallelism as readily as sericite. The random pattern of the biotite and its occurrence interleaved with chlorite and sericite in all stages from thin films to well-formed flakes indicates that the biotite has formed late and that it grew at the expense of the sericite and chlorite. In a few places biotite appears to

have altered to chlorite by retrogradation, but such instances are rare.

Garnet was formed near the peak of metamorphic intensity. Inclusions of garnet in porphyroblasts of albite suggest that the porphyroblasts are, in part at least, later than the garnet. Alternatively, the garnet may have formed by reconstitution of inclusions of chlorite, requiring diffusion of material through the albite lattice; the effectiveness with which albite armored the garnet during retrograde metamorphism militates against this interpretation. Garnet outside the albite porphyroblasts, particularly that in chlorite and sericite, was partly to completely retrograded to chlorite, whereas garnet within albite porphyroblasts remains unaltered. Garnet in granoblastic layers is generally rimmed with chlorite probably because grain boundaries served as channelways for diffusion of ions or movement of solutions to effect retrogradation.

Ilmenite, sphene, rutile, and leucoxene are all of metamorphic origin and formed approximately at the same period, but a sequential relation of sphene after ilmenite is evident. Laths of ilmenite, broken and separated along slip-cleavage surfaces, were formed prior to the end of orogenic movement. In many places the ilmenite then was altered at the margins to leucoxene, or completely to aggregate pseudomorphs of sphene after ilmenite. Single-crystal grains of sphene probably formed at this time by direct crystallization during reconstitution of sedimentary minerals. Ilmenite not associated with sphene is a stable relict; ilmenite that forms cores within sphene probably represents in some instances stable relicts in an environment without sufficient Ca to alter ilmenite completely to sphene, and in other instances unstable relicts that were protected by a sheath of sphene. Rutile is of the same general age as the ilmenite and sphene, and formed probably in an environment in which Fe^{+2} was not available to form ilmenite, nor Ca and Si to form sphene—for instance, in magnesian chlorite layers.

Some of the carbonate in the schist, particularly that showing layered distribution, is probably of sedimentary origin, and some probably was formed by CO_2 metasomatism. Free carbon is inferred to be of sedimentary origin and to reflect closely the distribution in the protolith. Some redistribution, probably mechanical during shearing, is indicated by concentrations along planes of spaced schistosity and slip cleavage. Most of the apatite is probably of metamorphic origin, derived from phosphatic material of sedimentary origin; but the concentration of some in granoblastic layers suggests that some may be detrital, though completely recrystallized.

The larger grains of zircon show no evidence of recrystallization and are inferred to be detrital; the tiny grains

in pleochroic halos in chlorite are probably of metamorphic origin. The tourmaline is probably chiefly of metamorphic origin, although some may be detrital, and some of the euhedral grains may even be ultimately of diagenic origin (see Pettijohn, 1949, p. 504). Epidote and allanite formed contemporaneously during metamorphism; the occurrence of allanite as cores in larger grains of epidote suggests that where rare earth elements were present allanite formed until the rare earths were used up, and that thereafter epidote formed.

The magnetite is presumably of metamorphic origin. The two distinct habits of pyrite suggest two ages, though probably all is ultimately of sedimentary origin. Irregular grains of pyrite elongated in the plane of schistosity were crystallized prior to or during orogeny, the cubic crystals later.

QUARTZITE

Quartzite is exposed only at the Mad River locality. Though distinctive and prominent in outcrop, it is quantitatively minor, and makes up probably less than 1 percent of the country rock. The quartzite is very uniform in appearance and composition. Quartz forms 98 percent or more of the rock; graphite, sericite, carbonate, zircon, and feldspar are persistent accessory minerals. A modal analysis of typical quartzite (MR-105) is given in table 1.4. The rock is dark bluish gray in overall appearance, but in detail contains thin layers 0.5 to 2 mm thick of various shades of gray ranging from almost white to very dark bluish gray. This contrast in color is the most conspicuous feature of bedding in the quartzite. The boundaries between layers are generally marked by thin films of graphite and sericite which form inconspicuous partings. Individual layers can commonly be traced for several feet or even tens of feet. In outcrop, the layering appears to be strictly parallel to the boundaries between quartzite and schist; these boundaries are gradational but very abrupt. The transition from quartzite to schist takes place by sharp increase in number and thickness of micaceous layers, and decrease in thickness of quartz layers.

In thin section, the rock consists of a granoblastic aggregate of slightly elongate quartz grains, segregated into fairly distinct layers of different grain size. The long axes of the grains are generally parallel to the layers, which are commonly marked by films of graphite and sericite.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

Quartz, the sole essential constituent of the quartzite, forms a mosaic of grains ranging from 0.04 to 0.4 mm in diameter. It contains a few inclusions of carbonate, sericite, and graphite. Nearly all grains show uniform extinction with no trace of strain shadows. Interference figures are uniaxial or very slightly biaxial.

Feldspar grains are dispersed sparsely throughout the rock. Their textural relations are identical with those of the quartz. Some of the feldspar shows irregular and shadowy polysynthetic twinning. All grains noted had indices astraddle that of Canada balsam, and were therefore identified as albite; potash feldspar may also be present.

Sericite occurs to a small extent as inclusions in quartz, but chiefly in thin films along bedding surfaces. The flakes of sericite are nearly all oriented parallel to the bedding. Graphite is concentrated chiefly with sericite in thin films along bedding surfaces. A proportionately small amount of graphite occurs as dustlike particles disseminated throughout the quartz layers, commonly at grain boundaries but also as inclusions within quartz grains. Carbonate occurs sparsely as small rounded inclusions in quartz. Well-rounded oval grains of zircon as large as 0.15 by 0.2 mm are scattered sparsely but conspicuously throughout the rock; the grains show no evidence of recrystallization.

PETROGENESIS

The textural features of the parent sedimentary rock have been modified only moderately by metamorphism. Bedding is preserved by variations in texture and mineralogic composition. Detrital outlines of most minerals have been obliterated, but zircon remains unchanged and the grain size of the rest appears but little modified. Sericite is probably the only mineral of metamorphic origin; it was formed by reconstitution of fine clay minerals. All other minerals are stable relicts from the parent sedimentary rock.

GREENSTONE GENERAL FEATURES

Greenstone occurs in significant quantity and forms mappable units only at the Mad River and Barnes Hill localities. Thin beds as much as 1 or 2 inches thick occur at Waterbury mine, but they are quantitatively negligible. The greenstone at the Barnes Hill locality is composed largely of actinolitic hornblende; where a distinction is necessary, it will be referred to as actinolitic greenstone. The greenstone at the Mad River locality contains some amphibole, locally in greater amount than chlorite, but in general chlorite is greatly predominant; it will be distinguished, where necessary, as chloritic greenstone. (See Barth, 1952, p. 320; Billings and White, 1950, p. 635-636).

The chloritic greenstone is composed essentially of chlorite and albite in various proportions. Epidote is commonly a major or minor constituent, and sphene is locally present in major proportions. The actinolitic greenstone is rather uniform in composition and appearance. It is composed essentially of actinolitic hornblende, albite, and epidote; chlorite and sphene are

persistent accessory constituents and are locally present in major proportions.

Selected modes of greenstone are given in table 1. No chemical analyses are available. An approximate composition of the chloritic greenstone, based upon modes of table 1C and mineral compositions inferred from optical data, is calculated to be as follows (weight percent):

SiO ₂ -----	45	K ₂ O-----	1.1
Al ₂ O ₃ -----	17	Na ₂ O-----	3.5
Fe ₂ O ₃ -----	1.0	TiO ₂ -----	2.0
FeO-----	10	P ₂ O ₅ -----	.2
MgO-----	9.0	CO ₂ -----	1.4
CaO-----	4.8	H ₂ O-----	5.0

An approximate average composition of the actinolitic greenstone, calculated similarly from modes in table 1B, is as follows (weight percent):

SiO ₂ -----	51	CaO-----	12
Al ₂ O ₃ -----	12	K ₂ O-----	.5
Fe ₂ O ₃ -----	2.3	Na ₂ O-----	3.0
FeO-----	6.5	TiO ₂ -----	.9
MgO-----	9.6	H ₂ O-----	2.2

The compositions of both approach that of basalt, the actinolitic greenstone somewhat more closely than the chloritic greenstone. The principal differences in composition are the lower content of Al₂O₃ and H₂O and the higher content of SiO₂ and CaO of the actinolitic greenstone.

The chloritic greenstone ranges in color on fresh surfaces from dull greenish gray to moderate grayish green. Weathered varieties with an appreciable content of carbonate are stained buff to rusty brown along cleavage surfaces and are pitted where carbonate grains have weathered out. The actinolitic greenstone is uniformly fine grained, and ranges in aspect from massive to slabby. On fresh surfaces it is dark greenish gray to grayish olive green or dusky yellow green. The variations in color are due principally to differences in content of epidote and chlorite. Weathered outcrops that contain appreciable carbonate are rusty and pitted, but otherwise the actinolitic greenstone is resistant to weathering and maintains a smooth surface with only a thin grayish-buff rind.

Nearly all the greenstone has for the most part a distinct layering, formed by the segregation of light and dark minerals in separate layers. The dark layers are rather uniformly 1 to 2 mm thick; the light-colored layers range from 0.2 to 2 mm thick. The grouping of these layers into sequences as much as 1 cm thick in which light and dark layers alternately predominate forms a coarser layering. Individual layers can generally be traced for several tens of centimeters, and the layered sequences are traceable for the extent of an outcrop. Locally, the layers of greenstone are intricately folded and crumpled, but in general they are

parallel to the boundaries of the map units. The light layers consist chiefly of albite and minor amounts of chlorite or amphibole. Quartz is locally abundant in the light layers of chloritic greenstone transitional into schist, where it is intermixed in various proportions ranging from traces to the principal constituent. The albite and quartz form an interlocking mosaic of sub-equant to somewhat elongate grains from 0.05 to 0.8 mm in mean diameter. The dark layers are composed chiefly of chlorite or amphibole, and contain most of the epidote and sphene in the rock. The epidote is randomly distributed, but the sphene is concentrated generally in thin zones parallel to the layering. Sericite, in types of greenstone transitional into schist, is interleaved with chlorite, and generally occurs in only part of the dark layers, where it is intermixed in various proportions ranging from traces to the principal constituent. The dark and light layers of both greenstone and amphibolite commonly intergrade by uniform change in the proportion of light and dark minerals. Sparse albite porphyroblasts occur in both light and dark layers.

Continuous schistosity in the chloritic greenstone ranges in quality from poor to excellent, in the actinolitic greenstone from imperceptible to good. In general the poorly layered varieties are nonschistose to weakly schistose, whereas the distinctly layered varieties have a fair to good or excellent schistosity; but some of the fairly distinctly layered greenstone has only a very weak schistosity. On the other hand, there is a constant direct relation between quality of schistosity and the degree to which the minerals are dimensionally parallel.

Some of the actinolitic greenstone has crenulations about 2 to 3 mm in wavelength, but with none is there associated a slip cleavage. Narrow shear zones 0.1 mm and less thick, irregularly and widely spaced but generally parallel to each other, transect the layering and schistosity in a few sections of actinolitic greenstone; flakes of chlorite and laths and fragments of amphibole within the shears are parallel to the shears, and impart a weak spaced schistosity, observable locally in outcrop.

Small veinlets as much as 1 mm thick, composed of grains of clinozoisite and diversely oriented flakes, of chlorite, are common in the actinolitic greenstone but nowhere abundant. The veinlets are commonly cross-cutting, and are of irregular thickness. Borders of the veins are irregular and nonmatching.

Locally, at the border of the ultramafic body at Barnes Hill, masses of actinolitic greenstone as much as a foot thick and of undetermined shape and extent, are highly carbonatized (see mode of specimen B-DDH-12-188, table 1D). These carbonatized masses have irregular boundaries and contain abundant fragments

and laths of amphibole in all stages of digestion by the carbonate.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

ALBITE

Albite is nearly everywhere a major constituent of the greenstone. The proportion of albite in the chloritic greenstone varies widely, ranging from about 2 to almost 70 percent, but in most places it ranges from 20 to 50 percent. Albite forms generally 20 to 30 percent of the actinolitic greenstone, though in a few layers as much as several inches thick albite is very sparse or entirely absent. The albite forms interlocking mosaic aggregates in the light layers and occurs as scattered grains in the dark layers. Porphyroblasts and polycrystalline aggregates of albite 1 mm or more across occur rarely. Much of the albite in chloritic greenstone contains sparse to moderately abundant tiny inclusions of epidote; that in actinolitic greenstone almost invariably contains abundant inclusions of clinozoisite. In some of the chloritic greenstone, inclusions of prismatic tourmaline crystals occur locally, and a few porphyroblasts of albite contain tiny dodecahedral garnet crystals. In the several slides of chloritic greenstone that contain amphibole, the albite contains abundant inclusions of amphibole laths, invariably in greater proportion than outside the albite.

Most of the albite is untwinned, but simple twins are not uncommon. Nearly all grains show uniform extinction. The optic angle is positive, $2V$ is about 75° , and $\beta=1.532$. These optical properties indicate a composition of nearly pure albite, $\text{NaAlSi}_3\text{O}_8$.

CHLORITE

Chlorite is everywhere a major constituent of the chloritic greenstone and rarely forms less than 40 percent of the rock except locally where amphibole is abundant, or in types transitional into schist. Chlorite is a persistent minor constituent of the actinolitic greenstone; it is commonly less than 5 percent of the rock, but is locally as much as 10 percent. In the chloritic greenstone, the chlorite occurs as irregular, interlocking flakes and shreds about 0.2 to 0.4 mm long. Its pattern in the dark layers ranges from diverse to marked dimensional parallelism. In a few places rounded patches of chlorite appear to be pseudomorphic after garnet. In a few thin sections the chlorite layers contain amphibole which has been partly replaced by chlorite (see below under "Amphibole"). In the actinolitic greenstone the chlorite occurs in three habits: in unevenly distributed, irregular patches and clusters of flakes in the amphibole layers; as diversely oriented flakes in small veinlets that commonly also contain epidote; and as parallel flakes that are the principal or only constituent in narrow shear zones.

Optical data on the chlorite are summarized in table 2A. The range for each rock type is considerable, but the chlorite in a given hand specimen invariably is uniform in optical properties—with the exception of that in pleochroic halos. There seem to be no consistent differences in optical properties between the chlorites of different habit. Indices of chlorite in the chloritic greenstone range from $\beta=1.612$ to 1.638, of that in the actinolitic greenstone from $\beta=1.612$ to 1.628. The optic angle ($2V$) is small to moderate. In the chloritic greenstone, chlorite with $\beta=1.627$ or higher is optically negative, whereas that with lower index is optically positive; all the chlorite in the actinolitic greenstone is optically positive. Optically negative chlorite shows positive elongation, and positive chlorite shows negative elongation. Pleochroism is moderate to strong except for chlorite of index less than $\beta=1.615$; the direction of greatest absorption is parallel to the cleavage. The low-index chlorite shows only faint abnormal brown interference colors. High-index material shows pronounced abnormal brown colors for positive chlorite and pronounced abnormal blue or purplish for negative chlorite. The composition of the chlorite in the chloritic greenstone, on the basis of figure 13, is inferred to range approximately from $(\text{Mg}_{3.0} \text{Fe}^{+2}_{1.8}) \text{Al}_{1.2} (\text{Si}_{2.8} \text{Al}_{1.2}) \text{O}_{10} (\text{OH})_8$ for $\beta=1.612$, to $(\text{Mg}_{1.6} \text{Fe}^{+2}_{3.0}) \text{Al}_{1.4} (\text{Si}_{2.6} \text{Al}_{1.4}) \text{O}_{10} (\text{OH})_8$ for $\beta=1.638$. Most of the chlorite in the actinolitic greenstone is approximately of the composition $(\text{Mg}_{2.1} \text{Fe}^{+2}_{2.6}) \text{Al}_{1.3} (\text{Si}_{2.7} \text{Al}_{1.3}) \text{O}_{10} (\text{OH})_8$ ($\beta=1.628$), but the composition ranges to that of index $\beta=1.612$.

AMPHIBOLE

Amphibole is generally the most abundant constituent of the actinolitic greenstone, commonly forming 45 to 60 percent of the rock. In a few places, epidote is more abundant in zones as much as 2 or 3 feet thick. The amphibole occurs as somewhat irregular, lathlike crystals as large as 0.3 by 0.4 mm, but commonly about 0.15 by 0.3 mm. Their arrangement ranges from diverse in massive varieties to generally parallel in distinctly layered varieties. Amphibole is generally absent from the chloritic greenstone, but in a few places forms as much as one-fourth of the rock. Amphibole in the chloritic layers is largely embayed and irregularly invaded by chlorite, so that it has a ragged, frayed outline, though many grains are of regular shape. Most of the amphibole that occurs as isolated crystals in the light layers is euhedral to subhedral and unaltered.

Optical data on amphibole are given in table 2B. The optical properties are generally uniform and similar in both rock types. Billings (1937, p. 477) concluded that an amphibole with similar optical properties and from rocks of comparable metamorphic grade was actinolitic

hornblende, on the basis of similarity in optical properties and metamorphic setting to analyzed actinolitic hornblende from Great Britain described by Wiseman (1934, p. 354-417; cited in Billings, 1937, p. 477). Using Foslief's (1945, fig. 1, p. 79) optical chart for amphibole, and taking the pleochroism, extinction angle of 19° to 20° , $2V$ of 75° , and negative optic sign as indicating the presence of a small amount of Al, a reasonable composition for the amphibole is deduced to be approximately $\text{Na}_{.2}\text{Ca}_{2.0}(\text{Mg}_{3.7}\text{Fe}^{+2}_{1.1}\text{R}^{+3}_{.2})(\text{Si}_{7.6}\text{Al}_{.4})\text{O}_{22}(\text{OH})_2$, where R^{+3} represents Fe^{+3} and Al.

EPIDOTE AND ALLANITE

Epidote is a persistent constituent of the chloritic greenstone and in many places is a major component; it is a major constituent of nearly all the actinolitic greenstone, where it generally constitutes a little more than 10 percent of the rock but is locally more abundant than either amphibole or albite. In both varieties of greenstone the epidote occurs principally in the dark layers as grains 0.05 to 0.3 mm across; rarely the grains are as large as 1 mm. Epidote occurs also throughout the albite as tiny inclusions that range in size from 0.001 to 0.1 mm across. In the actinolitic greenstone, epidote locally occurs in veins ranging in size from tiny irregular veinlets about 1 mm thick to tabular masses several inches thick. In the larger veins the epidote forms subhedral crystals as much as 1 inch across.

Allanite occurs in a few thin sections of chloritic greenstone as small cores in epidote grains. It is yellowish brown and slightly pleochroic.

Optical data on epidote in the greenstones are given in table 2E. All the larger grains in the chloritic greenstone have maximum birefringence colors of the third order, negative optic sign, large $2V$, and indices of $\beta = 1.738-1.753$. Most of the larger grains in the actinolitic greenstone show a similar range in optical properties, but some grains have low maximum birefringence, large $2V$, and positive sign. All the vein epidote has high index and high birefringence, and is optically negative. These data do not fit well on Winchell's diagram (1951, fig. 343, p. 449) but it is evident that most of the epidote is in the compositional range of pistacite (common epidote), averaging about $\text{Ca}_2\text{Fe}^{+3}_6\text{Al}_{2.4}\text{Si}_3\text{O}_{12}(\text{OH})$. The low-birefringent, optically positive epidote in the amphibolite may have a ratio of $\text{Fe}^{+3}:(\text{Fe}^{+3},\text{Al})$ of less than 0.1.

Epidote inclusions in the albite of the chloritic greenstone appear to have the same optical properties and inferred composition as the larger grains throughout the rock. Those included in the albite of the actinolitic greenstone consistently show low birefringence, with blue and lemon-yellow abnormal interference colors, and are inferred to be clinozoisite.

BIOTITE

Biotite is not generally present in the chloritic greenstone, but locally it forms as much as 17 percent of the rock. The biotite is associated exclusively with chlorite, with which it is interleaved, and has a pattern similar to that of the chlorite. Biotite occurs in only a few places in the actinolitic greenstone and is never present in more than minor amounts. It forms randomly oriented thin films and small flakes interleaved with chlorite in the amphibole layers.

Optical data on biotite are given in table 2D. The optical properties of biotite in the chloritic greenstone indicate an approximate composition (see discussion of biotite in the schist, p. 52) of $\text{K}[(\text{Fe}^{+2},\text{Mn})_{2.0}\text{Mg}_{.7}\text{R}^{+3}_{.3}[\text{R}^{+3}_{1.3}\text{Si}_{2.7}]\text{O}_{10}(\text{OH})_2]$. On the same basis, the biotite in the actinolitic greenstone is inferred to have a composition of about $\text{K}[(\text{Fe}^{+2},\text{Mn})_{1.4}\text{Mg}_{1.3}]\text{R}^{+3}_{.3}(\text{R}^{+3}_{1.3}\text{Si}_{2.7})\text{O}_{10}(\text{OH})_2$.

CARBONATE

Most of the chloritic greenstone contains no carbonate, but in a few places carbonate constitutes as much as 16 percent of the rock. The three thin sections that contain carbonate also contain small to moderate amounts of quartz, but much of the quartzose greenstone contains no carbonate. The carbonate occurs chiefly in the light layers in the same mosaic pattern as the albite and quartz, and partakes of the layering in the same manner as the albite and quartz; relatively small amounts of carbonate occur in the dark layers.

In the actinolitic greenstone, carbonate occurs rarely and in small amounts as small, irregular, disseminated grains.

In the small masses of carbonatized greenstone at the borders of the ultramafic body at Barnes Hill the carbonate commonly has a mosaic pattern, but locally a textural pattern inherited from the greenstone is apparent. Two habits are discernible that are suggestive of pseudomorphism: one, of about equidimensional grains similar in size and shape to the albite; the other of parallel elongate grains, many with the outline and cleavage of amphibole laths. The mosaic grains contain inclusions of highly digested feathery crystals of amphibole.

The index of refraction of the carbonate in the chloritic greenstone is $\omega = 1.662$, indicating relatively pure calcite, approximating a composition between $(\text{Ca}_{.95}\text{Mg}_{.05})\text{CO}_3$ and $[\text{Ca}_{.98-.99}(\text{Fe}^{+2},\text{Mn})_{.02-.01}]\text{CO}_3$.

No optical properties were obtained on carbonate disseminated throughout the actinolitic greenstone. The masses of carbonatized greenstone contain two varieties of dolomite (table 2C, specimen B-DDH-12-188). The main carbonate mass is made of dolomite of index $\omega = 1.691$. Small veinlets of dolomite within small masses of chlorite in the carbonate mass have an

index of $\omega=1.680$. The main mass of carbonate is inferred to have a composition of about $(\text{Ca}_{.50}\text{Mg}_{.44}\text{Fe}^{+2}_{.06})\text{CO}_3$, the veinlet a composition of about $(\text{Ca}_{.50}\text{Mg}_{.50})\text{CO}_3$.

ILMENITE, RUTILE, AND SPHENE

Ilmenite occurs only in parts of the greenstone transitional into schist, and is similar in all respects to the ilmenite in the schist.

Rutile occurs only in the chloritic greenstone and rarely in that. In the one section where it was noted rutile makes up 2.4 percent of the rock, and is associated chiefly with chlorite. The rutile forms lathlike aggregates of very fine grains that are almost opaque in thin section. The shape suggests that the rutile is pseudomorphic after ilmenite.

Sphene is a persistent minor constituent of both varieties of greenstone, and locally constitutes as much as 17 percent of the chloritic greenstone. The sphene occurs as anhedral to subhedral grains that range generally in size from 0.01 to 0.3 mm; a few grains are as large as 1 mm. It occurs principally in layers dominantly of chlorite or amphibole, but also forms scattered grains in albitic and quartzose layers.

OTHER MINERALS

Apatite is a persistent minor constituent of the chloritic greenstone but was not seen in the actinolitic greenstone. The apatite occurs scattered unevenly and unsystematically throughout the rock in oval grains with somewhat irregular borders and ranging from 0.05 to 0.2 mm in mean diameter. Optically, the apatite in the greenstone is similar to that in the schist and is considered to be of the same composition, $\text{Ca}_5\text{P}_3\text{O}_{12}\text{F}$ (see p. 53).

Garnet occurs very rarely in the chloritic greenstone, and then only in varieties transitional into schist; none was seen in the actinolitic greenstone. All the garnet observed was preserved as inclusions in albite, in the manner described for that in the schist (p. 52-53).

Tourmaline and pyrite were seen only in chloritic greenstone transitional into schist and have characteristics identical with those of the same minerals in the schist.

Magnetite occurs in much of the chloritic greenstone and in some of the actinolitic greenstone as sparsely scattered, irregular grains as much as 0.1 mm across; a few have octahedral form. The magnetite is distinguished from ilmenite solely on the basis of grain shape, absence of leucoxene, and magnetic properties.

Quartz and sericite occur only in greenstone transitional into schist. The quartz is predominantly in the light layers, sericite predominantly in the dark layers. The habits and properties are the same as in the schist.

PETROGENESIS

Sedimentary and metamorphic features of the two varieties of greenstone indicate a general similarity in parentage and metamorphic history, but record slight differences. Layering represents bedding modified by recrystallization and metamorphic differentiation. The composition of the actinolitic greenstone indicates that its protolith was probably a water-laid tuff or was composed almost entirely of detritus eroded from basalt lava flows. The higher content of Al_2O_3 and lower content of CaO in the chloritic greenstone suggests that its generally similar protolith contained appreciable intermixed clay minerals: the transition into schist and the quartzose interbeds support such a conclusion. The distribution of metamorphic minerals in the greenstones reflects the pattern of distribution of detrital minerals in the parent rock, as is attested by the preservation of bedding, and by the gradual and locally rhythmic variation from distinctly layered to a uniform intermixture of albite and chlorite or amphibole. Reaction to mechanical factors during metamorphism may have intensified bedding features, and may have originated some of the layering. Textural relations among the minerals have been considerably modified, but habit and grain size of original minerals in the parent rock are reflected in part in the metamorphic minerals.

In both varieties of greenstone, the inclusions of epidote or clinozoisite in the albite imply that the albite has formed by metamorphism of a calcic plagioclase. The relatively large proportion of such inclusions in the actinolitic greenstone implies a moderately calcic plagioclase; their sparseness in the chloritic greenstone indicates a considerably less calcic variety. The compositions thus inferred probably were those of the plagioclase in the protolith rather than compositions achieved at somewhat higher peaks of metamorphic intensity. The anorthite content indicated for the plagioclase of the actinolitic greenstone would have required peak physical conditions of the amphibolite facies (see Ramberg, 1945, p. 53; 1952, p. 53; Barth, 1952, p. 285), and the textural and mineralogical features indicate that the rocks were never at those conditions. The lower peak indicated by the small anorthite content of plagioclase in the chloritic greenstone does not preclude a metamorphic origin for plagioclase of the composition inferred, but the inferred composition appears at least equally probably to reflect that of the detrital mineral.

The amphibole has formed by reconstitution, during metamorphism, of the original mafic minerals of the

protolith. The absence of bent and strained crystals, and the tangential arrangement of the laths around small folds, indicates that the amphibole formed—or continued to recrystallize until—late, after folding had essentially ceased. The pattern of the amphibole laths, particularly the relationship between dimensional parallelism of the amphibole and perfection of layering in the rock (see p. 56), together with the evidence of late origin, indicates that the orientation pattern of the amphibole is mimetic after that of earlier minerals. The pattern may derive ultimately from a sedimentary fabric or from a tectonic fabric, or from a sedimentary fabric modified by a tectonic fabric.

The chlorite in the chloritic greenstone was formed chiefly during progressive metamorphism by reconstitution of preexisting mafic minerals. A very small part of the chlorite in a few slides was formed by retrograde alteration of garnet; in several slides, part of the chlorite has formed by alteration of amphibole, and if the abundance of fresh amphibole isolated within albite layers is an accurate criterion of its former abundance throughout the slide, the proportion of retrograde chlorite is high in those slides. In a few such slides the more abundant concentration of sphene in chlorite than in amphibole may possibly be taken as evidence that the chlorite was derived from amphibole, with consequent release of Ca to form sphene. In most slides, however, there is no evidence that amphibole was ever present, and the chlorite in these may have all formed during progressive metamorphism.

Chlorite in the actinolitic greenstone is everywhere sparse, and appears to have formed chiefly by retrogradation. That in the veins and shears transects the metamorphic fabric. The relations of the dispersed chlorite in the amphibole layers commonly do not show whether it formed before or after the amphibole, but in many places it irregularly embays laths of amphibole and appears to have replaced them. Therefore, the chlorite is interpreted as retrograde, though some, particularly that intergrown with biotite, may have persisted throughout progressive metamorphism.

Allanite, and epidote outside the plagioclase, were formed by reconstitution of preexisting mafic minerals. The occurrence in the chloritic greenstone of allanite as cores within grains of epidote is thought to be due to the early depletion of the rock of rare-earth elements, after which epidote formed rather than allanite. Epidote in small veinlets in the actinolitic greenstone is late, inasmuch as the veinlets transect the metamorphic fabric.

Quartz and carbonate in the chlorite greenstone are interpreted as of sedimentary origin, though now recrystallized by metamorphism, and the distribution

pattern probably reflects that in the protolith. The association of carbonate with quartzose beds in the greenstone is taken to reflect intervals of accumulation of strictly sedimentary as opposed to partly volcanic detritus.

The sparsely disseminated grains of carbonate in the actinolitic greenstone may be relicts of sedimentary origin, or they may be metamorphic. The carbonate in masses at the border of the ultramafic body is of replacement origin, as attested by the pseudomorphism after amphibole; it was probably formed during steatization, and may mark channels of relatively easy access of CO_2 to the ultramafic body.

Ilmenite, sphene, and rutile in the greenstone have relations similar to those in the schist and are considered to have generally the same modes of origin. Sphene formed by direct reconstitution of mafic minerals rather than by alteration of earlier ilmenite is predominant, however, because ilmenite is confined to varieties of greenstone transitional into schist. Some of the sphene heavily concentrated in chlorite may have formed during alteration of amphibole to chlorite by retrogradation.

Sericite, apatite, garnet, tourmaline, pyrite, and magnetite are considered to be identical in origin with the same minerals in the schist. (See p. 154–155.)

CARBONATE ROCK GENERAL FEATURES

The carbonate rocks differ among the three localities in appearance and composition, as well as in abundance and distribution (see under "General geology," p. 110–116.) Furthermore, there is a moderately large range of variation at each locality both in composition of the carbonate and in the proportion and distribution of other minerals.

BARNES HILL

The carbonate rocks at Barnes Hill, exposed only in septa or inclusions within the ultramafic rock, range in composition from magnesite to dolomite. The carbonate rock seems to grade into chlorite-quartz rock with but minor carbonate, both along the strike and down the dip, but the complete range of intergradation is not exposed. The "typical" carbonate rock is composed essentially of carbonate and contains minor amounts of quartz, chlorite, and accessory minerals. The rock is light buff to light greenish gray on the fresh surface, and weathers dark buff to rusty brown. It is generally massive, but in many places, especially on weathered surfaces, it is indistinctly layered by thin irregular chloritic partings, suggestive of bedding.

Locally, the carbonate rock is traversed at wide intervals by ladder veins consisting of a series of nearly horizontal quartz veins 1 to 2 cm wide, about 1 mm

thick, and of undetermined but much greater length, arranged about parallel to each other from 0.5 to 1 cm apart in the manner of shelves in a tall, deep, and narrow cupboard. Thin white veins of carbonate and quartz are common but not abundant in the carbonate rock. The boundaries of the veins are irregular on a very small scale. The quartz and carbonate form an aggregate of euhedral carbonate and anhedral quartz grains about 2 to 3 mm across.

In thin section the carbonate rock consists of an interlocking mosaic of subequant grains of carbonate from 0.2 to 0.5 mm across, throughout which quartz is dispersed rather uniformly and sparsely in small irregular subequant grains from 0.05 to 0.2 mm across; chlorite occurs both dispersed in small irregular patches and in thin irregular and discontinuous subparallel layers, a few as thick as 1 mm and continuous throughout the length of a thin section. The sparse grains of carbonate within the thicker layers of chlorite are commonly rhombic in outline. In types gradational into chlorite schist, as the chlorite content increases more carbonate grains are rhombohedral, and where chlorite predominates, most of the carbonate is euhedral to subhedral. Some of the accessory minerals are in layers parallel to the chlorite, and accentuate the layering; others are for the most part evenly disseminated throughout the rock. At the borders of septa the carbonate rock commonly contains moderate amounts of talc. The talc occurs as irregular masses that invade the carbonate rock along grain boundaries, and as tiny shreds included chiefly in the carbonate. In places the patches of talc contain tiny islands of quartz or of calcite in optical continuity with each other and with bordering large grains of quartz or calcite. Included shreds of talc are diversely oriented in quartz, but are generally arranged parallel to the cleavage in carbonate. In many carbonate grains the inclusions of talc are concentrated at the centers.

WATERBURY MINE

Carbonate rock is exposed at only one place at the Waterbury mine locality. It is dolomite, and contains various proportions of tremolite. Next to the schist, into which it grades abruptly, the carbonate rock contains a relatively small proportion of tremolite. Near the steatite, the tremolite content increases to 100 percent of the rock. The rock is fine grained, massive, and light to medium greenish gray. The carbonate forms an interlocking mosaic of subequant to slightly elongate grains about 0.5 mm across. Tremolite is dispersed throughout the rock as diversely oriented, prismatic crystals as much as 3 or 4 mm long, many of them irregularly embayed by carbonate.

MAD RIVER

The carbonate rocks at Mad River farthest from the borders of the ultramafic body or at the centers of the thicker septa consist of massive layers from about $\frac{1}{2}$ to 4 inches thick and composed almost entirely of carbonate, that alternate with schistose chlorite layers that range in thickness from a thin film to as much as one-half inch. Except for one thin bed of limestone, the carbonate rock is dolomite. The carbonate layers are medium to dark bluish gray, and the chlorite layers are moderate grayish green. Individual layers can commonly be traced across the length of an outcrop. They are very closely parallel to the boundaries of the carbonate rock.

Under the microscope the massive carbonate layers consist of an interlocking mosaic of carbonate grains 0.2 to 1 mm across, throughout which are dispersed small amounts of magnetite, amphibole, and chlorite and occasional grains of quartz, apatite, and pyrite. The carbonate grains are commonly somewhat elongate parallel to the layering. The chlorite layers are composed almost entirely of irregular chlorite flakes arranged parallel to the layering. Small grains of carbonate occur sparsely in the chlorite layers, and commonly are rhombohedral in form. Pyrite, magnetite, quartz, and apatite occur very sparsely in the chlorite layers. Locally, the carbonate rock is traversed by narrow widely spaced irregular shear zones. In one section of calcite marble in which actinolite is abundant, the actinolite is altered to chlorite bordering the shear zones, and the chlorite contains abundant small octahedra of magnetite. The calcite, on the other hand, contains only a very small amount of magnetite.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

CARBONATE

The carbonate shows similar textural features and paragenetic relations at all three localities. Where carbonate predominates it has a mosaic texture; in varieties in which chlorite predominates and the carbonate grains do not have mutual boundaries, the carbonate commonly forms rhombohedral crystals. Most of the carbonate shows considerable glide twinning, and in places many of the twin lamellae are bent.

Most of the carbonate at Barnes Hill is magnesite, but a specimen from a septum of carbonate rock in drill hole B-DDH-3-67 (see table 1) consists of dolomite. The index of refraction of the magnesite ranges from $\omega=1.700$ to 1.718, indicating a range in composition from MgCO_3 to about $(\text{Mg}_{.90}\text{Fe}^{+2}_{.10})\text{CO}_3$, if the variation in index is due solely to variation in Fe^{+2} content. The index of the dolomite is $\omega=1.679$, indicating nearly pure dolomite $(\text{Ca}_{.50}\text{Mg}_{.50})\text{CO}_3$.

The carbonate at Waterbury mine and Mad River localities is almost entirely dolomite except for one thin bed of calcite marble at the Mad River locality. The index of the dolomite ranges from $\omega=1.682$ to 1.689 , indicating a range in composition approximately from $(\text{Ca}_{.50}\text{Mg}_{.49}\text{Fe}^{+2}_{.01})\text{CO}_3$ to $(\text{Ca}_{.50}\text{Mg}_{.45}\text{Fe}^{+2}_{.05})\text{CO}_3$. The specimen of calcite marble has an index of $\omega=1.660$, that of nearly pure calcite. A chemical analysis of carbonate rock from Mad River locality (sample MR-3, tabulation 30) is given in table 3. A calculated mode for the analysis is shown in table 53, upon the basis of which the carbonate formula is calculated to be about $(\text{Ca}_{.52}\text{Mg}_{.42}\text{Fe}^{+2}_{.06})\text{CO}_3$.

AMPHIBOLE

Amphibole is a persistent constituent of most of the carbonate rock except at Barnes Hill, where it is entirely absent. At the Mad River and Waterbury mine localities, amphibole is commonly a major constituent. It forms small euhedral and subhedral prismatic crystals that are locally much embayed by carbonate, and in places the amphibole is so interpenetrated with carbonate that it has a poikiloblastic texture. Commonly amphibole crystals are distributed irregularly throughout the carbonate in diverse orientations, but in places it is concentrated in layers in which the crystals are approximately parallel.

The amphibole is uniformly nonpleochroic. Indices of refraction vary somewhat but are rather uniform at each locality. Optical data are summarized in table 2B. These data indicate that the amphibole is non-aluminous, of the tremolite-actinolite series. The approximate composition (Foslie, 1945, fig. 1, p. 79) of the material at Waterbury ($\gamma=1.643$) is $\text{Ca}_2(\text{Mg}_{4.3}\text{Fe}^{+2}_{.7})\text{Si}_8\text{O}_{22}(\text{OH})_2$. Most of the amphibole at Mad River is close to tremolite in composition, ranging approximately from pure tremolite ($\gamma=1.628$) to $\text{Ca}_2(\text{Mg}_{4.7}\text{Fe}^{+2}_{.3})\text{Si}_8\text{O}_{22}(\text{OH})_2$ ($\gamma=1.634$). The amphibole in the calcite marble ($\gamma=1.659$) is a high-iron actinolite with the approximate composition $\text{Ca}_2(\text{Mg}_{2.6}\text{Fe}^{+2}_{2.4})\text{Si}_8\text{O}_{22}(\text{OH})_2$.

CHLORITE

Chlorite is a persistent constituent of the carbonate rocks, both as the major component of the chlorite layers and as scattered shreds and small patches in the carbonate layers. The chlorite occurs as irregular flakes and shreds 0.2 to 0.6 mm long, diversely oriented in the carbonate layers, about parallel to the layering in the chlorite layers. In the more highly chloritic carbonate rocks, shreds of chlorite form abundant inclusions in both carbonate and quartz.

Most of the chlorite is similar in optical properties, which are summarized in table 2A. Interference colors are predominantly abnormal rich dusky brown

to normal moderate gray; in several thin sections the chlorite shows both abnormal brown and abnormal blue. Indices are mostly near $\beta=1.605$, but in chlorite showing normal gray interference colors they are as low as $\beta=1.594$. In sections that contain both abnormal-brown and abnormal-blue chlorite intimately intergrown, the two types show no detectable difference in indices. Chlorite with normal gray or abnormal brown interference colors shows negative elongation and positive optic sign. That with abnormal blue interference colors show positive elongation and negative optic sign. The optic angle, $2V$, where measurable, is small to moderate. The intermixed abnormal-brown and abnormal-blue chlorite appears to be nearly isotropic, and a satisfactory interference figure can almost never be obtained. Pleochroic halos in the chlorite generally occur around grains of zircon. The chlorite in the halos always shows abnormal blue interference colors, positive elongation, and higher indices than the host chlorite.

The composition of the chlorite, as deduced from optical properties, is chiefly about $(\text{Mg}_{3.3}\text{Fe}^{+2}_{1.6})\text{Al}_{1.1}(\text{Al}_{1.1}\text{Si}_{2.9})\text{O}_{10}(\text{OH})_8$ corresponding to chlorite of index $\beta=1.605$. The chlorite in the calcite marble, with index of $\beta=1.627$, is inferred to have a composition of about $(\text{Mg}_{2.2}\text{Fe}^{+2}_{2.6})\text{Al}_{1.2}(\text{Al}_{1.2}\text{Si}_{2.8})\text{O}_{10}(\text{OH})_8$. The intermixed abnormal-blue and abnormal-brown chlorite is inferred to have a composition such that it lies at the border between chlorite of positive and negative optic sign, hence very slight differences in composition between flakes result in differences in optic sign, sign of elongation, and interference colors.

OTHER MINERALS

Magnetite is disseminated unevenly throughout both the carbonate and the chlorite in much of the carbonate rock at Barnes Hill and Mad River localities. In the calcite marble at the Mad River locality, little magnetite occurs in the carbonate and actinolite, but it is heavily concentrated in the chlorite along shears. Most of the larger grains of magnetite are octahedral; the smaller grains are commonly anhedral.

Rutile is common in the carbonate rock only at Barnes Hill, where it forms as much as 5 percent of the rock. It occurs both in the carbonate and in chlorite layers, commonly more abundantly in the chlorite. Some is distributed haphazardly, but most is in streaks and runs parallel to the layering. The rutile is deep brownish yellow and occurs principally as tiny prismatic needles about 0.004 mm thick and 0.01 mm long and as oval grains as much as 0.02 by 0.03 mm; in a few places the needles form radial clusters.

Quartz occurs principally as sparsely scattered small, irregular grains. In highly chloritic varieties of car-

bonate rock the quartz commonly contains abundant inclusions of chlorite and, near the borders of septa of carbonate rock in ultramafic rock, inclusions of talc. Quartz in the ladder veins forms mosaic aggregates, and in the quartz-carbonate veins it forms anhedral grains. The quartz in general has uniform extinction and rarely shows abnormal biaxialism.

Albite occurs very rarely in the carbonate rock as small isolated grains, commonly simply twinned. Indices of refraction measured against Canada balsam indicate a composition near pure albite.

Relatively abundant apatite was noted in only one thin section of carbonate rock, from the Mad River locality, but sparsely scattered grains would be very difficult to detect routinely in carbonate rock. The apatite occurs as slightly irregular oval grains from 0.2 to 1 mm across, and is scattered rather uniformly throughout the carbonate, which commonly shows euhedral outline against the apatite. Optically, the apatite is identical with that in the schist, with very low birefringence and uniaxial (optically negative) figure. Indices were not determined.

Zircon was recognized in one thin section of carbonate rock from Barnes Hill, where it occurs in the chloritic layers as sparsely scattered grains from 0.002 to 0.02 mm in diameter; some of the larger grains are subhedral and in cross section show the form of rounded tetragonal prisms. Each grain of zircon is characteristically surrounded by a halo of pleochroic chlorite with positive elongation and abnormal blue interference colors.

Sericite occurs sparsely in one thin section of carbonate rock from Barnes Hill as tiny lath-shaped flakes disseminated through the carbonate.

PETROGENESIS

The intergradation between carbonate rock and schist, the small-scale interlamination of chloritic layers in the carbonate rock, the presence of sparsely disseminated grains of quartz, and of detrital grains of zircon and the occurrence in a few places of beds of calcitic marble within the predominantly dolomitic beds, point to a sedimentary origin for the parent carbonate rock. Most of the minerals have been completely recrystallized during metamorphism, and some new minerals were formed, but a few retain their detrital features.

Calcite, dolomite, and quartz are stable relicts from the sedimentary parent rock, though the composition of some of the ferroan and magnesian carbonate may have changed slightly during metamorphism, with separation of magnetite, as discussed below in connection with figure 15. Both carbonate and quartz have been extensively recrystallized, and twin lamellae in the carbonate indicate considerable deformation. Mag-

nesite in septa of carbonate rock, as at Barnes Hill, is inferred to have formed by metasomatic replacement of sedimentary carbonate rock, probably dolomite.

Chlorite and amphibole are of metamorphic origin, formed chiefly during progressive metamorphism in argillaceous carbonate beds of suitable composition. Chlorite bordering tiny shear zones that transect actinolite layers, particularly prominent in the calcite marble (see p. 61) has formed by alteration of actinolite, probably as the result of the ingress of material, either by mechanical movement of solutions along the shear zones, or by a diffusion through the solutions, during the stage of falling temperature following the peak of metamorphic intensity. The high iron content of such chlorite in the calcite marble, shown by the higher indices, reflects the high iron content of the actinolite from which the chlorite was derived.

A metamorphic origin for the disseminated magnetite is suggested by its rather common euhedral outline, but a diagenetic origin is possible. Figure 15 illustrates how the magnetite may have formed during metamorphism by release of iron oxide through partial dissociation of an originally more ferroan carbonate. The magnetite in the vein chlorite appears to be one of the products formed by the alteration of actinolite to chlorite.

The euhedral form of much of the rutile indicates a metamorphic origin; the layered distribution and association with chlorite layers suggests derivation from fine titaniferous sediments. Some of the larger oval grains may be of detrital origin. The tiny irregular grains of zircon in chlorite may be of metamorphic

FIGURE 15.—Schematic diagram to illustrate possible explanation of how progressive metamorphism of a slightly ferroan magnesian carbonate rock (limestone or dolomite) produces a less ferroan carbonate and magnetite. For simplicity, the Ca component is ignored. Carbonate rock of Mg:Fe ratio and temperature indicated by A, upon being raised to temperature B, dissociates into BD amount of a less ferroan carbonate C, and CB amount of $[(Fe, Mg)O + CO_2]$ of composition D. Oxidation of the $(Fe, Mg) O$ results in the formation of magnetite, probably simultaneously with decomposition of the carbonate. Dissociation temperatures of magnesite and siderite (373°C and 282°C, respectively, at 1 atmosphere pressure) are from Kracek (1942, p. 163), and are intended only to show the slope of the curve.

origin, but the rounded prismatic crystals are undoubtedly of detrital origin. Some of the apatite may be detrital, but the fact that in many places carbonate shows euhedral outline against apatite indicates a metamorphic origin for the apatite; the distribution of that apatite probably reflects the distribution of phosphatic material of organic origin in the parent sedimentary rock. Other minerals probably are of the same origin as in the schist.

ALBITE PORPHYROBLAST ROCK

Albite porphyroblast rock in typical exposures contains a high proportion of albite and is strikingly porphyroblastic in texture for a width of 3 to 5 inches; schistosity is largely obliterated, and locally the grains of albite are so crowded that a mosaic texture results. The porphyroblast rock grades within a distance of 1 or 2 inches into blackwall on one side and schist on the other. A tendency toward segregation into layers parallel to the schistosity commonly imparts a gneissic appearance to the rock. As in the albitic schist, porphyroblasts of albite interrupt and cut off slip cleavage and spaced schistosity, and also bulge them out slightly in a few places. Identical relationships hold for pseudomorphs of chlorite after albite (see fig. 16).

Analyses of albite porphyroblast rock are given in table 3, rock analyses 24 and 27.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

Most of the mineralogic, textural, and paragenetic features of the albite porphyroblast rock are inherited from the schist or imposed from the blackwall, and are fully described in the sections on the petrography of these rock types (p. 49-55; 65-71). Only those features peculiar to the albite gneiss will be described here.

ALBITE

Except for its much greater abundance, the albite in the porphyroblastic rock is similar to that in the schist (p. 50); very little is granoblastic. The concentration of albite is greatest at the outer border of the blackwall; it decreases abruptly toward the blackwall, somewhat less abruptly and more irregularly toward the schist. In the albite-rich zone the crystals are larger than in the schist, the clear rims are proportionately much wider, and more crystals lack cores.

In the transition zone into blackwall, albite crystals can be observed in all stages of replacement by chlorite, ranging from slightly embayed grains to tiny remnants. Surrounding many of the remnants, over an area approximately as large as the albite porphyroblasts in the schist, the chlorite is of a distinctly finer texture than elsewhere and is in all instances diversely oriented;

many similar patches contain no albite. Figure 16 shows aggregate pseudomorphs of chlorite after albite.

All the albite has an index of refraction of $\beta=1.532$; $2V=70^\circ$; optic sign (+). Extinction is nearly everywhere uniform. Polysynthetic twinning is more common in the albite of the gneiss, particularly in the clear rims of the porphyroblasts, than in the albite of the albitic schist, although untwinned or simply twinned crystals are predominant. The optical data indicate that the material is nearly pure albite.

CHLORITE

Chlorite is a major component of all the albite porphyroblast rock. It ranges in textural relations, optical properties, and composition from those of chlorite in the blackwall to those of chlorite in the schist. Each of the variations is gradational and takes place, in general, within the side toward the blackwall zone. Optical properties of the chlorite are summarized in table 2A. For discussion of the range of compositions encompassed see under "chlorite" in the sections on schist and blackwall (p. 51; 61-69).

ACCESSORY MINERALS

All the accessory minerals common in the schist and blackwall are present in the albite porphyroblast rock and show generally similar relations.

PETROGENESIS

Petrogenic features in the albite porphyroblast rock embrace those both of the schist and the blackwall. Only those features pertinent to the origin of the porphyroblast rock will be discussed here. For further details see the sections "Schist" (p. 53-55), and "Blackwall chlorite rock" (p. 70-71).

The albite of the porphyroblast rock is of the same general age and origin as that in the albitic schist, but it has been redistributed, recrystallized, and concentrated at the outer margin of the blackwall zone during formation of the blackwall. Critical textural and paragenetic features are the replacement relation of the blackwall chlorite to the albite, the pseudomorphs of chlorite after albite, and the greater size of clear rims of albite and the greater abundance of clear porphyroblasts of albite in the porphyroblast rock than in the schist. These features indicate that albite porphyroblasts existed in the rock prior to formation of the blackwall, or at least before formation of the blackwall was far advanced, and that the reconcentration of albite porphyroblasts in the albite zone was, in effect, the result of "flushing out" of albite by the advancing wave of chloritization that formed the blackwall.

The chlorite corresponds in origin in part with that of the schist, and in part with that of the blackwall.

Ilmenite, rutile, and sphene also show relations similar to those exhibited both by the schist and the blackwall. All these features confirm the conclusion that the origin of the albite porphyroblast rock is tied in with that of the blackwall.

ROCKS OF THE BLACKWALL ZONE

GENERAL FEATURES

Rocks in the blackwall zone comprise chlorite rock (true blackwall), tremolite rock, and talcose carbonate rock. Of these, chlorite rock predominates greatly at each of the three localities. Tremolite rock is prominent locally at the Mad River locality and occurs rarely at the Waterbury mine locality. Talcose carbonate rock occurs only at Barnes Hill at the borders of septa of carbonate rock. Representative modes of each are given in table 1.

BLACKWALL CHLORITE ROCK

The blackwall, in its typical development, consists almost entirely of chlorite and minor amounts of a few accessory minerals. Chemical analyses of several specimens of blackwall are given in table 3, rock analyses 19, 25, 26, 28, 32. The rock is dark greenish gray, fine grained, and generally has a poor to good schistosity. Normal to the schistosity the rock breaks with a hackly fracture. In a few places the blackwall has no discernible schistosity.

In thin section, the blackwall consists of a lepidoblastic aggregate of chlorite throughout which occur small amounts of accessory minerals of granular habit. The textural relations of both the lepidoblastic and the granular minerals vary considerably. In much of the blackwall, the chlorite flakes, laths, and blades are uniformly about 0.1 to 0.5 mm long, but in many places they range from as little as 0.02 mm to as much as 1 mm in length. Generally, in such instances, the coarser and finer flakes are segregated to a fair degree into layers of rather uniform grain size. Such layering is commonly accentuated by the distribution of a large part of the accessory minerals parallel to the layers in patterns that range from sharply delimited thin laminae to broad and rather vaguely layered concentrations. The concentration of accessory minerals into layers is, in general, most pronounced where the rock has a good schistosity and a fair textural layering in the chlorite. Where all the chlorite is diversely oriented, the accessory minerals rarely show pronounced segregation. Even where segregation is most pronounced, a small proportion of accessory minerals is disseminated.

The orientation of the chlorite varies from marked dimensional parallelism to apparently random orientation. The predominant relationship is a spaced schistosity, whereby the rock is traversed by narrow parallel

shears from 0.02 to 0.1 mm in width and spaced generally 0.01 to 0.1 mm apart. In a few thin sections the shears are uniformly only 0.002 to 0.005 mm apart, and in some they are irregularly spaced as much as 1 mm apart. Within the shears chlorite flakes are arranged parallel to the shears; between the shears the flakes are diversely oriented. Figures 4 and 5 illustrate spaced schistosity in blackwall. In a few specimens of slightly talcose blackwall, fragments that appear to have been formerly single flakes of talc are offset along shears by distances of 0.02 to 0.05 mm, but such relations are very rare. Continuous schistosity is less common. In specimens of blackwall that contain layers of coarse and of fine chlorite, the chlorite in the fine layers is commonly oriented about parallel to the layering whereas the chlorite in the coarse layers is diversely oriented. A few specimens of blackwall contain only diversely oriented chlorite. Rarely are either the spaced schistosity or the continuous schistosity crenulated, but in a few places each is crenulated locally and an incipient slip cleavage has formed about parallel to the axial planes of the crinkles and about normal to the schistosity. In one thin section from Barnes Hill the textural layering in the chlorite (accentuated by the distribution of accessory minerals) has the pattern of a tightly compressed fold 5 mm in amplitude. Within the fold the chlorite flakes are about parallel to the axial plane of the fold. Elsewhere, the chlorite is parallel to the layering.

In many places where blackwall is bordered by albite porphyroblast rock, specimens from the outer part of the blackwall show, in thin section, numerous oval spots from 1 to 2 mm in diameter consisting of fine diversely oriented flakes of chlorite in a matrix of coarser chlorite that commonly has either a spaced or a continuous schistosity. The distribution of these spots is identical with that of the albite in the porphyroblastic rock, and the individual spots commonly transect the schistosity and are nowhere transected by it.

TREMOLITE ROCK

Tremolite rock of the blackwall zone has the gross textural features of the adjacent carbonate rock. At the Mad River locality the tremolite rock consists of layers as much as an inch thick of felted tremolite and sparsely disseminated chlorite, alternating with layers of schistose chlorite commonly less than one-fourth inch thick. The tremolite rock grades irregularly into carbonate rock; the persistence of tremolite in varying amounts throughout most of the carbonate rock makes the transition difficult to determine. The transition from tremolite rock to steatite is abrupt, commonly taking place in less than an inch, although small amounts of tremolite may locally persist in the steatite for as much as a foot from the tremolite rock. The

relations at the Waterbury mine locality are similar, except that interlayering with chlorite is absent or very faint and irregular.

TALCOSE CARBONATE ROCK

Talcosed carbonate rock in the blackwall zone is exposed only at Barnes Hill in septa of carbonate rock in talc-carbonate rock and steatite. Relations are not known because of poor exposure, but the talc appears to occur in moderate proportions at the borders of the septa throughout a zone that varies in thickness from as little as 3 inches to somewhat more than a foot. The transition into carbonate rock is gradual, but that into steatite or talc-carbonate rock is abrupt. The mineralogic composition is similar to that of the carbonate rock except for the presence of as much as 15 or 20 percent of talc and a proportionate reduction in the amount of carbonate, quartz, and chlorite. Modes of talcosed carbonate rock are given in table 1D.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

CHLORITE

Chlorite is commonly the sole major constituent of the true blackwall, and except in the zone of gradation into schist or steatite always constitutes about 90 per-

cent of the rock. The chlorite occurs in a variety of habits, but predominantly as irregular flakes and shreds. Other, less common habits are lathlike and irregularly oval grains. The chlorite shows a variety of textural relations that have been described above under the section on "General Features." In a few places within the ultramafic body, small, slablike inclusions of chlorite rock that appear to be essentially of the same origin as blackwall are made up of randomly oriented books of chlorite with hexagonal cross section about 0.15 mm in diameter and as much as 0.4 mm long. The books are commonly curved and recurved so that they present a vermiform appearance.

In the transition zone between blackwall and schist—or albite porphyroblast rock—the chlorite of the blackwall everywhere bears an unmistakable replacement relationship to all the minerals of the schist. It invades them irregularly, transects those that were formerly single grains, and in some instances forms aggregate pseudomorphs after the replaced minerals. Identifiable pseudomorphs are after albite, amphibole, and probably sphene. Those after amphibole and sphene are relatively rare. The aggregate pseudomorphs after albite are common in the outer portion of the blackwall adjacent to albite porphyroblast rock; they have been described under "albite porphyroblast rock", and are illustrated in figure 16. Other habits and textures, although not identifiable as pseudomorphic, appear to reflect in a general way the shape and distribution of the mineral that was replaced, to the extent that it appears possible in some places to distinguish layers that were formerly of contrasting mineralogic composition and texture, such as lepidoblastic and granoblastic layers.

Chlorite in the tremolite rock and talcosed carbonate rock has the same general pattern of distribution as in the carbonate rock, but is rather less abundant; in addition, some of the chlorite irregularly invades tremolite and is replaced in turn by talc near the contact with steatite.

Optical data on chlorite in the rocks of the blackwall zone are summarized in table 2A. In the chlorite rock (true blackwall) there are no significant differences in the optical properties of the chlorite among the three localities, nor does the nature of the parent rock from which the blackwall was derived affect ultimately the properties of the chlorite. All the chlorite is non-pleochroic or only faintly pleochroic in pale greens. Birefringence colors are predominantly moderate gray, but locally show faint tinges of abnormal brown. The optic angle is predominantly small, the optic sign uniformly positive, and the sign of elongation negative. Indices fall chiefly in the range between $\beta=1.597$ and 1.610, and average about 1.600. Optical properties of

FIGURE 16.—Photomicrograph of blackwall chlorite rock, showing aggregates of chlorite pseudomorphic after porphyroblasts of albite. The large elongate parallel flakes of chlorite were formed by replacement of the groundmass of an albite-porphyroblast rock. The oval areas made up of nearly round grains of chlorite showing diverse optical orientation mark the former locations of anhedral porphyroblasts of albite. The general pattern of the aggregate pseudomorphs of chlorite is identical with that of albite porphyroblasts in the adjacent albite-porphyroblast rock into which the blackwall grades. $\times 30$. Crossed nicols.

FIGURE 17.—Diagram illustrating the variation in index of refraction and of the ratio of $\text{Fe}^{2+}:\text{Mg}$ of chlorite in the blackwall. The several specimens, though from different locations, are shown in approximately correct position (marked by the symbol "x") with respect to the nearest contact (that is, either that with the steatite or with the schist). The break at the center of the blackwall zone indicates that the zone varies slightly in thickness. Specimens of schist that fall more than 2 inches outside the blackwall zone are located to the right of the "break" in the schist zone of the diagram, and their position indicated by the symbol "x" with a value for the distance from the blackwall. The shaded area represents the range in variation of most of the chlorite in the schist. Subscripts (for instance, 164B₁ and 164B₂) indicate that chlorite from different positions in the same specimen was measured.

chlorite in the tremolite rock and talcose carbonate rock do not differ significantly from those of chlorite throughout most of the carbonate rock, summarized on page 62.

Many scattered observations and several observations on suites of specimens across the blackwall zone indicate that the optical properties of the chlorite vary systematically with respect to position relative to the contacts of the zone. The changes are imperceptibly gradational, but they take place over short distances. Chlorite immediately at the contact with steatite appears generally to be of lower index than that an inch or more from the steatite, though the difference is not great. Throughout most of the blackwall zone—that is, more than about an inch from either contact—

the chlorite is rather uniformly of index of about $\beta=1.600$, though there is a suggestion of very slight uniform increase in index throughout this central zone with increasing distance from the steatite. At about one inch from the schist, the index of the chlorite of the blackwall begins to increase sharply but uniformly, and grades without break into that of the chlorite of the schist. The variation is illustrated semiquantitatively in figure 17.

The composition of the blackwall chlorite, as inferred from optical data, falls chiefly in the range between $(\text{Mg}_{3.7} \text{Fe}^{+2}_{1.1}) \text{Al}_{1.2} (\text{Al}_{1.2} \text{Si}_{2.8}) \text{O}_{10} (\text{OH})_8$, and $(\text{Mg}_{3.0} \text{Fe}^{+2}_{1.6}) \text{Al}_{1.4} (\text{Al}_{1.4} \text{Si}_{2.6}) \text{O}_{10} (\text{OH})_8$, corresponding to a range in index from $\beta=1.597$ to 1.610. The composition corresponding to $\beta=1.600$, the approximate index

of most of the blackwall chlorite, is about $(\text{Mg}_{3.5} \text{Fe}^{+2}_{1.2}) \text{Al}_{1.3} (\text{Al}_{1.3} \text{Si}_{2.7}) \text{O}_{10} (\text{OH})_8$. The composition corresponding to the extreme upper range of index, $\beta = 1.615$, is approximately $(\text{Mg}_{2.8} \text{Fe}^{+2}_{1.8}) \text{Al}_{1.4} (\text{Al}_{1.4} \text{Si}_{2.6}) \text{O}_{10} (\text{OH})_8$. Though the composition of chlorite of very low index cannot be deduced from optical properties as reliably as that of higher index, it can safely be concluded that chlorite with indices in the range of $\beta = 1.577$ to 1.584 , the extreme lower limits of chlorite in the blackwall, has a very low Fe^{+2} and Al content. The average approximate composition ($\beta = 1.580$) is probably near $(\text{Mg}_{4.7} \text{Fe}^{+2}_{0.3}) \text{Al}_1 (\text{Al}_1 \text{Si}_3) \text{O}_{10} (\text{OH})_8$.

The composition of the chlorite in the tremolite rock and the talcose carbonate rock, on the basis of optical properties, ranges chiefly from about $(\text{Mg}_{3.9} \text{Fe}^{+2}_{0.8}) \text{Al}_{1.3} (\text{Al}_{1.3} \text{Si}_{2.7}) \text{O}_{10} (\text{OH})_8$ to $(\text{Mg}_{3.4} \text{Fe}^{+2}_{1.3}) \text{Al}_{1.3} (\text{Al}_{1.3} \text{Si}_{2.7}) \text{O}_{10} (\text{OH})_8$, corresponding to the range in index of most from $\beta = 1.593$ to 1.602 . The chlorite of index $\beta = 1.584$ and which shows both blue and brown abnormal interference colors and both positive and negative elongation is deduced to have a composition near $(\text{Mg}_{4.4} \text{Fe}^{+2}_{0.6}) \text{Al}_{1.0} (\text{Al}_{1.0} \text{Si}_{3.0}) \text{O}_{10} (\text{OH})_8$. The chlorite of index $\beta = 1.590$, positive elongation, and abnormal blue interference colors is unusual because most chlorite of that index shows normal gray or slightly abnormal brown colors and negative elongation. It indicates the unreliability of the birefringence curves on figure 13, which would require a chlorite with an Al content of appreciably less than $2 (\frac{1}{2} R^{+3} \text{ less than } 1)$ for such optical properties, whereas it appears generally that the Al in the Si position of chlorite is very near to one. The composition of this anomalous optically negative chlorite of index $\beta = 1.590$ is estimated to be $(\text{Mg}_{4.0} \text{Fe}^{+2}_{1.0}) \text{Al}_{1.0} (\text{Al}_{1.0} \text{Si}_{3.0}) \text{O}_{10} (\text{OH})_8$.

No chemical analyses strictly of the chlorite mineral of the blackwall are available. However, the mineralogic composition of the rock is very simple, and minerals other than chlorite are generally present in very small amounts and are of simple composition. It is, therefore, possible to calculate rather accurately from suitable rock analyses the composition of the chlorite. Four analyses of blackwall chlorite schist were made by the Geological Survey in the course of the present investigations, and one analysis is available from Phillips and Hess (1936). These are given in table 3, rock analyses 19, 25, 26, 28, and 32. Two of the specimens analyzed (analyses 25 and 26, specimens W-DDH-11-118 and B-DDH-11-76) proved unsatisfactory for determining the composition of the chlorite; the others yielded fairly satisfactory results. This is evident in the calculations shown in tables 48 to 52. Optical and chemical data on the five specimens of blackwall chlorite are assembled in table 4.

TABLE 4.—*Formula compositions and optical properties of black-wall chlorite*

[Optical determinations based on figure 13. Calculations are compiled in tables 48-52]

BARNES HILL

Specimen: Field No., B-DDH-8-367; Lab. No., 50-2016 CW

Optical properties: $2V = 5^\circ$; optic sign (+); elong. (—); $\alpha \approx \beta = 1.596$; slightly pleochroic in pale greens; moderate-gray interference colors with abnormal brownish-yellow tinge

Formula composition:

From optics:

From chemical analysis:

Formula values¹: $n = 5.97$; $p = 1.29$; $2(n-2) = 7.94$

Specimen: Field No., B-DDH-11-76; Lab. No. 50-2014 CW

Optical properties: $2V$ small; optic sign (+); elong. (—); $\alpha \approx \beta = 1.599$; $\gamma = 1.605$; nonpleochroic; moderate-gray interference colors.

Formula composition:

From optics:

From chemical analysis:

Formula values¹: $n = 5.05$; $p = .81$; $2(n-2) = 6.10$

WATERBURY MINE

Specimen: Field No., W-38; Lab. No., 50-2009 CDSW

Optical properties: $2V = 15^\circ$; optic sign (+); elong. (—); $\alpha \approx \beta = 1.615$; $\gamma = 1.619$; moderately pleochroic in shades of yellow green; abnormal yellowish-brown interference colors.

Formula composition:

From optics:

From chemical analysis:

Formula values¹: $n = 5.86$; $p = 1.25$; $2(n-2) = 7.72$

Specimen: Field No., W-DDH-11-118; Lab. No., 50-2013 CW

Optical properties: $2V = 20^\circ$; optic sign (+); elong. (—); $\alpha \approx \beta = 1.609$; $\gamma = 1.614$; faintly pleochroic in pale greens; moderate gray interference colors with slight abnormal brown tinge.

Formula composition:

From optics:

From chemical analysis²:

Formula values¹: $n = 4.68$; $p = 0.44$; $2(n-2) = 5.36$

MAD RIVER

Specimen: Field No., Vt. 118³

Optical properties: $\beta = 1.591$

Formula composition:

From optics:

From chemical analysis:

Formula values¹: $n = 6.01$; $p = 0.98$; $2(n-2) = 8.02$

¹ The symbols n and p are used as in Berman (1937, p.378). $2(n-2)$ represents the theoretical value of OH.

² Unsatisfactory; formula based on optics is better. See text discussion, p. 68.

³ From analysis and optical data in Phillips and Hess (1936). The β index of refraction is almost identical with that of chlorite in specimen MR-23, table 2A.

Chlorites B-DDH-8-367, Vt. 118, and W-38 show reasonably close agreement in the formula compositions as determined from optical data and from chemical analysis, particularly in view of the several possible causes of discrepancy inherent in figure 13 and in calculation from rock analyses. Furthermore, all three of the formulas based on chemical analyses approach fairly close the ideal chlorite formula, and values of n approach satisfactorily the ideal value of 6 that Berman lists for true chlorite, and the p values fall well within the range shown in Berman's tabulation (1937, p. 379, fig. 5). A feature of interest in specimen Vt. 118 is that the calculated formula composition agrees somewhat better with the ideal chlorite formula if Na and K are considered to enter into the composition of the chlorite than if they are computed to be in albite and sericite. Such chemical evidence alone is only speculative, but it suggests the possibility that part of the substitution of Al for Si is compensated for by addition of Na and K. In table 52, the formula composition of chlorite Vt. 118 is calculated both with and without Na and K, for the sake of comparison.

Chlorites B-DDH-11-76 and W-DDH-11-118 do not show good agreement between formulas based upon optical data and upon chemical analyses, nor do the formulas based upon analyses approach closely the ideal chlorite formula. Thin sections adjoining the specimens submitted for analysis showed only sphene and epidote as appreciable contaminants of the chlorite, but microscopic examination of the powdered material prepared for analysis disclosed the presence of appreciable actinolite in both B-DDH-11-76 and W-DDH-11-118. The variation between the analyzed samples and the thin sections appears to be too great to permit satisfactory calculation of the chlorite formula from the rock analyses, for these specimens; the chlorite formulas determined from optical properties are better.

ILMENITE, RUTILE, AND SPHENE

The proportions and relationships of the titanium minerals ilmenite, sphene, and rutile differ conspicuously in different parts of the blackwall, and the general pattern of the variations, though in places obscure and incomplete, illustrates an orderly progressive alteration: ilmenite→rutile→sphene. Only ilmenite and sphene were observed in the tremolite rock, and only in one specimen; the relations there are consistent with those in the blackwall. None of the titanium minerals was observed in the talcose carbonate rock.

Ilmenite is sparse or absent throughout most of the blackwall, but near the outer border of the zone it is common, and locally abundant; there it generally is the chief or sole titanium mineral of the three and forms small laths, commonly without associated sphene or

rutile but nearly always with a coating of leucoxene. Elsewhere, ilmenite occurs, with very few exceptions, only as cores at the centers of granular aggregates of sphene or rutile.

Rutile is common in the blackwall at Barnes Hill and the Waterbury mine but only rarely constitutes more than 1 percent of the rock; none was observed at the Mad River locality. Rutile occurs both in the form of tiny prismatic crystals and in irregular oval grains made up of an aggregate of microscopic to submicroscopic grains. The rutile needles commonly form radiating clusters about tiny irregular laths of ilmenite, but they also occur as isolated needles and as clusters of needles with which no ilmenite is associated. The aggregate grains of rutile also commonly, but not everywhere, have an irregular core of ilmenite.

Sphene is persistent throughout most of the blackwall and is generally greatly predominant over both rutile and ilmenite; locally, sphene makes up more than 8 percent of the rock. Sphene occurs both as single-crystal commonly diamond-shaped grains, and as aggregates of tiny grains. The aggregate grains of sphene commonly, but not everywhere, enclose small cores of ilmenite or rutile, or both. The single crystals nowhere were observed to show such a relation.

The overall relationship between the three minerals throughout the blackwall is thus: Ilmenite enclosed by rutile enclosed by sphene. Ilmenite may occur alone, be surrounded by a rim of rutile or a rim of sphene, or be surrounded by successive rims of rutile and sphene. Rutile, either with or without a core of ilmenite, may be rimmed by sphene or may occur alone. And sphene may occur in any of the above associations or alone.

The modes of schist and blackwall in table 1 show that, in general, sphene and rutile are proportionately more abundant in the blackwall than in the schist. Adjacent specimens, such as are tabulated in table 10, particularly B-DDH-8-95 and B-DDH-8-99, B-DDH-11-76 and B-DDH-11-78, and W-4 and W-2, illustrate this general condition particularly well. Furthermore, as a general rule, sphene in the blackwall appears to form somewhat larger grains than in the schist.

MAGNETITE

Magnetite is present in small amounts locally in the blackwall, but is not common. It commonly forms scattered irregular grains 0.1 mm or less across. In a few places magnetite is abundant enough to make the rock noticeably magnetic. In a 2-foot-thick septum of chlorite schist near the eastern edge of the main ultramafic body at the Mad River locality, in the eastern wall of the northeastern quarry, magnetite forms more than 12 percent of the rock. There

the magnetite occurs as irregular grains with a layered distribution parallel to the intricately crinkled schistosity.

The magnetite is distinguished from ilmenite solely on the basis of granular habit, absence of associated leucoxene, rutile, or sphene, and magnetic properties. There is no information on its composition.

TREMOLITE

Tremolite is the major constituent of tremolite rock of the blackwall zone, but is very rare in the blackwall chlorite rock, in which it was observed in very small amounts only in two specimens, one each from the Mad River and Waterbury mine localities. None occurs at Barnes Hill, though blackwall derived from actinolitic greenstone contains relict amphibole in places.

The tremolite forms a felted mass of needles in the tremolite rock; the needles are commonly less than 1 mm long and 0.1 to 0.2 mm thick, but in places are as long as 10 mm. In the transition from tremolite rock to steatite or tremolite rock to carbonate rock, tremolite in many places occurs in contact with talc, chlorite, and carbonate without embayment or other textural evidence of replacement. Not uncommonly, however, the needles of tremolite are irregularly embayed by chlorite, talc, and carbonate, and in places where carbonate is abundant tremolite is present commonly only in very irregular corroded remnants.

Tremolite in the blackwall occurs as widely separated randomly oriented needles. They are invariably extensively embayed by chlorite, and in many places only scattered remnants of former needles and laths of tremolite remain. In places chlorite appears to have completely replaced some crystals of tremolite to form aggregate pseudomorphs within which all the chlorite is oriented perpendicular to the long dimension of the needle.

Optical properties of the tremolite in tremolite rock are summarized in table 2B; none were obtained of tremolite in the blackwall. The two specimens from the Waterbury locality have nearly identical optical properties. The indices of $\gamma=1.640$ indicate a composition of about $\text{Ca}_2(\text{Mg}_{4.4}\text{Fe}^{+2}_{0.6})\text{Si}_5\text{O}_{22}(\text{OH})_2$. Indices of material from the Mad River locality range from $\gamma=1.628$ to 1.640, indicating a corresponding range in composition from nearly pure tremolite to about $\text{Ca}_2(\text{Mg}_{4.4}\text{Fe}^{+2}_{0.6})\text{Si}_5\text{O}_{22}(\text{OH})_2$.

CARBONATE

Carbonate occurs rarely as isolated rhombs and tiny veinlets in blackwall chlorite rock; the indices indicate nearly pure CaCO_3 . Carbonate in rocks of the blackwall zone associated with sedimentary car-

bonate rock is a relict of and has the same composition as the parent carbonate rock.

OTHER MINERALS

Zircon, apatite, and epidote are common minor constituents of the blackwall, but are present only in traces. All but zircon show evidence of "digestion" and replacement by chlorite. As a general rule, such evidence increases inward from the outer border of the blackwall, and there is probably a concomitant decrease in proportion of the accessory minerals. Other minerals of the schist persist only in transition zones of the blackwall.

PETROGENESIS

The geologic relations, textural features, and paragenetic relations make it evident that the blackwall has formed by profound alteration of the schist, whose petrogenesis has been discussed above. The alteration has produced an almost monomineralic rock composed essentially of chlorite, which bears a replacement relation to almost all the minerals of the schist. Most of the textural features of the schist have been destroyed, but the orientation of the chlorite locally reflects that of minerals of the schist, and in places pseudomorphic textures, particularly of albite porphyroblasts, are preserved in the chlorite. The titanium minerals underwent a progressive alteration ilmenite $\rightarrow$ rutile $\rightarrow$ sphene during formation of the blackwall. Not all sphene, and possibly not all rutile, were derived from ilmenite; the diamond-shaped single crystals of sphene were probably present as such in the parent schist, and a very small proportion of the rutile may have been. The evidence is inconclusive as to whether the magnetite in the blackwall was inherited from the schist or was formed during formation of the blackwall; perhaps both modes of origin are represented. Apatite and epidote are unstable relicts of the schist; zircon appears to be a stable relict.

It is impossible to distinguish between tremolite formed isochemically during regional metamorphism and that formed in the blackwall zone by metasomatism; furthermore, the distribution of tremolite rock is somewhat erratic and the textural features variable. For these reasons, interpretation is difficult. In general, the commonly greater abundance of tremolite at the contact between ultramafic and carbonate rock than elsewhere makes it appear that much of the tremolite in the blackwall zone is of metasomatic origin. The textural relations among tremolite, chlorite, talc, and carbonate—described above—indicate that tremolite, carbonate, talc, and chlorite formed a stable assemblage, in places, but that elsewhere tremolite was replaced by one or more of the other miner-

als. The sequence of alteration appears to be tremolite→chlorite→talc, and tremolite→carbonate. These contrasting features suggest local differences in physical conditions or changing conditions in time.

Talcose carbonate rock retains most of the features of the parent siliceous magnesite marble. The principal modification is wrought by the presence of scattered tiny veins and irregular patches of talc disseminated rather unevenly throughout the rock. The talc has formed by replacement, as is shown by the preservation in it of relict features of the fabric of the carbonate rock.

SERPENTINITE GENERAL FEATURES

The serpentinite at the Barnes Hill, Waterbury mine, and Mad River localities is similar in appearance and mineral composition, except for a fine layering that is conspicuous on weathered surfaces of more than half the serpentinite at Barnes Hill; such layering is exposed at no other localities. In detail—on a scale such that an average hand specimen is representative of a rock type—the serpentinite is varied in aspect and ranges from dark greenish black and massive, or layered, to grayish green and highly sheared. In terms of larger units, however, the serpentinite is rather uniform; it consists of relatively unsheared polyhedral masses from an inch or less to several feet across, bounded by shells of highly sheared serpentinite from a fraction of an inch to several inches in thickness and traversed sparsely by irregular, weak, and discontinuous small shear zones. In places the massive units are uniformly a few inches to less than an inch across, and the rock consists principally of sheared serpentinite. Elsewhere, the massive units are of such large size that an entire outcrop is relatively unsheared. Where the serpentinite is layered at Barnes Hill, the layers generally extend across an entire unsheared, polyhedral unit and terminate against the bounding shells of highly sheared serpentinite. At the Mad River and Waterbury mine localities the highly sheared serpentinite surrounding relatively small massive units occurs predominantly near the margins of the ultramafic body, though such rock also occurs in irregular zones throughout the central mass of serpentinite. In the central part of the core of serpentinite the massive units are proportionately larger and may attain dimensions of several tens of feet. At Barnes Hill, numerous lenticular masses of serpentinite surrounded by talc-carbonate rock form a complex core; the smaller masses consist principally of relatively highly sheared serpentinite whereas the larger masses are highly sheared chiefly near the borders.

Most of the serpentinite is of fairly uniform composition outside of zones transitional into talc-carbonate

rock, and consists essentially of serpentine and minor amounts of magnetite, carbonate, and rare grains of chromite. In places, relatively large volumes of the highly sheared serpentinite are veined and mottled irregularly with carbonate, which constitutes as much as 15 to 25 percent of the rock and imparts a variegated appearance. When polished, this rock presents a very pleasing appearance and is highly prized for decorative purposes. It is quarried near Roxbury, and Rochester, Vt., and is sold as dimension stone under the trade name of "verde antique marble". Variegated serpentinite is more abundant at Waterbury mine than at Barnes Hill and Mad River, but at all three localities it constitutes a relatively small percentage of the total volume of serpentinite. Chemical analyses of serpentinite are given in table 3, rock analyses 15 to 17 and 20.

On fresh surfaces the massive serpentinite is dark green to dark greenish black; the sheared serpentinite is commonly dark green to grayish green. Thin flakes are lustrous translucent dusky yellow green. Layered serpentinite is not conspicuously different on fresh surfaces from massive unlayered serpentinite; different layers are marked commonly by slightly different shades of dark green, and a few thin layers are markedly lighter green. On weathered surfaces the serpentinite has a pale-bluish-green to very light greenish buff rind, and is characteristically traversed by a reticulate system of sharply cut lines. The resemblance to the weathered surface of dolomite—aptly described by an early geologist (Wing, 1867; cited in Cady, 1945, p. 550) as resembling "thread-scored beeswax"—is striking. Different layers in layered serpentinite at Barnes Hill weather to different shades of gray, green, and buff, thereby accentuating the layering and making it conspicuous on weathered surfaces.

Small veinlets of chrysotile asbestos are common but not abundant in the serpentinite at the Mad River and Barnes Hill localities, and are very rare at the Waterbury mine. Asbestos constitutes a few percent of several hand specimens, but nowhere was it observed to form as much as 1 percent of an outcrop area of several square feet. The asbestos occurs in cross-fiber veins, oblique-fiber veins, and as slip fiber consisting of short fibers in shingled arrangement. Most of the fiber is less than one-sixteenth inch long, but a few veins one-fourth inch or slightly more in thickness were observed at Mad River.

The thin tabular dikelike masses of serpentinite within the central core of serpentinite in the main ultramafic body at the Mad River locality consist of massive serpentinite nearly indistinguishable in texture and general appearance from that outside the dikes. Subtle differences in weathering characteristics and certain structural and textural features distinguish the

dikes and make them discernible. The weathered surface of the dikes commonly is smoother and of a more uniform pale green hue than that of the adjacent serpentinite, which at the borders of the dikes commonly is pale buff or indistinctly mottled in pale buff and pale green, and contains a reticulate pattern of very fine dark-buff lines. In places the serpentinite bordering the dikes is highly sheared parallel to the walls. In surface exposure the margins of the dikes are commonly marked by deep indentations that extend nearly continuously throughout the length of the dike. In several places small veins of chrysotile asbestos occur at the borders of a dike and are oriented parallel to the walls. Numerous small, parallel crevices from 1 to 3 inches apart extend across the dikes from wall to wall; these crevices have the pattern of transverse joints. The dikes occur within the massive unshaped units of serpentinite and are cut off or offset by the surrounding shells of highly sheared serpentinite.

In several places at all three localities, linear belts of serpentinite possess a rude to excellent schistosity. These schistose zones, which are as much as several hundred feet long, transect all previously described features of the serpentinite.

The serpentinite consists of a felted mass of flakes, shreds, and blades of antigorite from 0.0005 to 0.3 mm long throughout which are disseminated dustlike particles and small grains of magnetite and a few grains of chromite. Figures 18 and 19 are photomicrographs

FIGURE 18.—Photomicrograph of serpentinite composed entirely of antigorite, showing felted pattern of bladelike particles in a fine groundmass of smaller subequant particles. $\times 90$. Crossed nicols.

FIGURE 19.—Photomicrograph of serpentinite composed entirely of antigorite, showing subequant grains in a pattern resembling that of galvanized iron. $\times 90$. Crossed nicols.

illustrating textures typical of serpentinite composed wholly of antigorite. In a few thin sections that contain veins of asbestos, chrysotile occurs in the groundmass of antigorite in aggregates of parallel fibers; the aggregates have flaky, shredded, or elliptical outline. Figure 20 illustrates such occurrences of chrysotile in antigorite. Generally, particles of different size are intermixed, but in the layered serpentinite particles of fairly uniform size are segregated into layers of contrasting particle size. The selective concentration of fine magnetite within certain layers accentuates the layering; it is further accentuated in some places by the pervasive alteration of some layers to talc and the impregnation of some with carbonate. Both the schistose serpentinite from throughgoing schistose zones and the highly sheared serpentinite from the thin shells that surround polyhedral blocks of massive serpentinite are characterized by a spaced schistosity. The shears that impart the schistosity are 0.01 to 0.1 mm wide and particles of serpentine within them are aligned parallel to the shears. The regularity and spacing of the shears determine the perfection of the schistosity and the ease with which the rock splits along it. The highly sheared serpentinite around the polyhedral blocks is characterized by very closely spaced but very irregular and discontinuous spaced schistosity. The spaced schistosity in the throughgoing schistose zones in the serpentinite is more regular and more continuous.

In thin sections that show a rude schistosity, groups of closely spaced shears form pinching and swelling bands separated by bands with only a few widely spaced shears. Some of the schistose serpentinite at the Mad River locality contains a very regular spaced schistosity. The shear planes are uniformly about 0.02 to 0.1 mm apart, and between them the serpentine particles commonly show a rude planar orientation so that thin sections exhibit mass extinction and mass sign of elongation for as much as 70 percent of the serpentine. The rest is diversely oriented. Figures 6 and 7 illustrates spaced schistosity in serpentinite. In general, the better and more regular the spaced schistosity the greater the degree to which serpentine particles between shears approach uniform dimensional parallelism, but exceptions occur. In the massive serpentinite the particles of serpentine are almost entirely randomly oriented, though a few specimens exhibit weak mass extinction and mass sign of optical elongation. The massive serpentinite is traversed locally by widely and erratically spaced shears identical to those of the spaced schistosity.

In a few places at Barnes Hill and in the main ultramafic bodies at the Mad River and Waterbury mine localities, ghosts of olivine and pyroxene are preserved in the massive serpentinite. Some thin sections of serpentinite are traversed by irregular fractures and by tiny veinlets of carbonate whose general pattern is like that of the fractures. Veinlets of chrysotile asbestos are slightly offset along the fractures in some places.

The serpentine bordering most of the fractures and veinlets of carbonate contains relatively abundant disseminated flakes of talc, which sharply diminishes in abundance away from the vein or fracture.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

SERPENTINE

Serpentine constitutes about 95 to 99 percent of most of the serpentinite that has been little altered to talc, although highly sheared serpentinite that is veined with carbonate contains as little as 70 percent serpentine. Antigorite predominates greatly over chrysotile and constitutes probably more than 99 percent of the total serpentine at each locality. Chrysotile occurs chiefly in veins as asbestos, but in a few thin sections it forms part of the groundmass of the rock; in one thin section from the Mad River locality chrysotile makes up nearly 17 percent of the groundmass.

Antigorite

By far the greater part of the antigorite has a lamellar or platy habit and occurs as blades, flakes, and irregular shreds. A small proportion of antigorite has a columnar or fibrous-appearing structure; some of this fibrous-appearing antigorite is very similar in habit to chrysotile asbestos. However, all the fibrous-appearing antigorite is very brittle and is not separable into individual fibers, but breaks into small columns. Furthermore, the fibers appear in thin section to be somewhat coarser and generally less regular than those of chrysotile.

Optical data on antigorite are summarized in table 2F. Several specimens of antigorite were examined by X-ray photography and differential thermal analysis by G. T. Faust, of the U.S. Geological Survey. Preliminary reports¹¹ corroborate in all cases the optical identification of the serpentine mineral as antigorite (Faust, oral communication, 1954). The indices of antigorite are generally similar for all three localities, but there are persistent small differences. Antigorite from Barnes Hill ranges in index from $\beta \approx \gamma = 1.565$ to 1.571, and averages about 1.569; that from the Waterbury locality ranges from $\beta \approx \gamma = 1.571$ to 1.578 and averages about 1.575; that from the Mad River locality ranges from $\beta \approx \gamma = 1.565$ to 1.578 and averages about 1.571. Thus the index of antigorite from Barnes Hill ranges through an interval about as large as that for antigorite from the Waterbury mine locality, but is consistently lower. The index of antigorite from the Mad River locality extends through the combined range of that from Barnes Hill and the Waterbury mine locality; the average index is intermediate between that of the other two. In all other optical character-

FIGURE 20.—Photomicrograph of serpentinite, showing irregular veinlets of chrysotile asbestos in a groundmass composed predominantly of antigorite but containing appreciable wispy shreds of chrysotile. $\times 90$. Crossed nicols.

594234 O—62—6

¹¹ The material examined is being incorporated in a more extensive study of serpentinite by Faust, and final results are not yet available.

istics the antigorite from the three localities is nearly identical. The optic angle ($2V$) is small to moderate, the optic sign is negative, and the sign of elongation is positive. Particles oriented so that the apparent birefringence is very low exhibit anomalous blue interference colors; hence all slides have a grayish-blue tinge under crossed nicols. The overall effect varies from light bluish gray to bluish gray.

Specific variations and differences in chemical composition of the antigorite cannot be deduced from the variations and differences in optical properties; differences in both Fe^{+2} and $(\text{Al}, \text{Fe}^{+3})$ content may be involved, but the relationships are not known. Probably the proportion of Fe^{+2} has the greatest effect.

No chemical analyses of pure antigorite were obtained. However, four rock analyses of serpentinite (rock analyses 15 to 17 and 20, in table 3) were made, and because only small amounts of impurities, all of relatively simple composition, are present, it is possible to calculate from them satisfactory formula compositions for the antigorite. The principal factor that may result in inaccuracies in the calculated compositions is that the analyzed specimen may not correspond closely enough with the thin section upon which are based estimates of the amount of Al , Fe^{+3} , Mg , and

Fe^{+2} that enter into magnetite and carbonate. Failure of the computations of the percentage of talc (see appendix G) to agree with reality is also a possible source of error. Uncertainties about the composition of magnetite (see below, p. 75-76 and appendix E) are of no practical consequence. None of the possible sources of error appear to have operated significantly, judging by the approach to ideality of the calculated formulas. One sample, B-DDH-9B₁-432, contains small amounts of chrysotile, but not enough (less than 0.1 percent in thin section) to be reflected in the formula. Table 5 is a compilation of the calculated formulas. It is readily apparent that these formulas agree extremely well with the ideal. The principal difference among localities is in the lower content of Fe^{+2} , both for the mineral serpentinite and the rock serpentinite, at Barnes Hill than at the other two localities.

Chrysotile

All the chrysotile has a very fine fibrous habit; hence in thin section it presents a very smooth, silky appearance. In veins of asbestos the fibers are predominantly about perpendicular to the walls or oblique to them, but a few veins were observed in which the fibers were parallel to the wall and many times longer than the thickness of the vein. Chrysotile in the groundmass forms irregular lenticular particles in which it is generally possible, under highest magnification, to make out very fine fibers. They generally show parallel arrangement, but in some flakes swirl in irregular fashion.

Optical data on chrysotile are included in table 2F. The optical properties of chrysotile in the groundmass are identical with those of associated chrysotile asbestos. Chrysotile from Barnes Hill has indices of $\gamma = 1.557$ to 1.560 ; that from the Mad River locality has indices of $\gamma = 1.55$ to 1.552 . This relationship is the reverse of that exhibited by antigorite from the two localities. Birefringence of the chrysotile is uniformly about 0.012. Interference colors are normal straw yellow. The sign of elongation of the fibers is consistently positive, and the extinction is parallel.

Chrysotile was not chemically analyzed, and the chemical composition cannot be deduced from its optical properties. It is probable that the Mg and Fe^{+2} content are similar to that of the antigorite, and that the $(\text{Al}, \text{Fe}^{+3})$ content is lower. An analysis of chrysotile asbestos from Deloro Township, Quebec (table 3, rock analysis 33), that was carefully selected and prepared for analysis by Cooke (1937, p. 101, table IV, sample 8) gives the following formula composition, calculated on the basis of O plus (OH) equals 9 (table 32): $(\text{Mg}_{3.00}\text{Fe}^{+2}{}_{.007}\text{Ca}{}_{.007}\text{Al}{}_{.008}\text{Fe}^{+3}{}_{.03})\text{Si}_{1.98}\text{O}_{5.08}(\text{OH})_{3.92}$. This formula departs slightly from the ideal

TABLE 5.—*Formula compositions of antigorite, computed from chemical analyses of serpentinite, with measured optical properties*

[See tables 39-42]

BARNES HILL

Specimen: Field No., B-DDH-9B₁-432; Lab. No., 50-2003 CDSW

Antigorite formula (from chemical analyses of rock):

Optical properties of the antigorite:

$2V$ small; optic sign (—); $\beta \approx \gamma = 1.565$

WATERBURY MINE

Specimen: Field No., W-DDH-13-65; Lab. No., 50-2002 CDSW

Antigorite formula (from chemical analysis of rock):

Optical properties of the antigorite:

$2V$ small; optic sign (—); $\beta \approx \gamma = 1.572$

MAD RIVER

Specimen: Field No., MR-13; Lab. No., 50-2000 CW

Antigorite formula (from chemical analyses of rock):

Optical properties of the antigorite:

$2V$ 15° ; optic sign (—); $\beta \approx \gamma = 1.574$

Specimen: Field No., MR-103; Lab. No., 50-2001 CDSW

Antigorite formula (from chemical analysis of rock):

Optical properties of the antigorite:

$2V$ small; optic sign (—); $\beta \approx \gamma = 1.569$

formula; nevertheless it indicates clearly the low content of $(\text{Fe}^{+3}, \text{Al})$ and of Fe^{+2} in the chrysotile as compared with the antigorite in table 5. Comparisons between specimens from different localities should be made with caution; however, the chrysotile from the Barnes Hill, Waterbury mine, and Mad River localities, occurring as it does in the same petrogenic belt, probably shows a generally similar relation to the antigorite.

The differences in composition that cause the indices of chrysotile from Barnes Hill to be higher than those of chrysotile from Mad River cannot be definitely ascertained. The lower indices of antigorite from Barnes Hill, and chemical analyses of serpentinite from the three localities, indicate that the ultramafic body at Barnes Hill has a lower Fe^{+2} content than those at the Waterbury mine and Mad River localities; therefore it is reasonable to suppose that the higher index of the chrysotile from Barnes Hill reflects a higher Al content, rather than a higher Fe^{+2} content.

MAGNETITE AND CHROMITE

The terms magnetite, chromian magnetite, and chromite are used herein to designate varieties of spinellid distinguished on the basis of habit and optical properties. Spinellid distinctly transparent in thin section is designated as chromite; it is reddish brown in transmitted light, brownish black in reflected light, and weakly or nonmagnetic. Opaque spinellid, steely black in reflected light and, at least in part, strongly magnetic, is designated generally as magnetite. Much of the opaque spinel mineral, particularly the larger grains and the opaque rims around transparent cores of chromite, is probably not simple magnetite, but may be chromite low in Al and Mg; it will be referred to as chromian magnetite.

Magnetite and chromite are persistent constituents of the serpentinite. Magnetite, including chromian magnetite, constitutes as much as 8.6 percent of a few thin sections, but most of the serpentinite at the Barnes Hill and Mad River localities contains 3 to 4 percent, and that at the Waterbury mine locality contains consistently less than 1 percent. Chromite was noted only at the Barnes Hill and Mad River localities, but doubtless occurs also at the Waterbury mine locality. Chromite generally forms not more than 0.1 to 0.5 percent of the serpentinite and is commonly absent, but it constitutes 2.4 percent of one thin section from the Mad River locality.

The magnetite occurs as dustlike particles and small grains; larger anhedral grains as much as 1.5 mm across and rims surrounding cores of chromite are inferred to be chromian magnetite. The dustlike particles are, in general, rather uniformly disseminated throughout the rock, but in layered serpentinite they commonly

vary in abundance in different layers. The larger anhedral grains of chromian magnetite are highly fractured and the fragments separated in varying degree in what may be described as "explosion texture." Ghosts of pyroxene and olivine have small grains of magnetite aligned along relict cleavage surfaces, fractures, and grain boundaries.

The chromite occurs as transparent reddish-brown grains as much as 2 mm across, bordered by opaque rims herein designated chromian magnetite. Similar opaque rims commonly border either side of fractures in the chromite; these rims bordering fractures are commonly narrower than those at the borders of the grains, and are entirely absent along some fractures.

The composition of the magnetite and chromite cannot be determined precisely from present information. Chemical analyses of magnetic concentrates from serpentinite are given in table 3, mineral analyses 11, 12, and 13. Formula representations of the composition of the mixtures of magnetite and chromite in the magnetic concentrates are given in table 6. These formulas are not entirely satisfactory representations (see appendix E and tables 35 to 37 for computations and discussion of the limitations of the analyses), but probably characterize roughly the composition of the mixture. In concentrating the samples for analyses (appendix E, p. 148-150), proportionately more of the dustlike particles of magnetite than of the larger grains were discarded with the silicate and carbonate, so that the samples are more nearly representative of the larger grains than of the finer particles. Furthermore, because the transparent chromite is less magnetic, it is probable that proportionately more of it than of the magnetite grains was discarded in the separation. Within these limitations, the chemical data, optical features, and genetic relations probably warrant the following general conclusions: The disseminated dustlike particles and most of the smaller scattered grains of magnetite are inferred on genetic

TABLE 6.—*Formula representations of the average composition of intermixed magnetite and chromite in serpentinite*

[For details of the analyses and of the computations, see tables 35-37]

WATERBURY MINE

Specimen: Field No., W-DDH-13-35-50; Lab. No., 51-1072
MCW

BARNES HILL

Specimen: Field No., B-DDH-9B₁-432; Lab. No., 51-1073a
MCW

Specimen: Field No., B-DDH-9B₁-407; Lab. No., 51-1073b
MCW

grounds (see p. 77) to approach the simple composition of magnetite. It must contain little or no Mg. The chromite has appreciable Al as well as Cr, and appreciable Mg is suggested by the reddish-brown color. It is probable that the opaque rims of the transparent chromite, and some of the larger opaque grains, are in reality highly chromian magnetite or chromite low in Mg and Al.

CARBONATE

Carbonate typically forms about 1 percent or less of the serpentinite, although sheared serpentinite that is veined with carbonate contains as much as 15 to 25 percent carbonate. In the massive serpentinite the carbonate occurs in tiny veinlets and as scattered anhedral to subhedral grains from 0.1 to 0.5 mm, rarely as large as 2 mm, across. Both in the tiny veins and in isolated grains, much of the carbonate contains abundant inclusions of serpentine, and locally the carbonate contains inclusions of talc; in the highly sheared serpentinite veined with carbonate the inclusions are almost entirely of talc. Carbonate selectively replaces veinlets of chrysotile asbestos in a few places. Fine dustlike inclusions of magnetite are common and locally abundant in isolated grains of carbonate. Two species of carbonate are present, dolomite and magnesite. Of the two, magnesite predominates greatly, both in veins and isolated grains. No dolomite was found in the serpentinite from Barnes Hill.

Optical data on carbonate in the serpentinite are summarized in table 2C. The index of magnesite from both Barnes Hill and the Mad River locality is $\omega=1.702$ to 1.706; that from the Waterbury locality is consistently $\omega=1.718$. Dolomite at different localities is not significantly different in index and ranges from $\omega=1.684$ to 1.691. The indices indicate an approximate range in composition of the magnesite from $(\text{Mg}_{.98}\text{Fe}^{+2}_{.02})\text{CO}_3$ to $(\text{Mg}_{.90}\text{Fe}^{+2}_{.10})\text{CO}_3$, and of the dolomite from $(\text{Ca}_{.50}\text{Mg}_{.47}\text{Fe}^{+2}_{.03})\text{CO}_3$ to $(\text{Ca}_{.50}\text{Mg}_{.44}\text{Fe}^{+2}_{.06})\text{CO}_3$.

Two analyses of carbonate from serpentinite are given in table 3, mineral analyses 5 and 6. Sample W-DDH-13-146 is of highly sheared serpentinite heavily veined and mottled with carbonate; the carbonate contains considerable talc and magnetite as inclusions. Sample B-DDH-9B₁-380 is lightly veined with carbonate and contains a small amount of carbonate in disseminated grains; a small amount of serpentine, and possibly a very small amount of talc, is contained as inclusions in the carbonate. The carbonate was separated and prepared for analysis by Marie L. Lindberg in the Geological Survey laboratories. She states the following pertinent facts about the procedure followed:

[The material was] ground to pass 80-mesh, and the 200-mesh size was separated in methylene iodide, followed by a separation

in the Franz isodynamic separator, which removed more and less magnetic materials from the carbonates. There are no separate grains of impurities, though a very small amount of inclusions, both opaque and nonopaque, occurs in the carbonate samples.

The formula compositions of the two samples of carbonate in serpentinite are given in table 7, corrected for impurities. The calculations are summarized in tables 29 and 30 and are based on the procedures discussed in appendix C. The compositions deduced from optical properties agree closely with those calculated from chemical analyses. The chief differences are in the presence of a small but persistent amount of Mn which could not be distinguished from Fe^{+2} on the basis of the optical data, and in the persistent presence of very small amounts of Co.

TABLE 7.—*Formula compositions of carbonate in serpentinite, calculated from chemical analyses, with measured optical properties*

[The calculations are compiled in tables 29-30]

BARNES HILL

Specimen: B-DDH-9B₁-380; Lab. No., 50-1994-CDMSW

Carbonate formula (from chemical analysis):

Optical properties:

$$\omega = 1.702$$

WATERBURY MINE

Specimen: W-DDH-13-146; Lab. No., 50-1993-CDMSW

Carbonate formula (from chemical analysis):

Optical properties:

$$\omega = 1.713$$

PYRITE AND PYRRHOTITE

Pyrite and pyrrhotite occur sparsely as small grains and blebs in the serpentine. In a few places in the serpentinite at Waterbury, irregular veins consisting of pyrrhotite and minor amounts of pyrite are as much as one-fourth inch wide and can be traced for as much as a foot. The veins and elongate blebs are parallel to the schistosity and shear surfaces.

TALC

Talc occurs only sparsely in most of the serpentinite, chiefly as disseminated flakes in the massive serpentinite and in moderately abundant concentrations along the borders of shears and veinlets of carbonate. Not all shears and veinlets of carbonate have talc associated with them, but the relationship is common. Locally, small concentrations of talc are associated with clusters of small grains of magnetite. In a few places, talc of fibrous habit occurs in veinlets along with chrysotile asbestos, and is clearly pseudomorphic after asbestos.

The optical properties of talc in the serpentine are nearly identical with those of talc in the talc-carbonate

rock and steatite and show the same relations between localities, except that talc pseudomorphic after asbestos appears to have indices about 0.001 to 0.003 lower than that in the talc-carbonate rock and steatite. Discussion of optical properties and composition will therefore be deferred until the description of talc in the section on "Talc-carbonate rock, steatite, and talc-carbonate veins".

PETROGENESIS

No primary igneous rock is preserved in the ultramafic bodies at the three localities. The composition and intrusive relations of the ultramafic bodies, and the preservation in similar bodies elsewhere in Vermont (see Chidester, Billings, and Cady, 1951, p. 4-5) of large masses of the primary igneous rock indicate that the parent rock of the serpentinite was dunite or peridotite. The textural relations of the serpentinite have almost completely obliterated those of the parent rock except for rare pseudomorphs. The minerals are almost entirely metamorphic; only chromite, and perhaps the chromian magnetite, remain as relicts of the primary rock.

The textural relations of the antigorite are not, for the most part, diagnostic of mode of origin. The few ghosts of pyroxene and olivine, however, show that the antigorite has formed in part by alteration of those minerals and suggest that all the platy antigorite is so derived. The similarity in textural and structural features of columnar and fibrous antigorite to veins of slip- and cross-fiber chrysotile asbestos, and of fibrous antigorite of the groundmass to chrysotile of the groundmass suggests that fibrous and columnar antigorite are pseudomorphic after chrysotile. Nagy (1953, p. 596) suggests that such a relation may be common. The textural features are not susceptible of unqualified interpretation, however, and they may perhaps as well be interpreted to indicate direct formation (in veins or by alteration of olivine and pyroxene) of serpentine near antigorite in composition but of low enough alumina content to impart a crude to good fibrous form; or they may even be interpreted to represent partial alteration of antigorite to chrysotile. The structural and compositional relations between antigorite and chrysotile discussed on pages 46-48 suggest to the writer that either alteration of chrysotile to antigorite or direct formation of fibrous and columnar antigorite are the more probable alternatives. Possibly both processes have operated.

The pattern of the larger chrysotile asbestos veins indicates that they are fracture controlled. The irregular boundary between fibers and wall rock indicates some replacement. Generally matching walls of some of the larger veins indicate that in them replacement was minor and that the fibers grew in fissures, which

probably opened simultaneously with growth of fibers. Chrysotile in the groundmass appears to have formed in essentially the same manner as antigorite, probably by direct replacement of olivine and pyroxene.

The small grains and dustlike particles of magnetite appear to be products of the alteration of olivine (and pyroxene) to serpentine, and to represent the iron contained in the olivine that could not be accommodated in the replacing serpentine. The somewhat larger grains concentrated along relict cleavage surfaces of ghosts of pyroxene and in the relict fractures of ghosts of olivine are probably of the same origin. The large anhedral grains and the opaque rims of chromian magnetite may be relict primary minerals of the peridotite or altered grains of chromite, or both. The alteration may have been late magmatic or may have occurred during serpentization, or both. (See Thayer, 1956, p. 29-32 for a discussion of the alteration of chromite.)

The veins and veinlets of carbonate are largely localized along shear surfaces and fractures, but the carbonate has formed almost entirely by replacement of serpentine, in part with simultaneous formation of talc. The generally greater abundance of fine magnetite in the carbonate than in the serpentine indicates that magnetite was one of the products of the alteration of serpentine to carbonate.

Talc appears generally to have replaced the serpentine, and talc pseudomorphic after asbestos has clearly replaced chrysotile. A small part of the talc, in particular that disseminated sparsely in the massive serpentinite, may be essentially contemporaneous with or earlier than the serpentine, on genetic grounds, but is indistinguishable.

Chromite is an unstable relict inherited from the primary dunite or peridotite. Some pyrite and pyrrhotite occupies fractures in serpentinite, and are therefore later than the serpentinite, but some may be of igneous origin.

TALC-CARBONATE ROCK, STEATITE, AND TALC-CARBONATE VEINS

GENERAL FEATURES

TALC-CARBONATE ROCK

The talc-carbonate rock at the three localities varies considerably in composition and appearance on a scale for which a hand specimen is representative. On a scale as large as a few cubic feet, the talc-carbonate rock—outside of zones transitional into steatite or serpentinite—is generally uniform in composition at a given locality. Small differences are apparent between localities. Because of its variability on a small scale, and because it has been mined out in most places that are accessible at the Waterbury mine and Mad River localities, the average mineral composition is difficult to estimate. Talc and carbonate are the essential

minerals and are in roughly equal proportions. Table 1J, in which are tabulated modal analyses of talc-carbonate rock, indicates the general range in mineral composition of talc-carbonate rock from Barnes Hill and the Waterbury mine locality. Chemical analyses given in table 3 (rock analyses 21-23) are of material generally lower in content of carbonate than average for talc-carbonate rock. No samples were obtainable at the Mad River locality, but information supplied by the operators in 1945 indicates that much of the ore mined was talc-carbonate rock similar to that from the Waterbury mine. Commercial determination of solubility in HCl on approximately 500 feet of drill core from talc-carbonate rock at the Barnes Hill locality (Chidester, 1951, table 2, p. 23) indicates an approximate composition, in volume percentage, of 60 percent talc and accessories, and 40 percent carbonate. Talc-carbonate rock at the Waterbury mine and Mad River localities probably contains a slightly lower proportion of carbonate. Table 59 contains a calculated chemical analysis representative of the average talc-carbonate rock. Magnetite is a persistent minor constituent.

The talc-carbonate rock consists of a fine-grained groundmass of talc throughout which are scattered irregular anhedral to subhedral grains and aggregates of carbonate. On fresh surfaces the talc-carbonate rock ranges in color from medium gray to light gray, commonly with a faint greenish cast. The porphyroblasts of carbonate are generally lighter colored than the groundmass of talc and impart a faint mottled appearance. Weathered talc-carbonate rock is commonly rusty brown from iron stain formed by the decomposition of iron-bearing carbonate. On prominent weathered surfaces that are well drained the iron stain is commonly leached out, leaving a light-gray translucent rind of talc marked by numerous pits from which carbonate has been dissolved. Where the talc carbonate rock at Barnes Hill has altered from layered serpentinite, relict layering is visible on such leached surfaces.

Most of the talc-carbonate rock is massive, but in a few places it possesses a rude schistosity. In thin section, the massive talc-carbonate rock shows a groundmass of randomly oriented flakes, shreds, and blades of talc from 0.01 to 0.1 mm long and in places as large as 1 mm, throughout which are scattered anhedral to subhedral porphyroblasts and glomeroporphyroblasts of carbonate.

The porphyroblasts are predominantly 1 to 3 mm across; some of the glomeroporphyroblasts are as large as 3 cm. Layering in the talc-carbonate rock is due to the layered distribution of magnetite dust and grains of carbonate. The schistose talc-carbonate rock is similar in textural features to the massive kind but is traversed irregularly by a spaced schistosity formed by

closely spaced shears 0.01 to 0.05 mm wide in which flakes of talc are arranged parallel to the shears. The porphyroblasts of carbonate transect the spaced schistosity in most places, but some of the more pronounced shears cut across the grains. These shears differ from those that are transected by the carbonate in that they commonly contain chlorite. The talc-carbonate rock commonly contains veins and veinlets of carbonate; the pattern is similar to that in the serpentinite, modified locally and slightly by later veins. Some veins are concordant with the spaced schistosity, others cut across it. In places these veins cut across each other in a complicated manner. Commonly the veins are all of one species of carbonate. Where both magnesite and dolomite are present, a vein of either species may be cut by a vein of the other. Near talc-carbonate veins, small veinlets of dolomite in talc-carbonate rock generally cut all other features.

STEATITE

The steatite is uniform in composition except in the zones of transition into talc-carbonate rock and black-wall. Talc forms more than 95 percent of the rock. Small amounts of magnetite are generally present, and other minerals such as chlorite and serpentine persist locally as relicts. Modes of steatite are given in table 1I; chemical analyses are given in table 3, analyses 8, 18, 31.

The steatite is uniformly fine grained and medium gray to light greenish gray on fresh surfaces. It weathers light buff. Locally the steatite is massive, but most of it has a schistosity. The massive steatite is composed of shreds, flakes, and blades of talc predominantly about 0.01 to 0.1 mm long, but locally as large as 0.3 mm, with diverse orientations. The schistose steatite is in most places similar to the massive steatite except that it is traversed by narrow shears from 0.005 to 0.1 mm wide. In steatite with very good schistosity the shears are spaced uniformly 0.005 to 0.01 mm apart and are very regular. Figure 3 illustrates spaced schistosity in steatite. Between shears the talc is diversely oriented in most places, but locally it has a very regular dimensional orientation (a continuous schistosity) parallel to the spaced schistosity. In a few places the schistosity is crinkled, and in one place there are two sets of crinkles, one with amplitudes of about 0.2 mm and wave lengths of 3 to 5 mm, the other with amplitudes of less than 0.05 mm and wave lengths of 0.01 to 0.2 mm. In hand specimen these two sets form a coarse and a fine lineation which diverge by about 55 degrees. The coarse-crinkle lineation has an associated weak slip cleavage about parallel to the axial planes of the crinkles. No slip cleavage is associated with the fine crinkles.

TALC-CARBONATE VEINS

Talc-carbonate veins are exposed and accessible to observation only at the Waterbury mine locality, but were also encountered in drill holes at Barnes Hill. Veins identical in mineralogic composition, form, and structural relations have been noted in many other ultramafic bodies in Vermont, and those at the Barnes Hill locality are inferred to be similar.

The talc-carbonate veins are composed of dolomite and talc in roughly equal proportions, finely disseminated traces of magnetite, and small blebs of pyrite. The dolomite occurs in coarse, anhedral, white crystals from $\frac{1}{4}$ to $1\frac{1}{2}$ inches across; the talc forms fan-shaped aggregates of pale-green translucent folia as large as 1 inch across. Carbonate is predominantly near the centers of the veins and talc at the borders, but the relationship is irregular and many exceptions to the general pattern occur. Masses of carbonate from the veins are irregularly embayed and pitted, and in thin section wedge-shaped masses of talc are seen to extend into the carbonate.

The talc-carbonate veins commonly are joint controlled, though some are very irregular. Where joint control is apparent, the joints dip rather gently, though the direction of dip is variable. In a few places, where two or three sets of joints form a conjugate system, only the gently dipping set has a talc-carbonate vein along it, and the other joints are unmineralized. Not all gently dipping joints, however, have talc-carbonate veins along them.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

TALC

Optical data on talc are summarized in table 2*G*. The talc at a given locality is uniform in index except for that in talc-carbonate veins and in pseudomorphs after chrysotile asbestos, which has an index from 0.001 to 0.004 lower than the average. On the other hand, talc from Barnes Hill has a consistently lower index than that from the Waterbury mine and Mad River localities; talc from Barnes Hill averages about $\beta \approx \gamma = 1.585$, whereas that from both the Waterbury mine and Mad River localities averages about $\beta \approx \gamma = 1.591$. Only a few measurements of the α index were made; they indicate a birefringence of about 0.044 to 0.048, but the measurement of α is not as reliable as that of $\beta \approx \gamma$. The optic angle ($2V$) is consistently small, but varies from 0° to 25° . However, determinations of $2V$ are not reliable because of the probable superposition of layers of talc with c axes parallel but with the other axes randomly oriented with respect to each other. Extinction is parallel, the optic sign negative, and the sign of elongation is positive. The talc is colorless in thin section.

Two chemical analyses of nearly pure specimens of talc are given in table 3 (mineral analyses 7 and 8). One of these (J-103), from the Johnson talc mine, Johnson, Vt., is included because specimens for chemical analysis of the pure mineral were not obtainable from the Mad River and Barnes Hill localities, and the specimen from the Johnson mine represents talc from the steatite zone of a purity not obtainable at the other deposits. It is of fine-grained pale-green talc that is distributed irregularly in the steatite in a branching veinlike pattern; no contaminating minerals are visible either megascopically or in thin section, but the analysis indicates the presence of small amounts of carbonate. Specimen W-83 is from a vein of coarse talc and carbonate. The only contaminating minerals are very small amounts of dolomite and traces of pyrite.

In addition to the chemical analyses of the mineral talc, there are two analyses of steatite (analyses 18 and 31) and three analyses of talc-carbonate rocks (analyses 21, 22, and 23). The steatite commonly contains only traces of dustlike particles of magnetite as visible contaminants, but locally small amounts of colorless chlorite occur also. The talc-carbonate rock specimens contain variable amounts of carbonate and small amounts of magnetite. By subtracting the appropriate amounts of oxides for the minerals other than talc in each rock, it is possible to approximate rather closely the chemical analysis of talc in each specimen.

The calculated formula compositions of the talc in each of the two analyses of the mineral and five analyses of steatite and talc-carbonate rock are given in table 8. Tables 33 to 34, and 43 to 47 show the calculated modes and the derivation of the formula compositions. The formula compositions calculated from analyses of steatite and talc-carbonate rock are not as accurate as those based on analyses of talc, but they probably represent closely the actual composition of the talc. In each case appropriate corrections were made for recognized contaminant minerals in the sample. No corrections were made for chlorite in W-23 because there was no basis for estimating how much, if any, is present. The slightly high content of (OH) and of R^{+2} plus R^{+3} suggests the presence of a small amount of chlorite; the amount, however, must be so small that it does not significantly affect the formula composition other than to make the (Al,Fe⁺³) content appear very slightly higher than is actually the case. The very small amounts of K₂O and Na₂O in each analyses were ignored in making the calculations.

It is not known whether the Al and Fe⁺³ indicated in the analyses substitutes directly for Mg by partial replacement of 3Mg for 2(Al,Fe⁺³), or by coupled substitution for Si and Mg. Samples that contain very little alumina approach the ideal formula almost

equally well computed in either way. Samples that contain appreciable alumina approach the ideal formula more closely if Al is considered to be in coupled substitution for Si and Mg. In all the talc formulas it is assumed that the Al is in coupled substitution for Si and Mg.

TABLE 8.—*Formula compositions of talc, calculated from chemical analyses of minerals and rocks*

[The calculations are compiled in tables 33-34 and 43-47]

TALC FROM TALC-CARBONATE ROCK

Specimen: Field No., J-106; Lab. No., 50-2004 CW. **Locality:** Johnson mine

Talc formula (from chemical analyses of talc-carbonate rock):

Optical properties: $\beta \approx \gamma = 1.588$

Specimen: Field No., W-89. **Lab. No.,** 50-2005 CW. **Locality:** Waterbury mine

Talc formula (from chemical analysis of talc-carbonate rock very low in carbonate):

Optical properties: $\beta \approx \gamma = 1.593$

Specimen: Field No., R-DDH-8-160; Lab. No., 50-2006 CW. **Locality:** Rousseau prospect

Talc formula (from chemical analysis of talc-carbonate rock):

Optical properties: $\beta \approx \gamma = 1.592$

TALC FROM TALC-CARBONATE VEIN

Specimen: Field No., W-83; Lab. No., 50-1995 CDSW. **Locality:** Waterbury mine

Talc formula (from chemical analysis of vein talc):

Optical properties: $\beta \approx \gamma = 1.589$

TALC FROM VEIN STEATITE

Specimen: Field No., J-103; Lab. No., 50-1996 CDSW. **Locality:** Johnson mine

Talc formula (from chemical analysis of steatite from translucent pale green veinlike mass):

Optical properties: $\beta \approx \gamma = 1.592$

TALC FROM STEATITE

Specimen: Field No., W-23; Lab. No., 50-2007 CDSW. **Locality:** Waterbury mine

Talc formula (from chemical analysis of steatite):

Optical properties: $\beta \approx \gamma = 1.593$

Specimen: Field No., R-DDH-2-310; Lab. No., 50-2020 CW. **Locality:** Rousseau prospect

Talc formula (from chemical analysis of steatite derived from schist):

Optical properties: $\beta \approx \gamma = 1.593$

CARBONATE

Three species of carbonate occur in the various talc-bearing rocks: magnesite, dolomite, and calcite. The talc-carbonate rock contains only magnesite and dolomite except in one place at Barnes Hill where a few small veinlets of manganiferous calcite(?) were noted. (See below under discussion of carbonate of index $\omega = 1.670$.) Each species of carbonate occurs

both in porphyroblasts and in veins. Generally, only one species of carbonate occurs in a given hand specimen. Where both magnesite and dolomite occur together, one is generally in veinlets and the other in porphyroblasts. At all localities magnesite predominates markedly over dolomite in the talc-carbonate rock. Steatite outside the transition into talc-carbonate rock contains very small amounts of magnesite, calcite, and dolomite. Little information is available on their relative abundance, but all together represent a very small proportion of the steatite. The talc-carbonate veins contain only dolomite. In the total volume of talc rock at each locality, magnesite is far more abundant than dolomite, and the total amount of calcite is negligible.

Optical data on the carbonate are summarized in table 2C. The indices indicate a range in composition of the magnesite from about $(\text{Mg}_{.97}\text{Fe}^{+2}{}_{.03})\text{CO}_3$ for $\omega = 1.704$ to $(\text{Mg}_{.32}\text{Fe}^{+2}{}_{.18})\text{CO}_3$ for $\omega = 1.732$; of the dolomite from about $(\text{Ca}_{.50}\text{Mg}_{.47}\text{Fe}^{+2}{}_{.03})\text{CO}_3$ for $\omega = 1.684$ to $(\text{Ca}_{.50}\text{Mg}_{.44}\text{Fe}^{+2}{}_{.06})\text{CO}_3$ for $\omega = 1.691$. Most of the calcite is fairly pure. An index of $\omega = 1.662$ indicates a composition between $[\text{Ca}_{.98-.99}(\text{Fe}^{+2}, \text{Mn})_{.02-.01}]\text{CO}_3$ and $[\text{Ca}_{.95}\text{Mg}_{.05}]\text{CO}_3$; the specimen of index $\omega = 1.670$ may, on the basis of index alone, have a composition between $[\text{Ca}_{.95-.93}(\text{Fe}^{+2}, \text{Mn})_{.05-.07}]\text{CO}_3$ and $(\text{Ca}_{.73}\text{Mg}_{.27})\text{CO}_3$. Such high-Mg calcite (or high-Ca dolomite) as the latter formula represents is unknown; therefore the calcite is believed to contain, in addition to Ca, chiefly Mn and Fe^{+2} , rather than Mg.

In the talc-carbonate rock, each species of carbonate exhibits a small range of index at each locality. Among localities the variation is considerably larger. Thus at Barnes Hill the magnesite ranges in index from $\omega = 1.703$ to 1.710, averaging about $\omega = 1.705$, and the dolomite has an index of $\omega = 1.684$. The inferred average compositions are, respectively, $(\text{Mg}_{.97}\text{Fe}^{+2}{}_{.03})\text{CO}_3$ and $(\text{Ca}_{.50}\text{Mg}_{.47}\text{Fe}^{+2}{}_{.03})\text{CO}_3$. At the Waterbury mine locality the magnesite ranges in index from $\omega = 1.718$ to 1.732, averaging about $\omega = 1.725$, and the dolomite from $\omega = 1.688$ to 1.691, averaging about $\omega = 1.690$. The inferred average compositions are, respectively, $(\text{Mg}_{.86}\text{Fe}^{+2}{}_{.14})\text{CO}_3$ and $(\text{Ca}_{.50}\text{Mg}_{.44}\text{Fe}^{+2}{}_{.06})\text{CO}_3$. In the talc carbonate veins the carbonate exhibits almost no variation either at a given locality or among localities. The index of about $\omega = 1.687$ indicates a composition of about $(\text{Ca}_{.50}\text{Mg}_{.46}\text{Fe}^{+2}{}_{.03}\text{Mn}_{.01})\text{CO}_3$.

Four analyses of carbonate from talc-carbonate rock and two of carbonate from talc-carbonate veins are given in table 3, analyses 1-4, 9-10. Of the carbonate from talc-carbonate rock, one analysis (B-DDH-9B₁-325) is of dolomite, the others are of ferroan magnesite. An analysis from the Johnson mine, Johnson, Vt., and one from the Rousseau talc

prospect, Cambridge, Vt., are included because at each large volumes of talc-carbonate rock are particularly well exposed and representative samples of the carbonate are readily obtainable. Of carbonate from talc-carbonate veins, one analysis from the Johnson mine is included because suitable samples were not obtainable at the Barnes Hill and Mad River localities, and it was desirable to ascertain the carbonate at more than one locality. The compositions calculated from analyses (table 9) agree well with those deduced from index, but show in addition the persistent presence of small amounts of Ca (in the magnesite) and Mn and negligible traces of Co in all the carbonates.

TABLE 9.—*Formula compositions of carbonate in talc-carbonate rock and talc-carbonate veins calculated from chemical analyses, with measured indices*

[The calculations are compiled in tables 25–28 and 31–32]

CARBONATE FROM TALC-CARBONATE ROCK

Specimen: Field No., W-71; Lab. No., 50-1989 CDMSW. Locality: Waterbury mine.

Carbonate formula: $(\text{Ca}_{.008}\text{Mg}_{.817}\text{Fe}^{+2} .164\text{Mn}_{.013})\text{CO}_3$

Index of refraction: $\omega=1.732$

Specimen: Field No., B-DDH-9B₁-325; Lab. No., 50-1991 CDMSW. Locality: Barnes Hill.

Carbonate formula: $(\text{Ca}_{.483}\text{Mg}_{.505}\text{Fe}^{+2} .009\text{Mn}_{.003})\text{CO}_3$

Index of refraction: $\omega=1.684$

Specimen: Field No., J-106; Lab. No., 50-1990 CDMSW. Locality: Johnson mine.

Carbonate formula: $(\text{Ca}_{.010}\text{Mg}_{.890}\text{Fe}^{+2} .127\text{Mn}_{.003})\text{CO}_3$

Index of refraction: $\omega=1.720$

Specimen: Field No., R-DDH-8-145; Lab. No., 50-1992 CDMSW. Locality: Rousseau prospect.

Carbonate formula: $(\text{Ca}_{.008}\text{Mg}_{.866}\text{Fe}^{+2} .119\text{Mn}_{.007})\text{CO}_3$

Index of refraction: $\omega=1.719$

CARBONATE FROM TALC-CARBONATE VEINS

Specimen: Field No., W-43; Lab. No., 50-1997 CDSW. Locality: Waterbury mine.

Carbonate formula: $(\text{Ca}_{.505}\text{Mg}_{.448}\text{Fe}^{+2} .031\text{Mn}_{.011}\text{Sr}_{.001})_{.996}(\text{CO}_3)_{1.004}$

Index of refraction: $\omega=1.687$

Specimen: Field No., J-50; Lab. No., 50-1998 CDSW. Locality: Johnson mine.

Carbonate formula: $(\text{Ca}_{.503}\text{Mg}_{.459}\text{Fe}^{+2} .024\text{Mn}_{.009}\text{Sr}_{.002})_{.997}(\text{CO}_3)_{1.003}$

Index of refraction: $\omega=1.687$

The formulas of the carbonates from talc-carbonate rock come out ideally because they were calculated to ideal values in correcting for inclusions of talc and magnetite. The carbonate from talc-carbonate veins contained only magnetite inclusions, and all Fe^{+3} was assumed to be in magnetite. Therefore the correspondence between calculated and ideal formulas for carbonate from the talc-carbonate veins is a measure either of the correctness of the analysis or the correctness of the assumption that all Fe^{+3} is present in

magnetite. The departure from ideality of both formulas is small.

CHLORITE

Chlorite is rare in the talc-carbonate rock and is absent in steatite except in the transition into blackwall; none occurs in the talc-carbonate veins. Except in inclusions of chloritized schist, chlorite in the talc-carbonate rock occurs in relatively rare small shears and in a few places as narrow halos around grains of magnetite and chromite. Because it occurs so sparsely, no indices were obtained on the chlorite. All that was observed showed normal gray or slightly abnormal brown birefringence colors, very weak pleochroism, and negative elongation. The composition, therefore, probably is near that of the chlorite in the blackwall.

MAGNETITE AND CHROMITE

Magnetite is common in the talc-carbonate rock and commonly makes up from 1 to 4 percent of the rock, in which it occurs as dustlike particles and fractured grains. Fragments of fractured grains are commonly partly digested, and some grains are irregularly invaded by talc. Magnetite is persistently less than 1 percent of the steatite in which it occurs only as dustlike particles. Chromite occurs very rarely in talc-carbonate rock in the form of small transparent reddish-brown cores of large grains of opaque chromian magnetite.

GERSDORFFITE(?) AND UNIDENTIFIED OPAQUE MINERAL

Two thin sections of talc-carbonate rock from Barnes Hill (B-DDH-6-76 and B-DDH-6-84) contain abundant grains from 0.02 to 2 mm across that are composed of two minerals—one brownish black in reflected light and the other bluish gray. In some grains, the grayish-blue mineral forms a core and the black mineral a complete rim around it; in some grains the relation is reversed. In many grains the relationship is irregular, and a few grains are entirely grayish blue or brownish black.

Clemmer and Cooke (1936, p. 12) report gersdorffite in small quantities from milled talc ore from the Johnson mine, Johnson, Vt. No complete analyses of talc-carbonate rock were made, but those of serpentinite and steatite all show the presence of small amounts of arsenic. The grayish-blue mineral is therefore tentatively identified as gersdorffite (NiAsS). The brownish-black mineral has not been identified.

PETROGENESIS

The geologic and paragenetic relations indicate that talc-carbonate rock has formed by the alteration of serpentinite, and steatite by alteration of serpentinite and (to a minor extent) the rocks of the blackwall zone, chiefly blackwall chlorite schist. Talc-carbonate veins

were formed by replacement along joints in serpentinite and talc-carbonate rock. The textural pattern of the talc reflects to some extent that of the serpentine, but is commonly somewhat coarser; the porphyroblasts of carbonate dominate the textural pattern of the talc-carbonate rock. Only a few relict primary accessory minerals remain.

Textural relations of talc to other minerals are commonly ambiguous, but locally relicts of serpentine and chlorite in talc, and pseudomorphs of talc after chrysotile asbestos, show that talc has replaced those minerals. Digestion at the borders of fragments of fractured grains of magnetite, and irregular invasion of some large grains by talc, locally leaving only corroded remnants of the original grains, indicate that talc has replaced magnetite to some extent. The talc in the talc-carbonate veins is later than the rest of the talc in the ultramafic body. It has formed chiefly by replacement, though fissure filling may have played a small part.

The textural features of the carbonate, described above, indicate that the carbonate in the talc-carbonate rock and steatite has formed predominantly by replacement. In places the distribution of a small proportion of the carbonate is clearly controlled by fractures, and a small part of the carbonate in veins has probably been emplaced by fracture filling. Carbonate formed during alteration of serpentinite to talc-carbonate rock and steatite cannot be distinguished from earlier carbonate of the serpentinite, but a small amount of carbonate in the talc-carbonate rock is probably a relict of the serpentinite. The locally complicated crosscutting relationships of veins of carbonate indicate that the carbonate was formed over a considerable period, and the relict carbonate from serpentinite adds to the complexity of the relationships. No consistent age relationships between species obtain except near talc-carbonate veins, where relatively rare small veinlets of dolomite in talc-carbonate rock are younger than all other features. The carbonate in the talc-carbonate veins formed simultaneously with the talc; possibly most of it was emplaced by fracture filling, though the irregular boundaries of the veins indicate some replacement. In places the very irregular pattern of the veins indicates that origin was entirely by replacement.

Most chlorite is the relict of incomplete replacement of inclusions of schist. Chlorite in the rare halos of chlorite around grains of magnetite and chromite was formed by the interaction of aluminous magnetite or chromite and enclosing silicates; it may be a relict from the dunite or the serpentinite, or contemporaneous with the talc-carbonate rock. Chlorite in tiny shear zones in talc-carbonate rock appears, from its distribution, to be late.

The fractured grains of magnetite are considered to be relicts of the serpentinite, and the dustlike particles must also be such relicts, at least in part. Formula compositions of serpentine and talc calculated from chemical analyses (see tables 5 and 8) indicate that the range in proportion of $\text{Fe}^{+2}:\text{Mg}$ is similar for both talc and serpentine. Magnesite also can contain considerable Fe^{+2} . Therefore, the alteration of serpentinite to steatite and talc-carbonate rock should not result in the formation of magnetite, and it is concluded that the magnetite is a relict from the serpentinite. Chromite is a relict mineral that has survived both the alteration of peridotite to serpentinite and of serpentinite to talc-carbonate rock.

Gersdorffite(?), and the unidentified brownish-black mineral associated with it, are of uncertain age relations. No veins of the minerals were noted. The granular habit suggests that they are relicts from the parent dunite or peridotite from which the serpentinite, talc-carbonate rock, and steatite are derived.

MAFIC DIKES

Mafic dikes are exposed at the Waterbury mine and Mad River localities. The dike rocks are generally similar in mineralogic composition and appearance at both places, but those at the Mad River locality have a higher ratio of pyroxene to plagioclase and are hornblende. Thin dikes are very fine grained throughout, so that individual minerals and textural features are not discernible in hand specimen. Thick dikes have a fine-grained border selvage and are progressively coarser toward the center, so that in dikes as much as 5 feet thick, individual laths of plagioclase and irregular grains of pyroxene are visible to the naked eye. In a few places the dike rock contains sparse angular inclusions of rock fragments, chiefly quartz grains, 1 to 3 mm across.

The coarser phases of the dike rocks are holocrystalline, and the texture ranges from diabasic to ophitic (in the sense of Rosenbusch and Kemp; Johannsen, 1939, v. 1, p. 225). Augite—commonly slightly to highly altered to a fine mixture of green biotite, sericite or talc, and chlorite—plagioclase, magnetite, and, in some dikes, hornblende, form phenocrysts in a groundmass of fine augite and tiny subhedral grains of plagioclase. Brown biotite and calcite are common accessory minerals. The fine phases are hypocrySTALLINE. Augite, plagioclase, and magnetite are phenocrysts; the groundmass is predominantly unresolvable glass with a few tiny irregular grains of plagioclase and augite. In many places the glassy groundmass contains a latticework arrangement of tiny needles that are thought to be rutile. The rock ranges in color from dark gray to grayish black.

MINERALOGY, TEXTURAL FEATURES, AND PARAGENESIS

AUGITE

Fresh augite is 13 to 24 percent of the rock in two measured sections (see table 1); altered pyroxene makes up an additional 7 to 20 percent. The augite occurs as euhedral to subhedral phenocrysts 0.05 to 0.2 mm across in both the holocrystalline and hypocrySTALLINE phases, as abundant tiny anhedral grains in the groundmass of the holocrystalline phase, and rarely as recognizable tiny grains in the glass of the hypocrySTALLINE rock. Most of the augite is slightly to almost completely altered to a mixture of green biotite, sericite or talc, and chlorite; the original euhedral form of the augite is generally clearly discernible in the outline of the alteration corona.

The augite is nonpleochroic and is nearly colorless in thin section. The $2V$ is 47° ; optic sign (+); extinction angle $\gamma \wedge c$ about 40° ; the optic plane parallel to (010); dispersion moderate $r > v$; and the birefringence about 0.020. Indices were not obtained. Twinning is common on (100). Many of the less altered phenocrysts are zoned, and the outer rim has a slightly smaller extinction angle than the core.

PLAGIOCLASE (An₅₅)

The plagioclase content of the dike rocks is highly variable, ranging from a little more than 1 percent of identifiable grains to as much as 55 percent. In general, the content of plagioclase is inversely proportional to the amount of glassy groundmass, though a real variation in composition of the rock is indicated by the fact that holocrystalline specimens vary from diabasic, in which plagioclase dominates over pyroxene, to ophitic, in which pyroxene predominates. Plagioclase forms lathlike phenocrysts about 0.1 by 0.2 mm in both the holocrystalline and hypocrySTALLINE phases, irregular grains and tiny laths in the groundmass of the holocrystalline rock, and barely discernible grains of vague outline in the glassy groundmass of the hypocrySTALLINE rock. The $2V$ of the plagioclase is 70° , optic sign (+), and the index is $\beta = 1.560$. These properties indicate a composition of about An₅₅.

HORNBLLENDE

Hornblende is a little more than 18 percent of the rock in one dike at the Mad River locality but is absent elsewhere. Where absent, it may have been present formerly but now be completely altered to a mixture of green biotite, sericite or talc, and chlorite. The hornblende occurs chiefly in stubby lath-shaped crystals about 0.1 mm long. Locally it is intergrown with, and in a few places irregularly penetrates, augite. The hornblende is strongly pleochroic, from

pale yellow to yellowish brown. The extinction angle $\gamma \wedge c$ is about 14° .

BIOTITE, SERICITE OR TALC, AND CHLORITE

Brown biotite was noted in one thin section, where it makes up 3.3 percent of the rock. It occurs in small isolated rectangular crystals less than 0.1 mm long. Pleochroism is strong, pale yellow to brown. The $2V$ is small, optic sign (—).

Augite (and hornblende?) are generally altered to a very fine shreddy aggregate of micaceous minerals that are difficult to identify. Green biotite (moderately pleochroic, strong birefringence, small $2V$, optic sign (—), elongation (+), and strongest absorption parallel to the elongation) is probably most abundant. Chlorite of markedly vivid green color and low birefringence is a prominent constituent of most of the shreddy patches. Some material is highly birefringent, but appears to be nonpleochroic; it is probably sericite or talc.

GLASS AND RUTILE

Originally glassy material makes up as much as 38 percent of the hypocrySTALLINE phases of the dike rocks. The glass is a dirty-appearing brownish mass that cannot, for the most part, be resolved into component minerals even under highest magnification. Locally, tiny grains of plagioclase and pyroxene with irregular outlines and vague boundaries can be recognized; these grains suggest partial devitrification of the glass.

Most of the glass contains sparse to abundant needles about 0.0005 mm thick and 0.006 to 0.03 mm long, arranged in a three-dimensional rectilinear latticework. In places they radiate out from grains of magnetite. The needles are too small for positive identification, but are thought to be rutile. Tiny radiating needles of apatite are abundant in the originally glassy material of a few slides.

MAGNETITE

Magnetite is 5 to 10 percent of the rock. It occurs both as small anhedral grains 0.01 to 0.1 mm across and as dustlike particles disseminated rather uniformly throughout the rock. In the glassy groundmass, rutile(?) needles commonly radiate from larger grains of magnetite. This relationship suggests that the magnetite is titaniferous.

CARBONATE AND QUARTZ

Carbonate is as much as 3.4 percent of the rock. It occurs as anhedral grains as much as 0.2 mm across. In places carbonate appears to have partially replaced phenocrysts of augite, and a few grains appear, from the cleavage and outline, to be pseudo-

morphic after augite. The carbonate is relatively pure calcite; the index, obtained on only one specimen, is $\omega=1.668$, which indicates a composition of about $\text{Ca}_{.95}(\text{Fe}^{+2}, \text{Mg}, \text{Mn})_{.05}(\text{CO}_3)$.

Quartz was noted in one thin section, in which it forms several angular fragments as much as 1.0 mm across. The fragments consist of several irregular grains with sutured boundaries, and are highly fractured. The quartz grains are interpreted as inclusions from the schist.

PETROGENESIS

The cross-cutting relations, the chilled borders, the diabasic and ophitic textures, the relatively unaltered character of the rock, and the absence of foliation or shearing indicate that the mafic dikes are igneous rocks that were emplaced after metamorphism of the enclosing schist and after serpentization and steatitization of the ultramafic rocks. The rock specimens that contain only augite of the pyrobole minerals might well be classified as diabase, but the abundance of hornblende and biotite in some specimens, and the fact that their absence in others may be due to late alteration, indicates that all the dikes should be grouped under the classification of either camptonite or spessartite, depending upon, respectively, whether or not a genetic relationship with alkalic igneous rocks is inferred (see Johannsen, 1939b, p. 64).

PETROLOGY AND GEOCHEMISTRY

This section of the report is concerned chiefly with detailed consideration of the process of steatitization—with the mineralogic and chemical changes involved in the alteration of serpentinite and schist to talc-carbonate rock and steatite, the migration of constituents, and the genetic relationship of steatitization to other geologic events. The ultramafic rocks of the localities under consideration offer little direct evidence relative to the problems of the origin of ultramafic igneous rocks and their serpentization. Those phases of the problem of ultramafic rocks are therefore considered in somewhat less detail. Current theories are reviewed briefly, and an attempt is made to evaluate them within the framework of the evidence afforded both by the regional geology and by the geology of the ultramafic bodies.

Detailed consideration of the regional metamorphism is beyond the scope of this report. Metamorphic effects unrelated to steatitization will be considered only insofar as necessary to define the metamorphic setting of the ultramafic rocks, and to establish the relationships between regional metamorphism and steatitization and serpentization.

METAMORPHISM

Rocks at the Barnes Hill, Waterbury mine, and Mad River localities fall into three main groups on the basis

of chemical composition: alkali aluminous, mafic aluminous, and ultramafic. The common mineral assemblages of the alkali aluminous rocks are quartz-sericite, quartz-sericite-chlorite, and quartz-sericite-chlorite-biotite, any of which may contain albite and graphite. Almandite is a common constituent of the alkali aluminous rocks at the Waterbury mine locality, occurs only as relics in albite at Barnes Hill, and is absent at the Mad River locality; biotite is common at the Waterbury mine, less common at Barnes Hill, and rare at the Mad River locality.

In the mafic aluminous rocks the common assemblages are albite-chlorite-epidote and albite-actinolitic hornblende-epidote-(minor) chlorite; chlorite alone is the essential mineral in blackwall chlorite schist. The mafic aluminous rocks at Barnes Hill are actinolitic greenstones in which actinolitic hornblende predominates markedly over chlorite, whereas those at the Mad River locality generally contain little or no amphibole, though in a few places actinolitic hornblende is a major constituent; biotite is a constituent only at the Mad River locality, and only locally.

The mineral assemblages of the ultramafic rocks are serpentine alone, talc-carbonate, and talc alone. Rock consisting wholly of talc (the steatite) predominates at the borders of the ultramafic bodies; rock wholly of serpentine predominates at the centers. The steatite, serpentinite, and talc-carbonate rock are virtually identical at the different localities in their major characteristics, but at the Waterbury mine and Mad River localities clusters of radiating needles of tremolite at the margins of steatite bordered by calcareous and chloritic layers in the schist are somewhat more conspicuous and coarser than at the Barnes Hill locality.

Virtually all the rocks, including the ultramafic rocks and the individual zones of marginal alteration, contain approximately equilibrium assemblages. (The special problem of the marginal alteration zones is discussed in detail in a later section, p. 89–124). Retrograde effects are apparent at both the Waterbury mine and Barnes Hill, but are in all instances relatively slight: at the Waterbury mine much of the almandite in the chloritic layers is rimmed or irregularly altered to chlorite; at Barnes Hill the almandite is preserved only within protecting grains of albite, and presumably it has been completely altered to chlorite elsewhere.

It is clear upon inspection of modal analyses that the metamorphic effects at the Waterbury mine and Barnes Hill are very similar and are of a kind generally attributed to slightly more intense metamorphic conditions than those at the Mad River locality. It is not immediately apparent, however, whether the metamorphic effects at the Waterbury mine, where almandite occurs relatively abundantly, represent a real difference with

respect to Barnes Hill in proportion of almandite that was in the rocks at maximum intensity of metamorphism, or whether stronger retrogradation (from nearly identical conditions of maximum intensity) at Barnes Hill is responsible for the absence there of almandite outside protective grains of albite. In either case, the difference is slight. For the purposes of the present discussion it is assumed that the retrograde effects at Waterbury mine and Barnes Hill are equal and small, so that the present condition of the rocks indicates the "effective maximum" in metamorphic intensity. Thus the rocks at Waterbury mine are considered to contain almandite in equilibrium, and those at Barnes Hill to contain no almandite.

The problem of distinguishing, among the three localities, differences in metamorphic effects due to differences in metamorphic intensity from those due to differences in composition is rendered more difficult because of the small areas being compared, with a resultant limited range in composition of a given rock type, and because of their geographic separation. Rather subtle variations in Fe:Mg ratio and in proportion of Ca may account for the presence or absence of almandite or amphibole, and relatively slight increase in the proportion of Mn has a marked effect in lowering the temperature at which garnet forms (Barth, 1936, p. 785; Ramberg, 1952, p. 57-59). In the following few paragraphs the relation between mineralogy and chemical composition of the rocks will be examined in an attempt to classify the rocks at each locality in terms of grade of metamorphism, and to attribute particular differences in metamorphic effects to particular causes.

Figures 21 to 23 are based upon selected representative rocks from the three localities. On a graph for each locality are plotted for each rock the $\text{Al}-(\text{K}+\text{Na}) : \text{Al}-(\text{K}+\text{Na})+\text{Fe}^{+2}+\text{Mg}+\text{Mn}$ versus $\text{Mg}:\text{Mg}+\text{Fe}^{+2}+\text{Mn}$ ratios of coexisting critical minerals and of their sums. Tabulations of the complete mineral assemblage for each specimen are keyed to the graphs by numbers.

The general similarities of the graphs for the three localities indicate a generally similar grade of metamorphism for the three localities. The association, at all three localities, of epidote and nearly pure albite indicates a grade of metamorphism at or below the lower epidote-amphibolite facies (Ramberg, 1952, p. 51). The occurrence of garnet at the Waterbury mine locality, and of biotite and amphibole at all three localities demonstrates a minimum grade of metamorphism near the lower epidote-amphibolite facies. Therefore, the grade of metamorphism at all three localities is in the greenschist facies very near the boundary with the epidote-amphibolite facies (Ramberg, 1952, p. 139-149).

Though of the same general metamorphic grade, the three localities exhibit slight differences of mineralogical character, and of mineral composition in similar assemblages, that indicate slight differences in metamorphic conditions. Most obvious is the occurrence of locally abundant almandite at the Waterbury mine locality, of only relict almandite at Barnes Hill, and of no almandite at the Mad River locality. This difference appears to be due to real, though slight, differences in metamorphic intensity rather than to differences in composition. A high manganese content is generally considered to play the chief role in lowering the temperature at which almandite forms; available analyses (W-DDH-11-60 and B-DDH-11-78, rock analyses 14 and 27 in table 3) indicate that the Mn content of the schist at Waterbury mine is not unusually high, and that the differences among localities is small. Furthermore, the presence of relict garnet in the Barnes Hill specimen (B-DDH-11-78), in which the content of Mn is about the same as for the Waterbury specimens, demonstrates that the formation of garnet was not dependent upon a high Mn content. Incidentally, the absence of garnet in Waterbury specimen W-DDH-11-60 is clearly attributable to a high Mg:Fe⁺² ratio. (See figs. 21-23.)

Differences between the mafic aluminous rocks at Barnes Hill, where all such rocks are actinolitic greenstone with low chlorite content, and at the Mad River locality, where all are chloritic greenstone, probably are due to slight differences in metamorphic intensity between the two localities. On the other hand, the spotty occurrence of amphibole as a constituent of the chloritic greenstone at the Mad River locality suggests that the local differences there are actually due to variations in content of Ca, dependent perhaps upon the calcite or calcium-feldspar content of the parent rock.

The diagrams of figures 21 to 23 suggest that the chlorite at, respectively, Waterbury mine, Barnes Hill, and Mad River localities shows an increasingly greater capacity to accommodate Fe⁺² in solid solution with Mg, though the data are somewhat erratic. More convincingly shown is the parallel manner in which the biotite exhibits an increasing capacity for Fe⁺², particularly at the Mad River locality as compared with the other two. Both relations support the conclusion that Waterbury mine, Barnes Hill, and Mad River localities show, in that order, decreasingly intense metamorphic effects (Barth, 1936, p. 784; Ramberg, 1952, p. 59-62).

In summary, it appears that the grade of metamorphism at all three localities is in the greenschist facies very near the boundary with the epidote-amphibolite facies. Though in the same general metamorphic

FIGURE 21

FIGURE 22

FIGURE 23

FIGURES 21-23.—Diagrams showing the plot of $Al-(K+Na):Al-(K+Na)+Mg+Fe^{2+}+Mn$ versus $Mg:Mg+Fe^{2+}+Mn$ in coexisting critical phases (chlorite, biotite, almandite, and amphibole) and the sums of those phases for selected specimens from Barnes Hill, Waterbury mine, and Mad River localities. Values are based upon atomic proportions. Coordinates of the abscissa ($Mg:Mg+Fe^{2+}+Mn$) radiate from the apex. Coordinates of the ordinate ($Al-(K+Na):Al-(K+Na)+Mg+Fe^{2+}+Mn$) are horizontal. A quantity equal to $(K+Na)$ is subtracted from Al in the ordinate so that the plots of biotite and amphibole are separated from that of chlorite sufficiently to be easily legible, and so that for biotite and amphibole the Al that contributes to the plot is that in coupled substitution in fourfold and sixfold coordination. For each specimen, tie lines join the plot of the sum of the critical minerals, represented by a circle, to the plots of the individual minerals, represented by a distinctive symbol for each mineral. The ratios of the lengths of the tie lines are inversely proportional to the amount of $Al-(K+Na)+Mg+Fe^{2+}+Mn$ contributed by each phase to the sum of the phases, and may be taken to indicate very roughly the reciprocals of the relative volume proportions of the minerals plotted. (The lengths of the tie lines would be exactly inversely proportional to the equivalent molecular proportions of the minerals, and thus approximately inversely proportional to the volume proportions, only if the sum of $Al-(K+Na)+Mg+Fe^{2+}+Mn$ per equivalent mineral unit was equal for all the minerals.)

Minerals in parentheses () constitute less than 5 percent of the rock. Minerals in brackets [] are present only as armored relicts. An asterisk (*) denotes specimens chemically analyzed. Mineral plots are based upon optical data.

Material analyzed in mineral assemblage Barnes Hill B-DDH-11-76 contained amphibole, which was not present in the thin section.

Mineral abbreviations are those shown in table 22.

21. Barnes Hill mineral assemblages:

1. B-2—Ho-ab-ep-chl-(bi-sph)
2. B-4—Ho-ab-ep-(sph-chl)
3. B-11—Chl-q-bi-ab-sph-ap-(ep-carb)
4. B-12—Ho-ep-ab-(chl-sph)
5. B-15—Ser-chl-q-(gra-ilm-sph)

grade, the rocks of the three localities show slight differences in metamorphic intensity, highest at Waterbury mine followed closely by Barnes Hill, and lowest at Mad River locality. The differences are particularly noticeable because the interval represented by the difference in conditions is nearly the range of transition between the greenschist facies and the epidote-amphibolite facies, but the total range of variation is small.

The inferred equilibrium relationships among the various mineral assemblages permit the conclusion that, at each locality, the steatite, talc-carbonate rock, serpentinite, and blackwall belong to the same facies—and therefore formed under essentially the same conditions of pressure and temperature—as the metamorphosed sedimentary and volcanic rocks; but the equilibrium relations, for the most part, do not demand that conclusion, as both talc and serpentine are stable far above the temperature of the transition from the greenschist facies to the epidote-amphibolite facies (see Bowen and Tuttle, 1949, p. 446–450; Ramberg, 1952, p. 145). The mode of origin subscribed to in this report (p. 88–89) for the serpentinite places it outside the realm of strictly regional metamorphism. The experimental evidence (Bowen and Tuttle, 1949) places the temperature of serpentinization at less than 500° C., and the geologic relations indicate that, at the time of emplacement, the serpentinite was not appreciably hotter than the enclosing schist (lower boundary of the epidote-amphibolite facies), but there is not a direct relationship between serpentinization and the regional metamorphism of the rocks adjacent to the ultramafic bodies. Steatitization, on the other hand, appears, on the basis of all the available evidence, to belong to the episode of regional metamorphism.

The occurrence locally at the Waterbury mine and the Mad River localities of tremolite at the outer margins of the steatite zone where the bordering rocks are of suitable composition indicates that the steatite formed at conditions appropriate to approximately the upper green-schist facies. Also, the petrogenic rela-

tions (see p. 81–82) favor the interpretation that the steatitization took place at and shortly after the peak of regional metamorphism. The blackwall shows replacement relations to metamorphic minerals in the schist and therefore appears to be later, because the regional metamorphic adjustments were approximately isochemical and probably were achieved fairly rapidly, whereas the steatitization and the formation of the blackwall were metasomatic and therefore probably continued longer. Furthermore, structural features in the steatite (schistosity, cleavage, folds) show that the closing stages of folding affected the steatite. It is concluded, therefore, that steatitization took place at the same general time as the regional metamorphism, and was probably a special, local effect of the general regional metamorphic process.

Detailed consideration of serpentinization and steatitization are taken up in the sections that follow.

ORIGIN OF THE PERIDOTITE AND SERPENTINITE

The ultramafic rocks have long attracted the attention of many able investigators, but the problem of their mode of origin remains a perplexing one. The problem concerns the source and manner of formation of peridotite, dunite, and pyroxenite, their mode of intrusion, and the manner and cause of serpentinization. Benson (1918) reviews and summarizes the pertinent geologic literature prior to 1918, and analyzes (1926) the tectonic conditions accompanying the intrusion of ultramafic rocks. Bowen (1927; 1947), Bowen and Schairer (1936) Bowen and Tuttle (1949), Hess (1938), and Bain (1936) review current opinion and have made recent contributions to the problem.

SOURCE AND DERIVATION OF THE PRIMARY IGNEOUS ROCKS

Early field workers regarded peridotite and dunite as the products of direct consolidation from a magma of their own composition. Bowen (1915, p. 79–80) first suggested that they were formed by crystal accumulation from a complex magma, and (Bowen, 1917, p. 237)

FIGURES 21–23—Continued.

6. B-DDH-1-45—Ser-ab-q-chl-(bi-sph-ilmm-pr-ap-gra)-[alm]
7. B-DDH-1-67—Q-ser-ab-bi-(chl-gra-ap-ilmm-sph)
8. B-DDH-8-42—Ep-ho-ab-chl-bi-(sph-mt)
9. *B-DDH-8-367—Chl-(sph-act-ap)
10. *B-DDH-11-76—Chl-act-sph-(pr)
11. *B-DDH-11-78—Ser-chl-ab-q-(sph-pr-ilmm-carb-ap)-[alm]
22. Waterbury mine mineral assemblages:
 1. W-1—Chl-ser-q-alm-(ab-ilmm-ap)
 2. W-2—Ser-ab-chl-bi-(ilmm-ap-sph-ep)
 3. W-14—Ab-ser-chl-(sph-q-ap-ru-alm)
 4. W-21—Ser-bi-(ab-chl-sph-alm-ap)
 5. W-31—Ser-ab-chl-q-(sph-ap)
 6. *W-38—Chl-(ilmm-sph-ep-z)
 7. W-56—Ser-ab-q-chl-(alm-sph-ap-ilmm-pr)
8. W-75—Ser-ab-q-chl-bi-(ilmm-ap-sph-alm)
9. W-76—Ser-ab-q-bi-chl-(alm-ap-ilmm-sph-gra)
10. W77a—Ser-ab-q-chl-bi-(alm-sph-ap-ilmm)
11. *W-DDH-11-60—Q-ser-ab-chl-(bi-sph-ilmm-ap-carb-hm)
12. *W-DDH-11-118—Chl-ep-(ab-ser-sph-ap)
13. W-DDH-13-210—Chl-ab-carb-sph-(q-ep)
23. Mad River mineral assemblages:
 1. MR-15—Q-chl-ser-carb-ab-(sph-ep-ap)
 2. MR-85—Ab-ep-ho-chl-(sph)
 3. MR-88—Chl-ep-ab-(ser-sph)
 4. MR-97—Ab-ho-carb-ep-chl-bi-(sph-mt-q)
 5. MR-99—Q-chl-ab-carb-(ru-ap-sph)
 6. MR-108—Ab-q-chl-bi-(ep-sph-ap)
 7. MR-112—Chl-ab-bi-sph-ep-(ap-ser)

that they may have been intruded as solid or substantially solid masses. Petrologists came generally to accept the derivation of dunite by crystal accumulation but J. H. L. Vogt (1921, p. 522; 1924, p. 97) and others held that the accumulated crystals were completely remelted upon settling, to form a (wholly liquid) magma of dunitic composition. The fluxing action of volatile constituents was generally invoked to lower the temperature of crystallization.

Hess (1938) suggested that peridotites in narrow belts associated with strongly deformed zones of the earth's crust and commonly isolated from other igneous rocks are derived from primary peridotite magmas formed by partial refusion of the peridotite layer in the earth. A high concentration of water was assumed to lower the temperature of crystallization drastically—apparently enough, in some instances at least, so that serpentine crystallized directly from the magma (Hess, 1938, p. 327). Buddington (1943) has presented a picture of earth development which suggests a possible means of producing a peridotite layer with a high concentration of hyperfusibles.

In 1949 Bowen and Tuttle published the results of their investigations of the system $\text{MgO-SiO}_2\text{-H}_2\text{O}$. Their data indicate that peridotite magma could exist only at temperatures well above $1,000^\circ\text{C}$. even if the water content was greater than 10 percent. They conclude (1949, p. 455) that “the possibility of the formation of dunites, serpentines, and peridotites from such supposed magma intruded at low temperatures is definitely excluded.” The low-temperature metamorphic effects evident at the contacts of most ultramafic bodies appear, therefore, to require the bodies to have been intruded in a completely crystalline state. Bowen and Tuttle (1949, p. 454–457) have developed this concept most fully. They picture the mass as moving by translation gliding and granulation, facilitated in the early stages—when the temperature is high enough that serpentine is not a stable phase¹²—by water vapor in pore spaces as suggested by Sosman (1938, p. 359). At later stages—that is, when the temperature became sufficiently low—serpentinization of the crystalline peridotite simultaneously with intrusion (see the section on “Serpentinization” below) may greatly increase the mobility of the mass and facilitate intrusion. An instructive example in California of reintrusion of serpentine at low temperatures is described by Thomas (1951, p. 462–465).

Regional geologic relations suggest that the ultramafic rocks under consideration herein may have

formed by fractionation of complex magma from which were derived the abundant greenstone and amphibolite (tuff, flows, detritus) of the region. It is, perhaps, equally plausible that the ultramafic rocks are derived from peridotite magma formed by partial refusion of the peridotite substratum. The experimental evidence allows equal choice on the question. In either case, the geologic evidence is conclusive that the ultramafic rocks were at low temperatures comparable with those of the schist (the temperature of the upper limit of the greenschist facies) when emplaced. This evidence, taken in conjunction with the experimental data of Bowen and Tuttle (1949) and supported by contact relations and by structural features in the serpentinite (shear polyhedrons; see p. 24, 71), demands the conclusion that the ultramafic rocks were intruded in the solid state.

SERPENTINIZATION

Current theories on the origin of serpentinite derived from ultramafic igneous rocks generally subscribe to one or more of the following modes of origin: (1) deuteric alteration of peridotite and dunite by a hydrous peridotite magma; (2) direct precipitation of serpentine from a hydrous peridotite magma; (3) alteration of dunite and peridotite by hydrothermal solutions; and (4) serpentinization during tectonic transport, with water supplied from the enclosing rocks. Weathering processes are now considered by most to apply only to special cases and to negligible volumes of serpentinite (see Bowen and Tuttle, 1949, p. 454; Bain, 1936, p. 1979).

Weinschenk (1891, 1894) first gave definite form to the concept of a hydrous peridotite magma; serpentine was described as forming both by direct crystallization from the magma and through later alteration of olivine (also formed by direct crystallization) by water emitted from the magma upon consolidation (Benson, 1918, p. 700–701). Much later, the concept was refined and revised by Hess (1938), who gave, for the first time, a full account of how such a hydrous peridotite magma could form. Hess gave detailed consideration to the consolidation of, and to autoserpentinization by, such a magma and presented an impressive body of supporting geologic evidence. Meanwhile, other workers attributed serpentinization to the action of hydrothermal solutions, generally presumed to come from granites younger than the peridotites (Graham, 1917; Gillson, 1927; Du Rietz, 1935). Others recognized the operation of two or all of the aforementioned modes of origin (Benson, 1918; Bain, 1936).

The tectonic theory conceives of serpentinization as the necessary consequence of solid intrusion of peridotite or dunite into an aqueous environment under favorable physical conditions—that is, below a limiting

¹² The temperatures above which serpentine is not stable (about 500°C . for peridotite and 400°C . for dunite) are maximum limiting temperatures that obtain only when the water in the rock is at the same temperature and pressure as the surrounding rock. Under most conditions in the earth's crust the limiting temperatures will be less (see Thompson, 1955, p. 96).

temperature that varies with other environmental factors, but whose maximum value is about 500° C. for peridotite and 400° C. for dunite. This hypothesis has been developed and advocated particularly by Bowen (1947, p. 269–271; Bowen and Tuttle, 1949, p. 454–457). According to the hypothesis a mass of peridotite mobilized under stress acquires water from the surrounding rocks, as was suggested by Hess (1938, p. 331), because of the low partial pressure of water in the peridotite in comparison with the surrounding wet rocks. Under proper conditions of temperature and pressure, serpentinization of the peridotite proceeds simultaneously with its transport and emplacement. The conditions of tectonic transport probably greatly facilitate serpentinization because of granulation of material and more ready access of water along shears. Serpentinization, in turn, makes the mass more mobile—because of the physical characteristics of serpentine—under conditions of stress.

The acceptance (see p. 88) of the conclusion that the ultramafic rocks were intruded as solid masses into their present positions demands almost as a corollary, under the temperature and pressure conditions that prevailed and with water probably freely available from the enclosing rocks, that serpentinization proceeded simultaneously with transport and emplacement of the ultramafic rocks. The general lack of evidence for either increase in volume or expulsion of Mg and Si into the surrounding schist supports the idea that serpentinization did not occur while the ultramafic rocks were in their present positions.

STEATITIZATION

PREVIOUS WORK ON STEATITIZATION

A great deal has been written about talc deposits and the processes by which they were formed. Extensive bibliographies are given in Engel (1949) and Du Rietz (1935). Many of the articles cited concern technical aspects of talc and the talc industry, or deal with deposits greatly different in origin from those treated in the present report—such as talc derived from sedimentary carbonate rocks, or soapstone deposits like those at Schuyler, Va., in which the ultramafic rocks are commonly associated with gabbro and have not undergone a separate episode of serpentinization (Hess, 1933a). No attempt will be made to take into account the geologic literature not bearing directly upon the type of talc deposits here under consideration, which is associated with ultramafic rocks that were extensively serpentinized prior to steatitization—the so-called “talc deposit type” of Hess (1933b, p. 639). In the following paragraphs a brief account will be given of the geologic literature that is considered particularly

pertinent to the development of conclusions arrived at in the present investigation.

Most modern students of ultramafic rocks and their alteration products agree that steatitization is later than serpentinization, and that the alteration to talc was effected by solutions, but there the general agreement ends. Jacobs (1914; 1916) concluded that the steatite and blackwall were formed by the alteration (by means of unspecified metamorphic processes) of the differentiation products of a “chonolithic injection of magma”; he further suggests that the “grit member” was produced by “infiltrating dolomite” (1916, p. 272–273). In this he vaguely suggests the germ of a distinction between the origin of the talc-carbonate rock and the origin of the steatite, a distinction made in the present paper.

Gillson (1927) studied several talc deposits in Vermont and reviewed studies of other talc deposits throughout the world. He concluded, for the Vermont deposits, that “the talc formed in the serpentine rocks, after the process of serpentinization was complete” (1927, p. 274). Gillson also recognized that some talc—indeed, it appears that in many or most instances he would have said “most of the talc”—has formed by replacement of the schist. He also recognized the blackwall bordering the steatite as a product of the process of steatitization. Gillson (1927, p. 275) attributes the steatitization to

hot alkaline solutions, low in silica, and toward the last rich in magnesia and carbon dioxide, which were given off by a large igneous body which extended at least from Central Massachusetts to Quebec . . .

Burfoot (1930) studied the talc deposits of Virginia. He concluded, of the talc deposits similar to those in Vermont (his “steatite type”), that the talc was formed by “hot magmatic solutions” that were distinctly separate from and later than, or “a decided rejuvenation of”, the solutions that had earlier accomplished the serpentinization (1930, p. 822–823). He attributed the source of the solutions to any of many igneous rocks in the region, or to “the mother magma of the basic [(ultramafic)] rocks themselves”. Incidentally, Burfoot notes (1930, footnote 5, p. 823) that “C. W. Ryan [(1929)] . . . holds that the schist and intrusives were changed to soapstone through the action of mineralizers derived from the country schists”. This hypothesis of Ryan has much in common with the mode of origin held in the present paper to be most probable.

Hess (1933a; 1933b; Phillips and Hess, 1936) has made an extensive study of talc deposits derived from ultramafic rocks. He considers steatitization (in the type of deposit that occurs in Vermont) to be later than and unrelated in any way to serpentinization (1933b, p. 647). He attributes the process of stea-

titization to "the action of dilute hot aqueous solutions from below." Hess considers "nearby younger acid intrusions" to be the most probable source of the hydrothermal solutions, but states that "dilute hot aqueous solutions from any other source should produce the same result." Thus Hess agrees generally with the conclusions of Gillson (see above), but places much less emphasis upon talc derived from schist, which he considers to be confined to the outer few inches of the deposits, and concludes that the solutions that brought about the alteration were of much simpler composition than postulated by Gillson (Hess, 1933b, p. 642-643). Hess concluded that steatitization took place under conditions of falling temperature, and, on the basis of talc pseudomorphs after actinolite, maintained that actinolite formed earlier than the talc.

Bain (1934), in a discussion of Hess' (1933b) paper, maintained that, although steatitization always follows serpentinization (where both have occurred), both are part of the same (hydrothermal) process. He also differed with Hess in favoring a rising-temperature sequence, maintaining that actinolite—which he considers to have formed at higher temperatures than the talc—formed later than the talc.

Read (1934) in his study of the zoned ultramafic bodies of Unst, Shetland Islands, and Phillips and Hess (1936) in their joint study of similarly zoned ultramafic bodies in Vermont, carried out almost concurrently but independently important investigations of the origin of the zoning—a hitherto neglected phase in the study of talc deposits associated with ultramafic rocks. They arrived at generally similar conclusions, and both attributed the zonal arrangement to metamorphic differentiation at the contacts of rocks of contrasting composition. They differed, however, in that Read (1934, p. 537) concluded that "the minerals of the different zones were of simultaneous formation", whereas Phillips and Hess (1936, p. 348) maintained that "a considerable length of time elapsed in every case between the start of metamorphic differentiation at a higher temperature stage and its completion at a lower temperature." Phillips and Hess thus appear to stress the time factor as the important element of their difference with Read. In my opinion, however, the fundamental element in their difference is not the time interval but the temperature. Read's idea of simultaneity for all the minerals demands them to have formed at the same temperature (unless a marked temperature gradient be postulated at the contacts of the ultramafic bodies), whereas Phillips and Hess' emphasis of the considerable time interval involved in the metamorphic differentiation stems from their conclusion that the minerals of the zones record a falling-temperature sequence. The

point in dispute thus boils down to whether the paragenetic relations shown by the minerals resulted from alterations wrought by changes in temperature or by metasomatic changes, or perhaps even by other factors such as local fluctuations in partial pressure of H_2O and CO_2 . This point will be developed further in later discussion (p. 94).

Du Rietz (1935) made a careful study of a large number of ultramafic bodies in northern Sweden. The Swedish talc deposits appear to resemble closely the Vermont deposits (Du Rietz, 1935, p. 245), and thus correspond in general to Hess' (1933b, p. 639) "talc deposit type", for which Hess' postulated mode of origin has been discussed above. Du Rietz (1935, p. 235-242), if I interpret correctly, infers for the deposits a series of alterations at successively lower temperatures, and postulates free access of solutions throughout. Slight chloritization of olivine was followed, successively and at decreasing temperatures, by serpentinization and alteration to talc. Actinolite and chlorite at the borders of ultramafic bodies are ascribed to interaction between ultramafic rock and schist at initially higher temperatures, and with decreasing temperatures the actinolite is thought to have been replaced by talc. Du Rietz considers the alterations to be hydrothermal and the hydrothermal solutions to have come from the pegmatites which abound in the region, but he believes also that in some instances additional material must have been derived from the adjacent country rock (1935, p. 240).

Conclusions reached in the present study concerning the operation of the steatitization process are similar in some aspects to those of each of the investigators cited above and are indebted in varying degree to all of them, as will become obvious in the discussion that follows. The areas in which conclusions of the present investigation differ most from those of earlier ones are: the source, nature, and role of the steatitizing solutions; the thermal history of the steatitization process; the nature of the genetic relation between steatite and talc-carbonate rock; and the precise nature of the chemical changes that accompanied steatitization.

A particularly great advantage which the present study has had over earlier ones—and this statement applies as well to other phases of the problem of ultramafic rocks, not just to steatitization—is in the availability of the results of experimental investigation of the system $MgO-SiO_2-H_2O$ (Bowen and Tuttle, 1949). These experimental data, and the clear analysis in that paper of the geologic implications of the experimental results, have made possible more precise evaluation of the geologic and petrologic relations, and more informed judgment on conflicting or opposing claims.

AGE OF STEATITIZATION

Steatitization followed serpentinization of the ultramafic rocks at the Waterbury mine, Barnes Hill, and Mad River localities, and is unrelated to it. The geologic evidence clearly indicates the sequential relationship, but the separateness of the two processes, though suggested by the weight of geologic evidence, rests largely upon the demands of the overall integrated picture of the intrusion, serpentinization, and steatitization of the ultramafic rocks and the metamorphic and tectonic history of the area. The talc-bearing rocks are in all instances distributed peripherally to a core (in some instances complex) of serpentinite, and it is generally evident on the basis of textural and geologic relations that the talc rock has replaced the serpentinite; nowhere does serpentinite surround a central core of talc rock, and nowhere does serpentine appear to replace talc. These features clearly indicate that serpentinization preceded steatitization at any given point, but they do not require the two processes to have been unrelated, because it is readily conceivable that a single episode of alteration would proceed in two steps that would result in a zonal arrangement and sequential relationship of the products of the two steps. The inference of separateness for the two processes rests chiefly, insofar as geologic relations are concerned, upon the fact that the extent of serpentinization is unrelated to the width of the steatite-talc-carbonate rock zones, even in large bodies such as at the Mad River locality, whereas a single episode of combined serpentinization and steatitization would be expected to produce such a relation. The evidence for separateness is not compelling, but the concept of two unrelated processes seems to account most simply for the facts, and fits best with the present overall interpretation of the geologic history of the ultramafic rocks.

Two possible minor exceptions to the above statements on the relative ages of talc and serpentine should be noted: (1) small, isolated flakes of talc disseminated sparsely and rather uniformly throughout much of the serpentinite may be stable relicts (Barth, 1952, p. 327) formed prior to steatitization in the manner discussed by Bowen and Tuttle (1949, p. 456-457) during cooling of the peridotite. Such stable relicts of talc would be especially likely in an ultramafic body that contained a relatively large proportion of pyroxene. (2) It is not entirely impossible, or improbable, that some serpentine may have formed as a byproduct of steatitization process. With the large quantities of water released by the alteration of serpentine to talc and carbonate (see p. 120-123), it is very likely that any relict grains of olivine, or even compact masses of dunite, that escaped the first serpentinization may have been partly or completely altered to serpentine during steatitization.

RELATIONS OF STEATITE AND TALC-CARBONATE ROCK

The total body of evidence developed in the following sections leads clearly to the conclusion that the talc-carbonate rock and steatite are of the same age and of related mode of origin, although the geologic evidence alone is inconclusive. Earlier investigators failed to make a clear distinction between steatite and talc-carbonate rock, and consequently appear not to have considered that they may have formed by distinctly different processes, and may not, therefore, be necessarily of identical age. Indeed, the spatial relationship of the steatite as a shell surrounding the talc-carbonate rock suggests a sequential relation in which the steatite has replaced the talc-carbonate rock, though admitting the possibility that both formed at essentially the same time. The talc-carbonate rock and steatite intergrade, and the textural relations of the minerals neither support nor oppose a replacement interpretation. The geologic evidence, therefore, permits a choice in interpretation of age relations, between essential simultaneity of talc-carbonate rock and steatite or a younger age for the steatite.

Inasmuch as the geologic evidence is inconclusive on the precise age relations between the talc-carbonate rock and steatite, a conclusion must be based on other considerations. In the several arguments developed in the following sections it will become evident that the chemical and mineralogical changes involved in the formation of the steatite and talc-carbonate rock are of such a character that they lead to a simple picture of essentially simultaneous origin for them, as two distinct phases of a single process.

Distinguishing between steatite and talc-carbonate rock also leads to slightly different conclusions about their distribution with respect to position in the ultramafic body. Hess, for instance (1933b, p. 640), shows the "talc" as being thick at the bottom of the lens and progressively thinner upward. This relation appears to be generally true for talc-carbonate rock but not generally so for steatite, as has been shown earlier in the section on General geology (p. 10-16). Consequently, the nature and role of solutions in steatitization, discussed in detail in a later section, is envisaged to be somewhat different from that pictured by Hess and others.

RELATIONS BETWEEN THE STEATITE AND THE ROCKS OF THE BLACKWALL ZONE

The blackwall is considered to be of the same age as and genetically related to steatitization, but that conclusion is not immediately evident. Several apparently equally probable alternative age relations and modes of origin come readily to mind. Jacobs (1916, p. 272-273) considered the blackwall (and steatite) to have

been formed by the alteration of magmatic differentiates. Contact metamorphism and alteration in connection with serpentinization are other possible alternatives.

The blackwall grades rather sharply into steatite, on the one hand, and into schist on the other. Where an albite porphyroblast rock occurs between blackwall and schist, it, too, is gradational into the rock on either side. Textural relations, pseudomorphs, and relict minerals furnish clear evidence of replacement in the order schist→albite porphyroblast rock→blackwall→steatite, and imply a sequential chronological development.

Where tremolite occurs at the outer contact of the steatite zone, it shows no textural evidence of disequilibrium with talc in most places, but not uncommonly crystals of actinolite are invaded and extensively replaced by talc. In a few places, where carbonate rock borders the steatite, tremolite crystals locally appear to be partially replaced by carbonate. Talc in magnesite rock replaces the carbonate and other minerals. The relations are not as clear cut as for the blackwall chlorite schist, but tremolite rock appears to have formed by the reaction between calcitic or dolomitic carbonate rock and ultramafic rock; talcose carbonate rock appears to have formed in somewhat siliceous magnesite rock at the borders of ultramafic bodies.

The fact that the steatite nowhere cuts across the blackwall indicates that the blackwall is probably related to steatitization, rather than to some earlier process such as serpentinization. The chemical changes in the rocks of the alteration zone (see p. 122–124) show conclusively that interchange of constituents between the zones has been an important factor in their development. Consideration of all the evidence, therefore, leads to the conclusion that the rocks of the alteration zone were formed essentially simultaneously during steatitization; the replacement relations indicate not so much chronological sequence as widening of the reaction zones with time, accomplished by replacement of the next outer zone. This conception of simultaneity for the various rocks of the zone agrees with that of Read (1934, p. 537) rather than with Phillips and Hess (1936, p. 348). Further consideration of this and of the mechanism of replacement will be deferred until consideration of the mechanism of steatitization (p. 94–124).

The blackwall is of remarkably uniform thickness at the margins of the ultramafic bodies, regardless of position, as has been shown earlier in the descriptions of the geologic relations (p. 10–16). This assertion differs markedly from Hess' contention (1933b, p. 640) that the blackwall is very thin at the keel of a lens of ultramafic rock, and very thick at the top. Perhaps

these very different conclusions, both based upon direct observation, are explained as follows: Hess' picture of the configuration of the blackwall zone appears to be based largely upon relations observed at Roxbury (Hess, 1933b, figs. 3 and 4, p. 640–641; Phillips and Hess, 1936, p. 349–351). R. H. Jahns has mapped many of the Roxbury ultramafic bodies in great detail, and I have participated in several field excursions that he has led in the area. Jahns (manuscript map, 1956) has shown conclusively that many of the ultramafic bodies are emplaced in greenstone (chlorite-epidote-amphibole schists). In particular, the ultramafic body figured prominently by Hess (1933b, fig. 4) and Phillips and Hess (1936, fig. 8) is bordered on the west by a greenstone dike. This dike is altered to blackwall chlorite for a few inches from the contact with the ultramafic rock, as shown by Phillips and Hess. However, their "outer part of the zone of altered country rock" (labeled "chlor.-ep.-amph." in their fig. 8) is not a part of the blackwall, but is "unaltered" greenstone. Hess' conclusion is a logical one under the conditions of exposure at the quarry figured, and it is only upon more extensive mapping that the identification of his "outer blackwall zone" with the greenstone becomes evident. It is thus probable that, if Hess' outer blackwall zone be discounted, his views on the configuration of the blackwall zone are readily reconciled with those in the present paper.

RELATION OF STEATITIZATION TO STRUCTURE AND REGIONAL METAMORPHISM

Structural features of the blackwall and steatite indicate that steatitization took place after the peak of tectonic activity but before movement had ceased entirely. The obliteration locally of earlier schistosity in blackwall and steatite, the seeming preservation of relict schistosity in many places in these rocks, and the evidence for recurrent movement along schistosity planes and of the development locally of fracture cleavage in steatite and blackwall (see also Chidester, 1953) all point toward this conclusion. Steatitization, therefore, bears about the same chronologic relation to orogeny as does regional metamorphism (see p. 84–87 above), and must therefore be of about the same age.

The replacement relationship between the blackwall and the metamorphic minerals of the schist—such as, especially, the albite porphyroblasts—indicates that steatitization occurred, or continued, after regional metamorphism had attained its peak. As with the rocks of the reaction zone, however, the evidence admits the possibility that steatitization and regional metamorphism were essentially simultaneous: though minerals of the outer blackwall zone are obviously later than the minerals (the albite porphyroblasts, for in-

stance) that they replace, the blackwall is not necessarily younger than the regional metamorphism; because, where both isochemical reconstitution of the schist and metamorphic differentiation between the schist and a rock of contrasting composition take place contemporaneously, the reaction zone necessarily bears a replacement relation to both the schist and the rock of contrasting composition. Such is the relationship shown by the blackwall and steatite to the schist and serpentinite. It has been demonstrated earlier (p. 87) that the steatite and blackwall probably formed at the same conditions of metamorphic intensity as the schists. Thus the sum of the geologic evidence appears to indicate rather strongly that steatitization took place concurrently with regional metamorphism. This conclusion is supported by inferences concerning the nature and source of the steatitizing solutions (p. 128).

Faults in the vicinity of bodies of ultramafic rock may have facilitated access of solutions (mainly CO_2) during steatitization, and may thus have been important factors in triggering and influencing the steatitization process. Sheared zones may have facilitated dissemination of solutions into the serpentinite; however, they did not exist as open channelways along which fluids migrated easily, as is attested by the generally uniform zonal distribution of steatite and talc-carbonate rock, though locally abnormal development of talc-carbonate rock, steatite, and blackwall in synclinal troughs and at other favorable structural controls indicates minor "channeling" of migrating fluids.

VOLUME RELATIONS IN STEATITIZATION

It has long been generally accepted that replacement in metamorphism occurs on an approximately volume-for-volume basis (Barth, 1952, p. 313). Ramberg (1952, p. 92-95) concludes that the volume-for-volume principle does not always apply. Poldervaart (1953, p. 481-504) questions the general validity of the equal-volume principle, particularly under conditions of regional metamorphism, and proposes a system of calculations based on the assumption that the content of $(\text{Si}, \text{Al})\text{O}_4$ tetrahedra in a rock remain constant.

In most places the geologic evidence on the volume relations of the products of steatitization is inconclusive. However, several lines of evidence suggest volume-for-volume replacement for each of the rocks of the alteration zone (blackwall, steatite, and talc-carbonate rock), whereas none of the evidence appears to indicate perceptible change in volume during replacement.

In numerous places at the Waterbury mine, partial to complete replacement of albite porphyroblasts by the chlorite of the blackwall can be observed in the

outer part of the blackwall zone. Even where the crystal of albite is very deeply and irregularly embayed, there is no evidence—such as fracturing of the albite grain around the embayment—to indicate that replacement was accompanied by significant change in volume. The textural relations of the chlorite to other minerals of the schist are generally inconclusive, but there is no reason to suppose, and no evidence to suggest, that they differed essentially from those shown by the albite.

Relict layering is preserved in a few thin sections of blackwall. Comparison of the pattern of the relict layering with that of the adjacent schist indicates that no large change in volume has occurred, but admits the possibility of moderate change. The best place for accurate evaluation of evidence for or against change in volume is where contacts between the schist and blackwall and steatite cut across layering in the schist, and relict layering is preserved in the blackwall and steatite. At the Mad River locality, layering in the schist can be traced across a slightly crosscutting, fairly sharp contact with the blackwall for as much as an inch into the blackwall without evidence of discontinuity or systematic distortion of the layering. The best megascopic evidence of this sort is at the old East Granville talc mine (see Chidester, Billings, and Cady, 1951, p. 25), in northeastern Granville township, where one contact of a small lens of steatite cuts across layering in the schist at an angle of as much as 20 degrees. Relict layering in the steatite and blackwall can be traced very clearly into the unaltered schist. None of the layers show discontinuity or systematic distortion at the boundaries of the different rocks. If any volume change had occurred during replacement, it is evident that, on either side of a given undistorted layer, successive layers should be displaced or distorted at the contact by increasingly large amounts in such a manner that the reference layer marks a plane of symmetry—unless, of course, it can be assumed that all the expansion took place parallel to the layers. There appears to be no reason why this assumption should hold; therefore, inasmuch as the layering exhibits no such distortion pattern, it appears that replacement in the formation of blackwall and steatite was on a volume-for-volume basis.

Textural features around irregular embayments of steatite into chlorite rock and of talc-carbonate rock into serpentinite furnish further evidence of volume-for-volume replacement. Such irregular embayments of talc into chlorite are common locally at the scale of a thin section, particularly in inclusions of chlorite rock within steatite. A particularly instructive example of serpentinite embayed by talc-carbonate rock was pointed out by R. H. Jahns at one of the verde antique quarries at Roxbury. The embayment was very irreg-

ularly sacklike and more than 10 feet in greatest dimension. The "mouth of the sack, at the border between the talc-carbonate rock zone and the serpentinite zone—the embayment is considered to lie within the general limits of the serpentinite zone—was perhaps a foot across, considerably narrower than the average diameter of the embayment. Nowhere around the embayment of talc-carbonate rock was there evidence in the serpentinite of expansion or contraction during the alteration of serpentinite to talc-carbonate rock. Similarly, none of the steatite tongues and embayments show evidence of change in volume during the alteration.

The positive evidence is thus seen to favor, in every case, constant-volume relations during formation of blackwall, steatite, and talc-carbonate rock.

TEMPERATURE RELATIONS DURING STEATITIZATION

Most earlier investigators have concluded that the geologic relations, particularly the textural relations among minerals considered to be diagnostic of different temperatures of formation, indicate marked changes in temperature during the course of steatitization. Bain favors a rising-temperature sequence, whereas Hess, Phillips and Hess, Burfoot, Du Rietz, and others favor a falling-temperature sequence. Read, however, concludes that the different zones were formed "simultaneously", and presumably, therefore, considers them to have formed at the same temperature conditions. (See earlier discussion, p. 87-90.)

It has been shown in foregoing sections of this report that the evidence from geological relations and mineral assemblages indicates that all the rocks formed during steatitization were formed under the same physical conditions as the adjoining schist, and that there was no significant temperature change during steatitization. These conclusions are reconciled with those of earlier investigators as follows:

It appears that both the rising-temperature and the falling-temperature hypotheses can be attributed to the idea that replacement of one mineral by another is almost invariably due to changes in temperature, particularly if one of the minerals is commonly regarded as indicative of higher temperatures than the other—as with tremolite and talc, biotite and chlorite. Experimental evidence shows, however, that some of the so-called low-temperature minerals, such as talc, are stable at relatively high temperatures (see, for instance, Bowen and Tuttle, 1949, p. 449), and cannot be taken unconditionally as indicating low temperatures (see Ramberg, 1952, p. 145).

Obviously, then, the sequence of alterations among minerals at the borders of the ultramafic bodies, such as of tremolite altered to talc, or chlorite to talc—and, incidentally, of biotite to chlorite in Phillips and Hess'

(1936, p. 341) high-temperature type of deposit—may reflect only changing bulk composition—or, more specifically, changing chemical potential of mobile constituents—at a given point, rather than changes in temperature. This statement becomes evident upon examination of equilibrium diagrams of the various minerals (for instance, Ramberg, 1945, p. 55; 1952, p. 64). The metasomatic changes in the reaction zones at the borders of the ultramafic rocks (see the following section) clearly are of the kind to bring about the replacement relations exhibited. Some local reversals of general trends in alteration sequences among the minerals—such as in the replacement of tremolite by carbonate—may possibly result from local variations in the chemical potential of H_2O or CO_2 or both. It therefore appears to be in accord with all the evidence to consider that steatitization and related changes were accomplished at essentially a constant temperature, though some minor alterations may have occurred during the period of falling temperature.

MECHANISM OF STEATITIZATION

In the foregoing discussion the evidence has been shown to indicate that steatitization took place contemporaneously with and at essentially the same temperatures as regional metamorphism, without notable change in temperature during the steatitization process. It now remains to determine as precisely as possible the mineralogical and chemical changes that accompanied the steatitization process, and, having determined those changes, to reconstruct as nearly as possible the operation of the process and to discover the probable sources of introduced constituents, particularly H_2O , CO_2 , and SiO_2 .

It has been long been recognized that direct comparison of chemical analyses given in terms of weight percent of oxides cannot result in an accurate description of chemical changes that took place during metamorphism, because such a comparison does not take proper account of material introduced or lost during the metamorphism: A given weight (W_o) of the original rock should be compared with a weight (W_f) of final rock equal to that of the original rock minus the weight of material lost (y) plus the weight of material gained (x), thus:

$$W_f = W_o + x - y.$$

Unfortunately, the values of x and y are precisely the unknowns that are sought, and a direct solution of the problem is not possible. An early practice was to assume that some constituent—commonly silica or alumina—remained constant during the alteration, and that the rest of the oxides varied accordingly; but that procedure is scarcely more satisfactory than direct

comparison of analyses. The more generally used modern methods compare the contents of equal volumes of rock, computed from chemical analyses and density measurements (see, for instance, Lovering, 1949; Poldervaart, 1953, p. 482-490). The contents are stated variously in terms of atoms per cubic centimeter of rock or of chemical compositions calculated to represent 1 cc or 100 cc of rock. Barth (1948; 1949; 1952, p. 82-85) has proposed a "standard cell" of 160 oxygen atoms as a basis for petrologic calculations. The method is based upon the observation that oxygen constitutes about 94 percent of most rocks, so that comparing rock volumes of equal oxygen content is approximately equivalent to comparing equal volumes of rock. A cell of 160 oxygen atoms was chosen because it contains about 100 electropositive ions, and gains and losses may therefore be regarded as in percentages of total electropositive ions. Poldervaart (1953, p. 481-504) has recently proposed a method of petrological calculations based upon the assumption that the (Si, Al) O_4 content of rocks remains approximately constant during metamorphism.

Barth's "standard cell" approximates a standard volume for many rocks closely enough for many purposes, but some common rocks differ in cell size by as much as 20 percent. The rocks under consideration herein, ranging from quartz-sericite schist and talc-carbonate rock to chlorite schist and serpentinite, differ widely because they are characterized by minerals of widely different equivalent volumes (see p. 129-131 and table 22); therefore, Barth's method cannot be used advantageously to determine the chemical changes that occurred during steatitization. Poldervaart's method is not applicable in the present study because the (Si, Al) O_4 content of the rocks has changed appreciably during steatitization.

For example, the alteration of albite to chlorite in the blackwall zone (see above, p. 64-68) would require approximately a twofold increase in volume if the (Si, Al) O_4 content of the rock had remained unchanged. The equivalent molecular volumes of albite and chlorite are very nearly equal (see table 22), but an equivalent mineral unit of albite ($1/5 NaAlSi_3O_8$) contains $4/5$ (Si, Al) O_4 tetrahedra, whereas an equivalent mineral unit of, say, clinocllore ($1/10 Mg_5Al_2Si_3O_{10}(OH)_8$) contains only $4/10$ (Si, Al) O_4 tetrahedra. Obviously, then, for the (Si, Al) O_4 tetrahedra to remain constant, the alteration of one equivalent mineral unit of albite would have to result in two equivalent mineral units of clinocllore, which would require about a twofold increase in volume. The evidence clearly rules out such an increase. Similar considerations show that neither can the (Si, Al) O_4 content of the rock have re-

mained constant during the alteration of blackwall and serpentinite to steatite, if the weight of evidence for volume-for-volume replacement be accepted.

In this report the chemical changes effected during metamorphism will be determined by comparison of volumes of rock of equal and standard size, designated the *modified standard cell*. In brief, and in general terms, the modified standard cell is a standard volume of rock that, for an average rock, contains about 100 electropositive ions. Precise definition, instructions for calculation, and sample calculations are given on pages 132-138. The method is basically similar to other methods that compare equal volumes of rock, cited above. It stems, however, from preliminary attempts to apply Barth's method of the standard cell, and retains certain desirable features of Barth's method. For most rocks, the modified standard cell—like Barth's standard cell—contains approximately 100 electropositive ions (cations); therefore, changes among such ions may be considered generally to be roughly in terms of percentages of their total in the parent rock. Barth's method of denoting the contents of his standard cell as a "rock formula" has also been retained.

The modified standard cell is, in my opinion, easier to compute and has several other advantages over other methods of calculating a cell of constant volume, particularly where modal compositions are also to be compared. Computation of the modified standard cell is integrated with a simple method of computing a mode in terms of equivalent molecular percent and volume percent, so that only a relatively small amount of additional computation is necessary to calculate the modified standard cell if a calculated mode has already been computed, and vice versa. The computations also integrate naturally with computations of the norm in terms of equivalent molecular percent, advocated recently by Barth (1948, p. 51-53; 1952, p. 76-82). The number denoting the abundance of each electropositive ion in the modified standard cell is roughly equivalent in value to the weight percent of the corresponding oxide, determined by chemical analysis; the cell contents are thus denoted in familiar form, and may even be compared, for rough purposes, directly with analyses in weight percent.

Changes in mineral composition are readily determined by comparison of volume percentages of minerals in the rocks—whether of figures obtained by direct methods by means of microscopic analyses of thin section, or of figures obtained by computing modes in volume percent from chemical analyses. All the available measured modes of suites of rocks across the contacts of the ultramafic bodies are assembled in table 10. Where it is desirable to compare mineral and chemical

changes, as in the present study, it is more satisfactory in many ways to compute volume percent modes from the chemical analyses.

Tables 11 to 20 and figures 24 to 33 assemble the basic data of the steatitization process, to show the mineralogical and chemical changes that occurred during the alteration of serpentinite to talc-carbonate rock and steatite and of schist to blackwall and steatite. Both the tables and the graphs in the text illustrations are, of course, predicated upon the conclusion that in the steatitization process changes in volume were negligible. Tables 11, 13, 15, 17, and 19 contain tabulations of the volume percentages of minerals, the contents of

the modified standard cell, and the gain or loss (with respect to the protolith, or parent rock) of each element, ion, or radical for each principal rock type formed during the steatitization process. In tables 12, 14, 16, 18, and 20 are tabulated the proportional gains and losses per zone (gain or loss per MSC times width of zone in feet) for selected elements, ions, and radicals. The albite porphyroblast zone is omitted from tables 12, 14, 16, 18, and 20 because the zone varies in such an irregular manner that it does not lend itself to such quantitative treatment. Figures 24 to 33 summarize, in graphic form, the essential information contained in tables 11 to 20.

TABLE 11.—*Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality*

[Country rock is nonalbitic]

A. CALCULATED MODE

[Values are given in volume percent]

Schist protolith				Serpentinite protolith					
Nonalbitic schist CA-1		Blackwall W-38		Steatite W-23		Talc-carbonate rock CA-2 [Modified after W-89 and W-71]		Serpentinite W-DDH-13-65	
Sericite	45. 77	Chlorite	95. 62	Talc	99. 88	Talc	64. 50	Antigorite	90. 76
Quartz	29. 79	Ilmenite	3. 93	Apatite	. 05	Carbonate	34. 48	Talc	7. 92
Chlorite	19. 50	Sericite	. 13	Magnetite	. 02	Pyrrhotite	. 78	Magnetite	1. 00
Sphene	1. 96	Carbonate	. 10	Pyrite	. 01	Apatite	. 04	Carbonate	. 13
Graphite	. 99	Albite	. 09	Other	. 04	Other	. 20	Pyrrhotite	. 10
Ilmenite	. 50	Rutile	. 09					Apatite	. 03
Apatite	. 51	Apatite	. 03		100. 00		100. 00	Other	. 06
Carbonate	. 49	Pyrite	. 01						100. 00
Pyrite	. 49								
	100. 00		100. 00						

TABLE 11.—*Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality—Continued*

B. ROCK FORMULAS

[Modified standard cell (MSC)]

Specimen	Formula	
CA-1-----	$\left[K_{.65}Na_{.00}Ca_{1.32}Mg_{6.00}Fe^{+2}_{2.93}Al_{24.44}Fe^{+3}_{1.17}Ti_{1.05}Si_{52.71}P_{.19}S_{.84}C_{3.84}O_{145.18}(OH)_{28.33}(CO_2)_{.27} \right]$	Cat. = 100.56 Oeq = 176.82
W-38-----	$\left[K_{.02}Na_{.02}Ca_{.01}Mg_{27.74}Fe^{+2}_{16.99}Mn_{.77}Ni_{.02}Co_{.01}Al_{22.51} \right.$	
	$\left. Fe^{+3}_{1.24}Ti_{2.64}Si_{25.83}P_{.01}S_{.02}As_{.0002}O_{101.79}(OH)_{72.66}(CO_2)_{.07} \right]$	Cat. = 97.87 Oeq = 174.61
W-23-----	$\left[K_{.04}Na_{.00}Ca_{.02}Mg_{41.37}Fe^{+2}_{3.74}Mn_{.07}Ni_{.16}Co_{.01}Al_{.94}Fe^{+3}_{.07}Cr_{.20}Ti_{.01}Si_{58.98}P_{.02}S_{.02}As_{T.O}O_{149.00}(OH)_{32.07} \right]$	Cat. = 105.54 Oeq = 181.11
CA-2-----	$\left[K_{.06}Na_{.15}Ca_{.27}Mg_{48.28}Fe^{+2}_{6.36}Mn_{.36}Al_{1.23}Fe^{+3}_{.89}Ti_{.01}Si_{38.34}P_{.01}S_{.87}O_{124.41}(OH)_{19.16}(CO_2)_{25.57} \right]$	Cat. = 121.52 Oeq = 195.57
W-DDH-13-65---	$\left[K_{.04}Na_{.00}Ca_{.00}Mg_{50.36}Fe^{+2}_{3.97}Mn_{.09}Ni_{.16}Co_{.01}Al_{1.13} \right.$	
	$\left. Fe^{+3}_{.76}Cr_{.22}Ti_{.01}Si_{39.23}P_{.01}S_{.11}As_{.003}O_{100.37}(OH)_{71.43}(CO_2)_{.10} \right]$	Cat. = 96.06 Oeq = 172.10

C. GAINS AND LOSSES (PER MSC) DURING STEATITIZATION

[Explanation: A plus sign (+) preceding a given value indicates a gain with respect to protolith; a minus sign (−) indicates a loss. An asterisk (*) standing alone indicates no change. The symbol "nd" means not determined]

	Nonalbitic schist protolith altering to—			Serpentine protolith altering to—	
	Blackwall W-38	Steatite W-23		Talc-carbonate rock CA-2	
Constituents					Constituents
K-----	− 6. 63	− 6. 61	(*)	+ 0. 02	K-----
Na-----	+ . 02	(*)	(*)	+ . 15	Na-----
Ca-----	− 1. 31	− 1. 30	+ 0. 02	+ . 27	Ca-----
Mg-----	+ 21. 74	+ 35. 37	− 8. 99	− 2. 08	Mg-----
Fe ⁺² -----	+ 14. 06	. 81	− . 23	+ 2. 39	Fe ⁺² -----
Mn-----	nd	nd	− . 02	+ . 27	Mn-----
Ni-----	nd	nd	(*)	nd	Ni-----
Co-----	nd	nd	(*)	nd	Co-----
Al-----	− 1. 93	− 23. 50	− . 19	+ . 10	Al-----
Fe ⁺³ -----	+ . 07	− 1. 10	− . 66	+ . 16	Fe ⁺³ -----
Cr-----	nd	nd	− . 02	nd	Cr-----
Ti-----	+ 1. 59	− 1. 04	(*)	(*)	Ti-----
Si-----	− 26. 88	+ 6. 17	+ 19. 65	− . 89	Si-----
P-----	− . 18	− . 17	+ . 01	(*)	P-----
S-----	− . 82	− . 82	− . 09	+ . 76	S-----
As-----	nd	nd	(*)	nd	As-----
C-----	− 3. 84	− 3. 84	nd	nd	C-----
O-----	− 43. 39	+ 3. 82	+ 48. 63	+ 24. 04	O-----
OH-----	+ 44. 33	+ 3. 74	− 39. 36	− 52. 27	OH-----
CO ₂ -----	− . 20	− . 27	− . 10	+ 25. 47	CO ₂ -----
Oeq-----	− 2. 21	+ 4. 29	+ 9. 01	+ 23. 47	Oeq-----

FIGURE 24.—Variation diagram based upon calculated modes in table 11, for specimens across the contact of the main ultramafic body at the Waterbury mine locality. Country rock nonalbitic.

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

FIGURE 25.—Variation diagram based upon rock formulas in table 11, for specimens across the contact of the main ultramafic body at the Waterbury mine locality. Country rock nonalbitic.

FIGURE 26.—Variation diagram based upon calculated modes in table 13, for specimens across the contact of the main ultramafic body at the Waterbury mine locality. Country rock albitic.

FIGURE 27.—Variation diagram based upon rock formulas in table 13, for specimens across the contact of the main ultramafic body at the Waterbury mine locality. Country rock albitic.

FIGURE 28.—Variation diagram based upon calculated modes in table 15, for specimens across the west contact of the ultramafic body at the Barnes Hill locality. Country rock albitic.

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

FIGURE 29.—Variation diagram based upon rock formulas in table 15, for specimens across the west contact of the ultramafic body at the Barnes Hill locality. Country rock albitic.

FIGURE 30.—Variation diagram based upon calculated modes in table 17, for specimens across the east contact of the ultramafic body at the Barnes Hill locality. Country rock albitic.

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

FIGURE 31.—Variation diagram based upon rock formulas in table 17, for specimens across the east contact of the ultramafic body at the Barnes Hill locality. Country rock albitic.

FIGURE 32.—Variation diagram based upon calculated modes in table 19, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist.

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

FIGURE 33.—Variation diagram based upon rock formulas in table 19, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist.

TABLE 12.—Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the contact of the main ultramafic body at the Waterbury mine locality

[Country rock is nonalbitic. Talc-carbonate rock sample CA-2 modified after W-89 and W-71]

	Nonalbitic schist protolith		Serpentine protolith	Combined black-wall and steatite	Serpentine protolith
	Blackwall W-38	Steatite W-23	Steatite W-23		Talc-carbonate rock CA-2
Width of zone.....feet.....	0.6	0.4	3.0	4.0	10.00
Magnesium:					
Amount per MSC in protolith ¹	6.00	6.00	50.36	-----	50.36
Proportional amount per zone in protolith ²	3.60	2.40	151.08	157.26	503.60
Gain or loss per MSC ³	+21.74	+35.37	-8.99	-----	-2.08
Proportional gain or loss per zone ⁴	+13.04	+14.15	-26.97	+ .02	-20.80
Percent gain or loss over protolith ⁵	+362	+590	-18	+ .01	-4
Ferrous iron:					
Amount per MSC in protolith.....	2.93	2.93	3.97	-----	3.97
Proportional amount per zone in protolith.....	1.76	1.17	11.91	14.84	39.70
Gain or loss per MSC.....	+14.06	+ .81	- .23	-----	+2.39
Proportional gain or loss per zone.....	+8.44	+ .32	- .69	+8.08	+23.90
Percent gain or loss over protolith.....	+480	+27	-6	+54	+60
Aluminum:					
Amount per MSC in protolith.....	24.44	24.44	1.13	-----	1.13
Proportional amount per zone in protolith.....	14.66	9.78	3.39	27.83	11.30
Gain or loss per MSC.....	-1.93	-23.50	- .19	-----	.10
Proportional gain or loss per zone.....	-1.16	-9.40	- .57	-11.12	+1.00
Percent gain or loss over protolith.....	-8	-96	-17	-40	+9
Silicon:					
Amount per MSC in protolith.....	52.71	52.71	39.23	-----	39.23
Proportional amount per zone in protolith.....	31.63	21.08	117.69	170.55	392.30
Gain or loss per MSC.....	-26.88	+6.17	+19.65	-----	- .89
Proportional gain or loss per zone.....	-16.13	+2.47	+58.95	+45.11	-8.90
Percent gain or loss over protolith.....	-51	+12	+50	+26	-2
Hydroxyl:					
Amount per MSC in protolith.....	28.33	28.33	71.43	-----	71.43
Proportional amount per zone in protolith.....	17	11.33	214.29	242.86	714.30
Gain or loss per MSC.....	+44.33	+3.74	-39.36	-----	-52.27
Proportional gain or loss per zone.....	+26.60	+1.50	-118.08	-90.42	-522.70
Percent gain or loss over protolith.....	+156	+13	-55	-37	-73
Carbon dioxide:					
Amount per MSC in protolith.....	.27	.27	.10	-----	.10
Proportional amount per zone in protolith.....	.16	.11	.30	.57	1.00
Gain or loss per MSC.....	- .20	- .27	- .10	-----	+25.47
Proportional gain or loss per zone.....	- .12	- .11	- .30	- .53	+254.70
Percent gain or loss over protolith.....	-75	-100	-100	-93	+25,470
Oxygen equivalent:					
Amount per MSC in protolith.....	176.82	176.82	172.10	-----	172.10
Proportional amount per zone in protolith.....	106.09	70.73	516.30	693.72	1721.00
Gain or loss per MSC.....	-2.21	+4.29	+9.01	-----	+23.47
Proportional gain or loss per zone.....	-1.33	+1.72	+27.03	+26.78	+234.70
Percent gain or loss over protolith.....	-1	+2	+5	+4	+14

¹ Obtained from rock formula of protolith, table 11.² Equal to the amount per MSC in protolith multiplied by width of zone.³ Obtained from table 11.⁴ Equal to the gain or loss per MSC multiplied by width of zone in feet.⁵ In terms of a unit of volume, and equal to the gain or loss per MSC divided by the amount per MSC in protolith.

TABLE 13.—*Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality*

[Country rock is albitic]

A. CALCULATED MODES

[Values are given in volume percent]

Albitic schist protolith					Serpentine protolith					
Albitic schist W-DDH-11-60		Albite porphyroblast rock W-DDH-11-116		Blackwall W-DDH-11-118	Steatite W-23		Talc-carbonate rock CA-2		Serpentine W-DDH-13-65	
Quartz----	40. 43	Albite-----	63. 11	Chlorite--- 90. 21	Talc----- 99. 88	Talc----- 64. 50	Antigorite- 90. 76			
Sericite----	27. 65	Biotite-----	13. 49	Epidote--- 7. 34	Apatite--- . 05	Carbonate- 34. 48	Talc----- 7. 92			
Albite-----	15. 43	Chlorite-----	8. 45	Albite----- 1. 59	Magnetite- . 02	Pyrrhotite- . 78	Magnetite- 1. 00			
Chlorite----	7. 97	Quartz-----	7. 59	Sericite---- . 72	Pyrite----- . 01	Apatite----- . 04	Carbonate- . 13			
Biotite-----	3. 57	Sericite-----	5. 44	Sphene----- . 09	Other ----- . 04	Other----- . 20	Pyrrhotite- . 10			
Sphene-----	. 85	Apatite-----	. 24	Apatite--- . 05			Apatite--- . 03			
Apatite-----	. 20	Epidote-----	. 09		100. 00	100. 00	Other----- . 06			
Carbonate---	. 16	Sphene-----	1. 34	100. 00						
Ilmenite----	. 43	Ilmenite-----	. 24				100. 00			
Other-----	3. 50	Graphite----	. 01							
	100. 00		100. 00							

B. ROCK FORMULAS

[Modified standard cell (MSC)]

Specimen	Formula	
W-DDH-11-60---	$\left[K_{4.50}Na_{3.19}Ca_{.53}Mg_{3.67}Fe^{+2}_{1.06}Mn_{.35}Al_{16.66}Fe^{+3}_{4.20}Ti_{.59}Si_{62.79}P_{.08}O_{159.81}(OH)_{15.76}(CO_2)_{.09} \right]$	Cat. = 97.70 Oeq = 175.75
W-DDH-11-116---	$\left[K_{2.6}Na_{13.1}Ca_{.68}Mg_{4.3}Fe^{+2}_{4.7}Mn_{.41}Al_{18.8}Fe^{+3}_{.92}Ti_{.65}Si_{56.6}P_{.09}S_{.09}C_{.05}O_{156.6}(OH)_{11.2} \right]$	Cat. = 102.9 Oeq = 167.9
W-DDH-11-118---	$\left[K_{.10}Na_{.32}Ca_{2.2}Mg_{38.3}Fe^{+2}_{6.2}Mn_{.21}Al_{12.7}Fe^{+3}_{.63}Ti_{.03}Si_{42.0}P_{.02}C_{.00}S_{.09}O_{122.1}(OH)_{58.1} \right]$	Cat. = 102.6 Oeq = 180.2
W-23-----	$\left[K_{.04}Na_{.00}Ca_{.02}Mg_{41.37}Fe^{+2}_{3.74}Mn_{.07}Ni_{.16}Co_{.01}Al_{.94}Fe^{+3}_{.07}Cr_{.20}Ti_{.01}Si_{58.88}P_{.02}S_{.02}As_{.01}O_{149.00}(OH)_{32.07} \right]$	Cat. = 105.54 Oeq = 181.11
CA-2-----	$\left[K_{.06}Na_{.15}Ca_{.27}Mg_{48.28}Fe^{+2}_{6.36}Mn_{.36}Al_{1.23}Fe^{+3}_{.89}Ti_{.01}Si_{38.34}P_{.01}S_{.87}O_{124.41}(OH)_{19.16}(CO_2)_{25.57} \right]$	Cat. = 121.52 Oeq = 195.57
W-DDH-13-65---	$\left[K_{.04}Na_{.00}Ca_{.00}Mg_{50.36}Fe^{+2}_{3.97}Mn_{.09}Ni_{.16}Co_{.01}Al_{1.13}Fe^{+3}_{.73}Cr_{.22} \right]$	
	$Ti_{.01}Si_{39.23}P_{.01}S_{.11}As_{.003}O_{100.37}(OH)_{71.43}(CO_2)_{.10}$	Cat. = 96.06 Oeq = 172.10

TABLE 13.—*Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the contact of the main ultramafic body at the Waterbury mine locality—Continued*

C. GAINS AND LOSSES (PER MSC) DURING STEATITIZATION

[Explanation: A plus sign (+) preceding a given value indicates a gain with respect to protolith; a minus sign (−) indicates a loss. An asterisk (*) standing alone indicates no change. The symbol "nd" means "not determined"]

Albitic schist protolith altering to—					Serpentine protolith altering to—				
	Albite porphyro- blast rock W-DDH-11-116	Blackwall W-DDH-11-118	Steatite W-23		Talc-carbonate rock CA-2				
<i>Constituents</i>							<i>Constituents</i>		
K	−1.9	−4.4	−4.46	(*)	+0.02		K		
Na	+9.9	−2.87	−3.19	(*)	+1.15		Na		
Ca	+1.15	+1.7	−.51	+0.02	+1.27		Ca		
Mg	+6	+34.6	+37.70	−8.99	−2.08		Mg		
Fe ⁺²	+3.6	+5.1	+2.68	−.23	+2.39		Fe ⁺²		
Mn	+0.06	−.14	−.28	−.02	+1.27		Mn		
Ni	nd	nd	nd	(*)	nd		Ni		
Co	nd	nd	nd	(*)	nd		Co		
Al	+2.1	−4.0	−15.72	−.19	+1.10		Al		
Fe ⁺³	−3.3	−3.6	−4.13	−.66	+1.16		Fe ⁺³		
Cr	nd	nd	nd	−.02	nd		Cr		
Ti	+0.06	−.56	−.58	(*)	(*)		Ti		
Si	−6.2	−20.8	−3.91	+19.65	−.89		Si		
P	+0.01	−.06	−.06	+0.01	(*)		P		
S	(*)	(*)	(*)	−.09	+1.76		S		
As	nd	nd	nd	(*)	nd		As		
C	(*)	−.05	−.05	nd	nd		C		
O	−3.2	−37.7	−10.81	+48.63	+24.04		O		
OH	−4.6	+42.3	+16.31	−39.36	−52.27		OH		
CO ₂	−.09	−.09	−.09	−.10	+25.47		CO ₂		
Oeq	−7.9	+4.5	+5.36	+9.01	+23.47		Oeq		

TABLE 14.—Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the contact of the main ultramafic body at the Waterbury mine locality

[Country rock is albitic. Talc-carbonate rock sample CA-2 modified after W-89 and W-71]

	Albitic schist protolith		Serpentinite protolith	Combined black-wall and steatite	Serpentinite protolith
	Blackwall W-DDH-11-118	Steatite W-23	Steatite W-23		Talc-carbonate rock CA-2
Width of zone.....feet.....	0.5	0.3	3.0	3.8	10
Magnesium:					
Amount per MSC in protolith ¹	3.67	3.67	50.36	-----	50.36
Proportional amount per zone in protolith ²	1.84	1.10	151.08	154.20	503.60
Gain or loss per MSC ³	+34.6	+37.70	-8.99	-----	-2.08
Proportional gain or loss per zone ⁴	+17.3	+11.31	-26.97	+1.43	-20.80
Percent gain or loss over protolith ⁵	+943	+1,027	-18	+9	-4
Ferrous iron:					
Amount per MSC in protolith.....	1.06	1.06	3.97	-----	3.97
Proportional amount per zone in protolith.....	.53	.32	11.91	12.76	39.70
Gain or loss per MSC.....	+5.1	+2.68	-23	-----	+2.39
Proportional gain or loss per zone.....	+2.6	+1.80	-69	-4.09	+23.90
Percent gain or loss over protolith.....	+481	+253	-6	-32	+60
Aluminum:					
Amount per MSC in protolith.....	16.66	16.66	1.13	-----	1.13
Proportional amount per zone in protolith.....	8.33	5.00	3.39	16.72	11.30
Gain or loss per MSC.....	-4.0	-15.72	-19	-----	+1.10
Proportional gain or loss per zone.....	-2.0	-4.72	-57	-7.29	+1.00
Percent gain or loss over protolith.....	-24	-94	-17	-44	+9
Silicon:					
Amount per MSC in protolith.....	62.79	62.79	39.23	-----	39.23
Proportional amount per zone in protolith.....	31.40	18.84	117.69	168.08	392.30
Gain or loss per MSC.....	-20.8	-3.91	+19.65	-----	-89
Proportional gain or loss per zone.....	-10.4	-1.18	+58.95	+47.19	-8.90
Percent gain or loss over protolith.....	-33	-6	+50	+28	-2
Hydroxyl:					
Amount per MSC in protolith.....	15.76	15.76	71.43	-----	71.43
Proportional amount per zone in protolith.....	7.88	4.73	214.29	227.14	714.30
Gain or loss per MSC.....	+42.3	+16.31	-39.36	-----	-52.27
Proportional gain or loss per zone.....	+21.2	+4.89	-118.08	-92.23	-522.70
Percent gain or loss over protolith.....	+268	+103	-55	-40	-73
Carbon dioxide:					
Amount per MSC in protolith.....	.09	.09	.10	-----	.10
Proportional amount per zone in protolith.....	.05	.03	.30	.38	1.00
Gain or loss per MSC.....	-.09	-.09	-.10	-----	+25.47
Proportional gain or loss per zone.....	-.05	-.03	-.30	-.38	+254.70
Percent gain or loss over protolith.....	-100	-100	-100	-100	+25,470
Oxygen equivalent:					
Amount per MSC in protolith.....	175.75	175.75	172.10	-----	172.10
Proportional amount per zone in protolith.....	87.88	52.73	516.30	657.51	1,721.00
Gain or loss per MSC.....	+4.5	+5.36	+9.01	-----	+23.47
Proportional gain or loss per zone.....	+2.3	+1.60	+27.03	+30.21	+234.70
Percent gain or loss over protolith.....	+3	+3	+5	+5	+14

¹ Obtained from rock formula of protolith, table 13.² Equal to the amount per MSC in protolith multiplied by width of zone.³ Obtained from table 13.⁴ Equal to the gain or loss per MSC multiplied by width of zone in feet.⁵ In terms of a unit of volume, and equal to the gain or loss per MSC divided by the amount per MSC in protolith.

TABLE 15.—*Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the west contact of the ultramafic body at Barnes Hill*

[Country rock is albitic]

A. CALCULATED MODES

[Values are given in volume percent]

Albitic schist protolith			Serpentinite protolith		
Albitic schist B-DDH-8-372	Blackwall B-DDH-8-367	Steatite CA-3	Talc-carbonate rock CA-4	Serpentinite B-DDH-9B ₁ -432	
Quartz----- 40. 81	Chlorite----- 91. 29	Talc----- 99. 90	Talc----- 59. 94	Serpentine----	85. 35
Sericite----- 28. 49	Sphene----- 2. 80	Apatite----- . 03	Carbonate----- 40. 00	Talc-----	5. 26
Albite----- 16. 12	Actinolite----- 2. 78	Magnetite----- . 02	Apatite----- . 03	Carbonate-----	4. 32
Chlorite----- 11. 67	Albite----- 1. 83	Pyrite----- . 01	Pyrite----- . 01	Apatite-----	. 03
Sphene----- 1. 56	Sericite----- . 68	Other----- . 04	Other----- . 02	Magnetite-----	4. 93
Epidote----- . 35	Apatite----- . 52			Pyrrhotite-----	. 06
Apatite----- . 20	Pyrite----- . 10	100. 00	100. 00	Other-----	. 05
Magnetite----- . 80					100. 00
100. 00	100. 00				

B. ROCK FORMULAS

[Modified standard cell (MSC)]

Formula

Specimen

B-DDH-8-372

B-DDH-8-367

B-DDH-9B₁-432

C. GAINS AND LOSSES (PER MSC) DURING STEATITIZATION

[Explanation: A plus sign (+) preceding a given value indicates a gain with respect to protolith; a minus sign (−) indicates a loss. An asterisk (*) standing alone indicates no change. The symbol "nd" means "not determined"]

Albitic schist protolith altering to—				Serpentinite protolith altering to—	
	Blackwall W-38	Steatite W-23		Talc-carbonate rock CA-2	
<i>Constituents</i>					<i>Constituents</i>
K-----	− 4. 1	− 4. 2	+ . 02	(*)	K-----
Na-----	− 3. 0	− 3. 4	(*)	(*)	Na-----
Ca-----	+ 1. 0	− . 81	− . 21	− . 22	Ca-----
Mg-----	+ 30. 2	+ 42. 0	− 8. 87	+ 2. 63	Mg-----
Fe ⁺² -----	+ 6. 6	− 2. 6	− . 91	− . 55	Fe ⁺² -----
Mn-----	+ . 13	+ . 02	+ . 08	+ . 17	Mn-----
Ni-----	nd	nd	+ . 08	+ . 09	Ni-----
Co-----	nd	nd	(*)	(*)	Co-----
Al-----	+ 4. 6	− 18. 0	− . 32	− . 69	Al-----
Fe ⁺³ -----	+ . 2	− 1. 2	− 4. 11	− 4. 12	Fe ⁺³ -----
Cr-----	nd	nd	+ . 03	− . 07	Cr-----
Ti-----	+ . 42	− . 57	(*)	(*)	Ti-----
Si-----	− 35. 4	− 3. 6	+ 24. 78	+ . 62	Si-----
P-----	+ . 12	− . 07	(*)	(*)	P-----
S-----	nd	nd	− . 02	− . 03	S-----
As-----	nd	nd	nd	nd	As-----
C-----	(*)	(*)	(*)	(*)	C-----
O-----	− 55. 6	− 7. 9	+ 51. 06	+ 20. 08	O-----
OH-----	+ 54. 3	+ 11. 8	− 35. 91	− 48. 11	OH-----
CO ₂ -----	(*)	(*)	− 3. 11	+ 26. 95	CO ₂ -----
Oeq-----	− 1. 1	+ 3. 9	+ 8. 86	+ 25. 81	Oeq-----

TABLE 16.—Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the west contact of the ultramafic body at Barnes Hill

[Country rock is albitic]

	Albitic schist protolith		Serpentine protolith	Combined blackwall and steatite	Serpentine protolith
	Blackwall B-DDH-8-367	Steatite CA-3	Steatite CA-3		Talc-carbonate rock CA-4
Width of zone.....feet.....	0.5	0.3	3.0	3.8	25
Magnesium:					
Amount per MSC in protolith ¹	2.0	2.0	52.86	-----	52.86
Proportional amount per zone in protolith ²	1.0	.6	158.58	160.27	1321.50
Gain or loss per MSC ³	+30.2	+42.0	-8.87	-----	+2.63
Proportional gain or loss per zone ⁴	+15.1	+12.6	-26.61	+1.00	+65.75
Percent gain or loss over protolith ⁵	+1500	+2100	-17	+6	+5
Ferrous Iron:					
Amount per MSC in protolith.....	3.4	3.4	1.75	-----	1.75
Proportional amount per zone in protolith.....	1.7	1.0	5.25	7.95	43.75
Gain or loss per MSC.....	+6.6	-2.6	-.91	-----	-.55
Proportional gain or loss per zone.....	+3.3	-.8	-2.73	-.23	-13.75
Percent gain or loss over protolith.....	+194	-80	-52	-3	-31
Aluminum:					
Amount per MSC in protolith.....	18.9	18.9	1.24	-----	1.24
Proportional amount per zone in protolith.....	9.5	5.7	3.72	18.92	31.00
Gain or loss per MSC.....	+4.6	-18.0	-.32	-----	-.69
Proportional gain or loss per zone.....	+2.3	-5.4	-.96	-4.06	-17.25
Percent gain or loss over protolith.....	+24	-95	-26	-21	-56
Silicon:					
Amount per MSC in protolith.....	63.9	63.9	35.51	-----	35.51
Proportional amount per zone in protolith.....	32.0	19.2	106.53	157.79	887.75
Gain or loss per MSC.....	-35.4	-3.6	+24.78	-----	+.62
Proportional gain or loss per zone.....	-17.7	-1.1	+74.34	+55.48	+15.50
Percent gain or loss over protolith.....	-55	-6	+70	+35	+2
Hydroxyl:					
Amount per MSC in protolith.....	18.6	18.6	66.35	-----	66.35
Proportional amount per zone in protolith.....	9.3	5.6	199.05	214.04	1658.75
Gain or loss per MSC.....	+54.3	+11.8	-35.91	-----	-48.11
Proportional gain or loss per zone.....	+27.2	+3.5	-107.73	-77.12	-1202.75
Percent gain or loss over protolith.....	+292	+63	-54	-36	-72
Carbon dioxide:					
Amount per MSC in protolith.....	.0	.0	3.11	-----	3.11
Proportional amount per zone in protolith.....	.0	.0	9.33	9.33	77.75
Gain or loss per MSC.....	.0	.0	-3.11	-----	+26.95
Proportional gain or loss per zone.....	.0	.0	-9.33	-9.33	+673.75
Percent gain or loss over protolith.....	.0	.0	-100	-100	+867
Oxygen equivalent:					
Amount per MSC in protolith.....	178.9	178.9	173.97	-----	173.97
Proportional amount per zone in protolith.....	89.5	53.7	521.91	665.35	4349.25
Gain or loss per MSC.....	-1.1	+3.9	+8.86	-----	+25.81
Proportional gain or loss per zone.....	-.6	+1.2	+26.58	+26.94	+645.25
Percent gain or loss over protolith.....	-.7	+2	+5	+4	+15

¹ Obtained from rock formula of protolith, table 15.² Equal to the amount per MSC in protolith multiplied by width of zone.³ Obtained from table 15.⁴ Equal to the gain or loss per MSC multiplied by width of zone in feet.⁵ In terms of a unit of volume, and equal to the gain or loss per MSC divided by the amount per MSC in protolith.

TABLE 17.—Calculated modes, rock formulas, and gains and losses during steatitization, for specimens across the east contact of the ultramafic body at Barnes Hill

[Country rock is albitic]

A. CALCULATED MODES

[Values are given in volume percent]

Albitic schist protolith			Serpentinite protolith		
Albitic schist B-DDH-11-78	Blackwall B-DDH-11-76	Steatite CA-3	Talc-carbonate rock CA-4	Serpentinite B-DDH-9B ₁ -432	
Sericite..... 28.30	Chlorite..... 78.83	Talc..... 99.90	Talc..... 59.94	Serpentine.....	85.35
Albite..... 25.80	Actinolite..... 17.96	Apatite..... .03	Carbonate..... 40.00	Talc.....	5.26
Quartz..... 22.88	Albite..... 1.32	Magnetite..... .02	Apatite..... .03	Carbonate.....	4.32
Chlorite..... 19.70	Sphene..... 1.23	Pyrite..... .01	Pyrite..... .01	Apatite.....	.03
Sphene..... .99	Sericite..... .58	Other..... .04	Other..... .02	Magnetite.....	4.93
Garnet..... .56	Apatite..... .08			Pyrrhotite.....	.06
Carbonate..... .46		100.00	100.00	Other.....	.05
Apatite..... .26	100.00				100.00
Ilmenite..... .53					
Pyrite..... .52					
100.00					

B. ROCK FORMULAS

[Modified standard cell (MSC)]

Formula

Specimen

B-DDH-11-78

$$\left[K_{.4}Na_{.4}Ca_{.31}Mg_{3.7}Fe^{+2}_{4.8}Mn_{.16}Al_{23.2}Fe^{+3}_{1.2}Ti_{.72}Si_{56.1}P_{.10}S_{.91}O_{143.2}(OH)_{21.9}(CO_2)_{.26} \right] \begin{matrix} \text{Cat.} = 100.8 \\ \text{Oeq} = 166.5 \end{matrix}$$

B-DDH-11-76

$$\left[K_{.08}Na_{.27}Ca_{3.2}Mg_{34.4}Fe^{+2}_{7.9}Mn_{.27}Al_{15.7}Fe^{+3}_{.55}Ti_{.44}Si_{40.2}P_{.03}S_{.09}O_{122.4}(OH)_{58.6} \right] \begin{matrix} \text{Cat.} = 103.0 \\ \text{Oeq} = 180.9 \end{matrix}$$

$$CA-3 \left[K_{.04}Na_{.00}Ca_{.02}Mg_{43.99}Fe^{+2}_{.84}Mn_{.15}Ni_{.15}Co_{.01}Al_{.92}Fe^{+3}_{.03}Cr_{.25}Ti_{.01}Si_{60.29}P_{.01}S_{.02}O_{152.38}(OH)_{30.44}(CO_2)_{.00} \right] \begin{matrix} \text{Cat.} = 106.70 \\ \text{Oeq} = 182.83 \end{matrix}$$

$$CA-4 \left[K_{.02}Na_{.00}Ca_{.01}Mg_{55.49}Fe^{+2}_{1.20}Mn_{.24}Ni_{.16}Co_{.01}Al_{.55}Fe^{+3}_{.02}Cr_{.15}Ti_{.01}Si_{36.13}P_{.01}S_{.01}O_{121.40}(OH)_{18.24}(CO_2)_{30.06} \right] \begin{matrix} \text{Cat.} = 124.08 \\ \text{Oeq} = 199.78 \end{matrix}$$

B-DDH-9B₁-432

$$\left[K_{.02}Na_{.00}Ca_{.23}Mg_{52.86}Fe^{+2}_{1.75}Mn_{.07}Ni_{.07}Co_{.01}Al_{.24}Fe^{+3}_{.14}Cr_{.22}Ti_{.01}Si_{35.51}P_{.01}S_{.04}As_{.04}O_{101.32}(OH)_{66.35}(CO_2)_{3.11} \right] \begin{matrix} \text{Cat.} = 99.37 \\ \text{Oeq} = 173.97 \end{matrix}$$

C. GAINS AND LOSSES (PER MSC) DURING STEATITIZATION

[Explanation: A plus sign (+) preceding a given value indicates a gain with respect to protolith; a minus sign (−) indicates a loss. An asterisk (*) standing alone indicates no change. The symbol "nd" means "not determined"]

Constituents	Albitic schist protolith altering to—			Serpentinite protolith altering to—		
	Blackwall W-38	Steatite W-33		Talc-carbonate rock CA-2	Constituents	
K.....	— .34	— .38	+ .02	(*)	.....	K
Na.....	— 5.1	— 5.4	(*)	(*)	.....	Na
Ca.....	+ 2.4	— .79	— .21	— .22	.....	Ca
Mg.....	+ 30.7	+ 40.3	— 8.87	+ 2.63	.....	Mg
Fe ⁺²	+ 3.1	— 4.0	— .91	— .55	.....	Fe ⁺²
Mn.....	— .11	— .01	+ .08	+ .17	.....	Mn
Ni.....	nd	nd	+ .08	+ .09	.....	Ni
Co.....	nd	nd	(*)	(*)	.....	Co
Al.....	— 7.5	— 22.3	— .32	— .69	.....	Al
Fe ⁺³	— .6	— 1.2	— 4.11	— 4.12	.....	Fe ⁺³
Cr.....	nd	nd	+ .03	— .07	.....	Cr
Ti.....	— .28	— .71	(*)	(*)	.....	Ti
Si.....	— 15.9	+ 4.2	+ 24.78	+ .62	.....	Si
P.....	— .07	— .09	(*)	(*)	.....	P
S.....	— .82	— .89	— .02	— .03	.....	S
As.....	nd	nd	nd	nd	.....	As
O.....	— 20.8	+ 9.2	+ 51.06	+ 20.08	.....	O
OH.....	+ 36.7	+ 8.5	— 35.91	— 48.11	.....	OH
CO ₂	— .26	— .26	— 3.11	+ 26.95	.....	CO ₂
Oeq.....	+ 14.4	+ 16.3	+ 8.86	+ 25.81	.....	Oeq

TABLE 18.—Gains and losses during steatitization, per zone, for selected elements and radicals, for specimens across the east contact of the ultramafic body at the Barnes Hill locality

[Country rock is albitic]

	Albitic schist protolith		Serpentine protolith	Combined black-wall and steatite	Serpentine protolith
	Blackwall B-DDH-11-76	Steatite CA-3	Steatite CA-3		Talc-carbonate rock CA-4
Width of zone-----feet-----	0.5	0.3	3.0	-----	25
Magnesium:					
Amount per MSC in protolith ¹ -----	3.7	3.7	52.86	-----	52.86
Proportional amount per zone in protolith ² -----	1.9	1.1	158.58	161.67	1,321.50
Gain or loss per MSC ³ -----	+30.7	+40.3	-8.87	-----	+2.63
Proportional gain or loss per zone ⁴ -----	+15.3	+12.1	-26.61	+7	+65.75
Percent gain or loss over protolith ⁵ -----	+805	+1,100	-17	+4	+5
Ferrous iron:					
Amount per MSC in protolith-----	4.8	4.8	1.75	-----	1.75
Proportional amount per zone in protolith-----	2.4	1.4	5.25	9.05	43.75
Gain or loss per MSC-----	+3.1	-4.0	-91	-----	-55
Proportional gain or loss per zone-----	+1.5	-1.2	-2.73	-2.43	-13.75
Percent gain or loss over protolith-----	+63	-86	-52	-27	-31
Aluminum:					
Amount per MSC in protolith-----	23.2	23.2	1.24	-----	1.24
Proportional amount per zone in protolith-----	11.6	7.0	3.72	22.32	31.00
Gain or loss per MSC-----	-7.5	-22.3	-32	-----	-69
Proportional gain or loss per zone-----	-3.7	-6.7	-96	-11.36	-17.25
Percent gain or loss over protolith-----	-32	-96	-26	-51	-56
Silicon:					
Amount per MSC in protolith-----	56.1	56.1	35.51	-----	35.51
Proportional amount per zone in protolith-----	28.0	16.8	106.53	151.39	887.75
Gain or loss per MSC-----	-15.9	+4.2	+24.78	-----	+62
Proportional gain or loss per zone-----	-7.9	+1.3	+74.34	+67.68	+15.50
Percent gain or loss over protolith-----	-28	+8	+70	+45	+2
Hydroxyl:					
Amount per MSC in protolith-----	21.9	21.9	66.35	-----	66.35
Proportional amount per zone in protolith-----	10.9	6.6	199.05	216.64	1,658.75
Gain or loss per MSC-----	+36.7	+8.5	-35.91	-----	-48.11
Proportional gain or loss per zone-----	+18.3	+2.6	-107.73	-86.92	-1,202.75
Percent gain or loss over protolith-----	+168	+39	-54	-40	-72
Carbon dioxide:					
Amount per MSC in protolith-----	.26	.26	3.11	-----	3.11
Proportional amount per zone in protolith-----	.13	.08	9.33	9.54	77.75
Gain or loss per MSC-----	-.26	-.26	-3.11	-----	+26.95
Proportional gain or loss per zone-----	-.13	-.08	-9.33	-9.54	+673.75
Percent gain or loss over protolith-----	-100	-100	-100	-100	+867
Oxygen equivalent:					
Amount per MSC in protolith-----	166.5	166.5	173.97	-----	173.97
Proportional amount per zone in protolith-----	83.2	50.0	521.91	655.35	4,349.25
Gain or loss per MSC-----	+14.4	+16.3	+8.86	-----	+25.81
Proportional gain or loss per zone-----	+7.2	+4.9	+26.58	+38.44	+645.25
Percent gain or loss over protolith-----	+9	+10	+5	+6	+15

¹ Obtained from rock formula of protolith, table 17.² Equal to the amount per MSC in protolith multiplied by width of zone.³ Obtained from table 17.⁴ Equal to the gain or loss per MSC multiplied by width of zone in feet.⁵ In terms of a unit of volume, and equal to the gain or loss per MSC divided by the amount per MSC in protolith.

TABLE 19.—*Calculated modes, rock formulas, and gains and losses during steatitization, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist*

[Country rock is albitic]

A. CALCULATED MODES

[Values are given in volume percent]

Albitic schist protolith					Serpentinite protolith						
Albitic schist CA-5		Albite porphyroblast rock CA-6		Blackwall CA-7		Steatite CA-8		Talc-carbonate rock CA-9		Serpentinite CA-10	
Quartz-----	39. 60	Quartz-----	8. 08	Chlorite----	97. 18	Talc-----	99. 92	Talc-----	61. 55	Serpentine--	97. 34
Sericite----	27. 65	Sericite----	4. 95	Sphene-----	2. 19	Magnetite--	. 02	Carbonate--	38. 32	Magnetite--	2. 56
Albite-----	15. 43	Albite-----	62. 45	Rutile-----	. 10	Pyrite-----	. 06	Magnetite--	. 03	Pyrrhotite--	. 10
Chlorite----	7. 97	Chlorite----	6. 05	Apatite----	. 23			Pyrrhotite--	. 10		
Biotite-----	3. 57	Biotite-----	12. 90	Pyrite-----	. 30		100. 00				100. 00
Garnet-----	2. 00	Garnet-----	. 96						100. 00		
Carbonate--	. 20	Carbonate--	. 14		100. 00						
Apatite-----	. 30	Apatite-----	. 30								
Epidote----	. 20	Epidote-----	. 10								
Sphene-----	. 85	Sphene-----	. 88								
Ilmenite----	. 43	Ilmenite----	. 37								
Pyrite-----	. 30	Rutile-----	. 02								
Graphite--	1. 50	Pyrite-----	. 30								
		Graphite--	2. 50								
	100. 00		100. 00								

B. ROCK FORMULAS

[Modified standard cell (MSC)]

Specimen

Formula

CA-5-	$\left[K_{4.52}Na_{3.19}Ca_{.68}Mg_{2.20}Fe^{+2}_{3.75}Mn_{.21}Ni_{.02}Co_{.01}Al_{18.64}Fe^{+3}_{.41}Cr_{.02}Ti_{.59}Si_{62.61}P_{.11}S_{.51}As_{.00}C_{5.80}O_{158.04}(OH)_{15.17}(CO_2)_{.11} \right]$	Cat. = 102.87 Oeq = 176.84
CA-6-	$\left[K_{2.48}Na_{12.89}Ca_{.63}Mg_{3.15}Fe^{+2}_{4.82}Mn_{.22}Ni_{.02}Co_{.01}Al_{19.59}Fe^{+3}_{.42}Cr_{.02}Ti_{.59}Si_{55.41}P_{.11}S_{.51}As_{.00}C_{9.67}O_{153.68}(OH)_{9.62}(CO_2)_{.08} \right]$	Cat. = 110.11 Oeq = 168.80
CA-7-	$\left[K_{.02}Na_{.01}Ca_{.96}Mg_{33.41}Fe^{+2}_{11.22}Mn_{.21}Ni_{.02}Co_{.01}Al_{24.68}Fe^{+3}_{.39}Cr_{.02}Ti_{.93}Si_{26.60}P_{.09}S_{.51}As_{.00}C_{.00}O_{100.16}(OH)_{76.45}(CO_2)_{.00} \right]$	Cat. = 98.56 Oeq = 177.31
CA-8-	$\left[K_{.00}Na_{.00}Ca_{.00}Mg_{42.17}Fe^{+2}_{2.47}Mn_{.07}Ni_{.16}Co_{.02}Al_{90}Fe^{+3}_{19}Cr_{.20}Ti_{.02}Si_{60.04}P_{.02}S_{.11}As_{.002}C_{.00}O_{151.74}(OH)_{30.33}(CO_2)_{.00} \right]$	Cat. = 106.27 Oeq. = 182.18
CA-9-	$\left[K_{.00}Na_{.00}Ca_{.00}Mg_{50.24}Fe^{+2}_{5.13}Mn_{.36}Ni_{.17}Co_{.01}Al_{.51}Fe^{+3}_{.50}Cr_{.12}Ti_{.01}Si_{36.83}P_{.01}S_{.11}As_{.003}C_{.00}O_{121.87}(OH)_{18.61}(CO_2)_{28.56} \right]$	Cat. = 122.46 Oeq = 197.71
CA-10-	$\left[K_{.00}Na_{.00}Ca_{.00}Mg_{50.24}Fe^{+2}_{4.50}Mn_{.06}Ni_{.17}Co_{.01}Al_{1.60}Fe^{+3}_{2.05}Cr_{.34}Ti_{.01}Si_{36.83}P_{.02}S_{.11}As_{.002}C_{.00}O_{97.68}(OH)_{73.69}(CO_2)_{.00} \right]$	Cat. = 95.83 Oeq = 171.49

TABLE 19.—*Calculated modes, rock formulas, and gains and losses during steatitization, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist—Continued*

C. GAINS AND LOSSES (PER MSC) DURING STEATITIZATION

[Explanation: A plus sign (+) preceding a given value indicates a gain with respect to protolith; a minus sign (−) indicates a loss. An asterisk (*) standing alone indicates no change]

Albitic schist protolith altering to—					Serpentine protolith altering to—	
	Albite porphyro- blast rock CA-6	Blackwall CA-7	Steatite CA-8		Talc-carbonate rock CA-9	
<i>Constituents</i>						<i>Constituents</i>
K	−2.04	−4.50	−4.52	(*)	(*)	K
Na	+9.70	−3.18	−3.19	(*)	(*)	Na
Ca	−.05	+ .28	−.68	(*)	(*)	Ca
Mg	+ .95	+31.21	+39.97	−8.07	(*)	Mg
Fe ⁺²	+1.07	+7.47	−1.28	−2.03	+0.63	Fe ⁺²
Mn	+ .01	(*)	−.14	+ .01	+ .30	Mn
Ni	(*)	(*)	+ .14	−.01	(*)	Ni
Co	(*)	(*)	+ .01	+ .01	(*)	Co
Al	+ .95	+6.04	−17.74	−.70	−1.09	Al
Fe ⁺³	+ .01	−.02	−.22	−1.86	−1.55	Fe ⁺³
Cr	(*)	(*)	+ .18	−.14	−.22	Cr
Ti	(*)	+ .34	−.57	+ .01	(*)	Ti
Si	−7.20	−36.01	−2.57	+23.21	(*)	Si
P	(*)	−.02	−.09	(*)	−.01	P
S	(*)	(*)	−.40	(*)	(*)	S
As	(*)	(*)	+ .002	(*)	+ .001	As
C	+3.87	−5.80	−5.80	(*)	(*)	C
O	−4.36	−57.88	−6.30	+54.06	+24.19	O
OH	−5.55	+61.88	+15.16	−43.36	−55.08	OH
CO ₂	−.03	−.11	−.11	(*)	+28.56	CO ₂
Oeq	−8.04	+ .47	+5.34	+10.69	+26.22	Oeq

TABLE 20.—Gains and losses during steatitization, per zone, for selected elements and radicals, for an idealized suite of specimens across the contact between an ultramafic body and albitic schist

[Country rock is albitic]

	Albitic schist protolith		Serpentine protolith	Combined black-wall and steatite	Serpentine protolith
	Blackwall CA-7	Steatite CA-8	Steatite CA-8		Talc-carbonate rock CA-9
Width of zone.....feet..	0. 456	0. 250	3. 000	3. 706	-----
Magnesium:					
Amount per MSC in protolith.....	2. 20	2. 20	50. 24	-----	50. 24
Proportional amount per zone in protolith.....	1. 00	. 55	150. 72	152. 27	-----
Gain or loss per MSC.....	+31. 21	+39. 97	-8. 07	-----	. 00
Proportional gain or loss per zone.....	+14. 22	+9. 99	-24. 21	. 00	-----
Percent gain or loss over protolith.....	+1, 422	+1, 816	-16	. 00	. 00
Ferrous iron:					
Amount per MSC in protolith.....	3. 75	3. 75	4. 50	-----	4. 50
Proportional amount per zone in protolith.....	1. 71	. 94	13. 50	16. 15	-----
Gain or loss per MSC.....	+7. 47	-1. 28	-2. 03	-----	+ . 63
Proportional gain or loss per zone.....	+3. 41	-. 32	-6. 09	-3. 00	-----
Percent gain or loss over protolith.....	+200	-34	-45	-19	+14
Aluminum:					
Amount per MSC in protolith.....	18. 64	18. 64	1. 60	-----	1. 60
Proportional amount per zone in protolith.....	8. 50	4. 66	4. 80	17. 96	-----
Gain or loss per MSC.....	+6. 04	-17. 74	-. 70	-----	-1. 09
Proportional gain or loss per zone.....	+2. 75	-4. 44	-2. 10	-3. 79	-----
Percent gain or loss over protolith.....	+32	-95	-44	-21	-68
Silicon:					
Amount per MSC in protolith.....	62. 61	62. 61	36. 83	-----	36. 83
Proportional amount per zone in protolith.....	28. 55	15. 65	110. 49	154. 69	-----
Gain or loss per MSC.....	-36. 01	-2. 57	+23. 21	-----	. 00
Proportional gain or loss per zone.....	-16. 42	-. 64	+69. 63	+52. 57	-----
Percent gain or loss over protolith.....	-58	-4	+63	+34	. 00
Hydroxyl:					
Amount per MSC in protolith.....	15. 17	15. 17	73. 69	-----	73. 69
Proportional amount per zone in protolith.....	6. 92	3. 79	221. 07	231. 78	-----
Gain or loss per MSC.....	+61. 28	+15. 16	-43. 36	-----	-55. 08
Proportional gain or loss per zone.....	+27. 94	+3. 79	-130. 08	-98. 35	-----
Percent gain or loss over protolith.....	+404	+100	-59	-42	-75
Carbon dioxide:					
Amount per MSC in protolith.....	. 11	. 11	. 00	-----	. 00
Proportional amount per zone in protolith.....	. 05	. 03	. 00	. 08	-----
Gain or loss per MSC.....	-. 11	-. 11	. 00	-----	+28. 56
Proportional gain or loss per zone.....	-. 05	-. 03	. 00	-. 08	-----
Percent gain or loss over protolith.....	-100	-100	. 00	-100	Very large gain
Oxygen equivalent:					
Amount per MSC in protolith.....	176. 84	176. 84	171. 49	-----	171. 49
Proportional amount per zone in protolith.....	80. 64	44. 21	514. 47	639. 32	-----
Gain or loss per MSC.....	+ . 47	+5. 34	+10. 69	-----	+26. 22
Proportional gain or loss per zone.....	+ . 21	+1. 34	+32. 07	+33. 62	-----
Percent gain or loss over protolith.....	+ . 3	+3	+6	+5	+15

¹ Obtained from rock formula of protolith, table 19.² Equal to the amount per MSC in protolith multiplied by width of zone.³ Obtained from table 19.⁴ Equal to the gain or loss per MSC multiplied by width of zone in feet.⁵ In terms of a unit of volume, and equal to the gain or loss per MSC divided by the amount per MSC in protolith.

Tables 11 to 18 and figures 24 to 31 are based upon chemical analyses of actual suites of rocks that extend from the schist to the serpentinite across the contact of a given deposit, or of partial suites supplemented either by additional chemical analyses or by calculated chemical analyses (see, for instance, calculated analyses CA-1 and CA-2, tables 58 and 59). The calculated analyses for most rocks are based upon modes measured in thin section; for talc-carbonate rock, thin-section measurements are supplemented by industrial tests that give a general measure of the carbonate content (see p. 77-78). The widths of the various zones (blackwall, steatite, and the others) are based upon numerous observations at scattered points, so that they can be regarded as reliably ascertained for general magnitude. However, most of the observations were made under conditions of exposure and accessibility that did not permit precise determination of thicknesses. The thickness of steatite derived from schist is particularly difficult to observe in the field, and is undoubtedly the least reliable figure. Individual determinations of the thickness of other zones may be in error by as much as 25 percent. Nevertheless, it will become clear in later discussion of the blackwall-steatite reaction that interchange of material among the zones, deduced on the basis of the width assigned in the tables, is so neatly integrated that the conclusion appears to be warranted that the zone widths assigned are probably essentially correct.

Tables 19 and 20 and figures 32 and 33 are based upon tables 11 to 18 and figures 24 to 31. They are constructed from idealized calculated chemical analyses, and are intended to present an idealized picture of the changes that take place during steatitization. They are, of course, interpretive to the extent that they are idealized. The leeway in interpretation is obvious on comparison with the other tables and text figures. The changes in some of the minor elements and of the less abundant and less common minerals are particularly subject to qualification as being unsatisfactorily substantiated. These qualifications will become clear in later discussion.

Table 21, based upon tables 12, 14, 16, 18, and 20, summarizes for the several suites the percentage gains and losses of principal constituents, relative to the original content of the protolith, that occurred among the alteration products during steatitization.

It is evident from the data of tables 11 to 20 and figures 24 to 33 that the talc-carbonate rock on the one hand, and the steatite and blackwall on the other, formed essentially independently of one another insofar as chemical interchange and introduction of material are concerned—though both alterations undoubtedly took place concurrently. It is readily conceivable,

TABLE 21.—Percentage gains and losses per modified standard cell of the principal constituents, relative to the original content of the protolith, for the rocks formed during steatitization

	Table	Gain (+) or loss (—), in percent, for—				
		Blackwall (from schist)	Steatite (from schist)	Steatite (from serpen- tinite)	Combined blackwall and steatite	Talc- carbonate rock (from serpentinite)
Mg----	12	+362	+590	-18	+0.01	-4
	14	+943	+1,027	-18	+9	+4
	16	+1,500	+2,100	-17	+6	+5
	18	+805	+1,100	-17	+4	+5
	20	+1,422	+1,816	-16	.0	.0
Fe ²⁺ ----	12	+480	+27	-6	+54	+60
	14	+481	+253	-6	-32	+60
	16	+194	-80	-52	-3	-31
	18	+63	-86	-52	-27	-31
	20	+200	-34	-45	-19	+14
Al-----	12	-8	-96	-17	-40	+9
	14	-24	-94	-17	-44	+9
	16	+24	-95	-26	-21	-56
	18	-32	-96	-26	-51	-56
	20	+32	-95	-44	-21	-68
Si-----	12	-51	+12	+50	+26	-2
	14	-33	-6	+50	+28	-2
	16	-55	-6	+70	+35	+2
	18	-28	+8	+70	+45	+2
	20	-58	-4	+63	+34	.0
OH-----	12	+156	+13	-55	-37	-73
	14	+268	+103	-55	-40	-73
	16	+292	+63	-54	-36	-72
	18	+168	+39	-54	-40	-72
	20	+404	+100	-59	-42	-75
CO ₂ ----	12	-75	-100	-100	-93	+25,470
	14	-100	-100	-100	-100	+25,470
	16	.0	.0	-100	-100	+887
	18	-100	-100	-100	-100	+887
	20	-100	-100	.0	-100	Very large gain
Oeq-----	12	-1	+2	+5	+4	+14
	14	+3	+3	+5	+5	+14
	16	-.7	+2	+5	+4	+15
	18	+9	+10	+5	+6	+15
	20	+3	+3	+6	+5	+15

therefore, that in some ultramafic bodies access of CO₂ was very limited or nil (locally, or entirely), that no talc-carbonate rock was formed, and that only the blackwall-steatite reaction operated effectively. It seems probable, however, that the talc-carbonate rock reaction was always accompanied by the blackwall-steatite reaction, which was not dependent upon introduction of material from outside the system and which was subject to the same general limitations of temperature and pressure as the talc-carbonate rock reaction. Possibly, also, the talc-carbonate rock reaction had a catalytic effect upon the blackwall-steatite reaction because of the release of abundant water from the serpentinite.

The relations at the Mad River locality, where the steatite and blackwall zones are thin and talc-carbonate rock absent about midway along the borders of the ultramafic body, and the steatite zone thicker at the ends of the body, where talc-carbonate rock is abundant, appear to illustrate particularly well not only the separateness of the talc-carbonate rock and the blackwall-steatite reactions but also the possible catalytic effect of the talc-carbonate rock reaction upon the blackwall-steatite reaction.

The above-mentioned tables and text figures contain the full account of quantitative gains and losses among the several rock types during steatitization. They are generally self-explanatory, but some of the data are erratic and some require qualification, even for the idealized ones. The remainder of this section will be devoted to discussion of the more important features of the tables and text figures and to examination of the processes and reactions by which the changes illustrated were brought about. In general, reference will be made to the idealized tables and graphs (tables 19 and 20 and figs. 32 and 33), because they lend themselves better to general discussion without overmuch qualification and illustrate better the various points to be made.

TALC-CARBONATE ROCK REACTION

The alteration of serpentinite to talc-carbonate rock may be represented approximately by the equation

where the Mg:Fe^{+2} ratio may differ for each mineral, and x and y vary in such a way that the total $(\text{Mg} + \text{Fe}^{+2} + \text{Fe}^{+3})$ is the same for both sides of the equation. The reaction involved chiefly the addition of CO_2 and the loss of H_2O . Gains or losses in other constituents appear for the most part to have been less than about 1 percent and may have been essentially zero for nearly all constituents except CO_2 and H_2O . The uncertainty arises from the fact that many of the constituents (such as Fe^{+2} , Fe^{+3} , and Al) present in small amounts are associated in appreciable proportion with minerals, such as magnetite and pyrite, whose distribution is spotty in both serpentinite and talc-carbonate rock, so that practical sampling procedures are inadequate for evaluating relative changes in those constituents. The case for each constituent will be discussed fully in the section on "Geochemistry of the rocks affected by steatitization," p. 124-128.

The calculations based upon the assumption of constant-volume replacement of serpentinite by talc-carbonate rock agree surprisingly well with field observations with respect to the proportion of talc and carbonate in talc-carbonate rock. In particular, the calculations agree strikingly with observed differences in carbonate content between Barnes Hill and Waterbury mine. Such agreement appears intuitively to furnish strong support for volume-for-volume replacement, as does also the simplicity of the alteration process—in which the formation of talc-carbonate rock is regarded

as being brought about simply by the addition of CO_2 and the loss of H_2O —that results from assuming constant-volume replacement. Such a conclusion would mean, if Si, Mg, and Fe were neither gained nor lost, that the composition of the talc and carbonate, and the proportion and composition of magnetite, along with the degree and nature of the alteration of the accessory minerals, varied in such a way that constant-volume relations were maintained. Thus the volume relations would be the immediate determining factor, within limits, controlling the composition of the talc and carbonate and also the proportion of magnetite; but the composition of all would rest fundamentally upon the composition of the original serpentinite.

If maintenance of constant-volume relations in the alteration of serpentinite to talc-carbonate rock is of paramount importance, the reaction can be represented essentially according to the equation

where a , b , and c are fractions that total less than 1 on either side of the equation, and V represents equal volumes of serpentinite and talc-carbonate rock; the short arrows under CO_2 and H_2O signify that they are mobile constituents that do not enter into considerations of volume relations. The volume proportion of talc in talc-carbonate rock depends upon the proportion of Si—and that probably negligible proportion of Al that may substitute for Si in talc—in the original rock, which controls the molecular proportion; upon the $\text{Mg}:\text{Fe}^{+2}$ ratio in the talc, which affects the equivalent molecular volume; and upon the proportion of accessory minerals. A marked sensitivity to pressure in the equilibrium relations between talc, carbonate, and magnetite is implied. Adjustment in the system would appear to depend chiefly upon variation of the $\text{Mg}:\text{Fe}^{+2}$ ratio in the different minerals and upon changes in the $\text{Fe}^{+3}:\text{Fe}^{+2}$ ratio, manifested by changes in content of magnetite, in the system. A necessary corollary to change in the $\text{Fe}^{+3}:\text{Fe}^{+2}$ ratio is that O was mobile. A logical inference of the entire line of reasoning is that the chemical potential of O is significantly sensitive to pressure, and that this sensitivity is one of the more important factors in maintaining constant-volume relations in the talc-carbonate rock reaction. The variation of equivalent molecular volume with the $\text{Mg}:\text{Fe}^{+2}$ ratio in talc is not known, and there are uncertainties about the crystal chemistry of talc. The many factors involved make it difficult to test the idea of constant-volume control over composition.

BOUNDARY BETWEEN TALC-CARBONATE ROCK AND SERPENTINITE

The alteration of serpentinite to talc-carbonate rock took place at a moving boundary, grossly concentric with the borders of the ultramafic body, that marked the position at which the chemical potential of CO_2 attained a value such that serpentine was replaced by talc and magnesite; magnetite decreased in volume and probably altered in composition. As the reaction proceeded and the alteration was completed at successive positions, the boundary migrated inward toward the center of the ultramafic body. The principal features of the reaction were ingress of CO_2 and egress of H_2O . Other changes were limited essentially to adjustments of the various components among the minerals serpentine, talc, magnesite, and magnetite.

SERPENTINITE-DUNITE BOUNDARY

Theoretical considerations indicate that, concurrently with the talc-carbonate rock reaction, another moving boundary was defined by the conversion to serpentine (and magnetite) of any relict grains of olivine or masses of dunite in the ultramafic body, by reaction with water released from the talc-carbonate rock reaction. This boundary marked the position at which the chemical potential of H_2O attained a value such that olivine was unstable and was replaced by serpentine; it was concentric with the outlines of dunite masses and olivine grains. As serpentinization was completed at successive positions the boundary migrated inward toward the centers of the dunite masses. Ingress of H_2O and loss of Mg were the principal features of the reaction. The Mg may have migrated to the talc-carbonate zone to form magnesite. However, it has been shown above (p. 91) that the proportion of olivine and dunite in the ultramafic bodies here considered was probably very small at the beginning of steatitization; the amount of serpentine formed by such reaction was probably negligible.

BLACKWALL-STEATITE REACTION

Within the limits of the system embraced by the blackwall and steatite, it is evident from table 20 that steatitization involved chiefly the addition of Si and the loss of H_2O . Interchange between rocks within the system of a few other constituents was relatively great, but the gains and losses to the system of these and of the remaining constituents was small. By enlarging the system to include a few feet (possibly as much as 10 feet) of the schist bordering the blackwall, the gains and losses to the system could be reduced essentially to zero except for H_2O , which could then be considered the sole mobile constituent. (CO_2 , though migrating freely through the blackwall-steatite zones, does not enter into the reactions in those zones in significant amounts, and plays a "transient" role.)

In other words, the steatite-blackwall alteration can be regarded as a metamorphic-differentiation reaction (Phillips and Hess, 1936, p. 333-362) in which only H_2O is gained or lost to the system, if the added SiO_2 is regarded as being derived from the schist bordering the blackwall and if the other minor changes originate or terminate in the schist within a few inches or a few feet of the blackwall. This condition is obviously true for Na, which migrates outward only as far as the albite porphyroblast zone bordering the blackwall. The evidence suggests, but is not conclusive, that the same is true of K and biotite. The migration of Al is partly tied in with that of Na and the development of albite porphyroblasts, and is consistent with the conditions postulated. The condition for the other elements is less easily checked, but there appears to be no evidence against the model picture in any instance, and it may be reasonably assumed that they, too, behave accordingly. With this model system as a basis for discussion, the blackwall-steatite reaction may be generalized about as follows:

Steatite and blackwall formed simultaneously by metamorphic differentiation, with the alteration of serpentinite to steatite supplying Mg and H_2O (the latter in excess) to the developing blackwall zone, and the alteration of schist to blackwall supplying Si to the developing steatite zone. Simultaneous alteration to steatite of the schist immediately next to the original contact of the serpentinite supplied Al to the developing blackwall zone. With continuation of the process the inner portion of the blackwall was altered to steatite, supplying Al to the continuously widening blackwall zone and deriving Si from the schists beyond; the steatite zone was also widening at the expense of serpentinite—at a much greater rate than at the expense of former schist—so that Mg was continuously supplied to the growing blackwall zone. Movement of other constituents, which was relatively unimportant in general, will be considered later under the section "Geochemistry of the rocks affected by steatitization."

Tremolite formed locally at the contact between blackwall and steatite where conditions, such as availability of Ca, were favorable. Physical conditions were very close to those of the lower limits at which actinolite is stable, so that the distribution of tremolite is spotty, the crystals comparatively small, and the amount distinctly limited. Progressive changes in bulk composition through addition of Mg from the serpentinite, loss of Si to the talc, and perhaps in loss of Ca to carbonate because of rising partial pressure of CO_2 with duration of metamorphism, resulted commonly in partial replacement of tremolite by talc.

The conspicuous albite porphyroblast zone at the outer border of the blackwall next to albitic schist

formed concurrently with the blackwall as a result of the outward displacement of Na (and, probably, in some instances, of Al) by the advancing wave of chlorite of the blackwall, which replaced nearly all minerals in its path. The displaced Na (and Al) reacted almost immediately beyond the advancing front of blackwall with constituents of the schist, particularly quartz, to form heavy concentrations of albite porphyroblasts. Biotite and muscovite and the associated K probably behaved somewhat analogously to albite and the associated Na, but the data are not so conclusive nor the results so striking; these minerals probably dispersed farther into the schist. Graphite appears to have been displaced by the chlorite of the blackwall as if "flushed out" so that it formed heavy concentrations at the contact between blackwall and schist.

Apatite, epidote, zircon, pyrite, ilmenite, sphene, and rutile were all relatively persistent during steatitization, but most were involved to some extent in the reactions. The general decrease, inward from the schist, of the content of apatite and epidote in the blackwall and outermost steatite, and the textural evidence of replacement shown by many of the grains, indicates that both were slowly but progressively replaced by chlorite and talc. Some of the P of apatite may have substituted for Si in chlorite and talc or all may have migrated outward. Ca from both apatite and epidote probably reacted with the titanium minerals in the blackwall zone in the manner discussed immediately below. The distribution of pyrite is so irregular that its behaviour during steatitization cannot be accurately deduced; some grains appear to have been partially replaced by chlorite. Zircon appears to have persisted without being affected by any reactions. Ilmenite, rutile, and sphene show general relationships (see p. 69) that indicate successive alteration of ilmenite $\rightarrow$ rutile $\rightarrow$ sphene. Both ilmenite and sphene are common in schist and greenstone, and laths of ilmenite are commonly bordered by rims of sphene, but the full sequence ilmenite $\rightarrow$ rutile $\rightarrow$ sphene was observed only in the blackwall. The alteration appears, therefore, to be associated in space and time with steatitization. There also appears to be a relative diminution of total titanium minerals at the inner border of the blackwall zone and in the steatite derived from schist.

The reactions among the titanium minerals could not have resulted primarily from changes in temperature, if the earlier conclusions on temperature relations during steatitization be correct (see p. 94); the reactions must, then, have occurred as a result of other factors, such as bulk chemical changes brought about by steatitization or the making available of elements released by other reactions. The alteration of ilmenite

(FeTiO_3) to rutile (TiO_2) involves loss of FeO; the alteration of rutile to sphene (CaTiSiO_5) requires addition of CaO and SiO_2 . These several restrictions suggest the following explanation for the reactions.

In the early stages of steatitization—or in the outer part of the blackwall zone—ilmenite altered to rutile because the blackwall, being composed entirely of chlorite, could accommodate much more iron than could the schist, and iron consequently diffused from the ilmenite to the chlorite. A similar reaction with biotite may have occurred where concentrations of biotite were formed just outside the blackwall. In the later stages of steatitization, near the inner blackwall zone, CaO released by the slow alteration of epidote and apatite—and perhaps from calcite—reacted with rutile and SiO_2 —migrating from the schist inward toward the steatite zone—to form sphene. Locally, agglomeration of finely dispersed grains—about relatively few nuclei appears to have occurred. Throughout the steatitization process the total content of ilmenite, rutile, and sphene in the rocks being altered to blackwall and steatite was reduced proportionately to the extent that Ti could enter into the structure of chlorite and talc.

The diverse reactions and interchanges of material deduced for the blackwall-steatite alteration are best understood and most simply interrelated if they are considered in terms of reaction at moving boundaries, each marking the position at which the chemical potential of a mobile constituent attained a value critical to a significant mineral reaction. Four such principal moving boundaries existed in the blackwall-steatite reaction.

STEATITE-SERPENTINITE BOUNDARY

The steatite-serpentine boundary marked the position at which the chemical potential of Si attained a value such that serpentine (and magnetite) were unstable and were replaced by talc. Addition of Si, and diffusion of Mg outward toward the schist, and loss of H_2O were important features of the reaction. The boundary was essentially concentric with the outlines of the ultramafic body, and migrated slowly inward toward the center of the body as the alteration of serpentine to talc was completed at successive positions.

BOUNDARY BETWEEN STEATITE AND THE TALC-CARBONATE ROCK

At most places throughout the duration of the blackwall-steatite alteration, talc-carbonate rock bordered the steatite zone inwardly, and the reaction was between steatite and talc-carbonate rock. The boundary between the two marked the position at which the chemical potential of Si attained a value such that magnesite was no longer stable, and the talc-magnesite assemblage was replaced by a talc assemblage. Addi-

tion of Si and H_2O and loss of Mg and CO_2 were the main features of the reaction. This boundary was between the border of the ultramafic body and the boundary between the talc-carbonate-rock and the serpentinite. As the steatite alteration proceeded, the steatite-talc-carbonate rock boundary migrated inward toward the center of the body at a slower rate than the talc-carbonate-rock serpentinite boundary.

BLACKWALL-SCHIST BOUNDARY

The blackwall-schist boundary was actually a narrow zone marking critical values in the chemical potentials of several components, principally Mg, Al, Si, Na, and K. In this zone, several reactions took place so close together in space as to be difficult to separate. Theoretically, successive reactions should have resulted in mineralogically distinct successive zones, but the smallness of the differences in chemical potential for the different components responsible for the successive reactions, and the slowness of the reactions, resulted in the telescoping of the different zones at the outer border of the blackwall zone. As critical values in the chemical potential of Mg and Al were reached, the minerals of the country rock—principally quartz, sericite, chlorite, and albite—were replaced by a monomineralic magnesian chlorite assemblage. The chief features of the reactions were the ingress of Mg and H_2O from the steatite-serpentinite boundary (or the boundary between the steatite and the talc-carbonate rock) and of Al from the steatite-blackwall boundary; and the displacement of Si, which migrated to the steatite-serpentinite boundary (or the boundary between the steatite and the talc-carbonate rock) and of K and Na, which moved outward toward the schist. The boundary marking the alteration of the minerals of the schist to chlorite migrated outward from the border of the ultramafic body into the schist as the reaction proceeded. Immediately in front of the advancing chlorite boundary, Na and K attained chemical potentials such that albite and biotite were formed.

Reactions involving apatite, epidote, zircon, pyrite, ilmenite, rutile, and sphene did not form well-defined boundaries, principally because the reactions were very slow. Some, such as the ilmenite $\rightarrow$ rutile $\rightarrow$ sphene reaction, appear to have resulted from local achievement of critical values in the chemical potentials of certain elements, such as Ca and Si, as a result of the alteration to chlorite of other minerals. All, except probably zircon and pyrite, appear to have altered slowly to chlorite under the mass effect of ingress of Mg, Al, and H_2O .

STEATITE-BLACKWALL BOUNDARY

The steatite-blackwall boundary marked the surface at which the chemical potential of Mg had a value such

that chlorite was replaced by talc. The principal features of the reaction were the ingress of Mg from the steatite-serpentinite (or steatite—talc-carbonate rock) boundary, and the migration outward toward the schist of the displaced Al, and release of H_2O . The boundary moved progressively outward toward the schist at the expense of the blackwall, probably at a somewhat slower rate than the blackwall-schist boundary advanced. Most of the original minerals of the schist were entirely replaced by chlorite of the blackwall by the time that the steatite-blackwall boundary advanced to a given point, but locally, such persistent minerals as apatite, zircon, and sphene persisted for a short distance inside the steatite-blackwall boundary.

GEOCHEMISTRY OF THE ROCKS AFFECTED BY STEATITIZATION

The distribution and relative movement of atoms, ions, and radicals among the rocks affected by steatitization is shown in tables 11, 13, 15, 17, and 19. The inferred relative movement is, of course, based upon the premise that replacement was on a volume-for-volume basis. The relations between some of the mineral changes and the movements of some constituents are obvious upon comparison of the graphs showing mineral composition of the rocks (figs. 24, 26, 28, 30; and 32) and those showing chemical composition of the modified standard cells (figs. 25, 27, 29, 31 and 33). For other constituents the relations are not so obvious. In the remainder of this section the geochemistry of each of the constituents on which information is available—the mineral associations of elements in the original rocks, the course of movement of elements during steatitization, and the final disposition of the elements—will be discussed briefly and subject to the limitations of data that are in some instances rather spotty.

POTASSIUM

Potassium is confined, as an essential constituent, to the schist, where the K_2O of conventional quantitative chemical analysis commonly forms as much as 3 to 4 weight percent of the rock, and where it occurs in the minerals muscovite and biotite. All the other rocks contain generally less than 0.1 percent of K_2O (by weight); but all, even such rocks as serpentinite and steatite, in which no minerals ordinarily regarded as containing potassium are detectable microscopically, contain a few hundredths percent. The reported presence of K_2O in such small amounts may result from contamination, from analytical errors, or from the actual presence of minute amounts of potassium in some form of substitution in talc and serpentine. In the serpentinite, talc-carbonate rock, and steatite, analytical error or contamination would seem to be likely explanations. In the blackwall and greenstone, minute

amounts of sericite or small amounts of amphibole may account for the K_2O , or small amounts of K may be accommodated within the chlorite structure, such as coupled with the substitution of Al for Si.

In the steatitization process K is removed almost entirely from the rock in the alteration of schist to blackwall and steatite. Local concentrations of biotite in the schist near the blackwall indicate that at least part of the K so displaced is stabilized almost immediately outside the blackwall zone. Probably all the K displaced comes to rest very near the blackwall zone, but the normal content of muscovite in the schist is so variable that such a conclusion must remain largely speculative. Significant changes in content of K probably do not occur during the alterations of serpentinite to talc-carbonate rock and steatite.

SODIUM

Sodium plays a conspicuous role locally in the changes effected during steatitization. Sodium occurs in significant proportions only in albitic varieties of schist, in greenstone, and in the albite porphyroblast rock that borders the blackwall locally. Na_2O commonly forms as much as 1 to 3 percent by weight of albitic schist and greenstone, and 6 to 8 percent of albite porphyroblast rock. In other varieties of schist Na_2O commonly forms not more than 0.X to 0.0X percent (by weight) of the rock. The Na appears to be contained almost entirely in albite. Substitution of Na for K in muscovite appears to be slight at most, and paragonite is generally absent from the schist.

Sodium is removed from the rock in the alteration of schist to blackwall and steatite, and is concentrated at the outer margin of the blackwall zone. The process involves the disintegration of albite within the blackwall zone and the deposition of albite in the albite porphyroblast zone, but the outward migration probably involves only Na, which reacts immediately beyond the influence of the advancing wave of chlorite with the requisite constituents to form albite, whereas the Si released from the albite diffuses toward the steatite, and the Al toward the blackwall or toward the albite porphyroblast zone, depending upon chemical requirements.

No movement of sodium is involved in the alteration of serpentinite to talc-carbonate rock and steatite.

CALCIUM

Calcium is an essential and generally major constituent of thin beds of sedimentary carbonate rock in the schist, of actinolitic greenstone, and of actinolite rock (between the blackwall and steatite); it is variable in proportion but generally rather abundant in chloritic greenstone; and it generally forms less than 1 percent

(weight percent CaO) of the schist and 0.0X percent of blackwall, steatite, talc-carbonate rock, and serpentinite. In the sedimentary carbonate beds the Ca occurs in the mineral dolomite. In schist, greenstone, and actinolite rocks the Ca is present in such calcian minerals as amphibole, epidote, sphene, apatite, and carbonate. In blackwall the generally very low content of Ca may possibly be accommodated partly within the chlorite structure, but most probably occurs in relict minerals such as epidote and amphibole, and in sphene; where the CaO content of the blackwall is much greater than 0.X percent, the presence of local segregations of epidote or sphene is generally indicated; in a few instances calcite rhombs that have formed by replacement after steatitization are responsible for a relatively high content of calcium. In steatite, talc-carbonate rock, and serpentinite the calcium appears to be contained almost entirely within carbonate, chiefly as a minor constituent of magnesite but in a few places in small amounts of dolomite.

During the steatitization process, Ca is released during the alteration of schist or greenstone to blackwall. A small part of the Ca released remains in the blackwall zone, entering into the chlorite structure or taking part in the reactions of the titanium minerals discussed above. The rest probably migrates to the talc-carbonate zone and enters into the composition of the carbonate being formed there.

MAGNESIUM

Magnesium is a persistent constituent of all the rocks and is a major component of the ultramafic rocks and those related to steatitization. The schist commonly contains less than 5 percent (by weight) of MgO , except where chlorite is very abundant. Beds of sedimentary carbonate rock (dolomite) are highly variable and contain 20 to 40 percent MgO . Serpentinite contains about 35 percent MgO , grit about 30 percent, steatite about 29 percent, and blackwall 15 to 25 percent. Greenstone ranges in content of MgO from about 10 to 20 percent. Actinolite rock contains about 20 percent MgO . The magnesium is contained almost entirely in serpentinite, talc, and carbonate in the ultramafic rocks, and in chlorite, amphibole, and biotite in the other rocks. Some Mg is probably contained in magnetite, particularly within the serpentinite and talc-carbonate rock, but the proportion of Mg to Fe is probably rather small.

Mg was immobile in the alteration of serpentinite to talc-carbonate rock, but was displaced during the alteration of serpentinite to steatite and migrated outward into the immediately adjacent schist. The chlorite of the blackwall, which formed in the adjacent schist concurrently with the steatite, took up the Mg displaced by the alteration of serpentinite to steatite.

IRON AND MANGANESE

Both ferrous and ferric iron are persistent constituents of all the rocks. Ferrous iron is a major constituent of the blackwall and chloritic greenstone, of which it constitutes 10 to 20 percent by weight of FeO ; it commonly forms about 5 percent of actinolitic greenstone, serpentinite, talc-carbonate rock, and steatite, and 1 to 2 percent or less of the schist. Ferric iron seldom forms more than 0.X percent of any of the rocks except for serpentinite, and locally talc-carbonate rock, which commonly contain 3 percent or more Fe_2O_3 .

The Fe^{+2} in all the rocks occurs principally in silicate minerals and in carbonate, in limited isomorphous substitution for Mg. The chief silicates that contain appreciable Fe^{+2} are serpentine (antigorite), chlorite, actinolitic hornblende and actinolite, and talc. Among the carbonates, most of the Fe^{+2} occurs in magnesite, but some also occurs in dolomite. Magnetite contributes appreciable amounts of Fe^{+2} in most serpentinite and talc-carbonate rock, and locally in sedimentary carbonate beds and in greenstone; some steatite contains small amounts of Fe^{+2} in dustlike particles of magnetite. Ilmenite contributes a small percentage of Fe^{+2} to much of the schist.

Fe^{+3} contained in magnetite is distributed among the different rocks as described above for Fe^{+2} , and accounts for most of the Fe^{+3} in serpentinite, talc-carbonate rock, steatite, and carbonate rock. Greenstone, and some schist, contains a relatively large proportion of total Fe^{+3} in epidote, in which the Fe^{+3} substitutes for Al. Other rocks contain Fe^{+3} chiefly in chlorite and biotite, in substitution for Mg, coupled with the substitution of Al for Si.

In the steatitization process it seems clear that Fe^{+2} is lost in the alteration of serpentinite to steatite, and that part of the Fe^{+2} thus displaced is concentrated in the chlorite in the blackwall zone. The evidence for gain or loss of Fe^{+2} and Fe^{+3} in the other zones is uncertain, chiefly because of the variable distribution of magnetite within serpentinite and talc-carbonate rock. The evidence suggests that total Fe remained about constant in the talc-carbonate rock reaction, and that Fe^{+2} increased slightly at the expense of Fe^{+3} (see tables 12, 14, 16, 18, and 20, figs. 25, 27, 29, 31, and 33) by reduction of Fe^{+3} in magnetite. Ingress of very small amounts of Fe^{+2} from the steatite zone into the talc-carbonate rock may have occurred in places, and Fe^{+2} may have been introduced rarely from outside the ultramafic body.

Manganese is a minor but persistent constituent of all the rocks. MnO commonly constitutes 0.X percent by weight of all the rocks except serpentinite and steatite, of which it generally makes up only 0.0X percent. The Mn is similar in chemical properties and

in atomic radius to Fe^{+2} , and the content of Mn shows a close relation, in most instances, to the proportion of Fe^{+2} . Consequently, Mn is distributed in a manner closely analogous to that of Fe^{+2} , but the carbonate minerals consistently contain a higher Mn: Fe^{+2} ratio than do the silicates. The movement of Mn during steatitization was probably very similar to that of Fe^{+2} .

NICKEL

Nickel, though ubiquitous, is always a very minor constituent, but it is clearly more abundant in rocks derived from ultramafic igneous rocks than in those derived from sedimentary rocks. Serpentinite, talc-carbonate rock, and steatite commonly contain 0.X percent of NiO by weight, whereas schist and blackwall contain 0.0X percent. Carbonate formed during serpentinization and steatitization contains about 10 times as much Ni as that in the late talc-carbonate veins: carbonate in talc-carbonate rock and serpentinite contains 0.0X percent Ni, whereas that in the late veins contains 0.00X percent (see table 3). Some Ni in the ultramafic rocks is contained in sulfarsenide minerals, but most occurs in silicates and in carbonates in substitution for Mg and Fe^{+2} . The Ni in the schist and blackwall presumably occurs in chlorite in similar substitution. No change in content of Ni as the result of steatitization is evident in any of the rocks.

COBALT

Cobalt occurs uniformly in very small amounts in all the rocks. No consistent difference in Co content is apparent between the ultramafic igneous rocks and the rocks derived from sedimentary rocks; in all, CoO constitutes about 0.0X weight percent of each rock. Mineral analyses of talc and carbonate (see table 3) show that the Co is contained partly in those minerals, but that the proportion is lower than in the rock as a whole, so that other minerals must also contain appreciable Co. Inasmuch as cobalt is a member of the iron family, the balance of the Co in the rocks probably occurs in silicate minerals in substitution for Mg in the same manner as Fe^{+2} and Mn. The Co content of the rocks shows no evidence of change during the steatitization process.

ALUMINUM

Aluminum is a major constituent of the rocks of sedimentary origin, of which Al_2O_3 commonly forms 15 to 25 percent by weight; but it is a minor constituent of the ultramafic rocks, of which Al_2O_3 forms only about 1 percent or less. Aluminum is associated principally with the silicates muscovite, biotite, chlorite, epidote, albite, and almandite in the rocks of sedimentary derivation. In the ultramafic rocks the small amounts of Al occur both in the silicates talc and

antigorite and in magnetite. In most of the silicates the Al is in coupled substitution in fourfold and sixfold coordination positions, but in talc and antigorite the Al is generally considered to substitute entirely or almost entirely for Mg, whereas in epidote and garnet Al is a stoichiometric constituent.

As for Fe^{+2} and Fe^{+3} , there is some uncertainty about the relative movement of Al during steatitization, because of the irregular distribution of magnetite in serpentinite and talc-carbonate rock. The alteration of serpentinite to talc-carbonate rock and steatite seems generally to have resulted in a diminution of Al. The Al so displaced migrated outward to enter into the chlorite in the blackwall reaction, or into the albite of the albite porphyroblast zone. The Al content of the blackwall zone increased or diminished with respect to that of the original schist depending upon whether the original schist was nonalbitic or albitic.

CHROMIUM

Chromium occurs in small amounts in all the rocks but is appreciably more abundant in the ultramafic rocks, where Cr_2O_3 forms 0.X weight percent, than in those of sedimentary derivation, where Cr_2O_3 forms 0.0X weight percent. Chromium occurs in the serpentinite and talc-carbonate rock chiefly in chromian magnetite, but in a few places occurs in translucent grains of chromite; both talc and serpentine also contain small amounts of Cr. In the metamorphosed sedimentary rocks (including the blackwall), the Cr presumably is contained entirely in the silicates such as chlorite and mica. No appreciable movement of Cr appears to have occurred during steatitization.

TITANIUM

Titanium occurs in both the metamorphosed sedimentary rocks and in the ultramafic rocks, but is generally tenfold to several hundredfold more abundant in the former. In most schist and greenstone TiO_2 forms 1 percent by weight or less of the rock, but in a few places it runs as high as 3 to 5 percent. The ultramafic rocks invariably contain no more than 0.0X percent TiO_2 .

In the schist, greenstone, and blackwall, the Ti is contained principally in the minerals ilmenite, sphene, and rutile; small amounts probably occur also in chlorite and biotite. The Ti in ultramafic rocks presumably occurs in the talc and antigorite.

Movement of Ti during steatitization appears to have been slight. The reactions involving ilmenite, rutile, and sphene in the blackwall have been discussed. The end stages of chloritization in the blackwall and the succeeding alteration of the innermost shell of blackwall to steatite appears to have displaced Ti outward.

SILICON

Silicon is a major component of all the rocks except the purer beds of sedimentary carbonate. The content of SiO_2 ranges from 0.X to X percent by weight in the carbonate beds, through 30 to 40 percent in the serpentinite, talc-carbonate rock, greenstone, and blackwall, to about 60 percent in the schist and steatite; many relatively thin beds of quartzite are nearly 100 percent SiO_2 . The principal silicates with which the Si is associated are quartz, muscovite, chlorite, albite, amphibole, talc, serpentine, epidote, and sphene.

The alteration of serpentinite to talc-carbonate rock required little or no movement of Si, but the blackwall-steatite reaction resulted in addition of Si to the steatite zone and loss of Si from the blackwall zone. The blackwall zone could supply only about one-third, generally, of the Si necessary for the steatite zone; the balance was contributed principally in small increments from throughout the schist adjacent to the ultramafic body.

PHOSPHORUS

Phosphorus occurs in very small amounts in all the rocks. The content of P_2O_5 in the metamorphosed sedimentary rocks is about 0.1 to 0.2 percent, and in the ultramafic rocks is 0.01 to 0.02 percent. The P in the rocks of sedimentary derivation is associated everywhere with apatite. No apatite was observed in steatite, talc-carbonate rock, or serpentinite. Presumably, therefore, the P in the ultramafic rocks occurs in silicates in the Si position.

Movement of P in steatitization was very slight. Apatite was very slowly replaced in the alteration of schist to blackwall and steatite; the very small amounts of P thus displayed may have remained essentially immobile, substituting for Si in either chlorite or talc.

CARBON

Carbon as CO_3 anions in carbonate is a major component of talc-carbonate rock and of sedimentary carbonate beds, and is a common minor constituent of the other rocks. Free carbon, probably both amorphous and as cryptocrystalline graphite, occurs only in varieties of schist, in quartzite, and in albite porphyroblast rock.

In the alteration of schist to blackwall and steatite, C (free) was displaced from the schist in the alteration to chlorite and was flushed ahead of the advancing wave, so that heavy concentrations of graphite were formed at the outer margin of the blackwall zone. Locally, residual enrichment may have been a factor in the concentration, but was not generally important. Carbon as CO_2 was highly mobile during steatitization; its introduction into the serpentinite was the most important factor in the alteration of serpentinite to talc-carbonate rock.

HYDROGEN

Hydrogen, in water or OH, is an essential constituent of all but the carbonate rocks and quartzite. The content of H₂O ranges from less than 2 percent by weight for some varieties of schist to nearly 12 percent in blackwall and serpentinite. The anion OH occurs in the silicates chlorite, serpentine, muscovite, biotite, amphibole, and epidote; and in apatite. Water was strikingly mobile in the steatitization process. The alteration of serpentinite to talc-carbonate rock and steatite resulted in the loss of much water, part of which was taken up in the blackwall by the alteration to chlorite, and part of which was expelled entirely from the system.

OXYGEN

Oxygen is, of course, a principal constituent of all the rocks and all the minerals except the sulfides and sulfarsenides, in terms both of molecular percent and volume percent, but particularly in terms of volume percent. On a volume basis, oxygen makes up about 94 percent of the ion volume of most rocks (Barth, 1952, p. 82). The movement of oxygen during steatitization was tied in primarily with movement of H₂O and CO₂, and the gains and losses of total oxygen in most rocks was relatively small. Some movement of oxygen appears to have been tied in with changes in valence state of metallic ions, particularly Fe⁺² and Fe⁺³. In blackwall and steatite derived from schist, the relative change in content of oxygen with respect to the content of oxygen in the parent rock varies considerably from place to place because of differences in the parent rock. On the other hand, talc-carbonate rock and steatite derived from serpentinite show consistent changes in total content of oxygen with respect to that of the parent rock because the serpentinite is generally uniform in composition. In both talc-carbonate rock and steatite, but particularly in the talc-carbonate rock, total oxygen per modified standard cell increases appreciably.

SULFUR AND ARSENIC

Sulfur is a common minor constituent of all the rocks but is erratically distributed. The S content of schist varies about from 0.0 to 0.X percent by weight; the ultramafic rocks generally contain not more than 0.1 to 0.2 percent, but in a few instances contain 0.5 percent or more. The S in the schist is contained entirely in pyrite. In the ultramafic rocks it is contained in pyrite, pyrrhotite, and sulfarsenides such as gersdorffite. The distribution of arsenic is partially known only for ultramafic rocks and blackwall. The content of As₂O₃ was 0.0003 weight percent in a single specimen of blackwall, and 0.0009 to 0.065 percent in four samples of ultramafic rock. The As occurs in sulfarsenides, such as gersdorffite. No movement pattern resulting from steatitization is discernible for the sulfur and arsenic.

NATURE OF THE STEATITIZING "SOLUTIONS"

The foregoing discussion clearly leads to the conclusion that in steatitization the formation of talc-carbonate rock from serpentinite requires only the introduction of CO₂, with the resulting expulsion of considerable amounts of H₂O. The formation of steatite requires the addition of Si, but that has been shown to be readily accounted for as derived principally from the blackwall zone and the adjacent schist through diffusion during metamorphic differentiation. It remains, therefore, only to account for the source of CO₂. Obviously, then, the "solutions" can be of extremely simple nature; they may have consisted almost entirely of CO₂. Locally, they appear to have transported small amounts of silica.

Most investigators ascribe steatitization to dilute hot aqueous solutions—presumably rich in CO₂—derived from nearby or underlying acid igneous rocks. The close connection shown to exist between regional metamorphism and steatitization suggests, however, that the CO₂ may simply have been derived from the rocks of sedimentary parentage during progressive metamorphism. A common reaction during progressive metamorphism that would lead to release of CO₂ is the reaction between carbonate and silica or silicates to form calcium and magnesium silicates and CO₂. Another possible source is suggested by the apparent antipathy between magnetite and graphite in regionally metamorphosed rocks, which suggests that hematite and free carbon react to form magnetite and CO₂. Dependence upon such reactions for a source of CO₂ is not required exclusively, of course, if regional metamorphism is attributed to magmatic effects, nor is such dependence ruled out; indeed, under such conditions, a mixed source for the CO₂—that is, a source both in the sediments and in the magma—seems likely. But the evidence of magmatic control of metamorphism in the area is less than compelling, and it seems likely that the "solutions" that affected steatitization were independent of a magmatic source.

ORIGIN OF THE TALC-CARBONATE VEINS

The talc-carbonate veins are clearly later than and unrelated to steatitization, as shown by the facts that they crosscut talc-carbonate rock, steatite, and serpentinite and that the coarse carbonate and talc are essentially undeformed. Their exact age cannot be determined, but the veins are obviously related to late joints, which may have formed as late as the joints along which were admitted the mafic dikes of probable Permian or Triassic age.

No talc-carbonate veins were observed to extend beyond the ultramafic bodies, but none was exposed sufficiently so that it could be proved that a given vein

did not extend into the country rock. The fact that no talc-carbonate veins were observed within the black-wall in thousands of feet of exposure is strong evidence that the veins are confined to the ultramafic rocks. Only for Ca does it appear necessary to call upon introduction from an outside source, which may well have been the immediately adjacent schist. The veins are clearly joint controlled, but were formed in considerable part by replacement, as is attested by the irregular boundaries. In contrast to structural conditions during steatitization (see p. 92-93), the joints probably formed relatively open channelways, and water probably pervaded all joints, fractures, and grain boundary spaces. Mg, Si, CO₂ (or CO₃), and Fe⁺² could readily have diffused into the veins from the bordering ultramafic rocks. Ca was introduced along the joints either by mechanical movement of material in solution or by diffusion through the solution. The veins grew probably both by deposition in open fissures—probably essentially simultaneously with opening of the fissures—and by replacement of adjoining steatite, talc-carbonate rock, or serpentinite.

APPENDIXES

In the following appendixes are assembled the calculations, tables, derivations, proofs, and detailed explanations the inclusion of which is necessary to the integrality of the report, but whose inclusion within the main body of the report would have distracted from orderly presentation of the main arguments. The appendixes are concerned with chemical analyses, and methods of calculation whereby the analyses are converted to more useful and meaningful form. They are divided on the basis of calculation procedures, most of which are closely related to type of material analyzed, as is evident in the headings of the several appendixes.

APPENDIX A. SOME BASIC PROCEDURES, DEFINITIONS, AND TERMINOLOGY

Chemical analyses are more meaningful for many purposes, and a variety of calculations are more conveniently performed upon them, if the analyses are expressed in terms of *molecular units*. Niggli (1936, p. 295-317; 1954, p. 80-83, 120-121) and Barth (1952, p. 74-79) advocate a system whereby the oxides are expressed in terms of *equivalent molecular units* that contain one electropositive ion or atom each, irrespective of the number of electronegative ions or atoms. To designate such units it is convenient to employ symbols such as MgO, SiO₂, KO_{1/2}, HO_{1/2}, CO₂, AlO_{3/2}, and PO_{5/2} to emphasize that each unit contains only one electropositive ion; atoms and ions such as C (in graphite) and S (in sulfide) are expressed also in terms

of one per unit. Such a manner of designation makes molecular units identical with equivalent molecular units and obviates the necessity of continually repeating "equivalent" throughout a discussion. The convention is employed throughout this report where appropriate.

The *equivalent molecular weight* of an equivalent molecular unit is the sum of the products of the atomic weights of the elements multiplied by their subscripts in the symbol. If the terms of an analysis expressed in weight percent are divided by their respective equivalent molecular weights, the quotients are *equivalent molecular numbers*. Equivalent molecular numbers may be derived from values other than weight percent—for instance, in some calculations it might be desirable to employ weight proportions not reduced to percentages—they will then be related to those derived directly from weight percent by a simple factor. Unless otherwise expressly stated, the term "equivalent molecular number" denotes the value derived directly from weight percent—the weight percent of a constituent divided by its equivalent molecular weight.

The term *weight proportion* is used to denote the relative weight of a constituent in an analysis on some basis of a total other than one hundred. Weight proportions are derived from various forms of an analysis in terms of equivalent molecular units—equivalent molecular percent, equivalent molecular numbers, the modified standard cell, and others—by multiplying each term by its equivalent molecular weight. The various sets of values are proportional. The source values for given weight proportions are generally evident from context; otherwise they are specified.

If the sum of the equivalent molecular numbers in an analysis is reduced to 100, then the constituents are in terms of *equivalent molecular percent*—identical with molecular percent if the oxides are symbolized in the manner described above. Various systems of calculation are possible, but for many purposes it is desirable to reduce to 100 the sum of the one-cation oxides—the equivalent molecular numbers exclusive of HO_{1/2}, S (as sulfide), F, Cl, and other electronegative ions or atoms. Associated anions are multiplied by the same factor and listed separately. Such *one-cation oxide percentages*—or, more simply, cation percentages—are particularly useful because the resulting values for the metallic oxides then correspond more closely to their values in terms of weight percent, and because of other factors that are evident in the remaining discussion in this appendix and in the calculations throughout the remaining appendixes. The most important of these factors involve the selection of the equivalent mineral

units, and the calculation of equivalent molecular percentages of minerals, discussed in the following paragraphs. Throughout this report the terms "equivalent molecular percent" and "molecular percent" are used in the sense of one-cation oxide percentages unless specifically stated otherwise; the terms may refer to values both of the one-cation oxides and of the associated anions.

Equivalent mineral units are herein defined so that the sum of the electropositive ions or atoms such as K, Mg, Al, Si, C, P, and S in SO_4 equals one, irrespective of the number of electronegative ions and atoms such as O, OH, F, Cl, and S in sulfide. Thus, for example, one equivalent mineral unit of quartz (1 Q) equals 1 SiO_2 ; of albite (1 Ab), $1/5 \text{ NaAlSi}_3\text{O}_8$; of muscovite (1 Ms), $1/7 \text{ KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$; of graphite (1 Gra), 1 C; of pyrite (1 Py), 1 FeS_2 ; of pyrrhotite (1 Prh), 1 FeS; and of calcite (1 Cc), $1/2 \text{ CaCO}_3$.¹³ With equivalent mineral units thus defined on the same basis as that for molecular percent of the constituents of an analysis, a mode may be derived simply and directly from an analysis expressed in molecular percent. The number of equivalent mineral units of a given mineral that are contained in an analysis stated in terms of equivalent molecular percent is calculated by adding the equivalent molecular percentages of the requisite oxides in the appropriate proportions. Thus, for an analysis of a rock in which all Na is known to be in albite, the equivalent molecular percentage of albite in the mode is equal to the molecular percentage of $\text{NaO}_{1/2}$ plus an equal amount of $\text{AlO}_{3/2}$ plus an amount of SiO_2 equal to three times the amount of $\text{NaO}_{1/2}$, or (percent Ab = $x\text{NaO}_{1/2} + x\text{AlO}_{3/2} + 3x\text{SiO}_2$), where x equals the molecular percentage of $\text{NaO}_{1/2}$ in the analysis; similarly, for muscovite, (percent Ms = $y\text{KO}_{1/2} + 3y\text{AlO}_{3/2} + 3y\text{SiO}_2$), where y equals the molecular percentage of $\text{KO}_{1/2}$. A mode or norm calculated on such a basis must total 100, and is therefore in terms of *equivalent molecular percentages of minerals*, which have the advantage, as defined herein, of being closely comparable to volume percentages of minerals for most mineral assemblages. In practice, it is simpler and clearer to obtain the equivalent molecular percentages of minerals by first adding all the constituents in each mineral and then subtracting the electronegative ions (such as S in sulfide and OH), which by definition do not contribute to the equivalent molecular percentage. These relations and procedures are evident in table 24, and in many of the calculations through the several appendixes.

¹³ Note that some of the equivalent mineral units listed here and in table 22, particularly those of carbonates and sulfides, do not correspond to those of Niggli (1954, p. 137). These different units were chosen because for them the equivalent volumes—discussed below in this appendix—approach more closely the average for silicates, and because such treatment seems more logical and permits simpler systematic treatment of calculations.

The *equivalent weight* (M_e) of a mineral is the gram-molecular weight of one equivalent mineral unit, and is equal to the molecular or usual formula weight of the mineral divided by the number of electropositive ions (excluding H) in the formula. For example, the equivalent weight of albite ($\text{NaAlSi}_3\text{O}_8$) is equal to $262.147 \div 5 = 52.43$; of quartz (SiO_2), 60.06; and of muscovite ($\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$), $398.20 \div 7 = 56.88$. The *equivalent volume* (V_e) is the volume of one equivalent mineral unit; it is equal to the equivalent weight divided by the density of the mineral ($V_e = \frac{M_e}{D}$).

The term *oxygen equivalent* (Oeq) denotes an oxygen ion or an amount of another ion or atom that occupies a volume approximately equivalent to that of an oxygen ion. The use of oxygen equivalents is discussed in appendix B and illustrated in table 24. The oxygen equivalents of the principal atoms or ions thus involved, for the most common rocks, are: O=1, S (as sulfide)=1, As (as arsenide)=1, and C (as free carbon)=1/2.

Two constants of use in calculating the modified standard cell are the cell factor for minerals (F_{min}), and the cell factor for rocks (F_{rk}). The use and significance of these factors are explained in appendix B. Here they will be merely defined.

The factor denoted by the symbol F_{min} is the value by which the analysis of a mineral in equivalent molecular percent must be multiplied, term by term, to obtain the number of equivalent molecular units of each constituent in the modified standard cell of the given mineral. F_{min} denotes, for each mineral, the number of equivalent mineral units per modified standard cell, and is equal to the volume of the modified standard cell (see appendix B) divided by 100 times the equivalent volume of the mineral, or

$$F_{\text{min}} = \frac{2064.8}{100 V_e}$$

The symbol F_{rk} denotes the factor—constant for a rock of given chemical and mineral composition—by which the rock analysis in terms of equivalent molecular percent must be multiplied to arrive at the contents of the modified standard cell for that rock. Several ways of determining the F_{rk} for a given rock are given in appendix B.

The *formula number* of an element or radical is the subscript for the symbol of the element or radical as written in a mineral formula or in the formula of the modified standard cell; which is meant is evident from the context. In computing formula numbers, the cal-

culated values are tabulated most conveniently under (in the rows of) the symbols (oxides, atoms, radicals) by which the analysis is stated. No confusion need result from this convention because it is readily apparent from the mineral or rock formula whether the metallic ion alone of the symbol, or all the elements represented in the symbol, are meant. Thus, in table 24-B in appendix B, in the column "Formula numbers" under "Chlorite", the values opposite SiO_2 , $\text{AlO}_{3/2}$, MgO , and $\text{HO}_{1/2}$ indicate, in the chlorite formula, 2.60 Si, 2.40 Al, 3.21 Mg, and 8.00 OH, respectively. Similarly, in the column "Formula Nos. in MSC" in table 24-A, the values opposite SiO_2 , $\text{AlO}_{3/2}$, MgO , CO_2 , S, and C indicate, in the formula of the modified standard cell, 52.71 Si,

24.44 Al, 6.00 Mg, 0.27 CO_2 , 0.84 S, and 3.84 C. In mineral formulas the subscript after a parenthesis enclosing a group of elements that substitute for each other is equal to the sum of the subscripts of the elements enclosed, and is preceded by an equal sign (=) to so indicate.

Table 22 is a tabulation of most of the minerals commonly encountered in metamorphic rocks, and a compilation for each mineral of several constants employed in calculations in the appendixes that follow. These constants have been discussed and defined in the foregoing paragraphs of this appendix. The meaning and derivation of most of the constants is evident from the table.

TABLE 22.—Formulas and symbols of equivalent mineral units, densities, equivalent weights, equivalent volumes, equivalent mineral units (EMU) per modified standard cell (MSC), and cell factors of some common minerals

[For most series that show partial or complete solid solution, the values for "end members" are given so that values for a given composition may be obtained by interpolation]

Name	Formula	Symbol of EMU	Density (D)	Equivalent weight (M_e)	Equivalent volume (V_e)	EMU per MSC	Cell factor (F_{mis})
Feldspar:							
Albite.....	$\frac{1}{2} \text{NaAlSi}_3\text{O}_8$	1 Ab	2.62	52.43	20.01	103.19	1.0319
Anorthite.....	$\frac{1}{2} \text{CaAl}_2\text{Si}_2\text{O}_8$	1 An	2.76	55.63	20.16	102.42	1.0242
Orthoclase.....	$\frac{1}{2} \text{KAlSi}_3\text{O}_8$	1 Or	2.55	55.65	21.82	94.63	.9463
Mica:							
Muscovite.....	$\frac{1}{4} \text{KAl}_2\text{Si}_2\text{O}_{10}(\text{OH})_2$	1 Ms	2.80	56.88	20.31	101.66	1.0166
Paragonite.....	$\frac{1}{4} \text{NaAl}_2\text{Si}_2\text{O}_{10}(\text{OH})_2$	1 Pa	2.85	54.58	19.15	107.82	1.0782
Annite.....	$\frac{1}{4} \text{KFe}^{+2}\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	1 Ann	3.4	63.98	18.82	109.71	1.0971
Phlogopite.....	$\frac{1}{4} \text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$	1 Ph	2.8	52.15	18.63	110.83	1.1083
Biotite.....	$\frac{1}{4} \text{K}(\text{Fe}^{+2}, .6\text{Mg}_{1.1})\text{Al}_{1.6}\text{Si}_{2.7}\text{O}_{10}(\text{OH})_2$	1 Bi	3.1	58.52	18.88	109.36	1.0936
Chlorite:							
Amesite.....	$\frac{1}{10} \text{Mg}_4\text{Al}_4\text{Si}_2\text{O}_{10}(\text{OH})_8$	1 At	2.79	55.73	19.97	103.40	1.0340
Daphnite.....	$\frac{1}{10} \text{Fe}^{+2}\text{Al}_4\text{Si}_2\text{O}_{10}(\text{OH})_8$	1 Da	3.08	68.35	22.19	93.05	.9305
Thuringite.....	$\frac{1}{10} \text{Fe}^{+2}\text{Al}_2\text{Si}_2\text{O}_{10}(\text{OH})_8$	1 Thg	3.1	71.94	23.01	89.73	.8973
Clinchlore.....	$\frac{1}{10} \text{Mg}_5\text{Al}_2\text{Si}_2\text{O}_{10}(\text{OH})_8$	1 Cli	2.7	55.58	20.59	100.28	1.0028
"Average" chlorite.....	$\frac{1}{10} (\text{Mg}_{2.1}\text{Fe}^{+2}, .9\text{Al}_{1.1})\text{Al}_{1.6}\text{Si}_{2.7}\text{O}_{10}(\text{OH})_8$	1 Chl	2.94	63.82	21.71	91.89	.9189
Serpentine:							
Antigorite.....	$\frac{1}{6} \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	1 Ant	2.6	55.42	21.32	96.85	.9685
Chrysotile.....	$\frac{1}{6} \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	1 Chrys	2.45	55.42	22.62	91.28	.9128
Amphibole:							
Tremolite.....	$\frac{1}{15} \text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Tr	3.00	54.15	18.05	114.39	1.1439
Actinolite.....	$\frac{1}{15} \text{Ca}_2\text{Mg}_4\text{Fe}^{+2}\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Act	3.16	58.35	18.47	111.79	1.1179
Ferrotremolite.....	$\frac{1}{15} \text{Ca}_2\text{Fe}^{+2}\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Fe-tr	3.40	64.66	19.02	108.56	1.0856
Mg-Anthophyllite.....	$\frac{1}{15} \text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Mg-anth	2.83	52.05	18.39	112.28	1.1228
Fe-anthophyllite.....	$\frac{1}{15} \text{Fe}^{+2}\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Fe-anth	3.5	66.76	19.07	108.27	1.0827
Anthophyllite.....	$\frac{1}{15} \text{Mg}_3\text{Fe}^{+2}\text{Al}_2\text{Si}_7\text{O}_{22}(\text{OH})_2$	1 Anth	3.2	58.46	18.27	113.02	1.1302
Hornblende.....	$\frac{1}{16} \text{Ca}_2\text{NaMg}_2\text{Fe}^{+2}\text{Al}_2\text{Si}_6\text{O}_{22}(\text{OH})_2$	1 Ho	3.2	56.17	17.55	117.65	1.1765
Pargasite.....	$\frac{1}{32} \text{Ca}_4\text{Na}_2\text{Mg}_2\text{Al}_2\text{Si}_{13}\text{O}_{44}(\text{OH})_4$	1 Par	3.19	52.19	16.36	126.21	1.2621
Cummingtonite.....	$\frac{1}{15} \text{Mg}_3\text{Fe}^{+2}\text{Si}_8\text{O}_{22}(\text{OH})_2$	1 Cum	3.31	60.46	18.27	113.02	1.1302
Pyroxene:							
Enstatite.....	$\frac{1}{2} \text{MgSiO}_3$	1 En	3.18	50.19	15.78	130.85	1.3085
Hypersthene.....	$\frac{1}{4} \text{MgFe}^{+2}\text{Si}_2\text{O}_6$	1 Hy	3.56	58.07	16.31	126.60	1.2660
Diopside.....	$\frac{1}{4} \text{CaMgSi}_2\text{O}_6$	1 Di	3.28	54.13	16.50	125.14	1.2514
Hedenbergite.....	$\frac{1}{4} \text{CaFe}^{+2}\text{Si}_2\text{O}_6$	1 He	3.55	62.01	17.47	118.19	1.1819
Augite.....	$\frac{1}{2} \text{Ca}_2\text{MgFe}^{+2}\text{Si}_4\text{O}_{12}$	1 Aug	3.45	58.07	16.83	122.69	1.2269
Ferrosilite.....	$\frac{1}{2} \text{Fe}^{+2}\text{SiO}_3$	1 Fs	3.93	65.96	16.78	123.05	1.2305
Olivine:							
Forsterite.....	$\frac{1}{2} \text{Mg}_2\text{SiO}_4$	1 Fo	3.20	46.90	14.65	140.94	1.4094
Fayalite.....	$\frac{1}{2} \text{Fe}^{+2}\text{SiO}_4$	1 Fa	4.40	67.92	15.44	133.73	1.3373
Chrysolite.....	$\frac{1}{2} \text{Mg}_{1.6}\text{Fe}^{+2}.4\text{SiO}_4$	1 Ol	3.44	51.10	14.85	139.04	1.3904
Garnet:							
Almandine.....	$\frac{1}{6} \text{Fe}^{+2}\text{Al}_2\text{Si}_2\text{O}_{12}$	1 Alm	4.32	62.21	14.40	143.39	1.4339
Pyrope.....	$\frac{1}{6} \text{Mg}_3\text{Al}_2\text{Si}_2\text{O}_{12}$	1 Pyp	3.51	50.39	14.36	143.79	1.4379
Spessartite.....	$\frac{1}{6} \text{Mn}_3\text{Al}_2\text{Si}_2\text{O}_{12}$	1 Spe	4.18	61.86	14.80	139.51	1.3951
Grossularite.....	$\frac{1}{6} \text{Ca}_3\text{Al}_2\text{Si}_2\text{O}_{12}$	1 Gro	3.53	56.30	15.95	129.45	1.2945
Andradite.....	$\frac{1}{6} \text{Ca}_3\text{Fe}^{+2}\text{Si}_2\text{O}_{12}$	1 Andr	3.83	63.62	16.58	124.54	1.2454
Miscellaneous silicates:							
Andalusite.....	$\frac{1}{2} \text{Al}_2\text{SiO}_5$	1 And	3.15	54.00	17.14	120.47	1.2047
Chloritoid.....	$\frac{1}{4} \text{FeAl}_2\text{SiO}_5(\text{OH})_2$	1 Chltd	3.5	62.97	17.99	114.77	1.1477
Clinzoisite.....	$\frac{1}{6} \text{Ca}_2\text{Al}_2\text{Si}_2\text{O}_{12}(\text{OH})_2$	1 Clz	3.35	56.78	16.95	121.82	1.2182
Cordierite.....	$\frac{1}{11} \text{Mg}_1.4\text{Fe}^{+2}.4\text{Al}_2\text{Si}_2\text{O}_{12}$	1 Cord	2.61	54.89	21.03	98.18	.9818
Epidote.....	$\frac{1}{6} \text{Ca}_2\text{Fe}^{+2}.4\text{Al}_2\text{Si}_2\text{O}_{12}(\text{OH})_2$	1 Ep	3.40	58.95	17.34	119.08	1.1908
Idocrase (vesuvianite).....	$\frac{1}{50} \text{Ca}_{20}\text{Al}_5\text{Mg}_2\text{Si}_{18}\text{O}_{88}(\text{OH})_4$	1 Ves	3.4	56.88	16.73	123.42	1.2342
Kaolinite.....	$\frac{1}{4} \text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	1 Kaol	2.61	64.53	24.72	83.53	.8353
Kyanite.....	$\frac{1}{2} \text{Al}_2\text{SiO}_5$	1 Ky	3.6	54.00	15.00	137.65	1.3765
Pyrophyllite.....	$\frac{1}{6} \text{Al}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	1 Pph	2.84	60.03	21.14	97.67	.9767
Quartz.....	$\frac{1}{2} \text{SiO}_2$	1 Q	2.654	60.06	22.63	91.24	.9124
Sillimanite.....	$\frac{1}{2} \text{Al}_2\text{SiO}_5$	1 Sil	3.25	54.00	16.62	124.24	1.2424
Sphene.....	$\frac{1}{2} \text{CaTiSiO}_5$	1 Sph	3.5	65.35	18.67	110.59	1.1059
Staurolite.....	$\frac{1}{15} \text{Fe}^{+2}\text{Al}_6\text{Si}_4\text{O}_{22}(\text{OH})_2$	1 Staur	3.77	56.78	15.06	137.10	1.3710
Talc.....	$\frac{1}{17} \text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$	1 Tc	2.82	54.17	19.21	107.49	1.0749
Zircon.....	$\frac{1}{2} \text{ZrSiO}_4$	1 Z	4.7	91.64	19.50	105.89	1.0589

TABLE 22.—*Formulas and symbols of equivalent mineral units, densities, equivalent weights, equivalent volumes, equivalent mineral units (EMU) per modified standard cell (MSC), and cell factors of some common minerals—Continued*

Name	Formula	Symbol of EMU	Density (D)	Equivalent weight (M _e)	Equivalent volume (V _e)	EMU per MSC	Cell factor (F _{min})
Spinel group:							
Magnetite.....	$\frac{1}{2} \text{Fe}^{+2}\text{Fe}^{+3}_2\text{O}_4$	1 Mt	5.20	77.18	14.84	139.14	1.3914
Chromite.....	$\frac{1}{2} \text{Fe}^{+2}\text{Cr}_2\text{O}_4$	1 Cm	5.22	74.62	14.30	144.39	1.4439
Picrochromite.....	$\frac{1}{2} \text{MgCr}_2\text{O}_4$	1 Picm	4.40	64.11	14.57	141.72	1.4172
Hercynite.....	$\frac{1}{2} \text{Fe}^{+2}\text{Al}_2\text{O}_4$	1 Herc	4.39	57.93	13.20	156.42	1.5642
Spinel.....	$\frac{1}{2} \text{MgAl}_2\text{O}_4$	1 Sp	3.57	47.42	13.28	155.48	1.5548
Carbonates:							
Calcite.....	$\frac{1}{2} \text{CaCO}_3$	1 Ce	2.717	50.05	18.42	112.10	1.1210
Magnesite.....	$\frac{1}{2} \text{MgCO}_3$	1 Mgs	3.08	42.17	13.69	150.83	1.5083
Dolomite.....	$\frac{1}{4} \text{CaMg}(\text{CO}_3)_2$	1 Do	2.87	46.11	16.07	128.49	1.2849
Siderite.....	$\frac{1}{2} \text{Fe}^{+2}\text{CO}_3$	1 Sid	3.95	57.93	14.67	140.75	1.4075
Rhodochrosite.....	$\frac{1}{2} \text{MnCO}_3$	1 Rh	3.70	57.47	15.53	132.96	1.3296
Miscellaneous minerals:							
Apatite.....	$\frac{1}{8} \text{Ca}_5\text{P}_3\text{O}_{12}(\text{OH}, \text{F})$	1 Ap	3.18	65.04	20.45	100.97	1.0097
Bruceite.....	$\frac{1}{2} \text{Mg}(\text{OH})_2$	1 Br	2.40	58.34	24.31	84.94	.8494
Graphite.....	1 C	1 Gra	2.25	12.01	5.34	386.67	3.8667
Gypsum.....	$\frac{1}{2} \text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	1 Gyp	2.32	86.09	37.11	55.64	.5564
Pyrite.....	1 FeS ₂	1 Pr	5.02	119.97	23.90	86.39	.8639
Pyrrhotite.....	1 FeS	1 Pyrr	4.77	87.91	18.43	112.03	1.1203
Hematite.....	$\frac{1}{2} \text{Fe}^{+3}_2\text{O}_3$	1 Hm	5.2	79.85	15.36	134.43	1.3443
Goethite (limonite).....	$\frac{1}{2} \text{FeO}(\text{OH})$	1 Go	4.28	88.86	20.76	99.46	.9946
Ilmenite.....	$\frac{1}{2} \text{Fe}^{+2}\text{TiO}_3$	1 Ilm	4.7	75.88	16.14	127.93	1.2793
Rutile.....	1 TiO ₂	1 Ru	4.2	79.90	19.02	108.56	1.0856

Throughout the calculations in the following appendices, equivalent molecular numbers are computed to five places, and are calculated from equivalent molecular weights based upon the chemical scale of atomic weights for 1948. To simplify arithmetic procedures, all further calculations are carried out to the equivalent of two decimal places in the original data. Final results are then rounded-off—to the accuracy with which the analysis was reported, for the modified standard cell; and to the number of figures considered significant, for calculated mineral compositions.

APPENDIX B. THE MODIFIED STANDARD CELL, CALCULATED MODES, AND MINERAL FORMULAS

Calculation of the modified standard cell, of modes, and of mineral formulas involves duplication of several steps in the procedures; they therefore integrate naturally and are advantageously discussed together. To facilitate discussion, a sample calculation is presented in table 24, which demonstrates a convenient format for integrating the calculations.

DEFINITION OF THE MODIFIED STANDARD CELL

The reasons for developing the modified standard cell, and some of its principal characteristics, have been described on pages 94–95. The choice of size for the cell was determined by the provision that for an average rock it should contain approximately 100 cations, thus permitting changes in cell content of cations to be considered as approximately in terms of percentages of total cation content of the protolith. Sedimentary rocks range rather widely in cation content per unit volume of rock—for instance, in the modified cell adopted here, orthoquartzite contains about 92 cations and dolomite about 128—but even for extreme types the purpose is moderately well served, and for most rocks the approach to true percentages is rather close.

Inasmuch as shale is the most abundant sedimentary rock, Leith and Mead's calculated mode of the average shale (Pettijohn, 1949, table 21) was selected as the standard by which to establish the size of the modified standard cell. It was necessary to resort to a calculated mode because no density data are available for chemical analyses of suitable average or composite shales.

Table 23 shows the calculations by which the volume that contains exactly 100 cations of Leith and Mead's average shale was determined. Basic to the calculations is the fact that, in the terminology defined in appendix A, 100 equivalent mineral units contain 100 equivalent molecular units of oxides, and therefore 100 cations. The total number of equivalent mineral units represented by the mode in volume percent is readily obtained by dividing the volume percent of each mineral by its equivalent volume (from table 22), and summing the quotients as in the last column of table 23. The volume of the modified standard cell is then obtained by dividing the sum of the volume percentages in the mode (100.00) by the sum of the equivalent mineral units associated (4.8432), which yields the volume per equivalent mineral unit or per cation, and then multiplying by 100 to get the volume per 100 cations (2,064.8).

If an equivalent mineral unit is regarded as consisting of 1 mole, or N "molecules" of a mineral, and the units of weight and volume in table 22 are taken as grams and cubic centimeters (where N is Avogadro's number = 6.0247×10^{23} ; DuMond and Cohen, 1953, p. 706), then the volume of the modified standard cell will be in terms of cubic centimeters. It is probably preferable and less confusing to regard an equivalent mineral unit as containing 1 "molecule" of a mineral, and the modified standard cell as containing 100 "molecules" of the minerals of Leith and Mead's

TABLE 23.—Calculations for determining the volume of 100 equivalent mineral units (EMU) of Leith and Mead's average shale.

[These calculations determine the size of the modified standard cell (MSC)]

	Volume percent	Equivalent Volume (V_e)	Equivalent mineral units (EMU)
Quartz.....	31.91	22.63	1.4101
Orthoclase.....	12.05	21.82	.5522
Albite.....	5.55	20.01	.2774
Sericite.....	18.40	19.75	.9316
Kaolin.....	10.00	24.72	.4045
Dolomite.....	7.90	16.07	.4916
Limonite.....	4.75	20.76	.2288
Gypsum.....	1.17	37.11	.0315
Chlorite.....	6.40	20.59	.3108
Carbon.....	.81	5.34	.1517
Miscellaneous.....	1.06	20.00	.0530
Total.....	100.00	-----	4.8432

$$V_{MSC} = \frac{100.00}{4.8432} \times 100 = 2,064.8$$

shale; then weights are in terms of N^{-1} grams and volumes in terms of N^{-1} cubic centimeters. By this convention the volume of 100 equivalent mineral units (which contains 100 cations) of Leith and Mead's average shale, as computed in table 23, is $2,064.8 \times N^{-1}$ cc, or $3,427.2 \times 10^{-24}$ cc. This volume is represented by a cube about 15.1×10^{-8} cm, or about 15.1 ang-

strom units on an edge. We are now able to frame a definition of the modified standard cell in terms of volume alone:

The *modified standard cell* is the volume of rock that contains $2,064.8 \times N^{-1}$ cc, or about $3,427.2 \times 10^{-24}$ cc. In actual practice it is convenient not to convert to cubic centimeters but to leave the volumes in terms of N^{-1} cubic centimeters and regard them as proportions. With this convention understood, it is not necessary to specify units involved.

CALCULATION OF THE CELL CONTENTS

The contents of the modified standard cell for any rock can be calculated from a chemical analysis in several ways. If the density of the rock is known, the cell contents can be calculated most conveniently and most accurately from that; otherwise, the mineral mode, either in volume or weight percent, provides a satisfactory basis of calculation. Table 24 contains a sample calculation of the modified standard cell, on the basis of both rock density and mineral mode—the mode both in volume percent and equivalent molecular percent—as well as sample calculations of the mode and of a mineral formula. The calculations relating to determination of the cell contents are in tables 24-A, 24-C, and 24-E. The method of procedure is as follows:

TABLE 24.—Sample calculation of the modified standard cell (MSC), the mode, and the formula of a mineral in the rock

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
SiO ₂ -----	54.96	0.91508	52.42	104.84	52.71
AlO _{3/2} -----	21.62	.42417	24.30	36.45	24.44
FeO _{3/2} -----	1.62	.02029	1.16	1.74	1.17
FeO-----	3.65	.05080	2.91	2.91	2.93
MgO-----	4.20	.10417	5.97	5.97	6.00
CaO-----	1.28	.02282	1.31	1.31	1.32
NaO _{1/2} -----	.00	.00000	.00	.00	.00
KO _{1/2} -----	5.43	.11530	6.61	3.31	6.65
HO _{1/2} +-----	4.43	.49179	28.17	14.09	28.33
TiO ₂ -----	1.45	.01815	1.04	2.08	1.05
CO ₂ -----	.21	.00477	.27	.54	.27
PO _{5/2} -----	.24	.00338	.19	.48	.19
S-----	.47	.01466	.84	.84	.84
C-----	.80	.06661	3.82	1.91	3.84
Total-----	100.36			176.47	
Less O for S-----	.18			.63	
Total-----	100.18	2.25199	129.01	175.84	
Less HO _{1/2} +S-----		.50645	29.01	14.93	
Total-----		1.74554	100.00	160.91	
Less HO _{1/2} +CO ₂ +C-----				16.54	
O-----				144.37	
Oeq-----					176.82
Cations-----					100.56
O-----					145.18

TABLE 24.—Sample calculation of the modified standard cell (MSC), the mode, and the formula of a mineral in the rock—Continued

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS

	Muscovite	Quartz	Sphene	Ilmenite	Apatite	Calcite	Pyrite	Graphite	Chlorite				Cation totals or averages
									Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂	19.83	27.03	0.72						4.84	9.68	5.20	2.60	52.42
AlO _{3/2}	19.83								4.47	6.71	3.60	2.40	24.30
FeO _{3/2}							0.42		.74	1.11	.60	.40	1.16
FeO.....				0.32					2.59	2.59	1.39	1.39	2.91
MgO.....									5.97	5.97	3.21	3.21	5.97
CaO.....			.72		0.32	0.27							1.31
NaO _{1/2}	.00												.00
KO _{1/2}	6.61												6.61
HO _{1/2} +.....	13.22				.06				14.89	7.45	4.00	8.00	28.17
TiO ₂			.72	.32									1.64
CO ₂						.27							.27
PO _{5/2}					.19								.19
S.....							.84						.84
C.....								3.82					3.82
Total.....	59.49	27.03	2.16	0.64	0.57	0.54	1.26	3.82	33.50	33.51	18.00	18.00	129.01
Less HO _{1/2} +S.....	13.22				.06		.84		14.89	7.45	4.00	8.00	29.01
Total (equivalent molecular percent).....	46.27	27.03	2.16	0.64	0.51	0.54	0.42	3.82	18.61	26.06	14.00	10.00	100.00
Less HO _{1/2} +CO ₂ +C.....										7.45	4.00		
O.....										18.61	10.00		
													Total
V _r	20.31	22.63	18.67	16.14	20.45	18.42	23.90	5.24	21.51				
Volume proportions.....	939.74	611.69	40.33	10.33	10.43	9.95	10.04	20.40	400.30				2053.21
Volume percent.....	45.77	29.79	1.96	.50	.51	.49	.99	19.50	19.50				100.00
Density.....	2.80	2.654	3.50	4.70	3.18	2.717	5.02	2.25	2.844				2.795

C. CALCULATION OF "CELL FACTOR" (F_{rk})

1. From density of the rock

$$W_{100} = \frac{100.18}{1.74554} \times 100 = 5739.2, \text{ weight of 100 equivalent molecules of rock}$$

$$\text{Density} = 2.795$$

$$V_{100} = \frac{W_{100}}{D} = 2053.4, \text{ volume of 100 equivalent molecules of rock}$$

$$F_{rk} = \frac{V_{MSC}}{V_{100}} = 1.0056$$

2. From mode of rock

	a. From mode, in volume percent			b. From mode, in equivalent molecular percent		
	Volume percent	F_{min}	EMU in MSC	Equiv. molec. percent	V_*	V_{100}
Muscovite.....	45.77	1.0166	46.53	46.27	20.31	939.74
Quartz.....	29.79	.9124	27.18	27.03	22.63	611.69
Sphene.....	1.96	1.1059	2.17	2.16	18.67	40.33
Ilmenite.....	.50	1.2793	.64	.64	16.14	10.33
Apatite.....	.51	1.0097	.51	.51	20.45	10.43
Calcite.....	.49	1.1210	.55	.54	18.42	9.95
Pyrite.....	.49	.8639	.42	.42	23.90	10.04
Graphite.....	.99	3.8667	3.83	3.82	5.34	20.40
Chlorite.....	19.50	.9598	18.72	18.61	21.51	400.30
Total.....	100.00		100.55	100.00		2053.21
$F_{rk} = \frac{\text{Total EMU in MSC}}{100} = 1.0055$				$F_{rk} = \frac{V_{MSC}}{V_{100}} = 1.0056$		

D. CHLORITE FORMULA

[Formula values: $n=6$; $p=1.4$; $2(n-2)=8$]

E. ROCK FORMULA, MODIFIED STANDARD CELL

The chemical analysis, in weight percent, is converted to equivalent molecular numbers by dividing each term by the appropriate equivalent weight (see appendix A). The equivalent molecular numbers are then converted to equivalent molecular percent by dividing each term by the sum of the equivalent molecular numbers less the values for $\text{HO}_{1/2}$, S (as sulfide), As (as arsenide), and any other electronegative ions included in the total for equivalent molecular numbers. Next, the oxygen equivalents (Oeq; see appendix A) associated with 100 equivalent molecular percent are calculated by multiplying the equivalent molecular percentage of each constituent by the number of oxygen ions (or their equivalent) in the symbol for the equivalent unit shown in table 24-A. For example, the equivalent molecular percentage of SiO_2 is multiplied by 2, of $\text{AlO}_{3/2}$ by $3/2$, of S by 1, and of C by $1/2$. The total oxygen equivalents are then determined by summation; a correction must be applied, where appreciable sulfide or arsenide minerals are present, by subtracting a sum equal to the amount of oxygen incorrectly calculated to be associated with iron combined in sulfides or arsenides¹⁴. The total number of oxygen ions not combined in OH, CO_2 , and similar radicals is then determined by subtracting from the corrected value of total oxygen equivalents the sum of $(2\text{HO}_{1/2} + \text{CO}_2 + \text{SO}_3 + \text{S} + \text{As} + \text{C} \dots)$, in terms of oxygen equivalents. A convenient procedure that is readily understood is shown in table 24-A in the column headed "Oeq."

If the density of the rock is known, the cell contents are then determined very simply, as shown in table 24-C-1. W_{100} , the weight of 100 equivalent molecules of rock (in terms of N^{-1} grams; see p. 132-133, is found by dividing the total weight percent (column 1, table 24-A) by the total equivalent molecular numbers corrected for $\text{HO}_{1/2}$ and S (bottom line entry, column 2, table 24-A) and multiplying by 100; thus,

$$W_{100} = \frac{100.18}{1.74554} \times 100 = 5739.2.$$

V_{100} , the volume of 100 equivalent molecules of rock (in terms of N^{-1} cc), is then obtained by dividing

¹⁴ Iron in pyrite is generally recorded as ferric iron (Nanz, 1953, p. 55); therefore, corrections for "Less O for S" in the "Oeq" column become, in terms of oxygen equivalents:

If S is in pyrite, "Less O for S" = $3/4$ S;

If S is in pyrrhotite, "Less O for S" = $3/2$ S.

In terms of weight percent, or weight proportions, the corrections are:

If S is in pyrite, "Less O for S" = $3/8$ S;

If S is in pyrrhotite, "Less O for S" = $3/4$ S.

If the analytical procedures were such that the iron in the sulfides was recorded as ferrous rather than ferric iron, the corrections would be, in terms of oxygen equivalents, $1/2$ S and S for pyrite and pyrrhotite, respectively; and, in terms of weight percent or weight proportions, $1/4$ S and $1/2$ S, respectively. In most analyses, As can be treated the same as sulfur if the oxygen in the symbol ($\text{AsO}_{3/2}$) is disregarded in determining the oxygen equivalent of the equivalent molecular unit.

In most rocks, sulfides of iron are the only appreciable minerals for which a correction must be applied. If for any rock appreciable quantities of other sulfides or arsenides are present, the corrections must be modified accordingly.

the weight of 100 equivalent molecules (W_{100}) by the density (D); thus,

$$V_{100} = W_{100}/D = \frac{5739.2}{2.795} = 2053.4$$

The ratio of the volume of the standard cell ($2064.8 \times N^{-1}$ cc) to the volume thus determined yields the factor (F_{rk}) by which the volume of 100 equivalent molecules of the rock under consideration must be multiplied to convert it to the volume of the modified standard cell. Consequently, the factor F_{rk} , multiplied by the equivalent molecular percentage of each constituent, yields the contents of the modified standard cell, which is what is being sought. The value of the total oxygen equivalents (Oeq) and of O not in OH, CO_2 , etc., is obtained in the same way from the Oeq column. The total number of cations (excepting H) is equal to $100 \times F_{rk}$. The procedure is evident in the last two columns of table 24-A. The contents of the modified standard cell for the sample calculation are shown in table 24-E.

If the density of the rock is not known, the mineral mode—either in volume percent or in equivalent molecular percent—readily yields a value for F_{rk} . (Modes are rarely expressed in weight percent, but such a mode could be converted to volume percent for calculation.) Table 24-C-2 contains sample calculations of F_{rk} from mineral modes in volume percent and equivalent molecular percent.

For a mode in volume percent (table 24-C-2a) the volume percentage of each mineral is multiplied by the mineral factor (F_{min}) for that mineral (defined in appendix A and tabulated for most of the common minerals in table 22) to obtain the number of equivalent mineral units of each mineral in a modified standard cell of the rock concerned. For instance, a rock composed entirely of sericite (muscovite) contains 101.66 equivalent mineral units per standard cell (see table 22); our sample rock contains 45.77 volume percent of sericite, and must therefore contain $45.77 \times 1.0166 = 46.53$ equivalent mineral units of muscovite per modified standard cell of sample rock; similarly for the other minerals in the rock. The sum of the products so obtained (last column of table 24-C-2a) gives the total equivalent mineral units, and therefore the total equivalent molecules of oxides, sulfides, and the like in a modified standard cell of the rock. Consequently, the F_{rk} , the number by which 100 molecular percent of the rock must be multiplied to obtain the contents of the standard cell, is equal to the sum of the products divided by 100; in table 24-C-2a this is $100.55/100 = 1.0055$.

For a mode in equivalent molecular percent (table 24-C-2b), the equivalent molecular percentage of each

mineral is multiplied by its equivalent volume to obtain the volume of that mineral per 100 equivalent molecules of rock (last column, table 24-C-2b). The sum of these products gives the volume of 100 equivalent molecules of the rock. The ratio of the volume of the standard cell to the volume thus obtained yields the factor sought, F_{rk} . In table 24-C-2b this is

$$F_{rk} = \frac{2064.8}{2053.21} = 1.0056.$$

The accuracy of the calculation based upon rock density, possible inaccuracies of the chemical analysis aside, is to within about 0.3 percent of the value stated for each component in the rock formula—that is, to about the third significant figure—if the density is accurate to the second decimal place; and to within about 0.03 percent—or to about the fourth significant figure—if the density is accurate to the third decimal place. Calculations based upon mineral modes are generally somewhat less accurate because of uncertainties about composition of the minerals and lack of information about densities of the minerals.

The rock formula by which the contents of the modified standard cell are represented, adopted from Barth (1952, p. 83) with only slight modification, is shown in table 24-E. In the sample, the values for the formula are taken directly from the last column of table 24-A. The number of cations is written after the formula so that percentage changes of constituents can be readily estimated. The value for Oeq permits easy transformation of the modified standard cell into Barth's standard cell of O=160 (by multiplying each term by 160/Oeq) if it is desirable to compare rocks calculated by Barth's method with rocks calculated in terms of the modified standard cell.

CALCULATION OF MINERAL MODES

Calculation of the mineral mode can readily be continued from and integrated with calculations of the modified standard cell. In some instances the calculated mode is the only means available, or is preferable for various possible reasons to the mode measured in thin section, for calculation of the modified standard cell. Table 24-B shows a sample calculation of a mineral mode so made. The values for the amounts of various oxides, ions, and atoms in each mineral are based upon the "Equivalent molecular percent" column in table 24-A; consequently, the equivalent mineral units must total 100 also, and the mode is in terms of equivalent molecular percent. Equivalent molecular percent is readily converted to volume percent, as shown in table 24-B, by multiplying the equivalent molecular percentage of each mineral (the line entry "Total (equiv. molec. percent)") by its equivalent

volume (line entry " V_e "; values obtained from table 22), and reducing the resulting volume proportions to percentages. (The last row, "Density," in table 24-B was used for calculating the density of the sample rock, and the modified standard cell, and has no bearing upon calculation of the mode.)

No hard and fast rules can be laid down for calculating the mode. The calculation should be based, if possible, upon a mode measured in thin section; otherwise, whatever knowledge is available—such as qualitative estimate of mineral composition, grade of metamorphism of the rock, and so on—must serve as a guide. In the calculations it is well to work from minerals of simple composition to those that are more complex. Certain oxides may be placed entirely in one mineral or another in most assemblages, and minerals whose compositions vary little can then readily be computed. In this manner, the range of choice for minerals of complex and variable composition is narrowed. For example, the sample calculation (table 24-B) was performed as follows:

Muscovite is the only mineral in the rock that contains potassium, and so all $KO_{1/2}$ in the rock is placed in the column headed "Muscovite"; $AlO_{3/2}$, SiO_2 , and $HO_{1/2}$ are added to the column in appropriate ratio. All CO_2 is in calcite; to that, in the column "Calcite", is added a like amount of CaO. The values to be placed in the columns "Graphite" and "Pyrite" are uniquely determined in a similar way. All $PO_{5/2}$ is placed in the column "Apatite," and CaO and $HO_{1/2}$ added in the proper ratios. The remaining CaO is placed in the "Sphene" column, and like amounts of TiO_2 and SiO_2 added. The remaining TiO_2 goes into "Ilmenite," along with a like amount of FeO. The remaining constituents go into "Chlorite," except for the amount of SiO_2 in "Quartz." The amount of quartz should be based upon thin section data, but the balance of SiO_2 can be adjusted between quartz and chlorite in accordance with optical or other information available upon the composition of the chlorite.

CALCULATION OF MINERAL FORMULAS

Formulas of minerals of unknown and variable composition can generally be calculated satisfactorily from rock analysis only if the mineral in question is the only one whose composition varies appreciably and if it is the predominant constituent in the rock. Many of the calculations in appendixes G, H, and I, being of almost monomineralic rocks, serve well to illustrate the procedure. The analysis in table 24, being idealized, serves as a satisfactory example for calculation of a mineral formula from a rock analysis even though the chlorite whose formula is sought constitutes only some-

what less than 20 percent of the rock. The calculation is shown in table 24-B. First, the number of oxygen ions associated with the equivalent units denoted in the "Equiv. molec. percent" column under "Chlorite" is calculated and tabulated in the "Oeq" column under "Chlorite". This column is then recalculated to the basis that the O written separately in the chlorite formula (that is, the oxygen not combined with H in OH) totals 10, in accordance with the general formula (Berman, 1937, p. 378). A convenient procedure is illustrated in the "Oeq" column; it consists of dividing each term in "Oeq" by total "Oeq" corrected for the O combined in OH. Thus, in the sample calculation, each term in Oeq is divided by the quantity total Oeq minus twice the oxygen equivalent in $\text{HO}_{1/2}$ (or by $33.51 - 7.45 - 7.45 = 18.61$). The formula numbers for the chlorite are found by multiplying each term in the "O = 10" column by the reciprocal of the subscript for O in the corresponding oxide unit. Thus "Si" in the chlorite formula is equal to $5.20 \times \frac{1}{2} = 2.60$, and so on. Table 24-D contains the calculated chlorite formula thus obtained.

APPENDIX C. CARBONATE IN ULTRAMAFIC ROCKS

All the calculations based upon analyses of carbonate in ultramafic rocks are assembled in tables 25 to 32. The calculations based upon analyses of relatively pure

samples of carbonate (tables 31 and 32) are straight forward and require little explanation. In both samples (W-43 and J-50), very small flakes of magnetite were the only impurity present. It was assumed that all Fe^{+3} in the analysis was present in magnetite, and so all $\text{FeO}_{3/2}$ and one-half that amount of FeO (in terms of molecular numbers) was subtracted before calculating the carbonate formula. The calculations are based upon the conventional formula in which the sum of the divalent metal ions and of the CO_3 radical equals two; therefore the formula numbers are obtained by reducing the values in the "Equiv. molec. Nos." column under "Carbonate" to the basis of their total equaling two.

The samples of carbonate represented by the analyses in tables 25-30 contained appreciable impurities of magnetite and talc or serpentine, ranging as high as 6 percent of talc or serpentine and 1 percent magnetite. Silica and water were not determined by analysis, but were readily calculated on the basis outlined below, so that a mineral mode could be calculated and a formula composition for the carbonate determined, corrected for impurities. The samples were very difficult to decompose (written communication, Jan. 5, 1952, Wilbur J. Blake, analyst), and even redeterminations of CO_2 appeared to be unreliable; therefore, calculated values of CO_2 were used rather than values determined by analysis.

TABLE 25.—Calculations upon analysis of carbonate in talc-carbonate rock, sample W-71, Waterbury mine

[Analysis 1, table 3. Index, $\omega=1.732$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C_1	C_2	Equivalent molecular percent
	Reported	Modified					
$\text{FeO}_{3/2}$	0. 60	0. 60	0. 00751	0. 00751	0. 60	.....	0. 34
FeO.....	12. 87	12. 87	. 17912	. 00376	12. 87	0. 17536	8. 15
MgO.....	35. 97	35. 97	. 89211	.....	35. 97	. 89211	40. 59
CaO.....	. 38	. 38	. 00678	.....	. 38	. 00678	. 31
CO_2	47. 12	.....	.....	.....	.....	.....	.....
MnO.....	. 96	. 96	. 01353	.....	. 96	. 01353	. 62
PbO.....	. 00	. 00	. 00000	.....	. 00	. 00000	. 00
ZnO.....	. 00	. 00	. 00000	.....	. 00	. 00000	. 00
CoO.....	. 0032	. 0032	. 00004	.....	. 00	. 00004	. 002
$\text{HO}_{1/2}$ + calculated.....	.....	. 19	. 02131	.....	.....	.....	. 97
SiO_2 calculated.....	.....	2. 56	. 04262	.....	.....	.....	1. 94
CO_2 calculated.....	.....	46. 47	1. 05586	.....	.....	.....	48. 05
Total.....	97. 90	100. 00	2. 21888	.....	50. 78	1. 08782	100. 97
Less $\text{HO}_{1/2}$.....	.....	.....	. 02131	.....	.....	.....	. 97
Total.....	.....	.....	2. 19757	.....	.....	.....	100. 00

TABLE 25.—Calculations upon analysis of carbonate in talc-carbonate rock, sample W-71, Waterbury mine—Continued

B. CALCULATED MODE, AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Talc	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2}	0. 34						
FeO.....	. 17	0. 10	7. 88	0. 1640	11. 78	13. 09	
MgO.....		1. 36	39. 23	. 8166	32. 93	36. 60	
CaO.....			. 31	. 0065	. 36	. 40	
CO ₂							
MnO.....			. 62	. 0129	. 91	1. 01	
PbO.....			. 00	. 0000	. 00	. 00	
ZnO.....			. 00	. 0000	. 00	. 00	
CoO.....			. 002	. 00004	. 003	. 003	
HO _{1/2} + calculated.....		. 97					
SiO ₂ calculated.....		1. 94					
CO ₂ calculated.....			48. 05	1. 0000	44. 01	48. 90	
Total.....	0. 51	4. 37	96. 09	2. 0000	89. 993	100. 00	
Less HO _{1/2}		. 97					
Total.....	0. 51	3. 40	96. 09				
V _e	14. 84	19. 21	13. 91				
Volume proportions.....	7. 57	65. 31	1, 336. 61				1, 409. 49
Volume percent.....	. 54	4. 63	94. 83				100. 00

C. CALCULATION OF HO_{1/2}, SiO₂, AND CO₂

$$\text{HO}_{1/2} + = \frac{100 - (C_1 + 44.01C_2)}{63.113} = \frac{100 - 50.78 - 44.01 \times 1.08782}{63.113} = 0.02131$$

$$\text{SiO}_2 = 2\text{HO}_{1/2} = 2 \times 0.02131 = 0.04262$$

$$\text{CO}_2 = C_2 - 3/2 \text{HO}_{1/2} = 1.08782 - 3/2 \times 0.02131 = 1.05586$$

D. CARBONATE FORMULA

TABLE 26.—Calculations upon analysis of carbonate in talc-carbonate rock, sample J-106, Johnson mine

[Analysis 2, table 3. Index, $\omega=1.720$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C ₁	C ₂	Equivalent molecular percent
	Reported	Modified					
FeO _{3/2} -----	0. 88	0. 88	0. 01102	0. 01102	0. 88	-----	0. 50
FeO-----	10. 27	10. 27	. 14294	. 00551	10. 27	. 13743	6. 44
MgO-----	38. 00	38. 00	. 94246	-----	38. 00	. 94246	42. 47
CaO-----	. 58	. 58	. 01034	-----	. 58	. 01034	. 47
CO ₂ -----	47. 56	-----	-----	-----	-----	-----	-----
MnO-----	. 26	. 26	. 00367	-----	. 26	. 00367	. 16
PbO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
ZnO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
CoO-----	. 0025	. 0025	. 00003	-----	. 00	. 00003	. 0013
HO _{3/2} + calculated-----	-----	. 27	. 02957	-----	. 00	-----	1. 33
SiO ₂ calculated-----	-----	3. 55	. 05914	-----	-----	-----	2. 66
CO ₂ calculated-----	-----	46. 19	1. 04957	-----	-----	-----	47. 30
Total-----	97. 55	100. 00	2. 24874	-----	49. 99	1. 09393	101. 33
Less HO _{3/2} -----	-----	-----	. 02957	-----	-----	-----	1. 33
Total-----	-----	-----	2. 21917	-----	-----	-----	100. 00

B. CALCULATED MODE, AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Talc	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2} -----	0. 50	-----	-----	-----	-----	-----	-----
FeO-----	. 25	0. 18	6. 01	0. 1271	9. 13	10. 31	-----
MgO-----	-----	1. 82	40. 65	. 8595	34. 66	39. 12	-----
CaO-----	-----	-----	. 47	. 0100	. 56	. 63	-----
CO ₂ -----	-----	-----	-----	-----	-----	-----	-----
MnO-----	-----	-----	. 16	. 0034	. 24	. 27	-----
PbO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
ZnO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
CoO-----	-----	-----	. 0013	. 00003	. 0022	. 0025	-----
HO _{3/2} + calculated-----	-----	1. 33	-----	-----	-----	-----	-----
SiO ₂ calculated-----	-----	2. 66	-----	-----	-----	-----	-----
CO ₂ calculated-----	-----	-----	47. 30	1. 0000	44. 01	49. 67	-----
Total-----	0. 75	5. 99	94. 59	2. 0000	88. 60	100. 00	-----
Less HO _{3/2} -----	-----	1. 33	-----	-----	-----	-----	-----
Total-----	0. 75	4. 66	94. 59	-----	-----	-----	-----
V _e -----	14. 84	19. 21	13. 87	-----	-----	-----	-----
Volume proportions-----	11. 13	89. 52	1, 311. 96	-----	-----	-----	1, 412. 61
Volume percent-----	. 79	6. 34	92. 87	-----	-----	-----	100. 00

C. CALCULATION OF HO_{3/2}, SiO₂ AND CO₂

$$\text{HO}_{3/2} + = \frac{100 - (C_1 + 44.01C_2)}{63.113} = \frac{100 - 49.99 - 44.01 \times 1.09393}{63.113} = 0.02957$$

$$\text{SiO}_2 = 2\text{HO}_{3/2} = 2 \times 0.02957 = 0.05914$$

$$\text{CO}_2 = C_2 - 3/2\text{HO}_{3/2} = 1.09393 - 3/2 \times 0.02957 = 1.04957$$

D. CARBONATE FORMULA

TABLE 27.—Calculations upon analysis of carbonate in talc-carbonate rock, sample B-DDH-9B₁-325, Barnes Hill[Analysis 3, table 3. Index, $\omega=1.684$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C ₁	C ₂	Equivalent molecular percent
	Reported	Modified					
FeO _{3/2} -----	0.35	0.35	0.00438	0.00438	0.35	-----	0.21
FeO-----	1.16	1.16	.01615	.00219	1.16	0.01396	.76
MgO-----	22.34	22.34	.55416	-----	22.34	.55416	25.91
CaO-----	27.32	27.32	.48717	-----	27.32	.48717	22.77
CO ₂ -----	43.28	-----	-----	-----	-----	-----	-----
MnO-----	.20	.20	.00282	-----	.20	.00282	.13
PbO-----	.00	.00	.00000	-----	.00	.00000	.00
ZnO-----	.00	.00	.00000	-----	.00	.00000	.00
CoO-----	.0025	.0025	.00003	-----	.00	.00003	.0014
HO _{1/2} + calculated-----	-----	.29	.03266	-----	-----	-----	1.53
SiO ₂ calculated-----	-----	3.92	.06532	-----	-----	-----	3.05
CO ₂ calculated-----	-----	44.41	1.00915	-----	-----	-----	47.17
Total-----	94.65	99.99	2.17184	-----	51.37	1.05814	101.53
Less HO _{1/2} -----	-----	-----	.03266	-----	-----	-----	1.53
Total-----	-----	-----	2.13918	-----	-----	-----	100.00

B. CALCULATED MODE, AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Talc	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2} -----	0.21	-----	-----	-----	-----	-----	-----
FeO-----	.10	0.21	0.45	0.0095	0.68	0.74	-----
MgO-----	-----	2.08	23.83	.5051	20.37	22.06	-----
CaO-----	-----	-----	22.77	.4827	27.07	29.32	-----
CO ₂ -----	-----	-----	-----	-----	-----	-----	-----
MnO-----	-----	-----	.13	.0028	.20	.22	-----
PbO-----	-----	-----	.00	.0000	.00	.00	-----
ZnO-----	-----	-----	.00	.0000	.00	.00	-----
CoO-----	-----	-----	.0014	.00003	.0022	.0024	-----
HO _{1/2} + calculated-----	-----	1.53	-----	-----	-----	-----	-----
SiO ₂ calculated-----	-----	3.05	-----	-----	-----	-----	-----
CO ₂ calculated-----	-----	-----	47.17	.9999	44.01	47.66	-----
Total-----	0.31	6.87	94.35	2.0000	92.33	100.00	-----
Less HO _{1/2} -----	-----	1.53	-----	-----	-----	-----	-----
Total-----	0.31	5.34	94.35	-----	-----	-----	-----
V _e -----	14.84	19.21	15.99	-----	-----	-----	-----
Volume proportions-----	4.60	102.58	1508.66	-----	-----	-----	1615.84
Volume percent-----	.28	6.35	93.37	-----	-----	-----	100.00

C. CALCULATION OF HO_{1/2}, SiO₂ AND CO₂

$$\text{HO}_{1/2} + = \frac{100 - (C_1 + 44.01C_2)}{63.113} = \frac{100 - 51.37 - 44.01 \times 1.05814}{63.113} = 0.03266$$

$$\text{SiO}_2 = 2\text{HO}_{1/2} = 2 \times 0.03266 = 0.06532$$

$$\text{CO}_2 = C_2 - 3/2\text{HO}_{1/2} = 1.05814 - 3/2 \times 0.03266 = 1.00915$$

D. CARBONATE FORMULA

TABLE 28.—Calculations upon analysis of carbonate in talc-carbonate rock, sample R-DDH-8-145, Rousseau prospect

[Analysis 4, table 3. Index, $\omega=1.719$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C ₁	C ₂	Equivalent molecular percent
	Reported	Modified					
FeO _{3/2} -----	1. 25	1. 25	0. 01565	0. 01565	1. 25	-----	0. 70
FeO-----	9. 86	9. 86	. 13723	. 00783	9. 86	0. 12940	6. 18
MgO-----	38. 23	38. 23	. 94816	-----	38. 23	. 94816	42. 67
CaO-----	. 47	. 47	. 00838	-----	. 47	. 00838	. 38
CO ₂ -----	48. 41	-----	-----	-----	-----	-----	-----
MnO-----	. 50	. 50	. 00705	-----	. 50	. 00705	. 32
PbO-----	. 00	. 00	. 00000	. 00000	. 00	. 00000	. 00
ZnO-----	. 00	. 00	. 00000	. 00000	. 00	. 00000	. 00
CoO-----	. 0047	. 0047	. 00006	-----	. 00	. 00006	. 0027
HO _{1/2} + calculated-----	-----	. 23	. 02511	-----	-----	-----	1. 13
SiO ₂ calculated-----	-----	3. 01	. 05022	-----	-----	-----	2. 26
CO ₂ calculated-----	-----	46. 45	1. 05538	-----	-----	-----	47. 49
Total-----	98. 72	100. 00	2. 24724	-----	50. 31	1. 09305	101. 13
Less HO _{1/2} -----	-----	-----	. 02511	-----	-----	-----	1. 13
Total-----	-----	-----	2. 22213	-----	-----	-----	100. 00

B. CALCULATED MODE, AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Talc	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2} -----	0. 70	-----	-----	-----	-----	-----	-----
FeO-----	. 35	0. 15	5. 68	0. 1196	8. 59	9. 71	-----
MgO-----	-----	1. 55	41. 12	. 8658	34. 91	39. 47	-----
CaO-----	-----	-----	. 38	. 0080	. 45	. 51	-----
CO ₂ -----	-----	-----	-----	-----	-----	-----	-----
MnO-----	-----	-----	. 32	. 0067	. 48	. 54	-----
PbO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
ZnO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
CoO-----	-----	-----	. 0027	. 00006	. 0045	. 0050	-----
HO _{1/2} + calculated-----	-----	1. 13	-----	-----	-----	-----	-----
SiO ₂ calculated-----	-----	2. 26	-----	-----	-----	-----	-----
CO ₂ calculated-----	-----	-----	47. 49	. 9999	44. 01	49. 76	-----
Total-----	1. 05	5. 09	94. 99	2. 0000	88. 44	100. 00	-----
Less HO _{1/2} -----	-----	1. 13	-----	-----	-----	-----	-----
Total-----	1. 05	3. 96	94. 99	-----	-----	-----	-----
V _e -----	14. 84	19. 21	13. 86	-----	-----	-----	-----
Volume proportions-----	15. 58	76. 07	1, 316. 56	-----	-----	-----	1, 408. 21
Volume percent-----	1. 11	5. 40	93. 49	-----	-----	-----	100. 00

C. CALCULATION OF HO_{1/2}, SiO₂, AND CO₂

$$\text{HO}_{1/2} = \frac{100 - (C_1 + 44.01C_2)}{63.113} = \frac{100 - 50.31 - 44.01 \times 1.09305}{63.113} = 0.02511$$

$$\text{SiO}_2 = 2\text{HO}_{1/2} = 2 \times 0.02511 = 0.05022$$

$$\text{CO}_2 = C_2 - 3/2\text{HO}_{1/2} = 1.09305 - 3/2 \times 0.02511 = 1.05538$$

D. CARBONATE FORMULA

TABLE 29.—Calculations upon analysis of carbonate in veins in serpentinite, sample W-DDH-13-146, Waterbury mine

[Analysis 5, table 3. Index, $\omega=1.713$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C ₁	C ₂	Equivalent molecular percent
	Reported	Modified					
FeO _{3/2} -----	0. 34	0. 34	0. 00426	0. 00426	0. 34	-----	0. 19
FeO-----	8. 83	8. 83	. 12289	. 00213	8. 83	0. 12076	5. 48
MgO-----	39. 64	39. 64	. 98313	-----	39. 64	. 98313	43. 81
CaO-----	. 06	. 06	. 00107	-----	. 06	. 00107	. 05
CO ₂ -----	44. 61	-----	-----	-----	-----	-----	-----
MnO-----	. 51	. 51	. 00719	-----	. 51	. 00719	. 32
PbO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
ZnO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
CoO-----	. 0063	. 0063	. 00008	-----	. 01	. 00008	. 0035
HO _{1/2} +-----	-----	. 24	. 02631	-----	-----	-----	1. 17
SiO ₂ -----	-----	3. 16	. 05262	-----	-----	-----	2. 34
CO ₂ -----	-----	47. 21	1. 07276	-----	-----	-----	47. 81
Total-----	94. 00	100. 00	2. 27031	-----	49. 39	1. 11223	101. 17
Less HO _{1/2} -----	-----	-----	. 02631	-----	-----	-----	1. 17
Total-----	-----	-----	2. 24400	-----	-----	-----	100. 00

B. CALCULATED MODE AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Talc	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2} -----	0. 19	-----	-----	-----	-----	-----	-----
FeO-----	. 09	0. 16	5. 23	0. 1094	7. 86	8. 93	-----
MgO-----	-----	1. 60	42. 21	. 8829	35. 60	40. 45	-----
CaO-----	-----	-----	. 05	. 0100	. 06	. 07	-----
CO ₂ -----	-----	-----	-----	-----	-----	-----	-----
MnO-----	-----	-----	. 32	. 0067	. 48	. 54	-----
PbO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
ZnO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
CoO-----	-----	-----	. 0035	. 00007	. 0052	. 0059	-----
HO _{1/2} + calculated-----	-----	1. 17	-----	-----	-----	-----	-----
SiO ₂ calculated-----	-----	2. 34	-----	-----	-----	-----	-----
CO ₂ -----	-----	-----	47. 81	1. 0000	44. 01	50. 00	-----
Total-----	0. 28	5. 27	95. 62	2. 0000	88. 02	100. 00	-----
Less HO _{1/2} -----	-----	1. 17	-----	-----	-----	-----	-----
Total-----	0. 28	4. 10	95. 62	-----	-----	-----	-----
V _e -----	14. 84	19. 21	13. 81	-----	-----	-----	-----
Volume proportions-----	4. 16	78. 76	1, 320. 51	-----	-----	-----	1, 403. 43
Volume percent-----	. 30	5. 61	94. 09	-----	-----	-----	100. 00

C. CALCULATION OF HO_{1/2}, SiO₂, AND CO₂

$$\text{HO}_{1/2} = \frac{100 - (C_1 + 44.01C_2)}{63.113} = \frac{100 - 49.39 - 44.01 \times 1.11223}{63.113} = 0.02631$$

$$\text{SiO}_2 = 2\text{HO}_{1/2} = 2 \times 0.02631 = 0.05262$$

$$\text{CO}_2 = C_2 - 3/2\text{HO}_{1/2} = 1.11223 - 3/2 \times 0.02631 = 1.07276$$

D. CARBONATE FORMULA

TABLE 30.—Calculations upon analysis of carbonate in veinlets in serpentinite, sample B-DDH-9B₁-380, Barnes Hill[Analysis 6, table 3. Index, $\omega=1.702$]

A. CALCULATION OF MODIFIED ANALYSIS AND EQUIVALENT MOLECULAR PERCENTAGES

Oxide	Weight percent		Equivalent molecular numbers	Magnetite	C ₁	C ₂	Equivalent molecular percent
	Reported	Modified					
FeO _{3/2} -----	0. 16	0. 16	0. 00200	0. 00200	0. 16	-----	0. 09
FeO-----	1. 26	1. 26	. 01754	. 00100	1. 26	0. 01654	. 75
MgO-----	46. 33	46. 33	1. 14906	-----	46. 33	1. 14096	49. 13
CaO-----	. 00	. 00	-----	-----	. 00	-----	-----
CO ₂ -----	50. 79	-----	-----	-----	-----	-----	-----
MnO-----	. 46	. 46	. 00649	-----	. 46	. 00649	. 28
PbO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
ZnO-----	. 00	. 00	. 00000	-----	. 00	. 00000	. 00
CoO-----	. 0036	. 0036	. 00005	-----	. 00	. 00005	. 0021
HO _{1/2} +calculated-----	-----	. 30	. 03385	-----	-----	-----	1. 45
SiO ₂ calculated-----	-----	1. 02	. 01693	-----	-----	-----	. 72
CO ₂ calculated-----	-----	50. 47	1. 14675	-----	-----	-----	49. 03
Total-----	99. 00	100. 00	2. 37267	-----	48. 21	1. 17214	101. 45
Less HO _{1/2} -----	-----	-----	. 03385	-----	-----	-----	1. 45
Total-----	-----	-----	2. 33882	-----	-----	-----	100. 00

B. CALCULATED MODE, AND CARBONATE FORMULA NUMBERS AND WEIGHT PERCENTAGES

Oxide	Magnetite	Serpentine	Carbonate				Total
			Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
FeO _{3/2} -----	0. 09	-----	-----	-----	-----	-----	-----
FeO-----	. 05	0. 09	0. 61	0. 0125	0. 90	1. 06	-----
MgO-----	-----	1. 00	48. 13	. 9817	39. 58	46. 63	-----
CaO-----	-----	-----	-----	. 0000	-----	. 00	-----
CO ₂ -----	-----	-----	-----	-----	-----	-----	-----
MnO-----	-----	-----	. 28	. 0057	. 40	. 47	-----
PbO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
ZnO-----	-----	-----	. 00	. 0000	. 00	. 00	-----
CoO-----	-----	-----	. 0021	. 00004	. 0030	. 0035	-----
HO _{1/2} +calculated-----	-----	1. 45	-----	-----	-----	-----	-----
SiO ₂ calculated-----	-----	. 72	-----	-----	-----	-----	-----
CO ₂ -----	-----	-----	49. 03	1. 0001	44. 01	51. 84	-----
Total-----	0. 14	3. 26	98. 05	2. 0000	84. 89	100. 00	-----
Less HO _{1/2} -----	-----	1. 45	-----	-----	-----	-----	-----
Total-----	0. 14	1. 81	98. 05	-----	-----	-----	-----
V _e -----	14. 84	21. 32	13. 71	-----	-----	-----	-----
Volume proportions-----	2. 08	38. 59	1, 344. 27	-----	-----	-----	1, 384. 94
Volume percent-----	. 15	2. 79	97. 06	-----	-----	-----	100. 00

C. CALCULATION OF HO_{1/2}, SiO₂, AND CO₂

$$\text{HO}_{1/2} = \frac{100 - (C_1 + 44.01C_2)}{6.03} = \frac{100 - 48.21 - 44.01 \times 1.17214}{6.03} = 0.03385$$

$$\text{SiO}_2 = \frac{1}{2} \text{HO}_{1/2} = \frac{1}{2} \times 0.03385 = 0.01693$$

$$\text{CO}_2 = C_2 - \frac{3}{4} \text{HO}_{1/2} = 1.17214 - \frac{3}{4} \times 0.03385 = 1.14675$$

D. CARBONATE FORMULA

TABLE 31.—*Calculations upon analysis of carbonate in talc-carbonate vein, sample W-43, Waterbury mine*[Analysis 9, table 3. Index, $\omega=1.687$]

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES OF CARBONATE

Oxide	Weight percentage	Equivalent molecular numbers	Magnetite equivalent molecular numbers	Carbonate			
				Equivalent molecular numbers	Formula numbers	Equivalent molecular percentage	Weight percentage
FeO _{3/2} -----	0. 64	0. 00802	0. 00802				
FeO-----	2. 65	. 03689	. 00401	0. 03288	0. 0311	1. 56	2. 38
MgO-----	19. 10	. 47371		. 47371	. 4479	22. 39	19. 28
CaO-----	29. 98	. 53460		. 53460	. 5054	25. 27	30. 25
CO ₂ -----	46. 73	1. 06180		1. 06180	1. 0038	50. 19	47. 16
MnO-----	. 81	. 01142		. 01142	. 0108	. 54	. 82
PbO-----	. 00	. 00000		. 00000	. 0000	. 00	. 00
ZnO-----	. 00	. 00000		. 00000	. 0000	. 00	. 00
CoO-----	. 0003	. 000004		. 000004	. 000004	. 0002	. 0003
SrO-----	. 11	. 00106		. 00106	. 0010	. 05	. 11
Total-----	100. 02	2. 12750	. 01203	2. 11547	2. 0000	100. 00	100. 00
CO ₂ -----		1. 06180		1. 06180	1. 0038		
R ⁺² + R ⁺³ -----		1. 06570		1. 05367	. 9962		

¹ Converted from spectrographic determination of Sr=0.09 (weight percent).

B. CARBONATE FORMULA

TABLE 32.—*Calculations upon analysis of carbonate in talc-carbonate vein, sample J-50, Johnson mine*[Analysis 10, table 3. Index, $\omega=1.687$]

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES OF CARBONATE

Oxide	Weight percentage	Equivalent molecular numbers	Magnetite equivalent molecular numbers	Carbonate			
				Equivalent molecular numbers	Formula numbers	Equivalent molecular percentage	Weight percentage
FeO _{3/2} -----	0. 58	0. 00726	0. 00726				
FeO-----	2. 09	. 02909	. 00363	0. 02546	0. 0239	1. 19	1. 84
MgO-----	19. 76	. 49008		. 49008	. 4592	22. 96	19. 81
CaO-----	30. 10	. 53673		. 53673	. 5029	25. 14	30. 19
CO ₂ -----	47. 10	1. 07021		1. 07021	1. 0028	50. 14	47. 23
MnO-----	. 69	. 00973		. 00973	. 0091	. 46	. 69
PbO-----	. 00	. 00000		. 00000	. 0000	. 00	. 00
ZnO-----	. 00	. 00000		. 00000	. 0000	. 00	. 00
CoO-----	. 0003	. 000004		. 000004	. 000004	. 0002	. 0003
SrO-----	. 24	. 00232		. 00232	. 0021	. 11	. 24
Total-----	100. 26	2. 14542	. 01089	2. 13453	2. 0000	100. 00	100. 00
CO ₂ -----		1. 07021		1. 07021	1. 0028		
R ⁺² + R ⁺³ -----		1. 07521		1. 06432	. 9972		

¹ Converted from spectrographic determination of Sr=0.2 (weight percent).

B. CARBONATE FORMULA

Equations for calculating $\text{HO}_{1/2}$, SiO_2 and CO_2 in a sample of carbonate that contains magnetite and either talc or serpentine, and only these, as impurities are derived as follows—each symbol represents one equivalent molecule in all the equations:

All $\text{FeO}_{3/2}$ in the analysis is assumed to be in magnetite, and all $\text{HO}_{1/2}$ in talc or serpentine. Let C_1 represent the sum of the weight percentages of metallic oxides reported in the analysis, and C_2 the sum of the equivalent molecular numbers of metallic oxides present in the pure carbonate and pure talc or serpentine. Then, letting MgO , FeO , and the like, represent the values tabulated in the "Equiv. molec. Nos." column of table 25, and 40.32, 71.85, and so on, the corresponding equivalent weights: $C_1 = (40.32 \text{ MgO} + 71.85 \text{ FeO} + 56.08 \text{ CaO} + 70.93 \text{ MnO} + 74.94 \text{ CoO} + 79.85 \text{ FeO}_{3/2}) =$ the sum of the weight percentages of the metallic oxides;

and

$$C_2 = (\text{MgO} + \text{FeO} + \text{CaO} + \text{MnO} + \text{CoO} - 1/2 \text{FeO}_{3/2}).$$

Then,

I. If the impurities are talc and magnetite:

From the properties of analyses expressed in weight percent of oxides, and from the formula of talc, $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$, the following equations can be derived:

$$44.01 \text{ CO}_2 + 60.06 \text{ SiO}_2 + 9.008 \text{ HO}_{1/2} = 100 - C_1, \quad (1)$$

$$\text{SiO}_2 - 2 \text{ HO}_{1/2} = \text{O}, \quad (2)$$

$$\text{CO}_2 + 3/2 \text{ HO}_{1/2} = C_2. \quad (3)$$

Solving (2) for SiO_2 and substituting in (1),

$$44.01 \text{ CO}_2 + 129.128 \text{ HO}_{1/2} = 100 - C_1; \quad (4)$$

multiplying (3) by 44.01,

$$44.01 \text{ CO}_2 + 66.015 \text{ HO}_{1/2} = 44.01 C_2; \quad (5)$$

subtracting (4) - (5),

$$63.113 \text{ HO}_{1/2} = 100 - C_1 - 44.01 C_2; \quad (6)$$

or

$$\text{HO}_{1/2} = \frac{100 - (C_1 + 44.01 C_2)}{63.113}. \quad (7)$$

From (2)

$$\text{SiO}_2 = 2 \text{ HO}_{1/2}, \quad (8)$$

and from (3)

$$\text{CO}_2 = C_2 - 3/2 \text{ HO}_{1/2}. \quad (9)$$

II. If the impurities are serpentine and magnetite:

In an analogous manner the following equations may be set up:

$$44.01 \text{ CO}_2 + 60.06 \text{ SiO}_2 + 9.008 \text{ HO}_{1/2} = 100 - C_1, \quad (10)$$

$$\text{SiO}_2 - 0.5 \text{ HO}_{1/2} = \text{O}, \quad (11)$$

$$\text{CO}_2 + 0.75 \text{ HO}_{1/2} = C_2; \quad (12)$$

and the following solutions obtained:

$$\text{HO}_{1/2} = \frac{100 - (C_1 + 44.01 C_2)}{6.03}, \quad (13)$$

$$\text{SiO}_2 = 1/2 \text{ HO}_{1/2}, \quad (14)$$

$$\text{CO}_2 = C_2 - 3/4 \text{ HO}_{1/2}. \quad (15)$$

By use of equations (7), (8), and (9), or of equations (13), (14), and (15) the proportions of the missing components are readily calculated. Thereafter, the mineral mode and the formula of the pure carbonate are easily determined. Using table 25 as an example, the procedure is as follows:

The reported analysis in weight percent (except for CO_2) is converted to equivalent molecular numbers by dividing the weight percentage of each oxide by its equivalent weight. The equivalent molecular numbers of the metallic oxides, less all the $\text{FeO}_{3/2}$ and half that amount of FeO (in terms of molecular numbers), are recorded in the column " C_2 "; the total of this column is the value to be substituted for C_2 in the equations above. The weight percentage of all the metallic oxides reported is recorded in column " C_1 ", and totaled to get the value of C_1 to be used in the equations. The values so obtained are then substituted and the calculated values of $\text{HO}_{1/2}$, SiO_2 , and CO_2 determined from the equations. The weight percentages of the three calculated components are readily determined by multiplying the equivalent molecular number of each by its equivalent molecular weight. Equivalent molecular numbers are converted to molecular percent by dividing by the difference of the equivalent molecular numbers minus the molecular numbers of $\text{HO}_{1/2}$. The mineral mode is calculated and the carbonate formula derived in a manner analogous to that described for the sample calculation (table 24) in appendix B: The amount of $\text{FeO}_{3/2}$ determines the amount of magnetite; the amount of $\text{HO}_{1/2}$ determines the amount of talc or serpentine; the balance goes into carbonate. The compositions of talc and serpentine in tables 25 to 30 are based upon data recorded and discussed in the sections on serpentinite, and steatite, talc-carbonate rock, and talc-carbonate veins under "Petrography." Lastly, for convenience in comparing with other analyses of carbonate that are given in the usual form of weight percent of oxides, the calculated analysis of pure carbonate is converted to weight percent, recorded in the next to last column of table 25-B.

APPENDIX D. TALC

The two analyses upon which are based the calculations in tables 33 and 34 are of nearly pure samples of talc that contained as contaminants only very small amounts of carbonate and traces of magnetite and

TABLE 33.—Calculations upon analysis of talc in talc-carbonate vein, sample W-83, Waterbury mine

[Analysis 7, table 3. Index, $\beta \approx \gamma = 1.589$]

A. CALCULATION OF FORMULA NUMBERS OF TALC

Oxide	Weight percent	Equivalent molecular numbers	Carbonate ¹	Talc ¹			
				Equivalent molecular numbers	Oeq	O=10	Formula numbers
SiO ₂ -----	62.44	1.03963	-----	1.03963	2.07926	7.986	3.99
AlO _{3/2} -----	.07	.00137	-----	.00137	.00206	.008	.01
FeO _{3/2} -----	.19	.00238	-----	.00238	.00357	.013	.01
FeO-----	2.21	.03076	0.00011	.03065	.03065	.118	.12
MgO-----	30.01	.74430	.00080	.74350	.74350	2.855	2.86
CaO-----	² .00	.00000	.00000	-----	-----	-----	-----
HO _{1/2} -----	.04	-----	-----	-----	-----	-----	-----
HO _{1/2} +-----	4.63	.51399	-----	.51399	.25700	.987	1.97
CO ₂ -----	.04	.00091	.00091	-----	-----	-----	-----
S-----	Tr	-----	-----	-----	-----	-----	-----
NiO-----	.13	.00174	-----	.00174	.00174	.007	.01
Sum-----	99.76	-----	-----	-----	-----	-----	-----
Less O for S-----	.00	-----	-----	-----	-----	-----	-----
Total-----	99.76	2.33508	.00182	2.33326	3.11778	11.974	8.97
Less HO _{1/2} -----	-----	.51399	-----	.51399	.25700	.987	1.97
Total-----	-----	1.82109	-----	1.81927	2.86078	10.987	7.00
Less HO _{1/2} -----	-----	-----	-----	-----	.25700	.987	-----
O-----	-----	-----	-----	-----	2.60378	10.000	-----

¹ Calculated mode, in equivalent molecular percent: talc, 99.90; carbonate, 0.10.² With this unfavorable ratio of calcium to magnesium, it is possible that as much as 0.1 percent of CaO may be missed.

B. TALC FORMULA

TABLE 34.—Calculations upon analysis of talc in veinlike mass in steatite, sample J-103, Johnson mine

[Analysis 8, table 3. Index, $\beta \approx \gamma = 1.592$]

A. CALCULATION OF FORMULA NUMBERS OF TALC

Oxide	Weight percent	Equivalent molecular numbers	Carbonate ¹	Talc ¹			
				Equivalent molecular numbers	Oeq	O=10	Formula numbers
SiO ₂ -----	62.24	1.03630	-----	1.03630	2.07260	7.978	3.99
AlO _{3/2} -----	.09	.00177	-----	.00177	.00266	.010	.01
FeO _{3/2} -----	.10	.00125	-----	.00125	.00187	.007	.01
FeO-----	4.22	.05873	0.00011	.05862	.05862	.226	.23
MgO-----	28.57	.70858	.00080	.70778	.70778	2.725	2.73
CaO-----	² .00	.00000	.00000	-----	-----	-----	-----
HO _{1/2} -----	.00	-----	-----	-----	-----	-----	-----
HO _{1/2} +-----	4.47	.49623	-----	.49623	.24812	.955	1.91
CO ₂ -----	.04	.00091	.00091	-----	-----	-----	-----
S-----	.00	.00000	-----	-----	-----	-----	-----
NiO-----	.18	.00241	-----	.00241	.00241	.009	.01
Sum-----	99.91	-----	-----	-----	-----	-----	-----
Less O for S-----	.00	-----	-----	-----	-----	-----	-----
Total-----	99.91	2.30618	.00182	2.30436	3.09406	11.910	8.88
Less HO _{1/2} -----	-----	.49623	-----	.49623	.24812	.955	1.91
Total-----	-----	1.80995	-----	1.80813	2.84594	10.955	6.97
Less HO _{1/2} -----	-----	-----	-----	-----	.24812	.955	-----
O-----	-----	-----	-----	-----	2.59782	10.000	-----

¹ Calculated mode, in equivalent molecular percent: talc, 99.90; carbonate, 0.10.² With this unfavorable ratio of calcium to magnesium, it is possible that as much as 0.1 percent CaO may be missed.

B. TALC FORMULA

sulfide. The calculations are simple: magnetite and sulfide, being negligible in amount, are ignored; carbonate is present in such small amount that the determination of CaO is unreliable. In the calculations all CaO is put into carbonate and the balance required to balance the CO₂ is made up from MgO. Consequently, the formula of the carbonate is greatly in error: the carbonate is dolomite, actually, rather than magnesite.

The calculation of the talc formula is analogous to that for chlorite described in the sample calculation in appendix B, and requires no further explanation. The assignment of ions within the formula is discussed in the section on steatite, talc-carbonate rock, and talc-carbonate veins under "Petrography," pages 79-80.

APPENDIX E. MAGNETITE AND CHROMITE

Tables 35 to 37 record computations by which the average composition of the intermixed magnetite and chromite in each of three samples was determined. The analyses were made upon very small samples (0.353g, 0.167g, and 2.434g, respectively) that were separated from serpentinite by the following procedure

(Marie L. Lindberg, written communication, April 4, 1952):

The samples were ground to pass 80-mesh, and a rough magnetic separation was made with the hand magnet. The magnetic fraction was further ground to pass 270-mesh, since the magnetite and accompanying serpentine was very fine grained. The bulk of the serpentine was decanted off, and a second magnetic separation was made. The magnetite fraction was then separated in Clerici solution, four times, to minimize the amount of light material mechanically carried down with the magnetite. During these separations, it was noted in two samples, B-DDH-9B₁-432 and W-DDH-13-35-50, that small quantities of a mineral with bronze luster were settling differentially faster than the magnetite.

The two samples in which a mineral with a bronze luster was separating differentially faster than magnetite were further studied. Since the different rate of settling did not effect a complete separation, magnetite made up the bulk of the material which was the first material to separate. The mineral with a bronze luster was identified as pyrrhotite(?) on the basis of 3 otherwise unaccounted lines on the X-ray powder photograph. These lines are 4.22 very weak, 2.998 very weak, and 2.020 medium strength. The pyrrhotite(?) had a slightly different cell size than standard pyrrhotite. These two samples were also spectographed. The results gave X0 percent Cr (W-DDH-13-35-50) and X percent Cr (B-DDH-9B₁-432) . . . Since reported analyses of pyrrhotite do not show any chromium, the magnetite in the sample is believed to be a chromian magnetite.

TABLE 35.—Calculations upon analysis of magnetic concentrate from serpentinite, sample W-DDH-13-35-50, Waterbury mine

[Analysis 11, table 3. An asterisk (*) signifies a component inferred to be present only as carbonate or silicate, and dropped in calculating the composition of the magnetite-chromite mixture]

	Weight percent	Equivalent molecular numbers	Magnetite-chromite		
			O in equivalent molecular numbers	O=4	Cations in formula
FeO	24	0.33403	0.334	0.8	0.8
FeO _{3/2}	28	.35066	.526	1.2	.8
MgO	1.0	.02480	(*)		
CrO _{3/2}	36.1	.47494	.712	1.7	1.1
SiO ₂	.4	.00666	(*)		
CO ₂	3.0	.06817	(*)		
S	.1	.00312	(*)		
AlO _{3/2}	4.4	.08633	.129	.3	.2
MnO	.7	.00987	.010	.02	.02
Total	97.7		1.711	4.0	2.9

Formula composition of magnetite-chromite mixture:

TABLE 36.—Calculations upon analysis of magnetic concentrate from serpentinite, sample B-DDH-9B₁-432, Barnes Hill

[Analysis 12, table 3. An asterisk (*) signifies a component inferred to be present only as carbonate or silicate, and dropped in calculating the composition of the magnetite-chromite mixture]

	Weight percent	Equivalent molecular numbers	Magnetite-chromite		
			O in equivalent molecular numbers	O=4	Cations in formula
FeO	24	0.33403	0.334	0.8	0.8
FeO _{3/2}	61	.76393	1.146	2.6	1.7
MgO	.1	.00248	(*)		
CrO _{3/2}	11.0	.14472	.218	.5	.3
SiO ₂	.4	.00666	(*)		
CO ₂	1.5	.03408	(*)		
S	.2	.00624	(*)		
AlO _{3/2}	1.3	.02551	.038	.09	.06
MnO	1.2	.01692	.017	.04	.04
Total	100.7		1.753	4.0	2.9

Formula composition of the magnetite-chromite mixture:

TABLE 37.—Calculations upon analysis of magnetic concentrate from serpentinite, sample B-DDH-9B₁-407, Barnes Hill

[Analysis 13, table 3. An asterisk (*) signifies a component inferred to be present only as carbonate or silicate, and dropped in calculating the composition of the magnetite-chromite mixture]

	Weight percent	Equivalent molecular numbers	Magnetite-chromite		
			O in equivalent molecular numbers	O=4	Cations in formula
FeO	29	0.40362	0.404	0.9	0.9
FeO _{3/2}	56	.70131	1.052	2.5	1.7
MgO	.2	.00496	(*)		
CrO _{3/2}	9.6	.12630	.189	.5	.3
SiO ₂	.7	.01166	(*)		
CO ₂	2.2	.04999	(*)		
S	.4	.01248	(*)		
AlO _{3/2}	1.6	.03139	.047	.1	.07
MnO	.7	.00987	.010	.02	.02
Total	100.4		1.702	4.0	3.0

Formula composition of magnetite-chromite mixture:

The magnetite-rich samples prepared for analysis contained less pyrrhotite. In sample W-DDH-13-35-50, the lines at 4.22 and 2.998A no longer appeared, and the line at 2.020 was weaker than in the heavier fraction. In samples B-DDH-9B₁-432 and 407 these 3 lines did not appear either in the heavier or in the magnetite fraction. Further work would be necessary if the strength of these lines were to be correlated with the chromium content. In all samples the presence of minerals of the light fraction was noted.

The samples were further treated with dilute H₂SO₄ and HF in the cold for 20 minutes. The amount of extraneous birefringent material was reduced, but the last traces of carbonate and silicate were not removed. The exact amount of Si and CO₂ should be determined by the chemist analyzing the samples, in order to determine the Mg combined as silicates and carbonates. The probable order of magnitude will be 0.0X to 0.X percent.

The recovery was in no sense quantitative, since in every stage of the purification fine-grained magnetite associated with large amounts of serpentine was sacrificed in order to improve the quality of the final samples.

The final magnetic concentrates contained small proportions of carbonate, serpentine, and pyrrhotite. The composition of the contaminant minerals is reasonably well known, and the proportion of each should be easily fixed from analysis—inasmuch as each contains one component present in none of the other minerals—so that the analyses should theoretically yield formula values that reflect accurately the composition of the mixture of magnetite and chromite. Simple computations based upon a calculated mode yield formulas that are deficient in Mg and that otherwise depart far from the ideal and probable reality. The analyses appear to

be in error, particularly in the determination of MgO, for that is insufficient to combine with the reported SiO₂ and CO₂ to form serpentine and magnesite. Redetermination of Mg and Ca did not appreciably improve the results, and the analyses cannot be satisfactorily reconciled with the mineral content of the sample. It is concluded that the best formula representation of the magnetite and chromite attainable from the analyses is that obtained merely by dropping MgO, SiO₂, CO₂, and S, in the manner shown in tables 35 to 37. The resulting formulas, though not entirely satisfactory, probably characterize fairly well the gross aspects of the chemical composition of the mixture of magnetite and chromite. Thus, the very low content of Mg, and the range of Al and Cr shown by the three formulas are probably reasonably close to reality.

APPENDIX F. CHRYSOTILE ASBESTOS

The analysis of chrysotile asbestos in table 38 is of a sample selected and prepared with great care by Cooke (1937, p. 99-103), who describes in detail the preparation and analysis of the sample. The calculations are simple, inasmuch as impurities are reported to be negligible, and need little explanation further than that given in foregoing appendixes. The formula based on the assumption is that $O + OH = 9$. Formulas (2) and (3) are simply derived from (1) by multiplying it, term by term, by appropriate factors.

TABLE 38.—Calculations upon analysis of high-grade chrysotile asbestos, Deloro township, Ontario, Canada

[Analysis 33, table 3]

	Weight percent	Equivalent molecular numbers	O	O+OH=9	Formula numbers
SiO ₂ -----	42. 40	0. 70596	1. 41192	3. 962	1. 98
AlO _{3/2} -----	. 14	. 00275	. 00413	. 012	. 008
FeO _{3/2} -----	. 97	. 01215	. 01822	. 051	. 03
FeO-----	. 19	. 00264	. 00264	. 007	. 007
CaO-----	. 14	. 00250	. 00250	. 007	. 007
MgO-----	43. 09	1. 06870	1. 06870	2. 999	3. 00
HO _{1/2} -----	. 45				
HO _{1/2} +-----	12. 60	1. 39876	. 69938	1. 962	3. 92
Total-----	99. 98	3. 19346	3. 20749	9. 000	-----
Less HO _{1/2} -----		1. 39876	. 69938	1. 962	-----
Total-----		1. 79470	2. 50811	7. 038	-----
Less O for OH-----			. 69938	1. 962	-----
O-----			1. 80873	5. 076	-----

Chrysotile formula:

APPENDIX G. SERPENTINITE

Tables 39 to 42 are based upon analyses of serpentinite, and contain calculations of the modified standard cell and of the formula composition of serpentine (antigorite) for each analysis. Calculation of the modified standard cell, from density determinations, follows methods described in detail in appendix B. Calculation of the antigorite formula is based upon calculations of the mineral mode for which certain assumptions and procedures for determining the proportions of talc and serpentine require some explanation:

Carbonate, sulfarsenides, and apatite are fixed by the amounts of CO₂, As and S, and PO_{5/2}, respectively. All FeO_{3/2} not in sulfarsenides is assumed to be in magnetite, whose composition in the mode is based upon that arrived at in the section on "Petrography" (p. 75-76), but for which factors evident in the analysis—such as high content of CrO_{3/2}—were also given weight. The constituents NaO_{1/2}, KO_{1/2}, TiO₂, and CoO not in sulfarsenides were simply eliminated by grouping them under "Other", because their place in the mineral composition was not known. The remainder was assumed to be in talc and antigorite.

TABLE 39.—*Calculations upon analysis of schistose serpentinite, sample MR-103, Mad River*[Analysis 15, table 3. Indices of serpentine: $\alpha = 1.564$; $\beta \approx \gamma = 1.569$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
SiO ₂ -----	41. 59	0. 69247	39. 37	78. 74	38. 28
AlO _{3/2} -----	. 36	. 00706	. 40	. 60	. 39
FeO _{3/2} -----	3. 85	. 04822	2. 74	4. 11	2. 67
FeO-----	4. 46	. 06207	3. 53	3. 53	3. 43
MgO-----	37. 11	. 92039	52. 32	52. 32	50. 87
CaO-----	. 36	. 00642	. 36	. 36	. 35
NaO _{1/2} -----	. 00	. 00000	. 00	. 00	. 00
KO _{1/2} -----	. 05	. 00106	. 06	. 03	. 06
HO _{1/2} -----	. 07				
HO _{1/2} +-----	11. 32	1. 25666	71. 44	35. 72	69. 45
TiO ₂ -----	. 01	. 00013	. 01	. 02	. 01
CO ₂ -----	. 64	. 01454	. 83	1. 66	. 81
PO _{5/2} -----	. 01	. 00014	. 01	. 03	. 01
S-----	. 01	. 00031	. 02	. 02	. 02
CrO _{3/2} -----	. 12	. 00158	. 09	. 14	. 09
NiO-----	. 28	. 00375	. 21	. 21	. 20
MnO-----	. 07	. 00099	. 06	. 06	. 06
CoO-----	. 01	. 00013	. 01	. 01	. 01
AsO _{3/2} -----	. 0009	. 00001	. 0006	. 0006	. 0006
Total-----	100. 32			177. 56	
Less O for S+As-----	. 01			. 03	
Total-----	100. 31	3. 01593	171. 46	177. 53	
Less HO _{1/2} +S+As-----		1. 25698	71. 46	35. 74	
Total-----		1. 75895	100. 00	141. 79	
Less HO _{1/2} +CO ₂ -----				37. 38	
O-----				104. 41	
Oeq-----					172. 59
Cations-----					97. 22
O-----					101. 51
W ₁₀₀ -----					5702. 8
Density-----					2. 685
V ₁₀₀ -----					2123. 9
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----					0. 9722

TABLE 39.—Calculations upon analysis of schistose serpentinite, sample MR-103, Mad River—Continued

B. CALCULATED MODE AND ANTIGORITE FORMULA NUMBERS

	Carbon- ate	Magnet- ite	Sulfar- senide	Apatite	Other	Talc and antigorite	Talc	Antigorite				Cation totals
								Equivalent molecular percent	Oeq	O=5	Formula numbers	
SiO ₂ -----						39.37	5.09	34.28	68.56	4.04	2.02	39.37
AlO _{3/2} -----		0.12				.28	.05	.23	.35	.02	.01	.40
FeO _{3/2} -----		2.72	0.02									2.74
FeO-----	0.02	.98				2.53	.32	2.21	2.21	.13	.13	3.53
MgO-----	.46	.44				51.42	3.43	47.99	47.99	2.83	2.83	52.32
CaO-----	.34			0.02								.36
NaO _{1/2} -----					0.00							.00
KO _{1/2} -----					.06							.06
HO _{1/2} -----												
HO _{1/2} +-----						71.44	2.54	68.90	34.45	2.03	4.06	71.44
TiO ₂ -----					.01							.01
CO ₂ -----	.83											.83
PO _{5/2} -----				.01								.01
S-----			.02									.02
CrO _{3/2} -----		.09										.09
NiO-----						.21	.01	.20	.20	.01	.01	.21
MnO-----	.01	.05										.06
CoO-----					.01							.01
AsO _{3/2} -----			.0006									.0006
Total-----	1.66	4.40	0.04	0.03	0.08	165.25	11.44	153.81	153.76	9.16	9.21	171.46
Less HO _{1/2} +S+ As-----			.02			71.44	2.54	68.90	34.45	2.08	4.16	71.46
Total-----	1.66	4.40	0.02	0.03	0.08	93.81	8.90	84.91	119.31	7.08	5.05	100.00
Less HO _{1/2} + CO-----									34.45	2.08		
O-----									84.86	5.00		
												Total
V _e -----	15.66	14.30	18.43	20.45	20.00		19.21	21.32				
Volume proportions-----	26.0	62.9	.4	.6	1.6		171.0	1,810.3				2,072.8
Volume percent-----	1.25	3.03	.02	.03	.08		8.25	87.34				100.00

C. ANTIGORITE FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

E. COMPUTATION OF PROPORTIONS OF TALC (T) AND SERPENTINE (S), IN EQUIVALENT MOLECULAR PERCENT OF THE ROCK

Substitute 93.91 for C in equation (1), p. 160:

$$T+S=93.81 \quad (1)$$

Substitute 39.37 for Si in equation (2), p. 160:

$$\frac{4}{7}T + \frac{2}{5}S = 39.37 \quad (2)$$

Multiply (2) by $\frac{7}{4}$:

$$T + \frac{14}{20}S = 68.90 \quad (3)$$

Subtract, (1) - (3):

$$\frac{6}{20}S = 24.91 \quad (4)$$

$$S = 83.03 \quad (5)$$

Substitute S=83.03 in (1):

$$T = 10.78 \quad (6)$$

Substitute 71.44 for HO_{1/2} in equation (3), p. 160:

$$\frac{2}{7}T + \frac{4}{5}S = 71.44 \quad (7)$$

Multiply (7) by $\frac{7}{2}$:

$$T + 2.8S = 250.04 \quad (8)$$

Subtract, (8) - (1):

$$1.8S = 156.23 \quad (9)$$

$$S = 86.80 \quad (10)$$

Substitute S=86.80 in (1):

$$T = 7.01 \quad (11)$$

Averages: S=84.91; T=8.90.

TABLE 40.—*Calculations upon analysis of massive serpentinite, sample W-DDH-13-65, Waterbury mine*[Analysis 16, table 3. Indices of serpentine: $\beta \approx \gamma$ 1.572]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
SiO ₂ -----	43. 10	0. 71762	40. 84	81. 68	39. 23
AlO _{3/2} -----	1. 06	. 02080	1. 18	1. 77	1. 13
FeO _{3/2} -----	1. 07	. 01340	. 76	1. 14	. 73
FeO-----	5. 22	. 07265	4. 13	4. 13	3. 97
MgO-----	37. 14	. 92113	52. 43	52. 43	50. 36
CaO-----	. 00	. 00000	. 00	. 00	. 00
NaO _{1/2} -----	. 00	. 00000	. 00	. 00	. 00
KO _{1/2} -----	. 03	. 00064	. 04	. 02	. 04
HO _{1/2} -----	. 11				
HO _{1/2} +-----	11. 77	1. 30662	74. 36	37. 18	71. 43
TiO ₂ -----	. 01	. 00013	. 01	. 02	. 01
CO ₂ -----	. 08	. 00182	. 10	. 20	. 10
PO _{5/2} -----	. 01	. 00014	. 01	. 03	. 01
S-----	. 06	. 00187	. 11	. 11	. 11
CrO _{3/2} -----	. 31	. 00408	. 23	. 35	. 22
NiO-----	. 22	. 00295	. 17	. 17	. 16
MnO-----	. 11	. 00155	. 09	. 09	. 09
CoO-----	. 01	. 00013	. 01	. 01	. 01
AsO _{3/2} -----	. 006	. 00006	. 003	. 003	. 003
Total-----	100. 32			179. 33	
Less O for S + As-----	. 05			. 17	
Total-----	100. 27	3. 06559	174. 47	179. 16	
Less HO _{1/2} + S + As-----		1. 30855	74. 47	37. 29	
Total-----		1. 75704	100. 00	141. 87	
Less HO _{1/2} + CO ₂ -----				37. 38	
O-----				104. 49	
Oeq-----					172. 10
Cations-----					96. 06
O-----					100. 37
W ₁₀₀ -----					5, 706. 8
Density-----					2. 655
V ₁₀₀ -----					2, 149. 5
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----					0. 9606

TABLE 40.—Calculations upon analysis of massive serpentinite, sample W-DDH-13-65, Waterbury mine—Continued

B. CALCULATED MODE AND ANTIGORITE FORMULA NUMBERS

	Carbonate	Magnetite	Sulfarsenide	Apatite	Other	Talc and antigorite	Talc	Antigorite				Cation totals
								Equivalent molecular percent	Oeq	O=5	Formula numbers	
SiO ₂ -----						40.84	4.95	35.89	71.78	3.99	2.00	40.84
AlO _{3/2} -----		0.10				1.08	.05	1.03	1.55	.09	.06	1.18
FeO _{3/2} -----		.65	0.11									.76
FeO-----	0.01	.20				3.92	.31	3.61	3.61	.20	.20	4.13
MgO-----	.09	.20		0.02		52.12	3.34	48.78	48.78	2.71	2.71	52.43
CaO-----	.00											.00
NaO _{1/2} -----					0.00							.00
KO _{1/2} -----					.04							.04
HO _{1/2} -----												
HO _{1/2} +-----						74.36	2.47	71.89	35.95	2.00	4.00	74.36
TiO ₂ -----					.01							.01
CO ₂ -----	.10											.10
PO _{5/2} -----				.01								.01
S-----			.11									.11
CrO _{3/2} -----		.23										.23
NiO-----						.17	.01	.16	.16	.01	.01	.17
MnO-----		.09										.09
CoO-----					.01							.01
AsO _{3/2} -----			.003									.003
Total-----	.020	1.47	0.22	0.03	0.06	172.49	11.13	161.36	161.83	9.00	8.98	174.47
Less HO _{1/2} +S+As-----			.11			74.36	2.47	71.89	35.95	2.00	4.00	74.47
Total-----	0.20	1.47	0.11	0.03	0.06	98.13	8.66	89.47	125.88	7.00	4.98	100.00
Less HO _{1/2} +CO ₂ -----									35.95	2.00		
O-----									89.93	5.00		
												Total
V-----	13.79	14.30	18.43	20.45	20.00		19.21	21.32				
Volume proportions-----	2.8	21.0	2.0	.6	1.2		166.4	1,907.5				2,101.5
Volume percent-----	.13	1.00	.10	.03	.06		7.92	90.76				100.00

¹ The unfavorable ratio of Mg to Ca makes it probable that some Ca was missed in the analysis; therefore enough Mg is borrowed to fill out the requirement for Ca in apatite.

C. ANTIGORITE FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[\text{K}_{.04}\text{Na}_{.00}\text{Ca}_{.00}\text{Mg}_{50.36}\text{Fe}^{+2}{}_{3.97}\text{Mn}_{.09}\text{Ni}_{.16}\text{Co}_{.01}\text{Al}_{1.13}\text{Fe}^{+3}{}_{.73}\text{Cr}_{.22}\text{Ti}_{.01}\text{Si}_{39.23}\text{P}_{.01}\text{S}_{.11}\text{As}_{.003}\text{O}_{100.37}(\text{OH})_{71.43}(\text{CO}_2)_{.10} \right] \begin{matrix} \text{Cations}=96.06 \\ \text{Oeq}=172.10 \end{matrix}$$

E. COMPUTATION OF PROPORTIONS OF TALC (T) AND SERPENTINE (S), IN EQUIVALENT MOLECULAR PERCENT OF THE ROCK

Substitute 98.13 for C in equation (1), p. 160: $T+S=98.13$	(1)	Substitute 74.36 for HO _{1/2} in equation (3), p. 160:	
Substitute 40.84 for Si in equation (2), p. 160:			
$\frac{4}{7}T + \frac{2}{5}S = 40.84$	(2)	$\frac{2}{7}T + \frac{4}{5}S = 74.36$	(7)
Multiply (2) by $\frac{7}{4}$: $T + 0.7S = 71.47$	(3)	Multiply (7) by $\frac{7}{2}$: $T + 2.8S = 260.26$	(8)
Subtract, (1) - (3): $0.3S = 26.66$	(4)	Subtract, (8) - (1): $1.8S = 162.13$	(9)
$S = 88.87$	(5)	$S = 90.07$	(10)
Substitute $S = 88.87$ in (1): $T = 9.26$	(6)	Substitute $S = 90.07$ in (1): $T = 8.06$	(11)
		Average: $S = 89.47$; $T = 8.66$	

TABLE 41.—Calculations upon analysis of massive serpentinite, sample B-DDH-9B₁-432, Barnes Hill[Analysis 17, table 3. Indices of serpentinite: B $\approx$ γ - 1.565]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
SiO ₂	38. 30	. 63770	35. 74	71. 48	35. 51
AlO _{3/2}	1. 14	. 02237	1. 25	1. 88	1. 24
FeO _{3/2}	5. 93	. 07426	4. 16	6. 24	4. 14
FeO.....	2. 25	. 03132	1. 76	1. 76	1. 75
MgO.....	38. 27	. 94916	53. 20	53. 20	52. 86
CaO.....	. 23	. 00410	. 23	. 23	. 23
NaO _{1/2}	. 00	. 00000	. 00	. 00	. 00
KO _{1/2}	. 03	. 00064	. 04	. 02	. 02
HO _{1/2}	. 07				
HO _{1/2} +	10. 73	1. 19116	66. 77	33. 39	66. 35
TiO ₂	. 01	. 00013	. 01	. 02	. 01
CO ₂	2. 46	. 05590	3. 13	6. 26	3. 11
PO _{5/2}	. 01	. 00014	. 01	. 03	. 01
S.....	. 02	. 00062	. 035	. 035	. 04
CrO _{3/2}	. 30	. 00395	. 22	. 33	. 22
NiO.....	. 22	. 00295	. 17	. 17	. 17
MnO.....	. 09	. 00127	. 07	. 07	. 07
CoO.....	. 01	. 00013	. 01	. 01	. 01
AsO _{3/2}	. 065	. 00066	. 037	. 037	. 04
Total.....	100. 14			175. 16	
Less O for S + As.....	. 05			. 09	
Total.....	100. 09	2. 97646	166. 84	175. 07	
Less HO _{1/2} + S + As.....		1. 19244	66. 84	33. 46	
Total.....		1. 78402	100. 00	141. 61	
Less HO _{1/2} + CO ₂				39. 65	
O.....				101. 96	
Oeq.....					173. 97
Cations.....					99. 37
O.....					101. 32
W ₁₀₀					5610. 4
Density.....					2. 70
V ₁₀₀					2077. 9
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀					0. 9937

TABLE 41.—Calculations upon analysis of massive serpentinite, sample B-DDH-9B₁-432, Barnes Hill—Continued

B. CALCULATED MODE AND ANTIGORITE FORMULA NUMBERS

	Carbonate	Apatite	Magnetite	Sulfarsenide	Other	Talc and antigorite	Talc	Antigorite				Cation totals
								Equiv. molec. percent	Oeq	O=5	Formula Nos.	
SiO ₂ -----						35.74	3.18	32.56	65.12	3.98	1.99	35.74
AlO _{3/2} -----			0.13			1.12	.03	1.09	1.64	.10	.07	1.25
FeO _{3/2} -----			4.14	0.02								4.16
FeO-----	0.03		.68			1.05	.20	.85	.85	.05	.05	1.76
MgO-----	2.88		1.52			48.80	2.14	46.66	46.66	2.85	2.85	53.20
CaO-----	.21	0.02										.23
NaO _{1/2} -----					0.00							.00
KO _{1/2} -----					.04							.04
HO _{1/2} -----												
HO _{1/2} +-----						66.77	1.59	65.18	32.59	1.99	3.98	66.77
TiO ₂ -----					.01							.01
CO ₂ -----	3.13											3.13
PO _{5/2} -----		.01										.01
S-----				.035								.035
CrO _{3/2} -----			.22									.22
NiO-----				.04		.13	.01	.12	.12	.01	.01	.17
MnO-----	.01		.06									.07
CoO-----				.01								.01
AsO _{3/2} -----				.037								.037
Total-----	6.26	0.03	6.75	0.14	0.05	153.61	7.15	146.46	146.98	8.98	8.95	166.84
HO _{1/2} +S+As-----				.07		66.77	1.59	65.18	32.59	1.99	3.98	66.84
Total-----	6.26	0.03	6.75	0.07	0.05	86.84	5.56	81.28	114.39	6.99	4.97	100.00
Less HO _{1/2} +CO ₂ -----									32.59	1.99		
O-----									81.80	5.00		
Total-----												
V-----	14.02	20.45	14.84	18.43	20.00		19.21	21.32				
Volume proportions-----	87.8	.6	100.2	1.3	1.0		106.8	1,732.9				2,030.6
Volume percent-----	4.32	.03	4.93	.06	.05		5.26	85.35				100.00

C. ANTIGORITE FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

E. COMPUTATION OF PROPORTIONS OF TALC (T) AND SERPENTINE (S), IN EQUIVALENT MOLECULAR PERCENT OF THE ROCK

Substitute 86.84 for C in equation (1), p. 160: $T+S=86.84$ (1)

Substitute 35.74 for Si in equation (2), p. 160:

$$\frac{4}{7}T + \frac{2}{5}S = 35.74 \quad (2)$$

Multiply (2) by $\frac{7}{4}$: $T+0.7S=62.55$ (3)Subtract (1) - (3): $0.3S=24.29$ (4)

$$S=80.97 \quad (5)$$

Substitute $S=80.97$ in (1): $T=5.87$ (6)Substitute 66.77 for HO_{1/2} in equation (1), p. 160:

$$\frac{2}{7}T + \frac{4}{5}S = 66.77 \quad (7)$$

Multiply (7) by $\frac{7}{2}$: $T+2.8S=233.70$ (8)Subtract (8) - (1): $1.8S=146.86$ (9)

$$S=81.59 \quad (10)$$

Substitute $S=81.59$ in (1): $T=5.25$ (11)Averages: $S=81.28$; $T=5.56$

TABLE 42.—Calculations upon analysis of massive serpentinite, sample MR-13, Mad River

[Analysis 20, table 3. Indices of serpentinite: $\beta \approx \gamma = 1.574$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂	38.8	38.8	0.64602	36.06	72.12	36.6
AlO _{3/2}	1.6	1.6	.03139	1.75	2.63	1.8
Total Fe as FeO _{3/2}	8.2					
Mg.....	32.8	32.8	.81349	45.40	45.40	46.1
CaO.....	3.6	3.6	.06419	3.58	3.58	3.6
NaO _{1/2}	.17	.17	.00548	.30	.15	.30
KO _{1/2}	.09	.09	.00191	.11	.05	.11
TiO ₂	.08	.08	.00100	.06	.12	.06
PO _{5/2}	.06	.06	.00085	.05	.13	.05
MnO.....	.09	.09	.00127	.07	.07	.07
Ignition loss.....	14.4					
Sum.....	100					
FeO.....	6.5	6.5	.09047	5.05	5.05	5.1
FeO _{3/2}	1.0	1.0	.01252	.70	1.05	.71
Gain from oxidation of FeO.....	.7					
Corrected ignition loss.....	15.1					
S.....	.12	.12	.00374	.21	.21	.21
HO _{1/2} + est. ¹		9.56	1.06128	59.23	29.62	60.1
CO ₂ est. ²		5.42	.12312	6.87	13.74	7.0
Total.....		99.89			173.92	
Less O for S.....		.05			.16	
Total.....		99.84	2.85673	159.44	173.76	
Less HO _{1/2} + S.....			1.06502	59.44	29.83	
Total.....			1.79171	100.00	143.93	
Less HO _{1/2} + CO ₂					43.36	
O.....					100.57	
Oeq.....						176.4
Cations.....						101.5
O.....						101.9
W ₁₀₀						5572.3
Density.....						2.74
V ₁₀₀						2033.7
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀						1.0153

¹ HO_{1/2} + est. = Corrected ignition loss less weight percent of CO₂ and S.² CO₂ est. is calculated on assumption that all CaO not in apatite is in carbonate of composition (Ca_{.51}Mg_{.45}Fe⁺²_{.03}Mn_{.01}) CO₃; equivalent molecular numbers of CO₂ = $\left(\frac{(\text{CaO} - \text{CaO in Ap})}{.51} \right) = 0.12312$.

TABLE 42.—Calculations upon analysis of massive serpentinite, sample MR-13, Mad River—Continued

B. CALCULATED MODE AND ANTIGORITE FORMULA NUMBERS

	Carbon- ate	Magne- tite	Pyrite	Apatite	Other	Talc and anti- gorite	Talc	Antigorite				Cation totals
								Equivalent molecular percent	Oeq	0=5	Formula numbers	
SiO ₂ -----						36.06	8.30	27.76	55.52	3.92	1.96	36.06
AlO _{3/2} -----		0.03				1.72	.09	1.63	2.45	.17	.11	1.75
FeO-----	0.21	.10				4.74	.42	4.32	4.32	.30	.30	5.05
FeO _{3/2} -----		.59	0.11									.70
Mg-----	3.09	.21				42.10	5.88	36.22	36.22	2.55	2.55	45.40
CaO-----	3.50			0.08								3.58
NaO _{1/2} -----					0.30							.30
KO _{1/2} -----					.11							.11
TiO ₂ -----					.06							.06
PO _{5/2} -----				.05								.05
MnO-----	.07											.07
S-----			.21									.21
HO _{1/2} + est-----				.02		59.21	4.20	55.01	27.50	1.94	3.88	59.23
CO ₂ est-----	6.87											6.87
Total-----	13.74	0.93	0.32	0.15	0.47	143.83	18.89	124.94	126.01	8.88	8.80	159.44
Less HO _{1/2} + S-----			.21	.02		59.21	4.20	55.01	27.50	1.94	3.88	59.44
Total-----	13.74	0.93	0.11	0.13	0.47	84.62	14.69	69.93	98.51	6.94	4.92	100.00
Less HO _{1/2} + CO ₂ -----									27.50	1.94		
O-----									71.01	5.00		
												Total
V _e -----	16.15	14.84	23.90	20.45	20.00		19.21	21.32				
Volume proportions-----	221.9	13.8	2.6	2.7	9.4		282.2	1,490.9				2,023.5
Volume percent-----	10.97	0.68	0.13	0.13	0.46		13.95	73.68				100.00

C. ANTIGORITE FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[\text{K}_{.11}\text{Na}_{.30}\text{Ca}_{3.6}\text{Mg}_{46.1}\text{Fe}^{+2}{}_{5.1}\text{Mn}_{.07}\text{Al}_{1.8}\text{Fe}^{+3}{}_{.71}\text{Ti}_{.06}\text{Si}_{36.6}\text{P}_{.05}\text{S}_{.21}\text{O}_{101.9}(\text{OH})_{60.1}(\text{CO}_2)_{7.0} \right] \begin{matrix} \text{Cations}=101.5 \\ \text{Oeq}=176.2 \end{matrix}$$

E. COMPUTATION OF PROPORTIONS OF TALC (T) AND SERPENTINE (S), IN EQUIVALENT MOLECULAR PERCENT OF THE ROCK

Substitute 84.62 for C in equation (1), p. 160: $T+S=84.62$	(1)	Substitute 59.23 for HO _{1/2} in equation (3), p. 160:	
Substitute 36.06 for C in equation (2), p. 160:		$\frac{2}{7}T + \frac{4}{5}S = 59.23$	(7)
$\frac{4}{7}T + \frac{2}{5}S = 36.06$	(2)	Multiply (7) by $\frac{7}{2}$: $T + 2.8S = 207.31$	(8)
Multiply (2) by $\frac{7}{4}$: $T + 0.7S = 63.11$	(3)	Subtract (8) - (1): $1.8S = 122.69$	(9)
Subtract, (1) - (3): $0.3S = 21.51$	(4)	$S = 68.16$	(10)
$S = 71.70$	(5)	Substitute $S = 68.16$ in (1): $T = 16.46$	(11)
Substitute $S = 71.70$ in (1): $T = 12.92$	(6)	Average: $S = 69.93$; $T = 14.69$	

Because of the practical impossibility of distinguishing quantitatively between talc and antigorite in a point-count analysis of a thin section, the equivalent molecular percentages of talc and antigorite are calculated by the solution of simultaneous equations that describe certain mathematical relations between the formulas of talc and serpentine and their modal values in terms of equivalent molecular percent. The simultaneous equations are derived as follows:

Let MgO , SiO_2 , $\text{HO}_{1/2}$, and the like, represent each 1 equivalent molecular percent of constituent; let T and S represent the equivalent molecular percentage of talc and serpentine, respectively, in the mode; and let C equal the sum of the metallic ions in talc and serpentine, which is equal to the sum of the equivalent molecular percent of talc and serpentine. Then, from the formulas of talc, $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$, and serpentine, $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$, the following relations are readily derived:

$$T + S = C, \quad (1)$$

$$4/7 T + 2/5 S = \text{Si}, \quad (2)$$

$$2/7 T + 4/5 S = \text{HO}_{1/2}, \quad (3)$$

and

$$3/7 T + 4/5 S = \text{Mg} + \text{Fe}'' + \text{Ni} + \text{Al}^1 \quad (4)$$

¹ All Al is assumed to substitute for Mg.

Solution of any two of these simultaneous equations, upon substitution of the proper values for C , Si , etc., theoretically will yield the molecular percentages of talc and antigorite in the mode. In practice, there are generally discrepancies between different solutions, and the averages of the solutions of two or more sets of equations is preferably used. Using table 39 as an example, the procedure is as follows:

In part *E*, using equations (1) and (2) and substituting the values of C and Si from the column "Talc and antigorite" in part *B*, the solutions $S=83.03$ and $T=10.78$ are obtained. Then, using equations (1) and (3), the solutions $S=86.80$ and $T=7.01$ are obtained. The averages $T=8.90$ and $S=84.91$ are then inserted in the lower "Total" line entry, which is equal to equivalent molecular percent, in the columns "Talc" and "Equivalent molecular percent" under antigorite, part *B*. The equivalent units of the various oxides in the talc, in the proportions indicated by compositions determined on pages 76-77, 79-80, under "Petrography", are then calculated on the basis of the formula. For example, the value 8.90 represents the sum of the electropositive ions exclusive of H which, in the formula notation, total 7. Consequently, the value for SiO_2 in the "Talc" column is $4/7 \times 8.90 = 5.09$. FeO , MgO , $\text{AlO}_{3/2}$, and NiO total very nearly 3 in the ideal formula (see p. 48); their total is thus equal to $3/7 \times 8.90 = 3.82$. This sum is then distributed among the several oxides by trial and error so that Mg and Fe^{+2} are about in the ratio of 1:10, and the other oxides approximately in the proportions indicated by the formula compositions referred to at several places in the above discussion. The values for the column "Equiv. Molec. percent" under antigorite are then determined by subtracting the values in the column "Talc" from the corresponding values in the column "Talc and antigorite". The "Equiv. Molec. percent" values having been determined, the antigorite formula is then calculated in a manner strictly analogous to that described for chlorite in the sample calculation of appendix B, except that the value of "O" is calculated to a total of 5. The composition of the antigorite is shown in formula notation in part *C* of the table.

APPENDIX H. STEATITE AND TALC-CARBONATE ROCK

Tables 43 to 47 contain calculations of the modified standard cell, of modes, and of the composition of talc based upon rock analyses of steatite and talc-carbonate rock. Computation of the modified standard cell is based upon measured rock densities, and follows procedures fully described in appendix B. The method of calculating the mode is pretty much self-evident in each table. All $\text{FeO}_{3/2}$ was used up in pyrrhotite and magnetite except where thin-section data on the percentage of magnetite appeared to affirm that some $\text{FeO}_{3/2}$ must occur in talc, as in specimen W-23 (table 43). All $\text{PO}_{5/2}$ was used up in apatite, though no apatite was seen in thin section, and some phosphorus may possibly occur in talc. The remaining CaO was used in

carbonate, the proportion of which was fixed by the CO_2 content of the sample. In specimen R-DDH-2-310 (table 44), whose geologic and microscopic features show it to have been derived from schist, and which contains identifiable sphene and muscovite, they and albite are calculated in the mode. In others, for which it appears improbable that any of these minerals are present, constituents whose place in the mineral composition is unknown are simply dropped by grouping them under "Other." The balance of the constituents of the analysis, in terms of equivalent molecular percent, was assumed to represent talc. Calculation of the talc formula is analogous to that of chlorite described in appendix B. The composition of the talc, in formula notation, is shown in part *C* of each table; the formula of the standard cell is shown in part *D*.

TABLE 43.—Calculations upon analysis of steatite, sample W-23, Waterbury mine

[Analysis 18, table 3. Indices of talc: $\beta \approx \gamma = 1.593$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
SiO ₂ -----	60. 48	1. 00699	55. 79	111. 58	58. 88
AlO _{3/2} -----	. 82	. 01609	. 89	1. 34	. 94
FeO _{3/2} -----	. 10	. 00125	. 07	. 11	. 07
FeO-----	4. 59	. 06388	3. 54	3. 54	3. 74
MgO-----	28. 52	. 70734	39. 20	39. 20	41. 37
CaO-----	. 02	. 00036	. 02	. 02	. 02
NaO _{1/2} -----	. 00	. 00000	. 00	. 00	. 00
KO _{1/2} -----	. 03	. 00064	. 04	. 02	. 04
HO _{1/2} -----	. 00				
HO _{1/2} +-----	4. 94	. 54840	30. 39	15. 20	32. 07
TiO ₂ -----	. 01	. 00013	. 01	. 02	. 01
CO ₂ -----	. 00	. 00000	. 00	. 00	. 00
PO _{5/2} -----	. 02	. 00028	. 02	. 05	. 02
S-----	. 01	. 00031	. 02	. 02	. 02
CrO _{3/2} -----	. 26	. 00342	. 19	. 29	. 20
NiO-----	. 20	. 00268	. 15	. 15	. 16
MnO-----	. 09	. 00127	. 07	. 07	. 07
CoO-----	. 01	. 00013	. 01	. 01	. 01
AsO _{3/2} -----	. 0023	. 00002	. 00001	. 00001	Tr
Total-----	100. 10			171. 62	
Less O for S + As-----	. 01			. 02	
Total-----	100. 09	2. 35319	130. 41	171. 60	
Less HO _{1/2} + S-----		. 54871	30. 41	15. 22	
Total-----		1. 80448	100. 00	156. 38	
Less HO _{1/2} -----				15. 20	
O-----				141. 18	
Oeq-----					181. 11
Cations-----					105. 54
O-----					149. 00
W ₁₀₀ -----					5, 546. 8
Density-----					2. 835
V ₁₀₀ -----					1, 956. 5
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----					1. 0554

TABLE 43.—Calculations upon analysis of steatite, sample W-23, Waterbury mine—Continued

B. CALCULATED MODE AND TALC FORMULA NUMBERS

	Magnetite	Pyrite	Apatite	Other	Talc				Cation totals
					Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----					55.79	111.58	7.91	3.96	55.79
AlO _{3/2} -----					.89	1.34	.09	.06	.89
FeO _{3/2} -----	0.02	0.01			.04	.06	.01	.01	.07
FeO-----	.01				3.53	3.53	.25	.25	3.54
MgO-----			¹ 0.01		39.19	39.19	2.78	2.78	39.20
CaO-----			.02						.02
NaO _{1/2} -----				0.00					.00
KO _{1/2} -----				.04					.04
HO _{1/2} -----									
HO _{1/2} +-----					30.39	15.20	1.08	2.16	30.39
TiO ₂ -----					.01	.02	.001	.001	.01
CO ₂ -----									
PO _{5/2} -----			.02						.02
S-----		.02							.02
CrO _{3/2} -----					.19	.29	.02	.02	.19
NiO-----					.15	.15	.01	.01	.15
MnO-----					.07	.07	.01	.01	.07
CoO-----					.01	.01	.001	.001	.01
AsO _{3/2} -----				.00001					.00001
Total-----	0.03	0.03	0.05	0.04	130.26	171.44	12.16	9.26	130.41
Less HO _{1/2} +S-----		.02			30.39	15.20	1.08	2.16	30.41
Total-----	0.03	0.01	0.05	0.04	99.87	156.24	11.08	7.10	100.00
Less HO _{1/2} -----						15.20	1.08		
O-----						141.04	10.00		
									Total
V _e -----	14.84	23.90	20.45	20.00	² 19.55				
Volume proportions-----	.30	.24	1.02	.80	1,952.7				1,955.06
Volume percent-----	.03	.01	.05	.04	99.87				100.00

¹ The unfavorable ratio of Mg to Ca makes it probable that some Ca was missed in the analysis; therefore enough Mg is borrowed to fill out the requirements for Ca in apatite.

² Calculated from formula composition; other values of V_e from table 22.

C. TALC FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 44.—Calculations upon analysis of steatite, sample R-DDH-2-310, Rousseau prospect

[Analysis 31, table 3. Optics of talc: $2V=0^\circ$; Optic Sign(-); $\beta \approx \gamma = 1.593$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂	59.6	59.6	0.99234	55.00	110.00	59.2
AlO _{3/2}	1.0	1.0	.01962	1.09	1.64	1.2
Total Fe as FeO _{3/2}	5.4					
MgO.....	27.8	27.8	.68948	38.21	38.21	41.1
CaO.....	.16	.16	.00285	.16	.16	.17
NaO _{1/2}	.15	.15	.00484	.27	.14	.29
KO _{1/2}	.05	.05	.00106	.06	.03	.06
TiO ₂	.08	.08	.00100	.05	.10	.05
PO _{5/2}	.00	.00	.00000	.00	.00	.00
MnO.....	.04	.04	.00056	.03	.03	.03
Ignition loss.....	5.1					
Sum.....	99					
FeO.....	4.7	4.7	.06541	3.63	3.63	3.9
FeO _{3/2}	.18	.18	.00225	.12	.18	.13
Gain from oxidation of FeO.....	.5					
Corrected ignition loss.....	5.6					
C.....	.00	.00	.00000	.00	.00	.00
S.....	<.05	<.05	<.00156	<.09	<.09	<.10
HO _{1/2} + est. ¹		4.5	.49964	27.69	13.85	29.8
CO ₂ est. ²		1.1	.02499	1.38	2.76	1.5
Total.....		99.36			170.76	
Less O for S.....						
Total.....		99.36	2.30404	127.69	170.76	
Less HO _{1/2} + S.....			.49964	27.69	13.88	
Total.....			1.80440	100.00	156.88	
Less HO _{1/2} + CO ₂					16.64	
O.....					140.24	
Oeq.....						183.8
Cations.....						107.6
O.....						150.9
W ₁₀₀						5,506.5
Density.....						2.87
V ₁₀₀						1,918.6
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀						1.0762

¹ Equivalent molecular numbers HO_{1/2} assumed = 1/2 [Si + 1/2(Al + Fe⁺³ - Na - 3K)].² Weight percent CO₂ assumed = corrected ignition loss less weight percent HO_{1/2}, S, and C.

TABLE 44.—Calculations upon analysis of steatite, sample R-DDH-2-310, Rousseau prospect—Continued

B. CALCULATED MODE AND TALC FORMULA NUMBERS

	Spheue	Albite	Muscovite	Carbonate	Talc				Cation totals
					Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----	0.05	0.81	0.18	-----	53.96	107.92	7.94	3.97	55.00
AlO _{3/2} -----	-----	.27	.18	-----	.64	.96	.07	.05	1.09
MgO-----	-----	-----	-----	1.17	37.04	37.04	2.72	2.72	38.21
CaO-----	.05	-----	-----	.11	-----	-----	-----	-----	.16
NaO _{1/2} -----	-----	.27	-----	-----	-----	-----	-----	-----	.27
KO _{1/2} -----	-----	-----	.06	-----	-----	-----	-----	-----	.06
TiO ₂ -----	.05	-----	-----	-----	-----	-----	-----	-----	.05
PO _{5/2} -----	-----	-----	.00	-----	-----	-----	-----	-----	.00
MnO-----	-----	-----	-----	-----	.03	.03	.002	.002	.03
FeO-----	-----	-----	-----	.10	3.63	3.63	.27	.27	3.63
FeO _{3/2} -----	-----	-----	-----	-----	.12	.18	.01	.01	.12
C-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
S-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
HO _{1/2} + est.-----	-----	-----	.12	-----	27.57	13.79	1.01	2.02	27.69
CO ₂ est.-----	-----	-----	-----	1.38	-----	-----	-----	-----	1.38
Total-----	0.15	1.29	0.54	2.76	122.99	163.55	12.02	9.04	127.69
Less HO _{1/2} +S-----	-----	-----	.12	-----	27.57	13.79	1.01	2.02	27.69
Total-----	0.15	1.29	0.42	2.76	95.42	149.76	11.01	7.03	100.00
Less HO _{1/2} +CO ₂ -----	-----	-----	-----	-----	-----	13.79	1.01	-----	-----
O-----	-----	-----	-----	-----	-----	135.97	10.00	-----	-----
									Total
V _e -----	18.67	20.01	20.31	14.14	19.21	-----	-----	-----	-----
Volume proportions-----	2.8	25.8	8.5	39.0	1,833.0	-----	-----	-----	1,909.1
Volume percent-----	.15	1.35	.45	2.04	96.01	-----	-----	-----	100.00

C. TALC FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 45.—Calculations upon analysis of talc-carbonate rock, with coarse carbonate, sample J-106, Johnson mine

[Analysis 21, table 3. Optics of talc: $2V=0^\circ$; Optic sign (-); $\beta \approx \gamma = 1.588$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	42. 8	42. 8	0. 71262	36. 26	72. 52	42. 7
AlO _{3/2} -----	1. 6	1. 6	. 03139	1. 60	2. 40	1. 9
Total Fe as FeO _{3/2} -----	5. 9					
MgO-----	32. 4	32. 4	. 80357	40. 88	40. 88	48. 2
CaO-----	. 30	. 30	. 00535	. 27	. 27	. 32
NaO _{1/2} -----	. 15	. 15	. 00484	. 25	. 13	. 29
KO _{1/2} -----	. 08	. 08	. 00170	. 09	. 04	. 11
TiO ₂ -----	. 05	. 05	. 00063	. 03	. 06	. 04
PO _{5/2} -----	. 02	. 02	. 00028	. 01	. 03	. 01
MnO-----	. 07	. 07	. 00099	. 05	. 05	. 06
Ignition loss-----	17. 2					
Sum-----	101					
FeO-----	5. 1	5. 1	. 07098	3. 61	3. 61	4. 3
FeO _{3/2} -----	. 24	. 24	. 00301	. 15	. 23	. 18
Gain from oxidation of FeO-----	. 6					
Corrected ignition loss-----	17. 8					
S-----	. 06	. 06	. 00187	. 10	. 10	. 12
HO _{1/2} + est. ¹ -----		3. 21	. 35631	18. 13	9. 06	21. 4
CO ₂ est. ² -----		14. 53	. 33015	16. 80	33. 60	19. 8
Total-----		100. 61			162. 98	
Less O for S-----		. 02			. 08	
Total-----		100. 59			162. 90	
Less HO _{1/2} +S-----			2. 32369 . 35818	118. 23 18. 23	9. 16	
Total-----			1. 96551	100. 00	153. 74	
Less HO _{1/2} +CO ₂ -----					42. 66	
O-----					111. 08	
Oeq-----						191. 9
Cations-----						117. 8
O-----						130. 9
W ₁₀₀ -----						5, 117. 8
Density-----						2. 92
V ₁₀₀ -----						1, 752. 7
F _{r,k} (cell factor)=V _{MSC} /V ₁₀₀ -----						1. 1781

¹ Equivalent molecular percent HO_{1/2} assumed equal to ½ S.² Weight percent CO₂ assumed equal to corrected ignition loss less weight percent HO_{1/2}, S, and C.

TABLE 45.—Calculations upon analysis of talc-carbonate rock, with coarse carbonate, sample J-106, Johnson mine—Continued

B. CALCULATED MODE AND TALC FORMULA NUMBERS

	Magnesite	Magnetite	Pyrite	Apatite	Other	Talc				Cation totals
						Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----						36.26	75.52	7.73	3.87	36.26
AlO _{3/2} -----						1.60	2.40	.26	.17	1.60
MgO-----	14.40					26.48	26.48	2.82	2.82	40.88
CaO-----	.25			0.02						.27
NaO _{1/2} -----					0.25					.25
KO _{1/2} -----					.09					.09
TiO ₂ -----						.03	.06	.006	.003	.03
PO _{5/2} -----				.01						.01
MnO-----	.05									.05
FeO-----	2.10	0.05				1.46	1.46	.15	.15	3.61
FeO _{3/2} -----		.10	0.05							.15
S-----			.10							.10
HO _{1/2} + est-----						18.13	9.07	.97	1.94	18.13
CO ₂ est-----	16.80									16.80
Total-----	33.60	0.22	0.15	0.03	0.34	83.96	111.99	11.94	8.95	118.23
Less HO _{1/2} +S-----			.10			18.13	9.07	.97	1.94	18.23
Total-----	33.60	0.22	0.05	0.03	0.34	65.83	102.92	10.97	7.01	100.00
Less HO _{1/2} +CO ₂ -----							9.07	.97		
O-----							93.85	10.00		
										Total
V _e -----	13.89	14.84	23.90	20.45	20.00	19.21				
Volume proportions-----	466.7	3.3	1.2	.6	6.8	1,264.6				1,743.2
Volume percent-----	26.77	.19	.07	.03	.39	72.55				100.00

C. TALC FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 46.—Calculations upon analysis of talc-carbonate rock, very low in carbonate, sample W-89, Waterbury mine

[Analysis 22, table 3. Indices of talc: $\beta \approx \gamma = 1.593$]

A. CALCULATIONS OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	59.0	59.0	0.98235	53.95	107.90	58.1
AlO _{3/2} -----	1.6	1.6	.03139	1.72	2.58	1.9
Total Fe as FeO _{3/2} -----	6.4					
MgO-----	28.6	28.6	.70932	38.95	38.95	42.0
CaO-----	.15	.15	.00267	.15	.15	.16
NaO _{1/2} -----	.12	.12	.00387	.21	.10	.23
KO _{1/2} -----	.07	.07	.00149	.08	.04	.09
TiO ₂ -----	.03	.03	.00038	.02	.04	.02
PO _{5/2} -----	.03	.03	.00042	.02	.05	.02
MnO-----	.06	.06	.00085	.05	.05	.05
Ignition loss-----	5.0					
Sum-----	101					
FeO-----	4.1	4.1	.05706	3.13	3.13	3.4
FeO _{3/2} -----	1.8	1.8	.02254	1.24	1.86	1.3
Gain from oxidation of FeO-----	.5					
Corrected ignition loss-----	5.5					
S-----	.72	.72	.02246	1.23	1.23	1.3
HO _{1/2} + est. ¹ -----		4.4	.49118	26.97	13.49	29.1
CO ₂ est. ² -----		.38	.00863	.48	.96	.52
Total-----		101.06			170.53	
Less O for S-----		.54			1.85	
Total-----		100.52			168.68	
Less HO _{1/2} +S-----			2.33461	128.20	14.72	
Total-----			.51364	28.20		
Less HO _{1/2} +CO ₂ -----			1.82097	100.00	153.96	
O-----					14.45	
Oeq-----					139.51	
Cations-----						181.7
O-----						107.7
W ₁₀₀ -----						150.3
Density-----						5,520.1
V ₁₀₀ -----						2.88
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----						1,916.7
						1.0773

¹ Equivalent molecular numbers HO_{1/2} assumed equal to ½ Si.² Weight percent CO₂ assumed equal to corrected ignition loss less weight percent HO_{1/2}, S, and C.

TABLE 46.—Calculations upon analysis of talc-carbonate rock, very low in carbonate, sample W-89, Waterbury mine—Continued

B. CALCULATED MODE AND TALC FORMULA NUMBERS

	Carbonate	Pyrrhotite	Apatite	Other	Talc				Cation totals
					Equiv. molec. percent	Oeq	O=10	Formula Nos.	
SiO ₂					53.95	107.90	7.78	3.89	53.95
AlO _{3/2}					1.72	2.58	.19	.13	1.72
MgO.....	0.33				38.62	38.62	2.78	2.78	38.95
CaO.....	.12		0.03						.15
NaO _{1/2}				0.21					.21
KO _{1/2}				.08					.08
TiO ₂				.02					.02
PO _{5/2}			.02						.02
MnO.....					.05	.05	.004	.004	.05
FeO.....	.03				3.10	3.10	.22	.22	3.13
FeO _{3/2}		1.24							1.24
S.....		1.23							1.23
HO _{1/2} +.....			.01		26.96	13.48	.97	1.94	26.97
CO ₂	.48								.48
Total.....	0.96	2.47	0.06	0.31	124.40	165.73	11.94	8.96	128.20
Less HO _{1/2} +S.....		1.23	.01		26.96	13.48	.97	1.94	28.20
Total.....	0.96	1.24	0.05	0.31	97.44	152.25	10.97	7.02	100.00
Less HO _{1/2} +CO ₂						13.48	.97		
O.....						138.77	10.00		
									Total
V _e	14.93	18.43	20.45	20.00	19.21				
Volume proportions.....	14.3	22.9	1.0	6.2	1,871.8				1,916.2
Volume percent.....	.75	1.20	.05	.32	97.68				100.00

C. TALC FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 47.—*Calculations upon analysis of talc-carbonate rock, with coarse carbonate, sample R-DDH-8-160, Rousseau prospect*[Analysis 23, table 3. Optics of talc: 2V small; Optic sign (-); $\beta \approx \gamma = 1.592$]

A. CALCULATIONS OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	45.0	45.0	0.74925	39.28	78.56	44.2
AlO _{3/2} -----	3.8	3.8	.07455	3.91	5.87	4.4
Total Fe as FeO _{3/2} -----	7.0					
MgO-----	30.3	30.3	.75149	39.39	39.39	44.3
CaO-----	.92	.92	.01641	.86	.86	.97
NaO _{1/2} -----	.14	.14	.00452	.24	.12	.27
KO _{1/2} -----	.08	.08	.00170	.09	.05	.10
TiO ₂ -----	1.5	1.5	.01877	.98	1.96	1.10
PO _{5/2} -----	.06	.06	.00085	.04	.10	.05
MnO-----	.04	.04	.00056	.03	.03	.03
Ignition loss-----	11.8					
Sum-----	101					
FeO-----	5.8	5.8	.08072	4.23	4.23	4.8
FeO _{3/2} -----	.56	.56	.00701	.37	.56	.42
Gain from oxidation of FeO-----	.6					
Corrected ignition loss-----	12.4					
S-----	.12	.12	.00374	.20	.20	.23
HO _{1/2} + est. ¹ -----		3.4	.37463	19.64	9.82	22.1
CO ₂ est. ² -----		8.88	.20177	10.58	21.16	11.9
Total-----		100.6			162.91	
Less O for S-----		.09			.30	
Total-----		100.5			162.61	
Less HO _{1/2} + S-----			2.28597	119.84	10.02	
Total-----			.37837	19.84		
Less HO _{1/2} + CO ₂ -----			1.90760	100.00	152.59	
O-----					30.98	
Oeq-----					121.61	
Cations-----						182.9
O-----						112.5
W ₁₀₀ -----						136.8
Density-----						5,268.4
V ₁₀₀ -----						2.87
F _{r,k} (cell factor) = V _{MSC} /V ₁₀₀ -----						1,835.7
						1.1248

¹ Equivalent molecular numbers HO_{1/2} assumed equal to ½ Si.² Weight percent CO₂ assumed equal to corrected ignition loss less weight percent HO_{1/2}, S, and C.

TABLE 47.—Calculations upon analysis of talc-carbonate rock, with coarse carbonate, sample R-DDH-8-160, Rousseau prospect—Con.

B. CALCULATED MODE AND TALC FORMULA NUMBERS

	Carbonate	Magnetite	Pyrrho- tite	Apatite	Other	Talc				Cation totals
						Equiv. molec. percent	Oeq	O=10	Formula Nos.	
SiO ₂ -----						39.28	78.56	7.25	3.63	39.28
AlO _{3/2} -----						3.91	5.87	.54	.36	3.91
MgO-----	8.72	0.03				30.64	30.64	2.83	2.83	39.39
CaO-----	.79			0.07						.86
NaO _{1/2} -----					0.24					.24
KO _{1/2} -----					.09					.09
TiO ₂ -----					.98					.98
PO _{3/2} -----				.04						.04
MnO-----						.03	.03	.003	.003	.03
FeO-----	1.07	.05				3.11	3.11	.29	.29	4.23
FeO _{3/2} -----		.17	0.20							.37
S-----			.20							.20
HO _{1/2} + est.-----				.01		19.63	9.82	.91	1.92	19.64
CO ₂ est.-----	10.58									10.58
Total-----	21.16	0.25	0.40	0.12	1.31	96.60	128.03	11.82	9.03	119.84
Less HO _{1/2} +S-----			.20	.01		19.63	9.82	.91	1.92	19.84
Total-----	21.16	0.25	0.20	0.11	1.31	76.97	118.21	10.91	7.11	100.00
Less HO _{1/2} +CO ₂ -----							9.82	.91		
O-----							108.39	10.00		
										Total
V-----	14.14	14.84	18.43	20.45	20.00	19.21				
Volume proportions-----	299.2	3.7	3.7	2.2	26.2	1,478.6				1,813.6
Volume percent-----	16.50	.20	.20	.12	1.44	81.54				100.00

C. TALC FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

APPENDIX I. BLACKWALL CHLORITE ROCK

Tables 48 to 52 contain calculations of the modified standard cell, of the mineral mode, and of the formula of chlorite, from rock analyses of blackwall chlorite rock. The computations of the modified standard cell are based upon measured rock densities, and follow procedures described fully in appendix B. The mineral modes are based upon thin section data except for that of specimen Vt. 118 (table 52), for which no such data are available. In tables 48 to 51, $KO_{1/2}$ was assumed to be in muscovite, and $NaO_{1/2}$ in albite. Two modes were calculated for specimen Vt. 118, one without muscovite and albite, and one with these

minerals. For all the analyses, CaO not used up in apatite, sphene, actinolite, and epidote was assumed to be in carbonate, the balance of which was filled out with MgO and FeO, in whatever proportions seemed probable from information available on the composition of the carbonate. Calculation of the chlorite formula has been described fully in appendix B. The composition of the chlorite, in formula notation, is given in part *C* of each table; the formula of the modified standard cell is shown in part *D*. Table 52 contains two chlorite formulas, one based upon a mode without muscovite and albite, and one upon a mode with these minerals.

TABLE 48.—Calculations upon analysis of blackwall chlorite rock, sample W-38, Waterbury mine

[Analysis 19, table 3. Indices of chlorite: $\alpha \approx \beta = 1.615$, $\gamma = 1.619$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
SiO ₂ -----	25.59	0.42607	26.39	52.78	25.83
AlO _{3/2} -----	18.93	.37140	23.00	34.50	22.51
FeO _{3/2} -----	1.64	.02054	1.27	1.91	1.24
FeO-----	20.14	.28031	17.36	17.36	16.99
MgO-----	18.45	.45759	28.34	28.34	27.74
CaO-----	.01	.00018	.01	.01	.01
NaO _{1/2} -----	.01	.00032	.02	.01	.02
KO _{1/2} -----	.02	.00042	.02	.01	.02
HO _{1/2} -----	.09				
HO _{1/2} +-----	10.80	1.19893	74.24	37.12	72.66
TiO ₂ -----	3.47	.04343	2.69	5.38	2.64
CO ₂ -----	.05	.00114	.07	.14	.07
PO _{5/2} -----	.01	.00014	.01	.03	.01
S-----	.01	.00031	.02	.02	.02
NiO-----	.02	.00027	.02	.02	.02
MnO-----	.90	.01269	.79	.79	.77
CoO-----	.01	.00013	.01	.01	.01
AsO _{3/2} -----	.0003	.000003	.0002	.0002	.0002
Total-----	100.16			178.43	
Less O for S+As-----	.01			.02	
Total-----	100.15	2.81387	174.26	178.41	
Less HO _{1/2} +S+As-----		1.19924	74.26	37.14	
Total-----		1.61463	100.00	141.27	
Less HO _{1/2} +CO ₂ -----				37.26	
O-----				104.01	

Oeq-----	174.61
Cations-----	97.87
O-----	101.79
W_{100} -----	6,202.7
Density-----	2.94
V_{100} -----	2,109.8
F_{rk} (cell factor) = V_{MSC}/V_{100} -----	0.9787

TABLE 48.—Calculations upon analysis of blackwall chlorite rock, sample W-38, Waterbury mine—Continued

B. CALCULATED MODES AND CHLORITE FORMULA NUMBERS

	Car- bonate	Rutile	Ilmen- ite	Apatite	Albite	Musco- vite	Pyrite	Chlorite				Cation total
								Equivalent molecular percent	Oeq	O=10	Formu- la num- bers	
SiO ₂ -----					0.06	0.06		26.27	52.54	5.50	2.75	26.39
AlO _{3/2} -----					.02	.06		22.92	34.38	3.60	2.40	23.00
FeO _{3/2} -----							0.01	1.26	1.89	.20	.13	1.27
FeO-----			2.59					14.77	14.77	1.54	1.54	17.36
MgO-----	0.06			¹ 0.02				28.26	28.26	2.96	2.96	28.34
CaO-----	.01											.01
NaO _{1/2} -----					.02							.02
KO _{1/2} -----						.02						.02
HO _{1/2} -----												
HO _{1/2} +-----						.04		74.20	37.10	3.88	7.76	74.24
TiO ₂ -----		0.10	2.59									2.69
CO ₂ -----	.07											.07
PO _{5/2} -----				.01								.01
S-----							.02					.02
NiO-----								.02	.02	.002	.002	.02
Mn-----								.79	.79	.08	.08	.79
CoO-----								.01	.01	.001	.001	.01
AsO _{3/2} -----							.0002					.002
Total-----	0.14	0.10	5.18	0.03	0.10	0.18	0.03	168.50	169.76	17.76	17.62	174.26
Less HO _{1/2} +S+As-----						.04	.02	74.20	37.10	3.88	7.76	74.26
Total-----	0.14	0.10	5.18	0.03	0.01	0.14	0.01	94.30	132.66	13.88	9.86	100.00
Less HO _{1/2} +CO ₂ -----									37.10	3.88		
O-----									95.56	10.00		
												Total
V-----	16.07	19.02	16.14	20.45	20.01	20.31	23.90	21.56				
Volume proportions-----	2.2	1.9	83.6	0.6	2.0	2.8	.2	2,033.1				2,126.4
Volume percent-----	.10	.09	3.93	.03	.09	.13	.01	95.62				100.00

¹ The unfavorable ratio of Mg to Ca makes it probable that some Ca was missed in the analysis; therefore enough Mg is borrowed to fill out the requirements for Ca in apatite.

C. CHLORITE FORMULA

[Formula values: $n=5.86$, $p=1.25$, $2(n-2)=7.72$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 49.—Calculations upon analysis of blackwall chlorite rock, sample W-DDH-11-118, Waterbury mine .

[Analysis 25, table 3. Indices of chlorite: $\alpha \approx \beta = 1.609$; $\gamma = 1.614$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	43. 4	43. 4	0. 72261	40. 98	81. 96	42. 0
AlO _{3/2} -----	11. 1	11. 1	. 21778	12. 35	18. 52	12. 7
Total Fe as FeO _{3/2} -----	9. 3					
MgO-----	26. 5	26. 5	. 65724	37. 28	37. 28	38. 3
CaO-----	2. 1	2. 1	. 03745	2. 12	2. 12	2. 2
NaO _{1/2} -----	. 17	. 17	. 00548	. 31	. 15	. 32
KO _{1/2} -----	. 08	. 08	. 00170	. 10	. 05	. 10
TiO ₂ -----	. 04	. 04	. 00050	. 03	. 06	. 03
PO _{5/2} -----	. 02	. 02	. 00028	. 02	. 04	. 02
MnO-----	. 25	. 25	. 00352	. 20	. 20	. 21
Ignition loss-----	8. 2					
Sum-----	101					
FeO-----	7. 6	7. 6	. 10578	6. 00	6. 00	6. 2
FeO _{3/2} -----	. 86	. 86	. 01077	. 61	. 91	. 63
Gain from oxidation of FeO-----	. 84					
Corrected ignition loss-----	9. 0					
C-----	. 00	. 00	. 00000	. 00	. 00	. 00
S-----	< . 05	< . 05	< . 00156	< . 09	< . 09	< . 09
HO _{1/2} + est-----		9. 0	. 99911	56. 67	28. 34	58. 1
CO ₂ est-----		. 00	. 00000	. 00	. 00	. 00
Total-----		101. 12			175. 63	
Less O for S-----						
Total-----		101. 12	2. 76222	156. 67	175. 63	
Less HO _{1/2} + S + C-----			. 99911	56. 67	28. 34	
Total-----			1. 76311	100. 00	147. 29	
Less HO _{1/2} + CO ₂ -----					28. 34	
O-----					118. 95	
Oeq-----						180. 2
Cations-----						102. 6
O-----						122. 1
W ₁₀₀ -----						5, 735. 3
Density-----						2. 85
V ₁₀₀ -----						2, 012. 4
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----						1. 0260

TABLE 49.—Calculations upon analysis of blackwall chlorite rock, W-DDH-11-118, Waterbury mine—Continued

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS

	Sphene	Apatite	Albite	Muscovite	Epidote	Chlorite				Cation totals
						Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----	0.03	-----	0.93	0.30	3.09	36.63	73.26	7.12	3.56	40.98
AlO _{3/2} -----	-----	-----	.31	.30	2.48	9.26	13.89	1.35	.90	12.35
MgO-----	-----	-----	-----	-----	-----	37.28	37.28	3.62	3.62	37.28
CaO-----	.03	0.03	-----	-----	2.06	-----	-----	-----	-----	2.12
NaO _{1/2} -----	-----	-----	.31	-----	-----	-----	-----	-----	-----	.31
KO _{1/2} -----	-----	-----	-----	.10	-----	-----	-----	-----	-----	.10
TiO ₂ -----	.03	-----	-----	-----	-----	-----	-----	-----	-----	.03
PO _{5/2} -----	-----	.02	-----	-----	-----	-----	-----	-----	-----	.02
MnO-----	-----	-----	-----	-----	-----	.20	.20	.02	.02	.20
FeO-----	-----	-----	-----	-----	-----	6.00	6.00	.58	.58	6.00
FeO _{3/2} -----	-----	-----	-----	-----	.61	-----	-----	-----	-----	.61
C-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
S-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
HO _{1/2} + est.-----	-----	.01	-----	.20	1.03	55.43	27.72	2.69	5.38	56.67
CO ₂ est.-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total-----	0.09	0.06	1.55	0.90	9.27	144.80	158.35	15.38	14.06	156.67
Less HO _{1/2} +S+C-----	-----	.01	-----	.20	1.03	55.43	27.72	2.69	5.38	56.67
Total-----	0.09	0.05	1.55	0.70	8.24	89.37	130.63	12.69	8.68	100.00
Less HO _{1/2} +CO ₂ -----	-----	-----	-----	-----	-----	-----	27.72	2.69	-----	-----
O-----	-----	-----	-----	-----	-----	-----	102.91	10.00	-----	-----
										Total
V-----	18.67	20.45	20.01	20.31	17.34	19.65	-----	-----	-----	-----
Volume proportions-----	1.7	1.0	31.0	14.1	142.9	1,756.1	-----	-----	-----	1,946.8
Volume percent-----	.09	.05	1.59	.72	7.34	90.21	-----	-----	-----	100.00

C. CHLORITE FORMULA

[Formula values: $n=4.68$, $p=.44$, $2(n-2)=5.2$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 50.—Calculations upon analysis of blackwall chlorite rock, sample B-DDH-11-76, Barnes Hill

[Analysis 26, table 3. Indices of chlorite: $\alpha \approx \beta = 1.599$; $\gamma = 1.605$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	40. 7	40. 7	0. 67766	39. 00	78. 00	40. 2
AlO _{3/2} -----	13. 5	13. 5	. 26486	15. 24	22. 86	15. 7
Total Fe as FeO _{3/2} -----	11. 4					
MgO-----	23. 4	23. 4	. 58036	33. 40	33. 40	34. 4
CaO-----	3. 0	3. 0	. 05350	3. 08	3. 08	3. 2
NaO _{1/2} -----	. 14	. 14	. 00452	. 26	. 13	. 27
KO _{1/2} -----	. 06	. 06	. 00127	. 08	. 04	. 08
TiO ₂ -----	. 60	. 60	. 00751	. 43	. 86	. 44
PO _{5/2} -----	. 04	. 04	. 00056	. 03	. 08	. 03
MnO-----	. 32	. 32	. 00451	. 26	. 26	. 27
Ignition loss-----	7. 8					
Sum-----	101					
FeO-----	9. 6	9. 6	. 13361	7. 69	7. 69	7. 9
FeO _{3/2} -----	. 74	. 74	. 00927	. 53	. 80	. 55
Gain from oxidation of FeO-----	1. 1					
Corrected ignition loss-----	8. 9					
S-----	<. 05	<. 05	<. 00156	<. 09	<. 09	<. 09
HO _{1/2} + est. ¹ -----		8. 9	. 98801	56. 86	28. 43	58. 6
CO ₂ est-----		. 00	. 00000	. 00	. 00	. 00
Total-----		101. 00			175. 63	
Less O for S-----						
Total-----		101. 00	2. 72564	156. 86	175. 63	
Less HO _{1/2} + S-----			. 98801	56. 86	28. 43	
Total-----			1. 73763	100. 00	147. 20	
Less HO _{1/2} + CO ₂ -----					28. 43	
O-----					118. 77	
Oeq-----						180. 9
Cations-----						103. 0
O-----						122. 4
W ₁₀₀ -----						5, 812. 5
Density-----						2. 90
V ₁₀₀ -----						2, 004. 3
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----						1. 0302

¹ Equal to corrected ignition loss.

TABLE 50.—Calculations upon analysis of blackwall chlorite rock, sample B-DDH-11-76, Barnes Hill—Continued

B. CALCULATED MODES AND CHLORITE FORMULA NUMBERS

	Apatite	Sphene	Albite	Muscovite	Actinolite	Chlorite				Cation totals
						Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----		0.43	0.78	0.24	10.40	27.15	54.30	6.39	3.19	39.00
AlO _{3/2} -----			.26	.24		14.74	22.11	2.60	1.73	15.24
MgO-----					5.72	27.68	27.68	3.26	3.26	33.40
CaO-----	0.05	.43			2.60					3.08
NaO _{1/2} -----			.26							.26
KO _{1/2} -----				.08						.08
TiO ₂ -----		.43								.43
PO _{5/2} -----	.03									.03
MnO-----						.26	.26	.03	.03	.26
FeO-----					.78	6.91	6.91	.81	.81	7.69
FeO _{3/2} -----						.53	.80	.09	.06	.53
S-----										
HO _{1/2} + est-----	.01			.16	2.60	54.09	27.05	3.18	6.36	56.86
CO ₂ est-----										
Total-----	0.09	1.29	1.30	0.72	22.10	131.36	139.11	16.36	15.44	156.86
Less HO _{1/2} +S-----	.01			.16	2.60	54.09	27.05	3.18	6.36	56.86
Total-----	0.08	1.29	1.30	0.56	19.50	77.27	112.06	13.18	9.08	100.00
Less HO _{1/2} +CO ₂ -----							27.05	3.18		
O-----							85.01	10.00		
										Total
V-----	20.45	18.67	20.01	20.31	18.10	20.04				
Volume proportions-----	1.6	24.1	26.0	11.4	353.0	1,548.5				1,964.6
Volume percent-----	.08	1.23	1.32	.58	17.96	78.83				100.00

C. CHLORITE FORMULA

[Formula values: $n=5.05$, $p=0.81$, $2(n-2)=6.10$]

$$(\text{Mg}_{3.26}\text{Fe}^{+2} .81) - 4.07(\text{Al}_{.92}\text{Fe}^{+3} .06) - .98(\text{Si}_{3.19}\text{Al}_{.81}) - 4.00\text{O}_{10.00}(\text{OH})_{6.36}^1$$

D. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[\text{K}_{.08}\text{Na}_{.27}\text{Ca}_{3.2}\text{Mg}_{34.4}\text{Fe}^{+2} .79\text{Mn}_{.27}\text{Al}_{15.7}\text{Fe}^{+3} .55\text{Ti}_{.44}\text{Si}_{40.2}\text{P}_{.03}\text{S} < .06\text{O}_{122.4}(\text{OH})_{58.6}(\text{CO}_2)_{.00} \right] \begin{matrix} \text{Cations}=103.0 \\ \text{Oeq}=180.9 \end{matrix}$$

¹ See text discussion, p. 68.

TABLE 51.—*Calculations upon analysis of blackwall chlorite rock, sample B-DDH-8-367, Barnes Hill*[Analysis 28, table 3. Optics of chlorite: $2V=5^\circ$; Optic sign (+); $\alpha \approx \beta = 1.596$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂	29. 2	29. 2	0. 48618	28. 72	57. 44	28. 5
AlO _{3/2}	20. 4	20. 4	. 40024	23. 65	35. 48	23. 5
Total Fe as FeO _{3/2}	15. 4					
MgO.....	22. 1	22. 1	. 54812	32. 38	32. 38	32. 2
CaO.....	1. 7	1. 7	. 03031	1. 79	1. 79	1. 8
NaO _{1/2}	. 22	. 22	. 00710	. 42	. 21	. 42
KO _{1/2}	. 08	. 08	. 00170	. 10	. 05	. 10
TiO ₂	1. 4	1. 4	. 01752	1. 04	2. 08	1. 0
PO _{5/2}	. 24	. 24	. 00338	. 20	. 50	. 20
MnO.....	. 32	. 32	. 00451	. 26	. 26	. 26
Ignition loss.....	10. 0					
Sum.....	101					
FeO.....	12. 2	12. 2	. 16980	10. 03	10. 03	10. 0
FeO _{3/2}	1. 9	1. 9	. 02379	1. 41	2. 12	1. 4
Gain from oxidation of FeO.....	1. 34					
Corrected ignition loss.....	11. 3					
S est.....		. 1	. 00312	. 18	. 18	. 2
HO _{1/2} + est. ¹		11. 2	1. 24334	73. 46	36. 73	72. 9
CO ₂ est.....		. 00	. 00000	. 00	. 00	. 00
Total.....		101. 06			179. 25	
Less O for S.....		. 04			. 14	
Total.....		101. 02	2. 93911	173. 64	179. 11	
Less HO _{1/2} + S.....			1. 24646	73. 64	36. 91	
Total.....			1. 69265	100. 00	142. 20	
Less HO _{1/2} + CO ₂					36. 73	
O.....					105. 47	
Oeq.....						177. 8
Cations.....						99. 3
O.....						104. 7
W ₁₀₀						5, 968. 2
Density.....						2. 87
V ₁₀₀						2, 079. 5
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀						0. 9929

¹ Equal to corrected ignition loss less S.

TABLE 51.—Calculations upon analysis of blackwall chlorite rock, sample B-DDH-8-367, Barnes Hill—Continued

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS

	Apatite	Sphene	Actinolite	Albite	Muscovite	Pyrite	Chlorite				Cation totals
							Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----		1.04	1.64	1.14	0.30		24.60	49.20	5.42	2.71	28.72
AlO _{3/2} -----			.04	.38	.30		22.93	34.40	3.79	2.53	23.65
MgO-----			.84				31.54	31.54	3.47	3.47	32.38
CaO-----	0.33	1.04	.42								1.79
NaO _{1/2} -----			.04	.38							.42
KO _{1/2} -----					.10						.10
TiO ₂ -----		1.04									1.04
PO _{5/2} -----	.20										.20
MnO-----							.26	.26	.03	.03	.26
FeO-----			.21				9.82	9.82	1.08	1.08	10.03
FeO _{3/2} -----						0.09	1.32	1.98	.22	.15	1.41
S est-----						.18					.18
HO _{1/2} + est-----	.07		.42		.20		72.77	36.39	4.01	8.02	73.46
CO ₂ est-----											
Total-----	0.60	3.12	3.61	1.90	0.90	0.27	163.24	163.59	18.02	17.99	173.64
Less HO _{1/2} + S-----	.07		.42		.20	.18	72.77	36.39	4.01	8.02	73.64
Total-----	0.53	3.12	3.19	1.90	0.70	0.09	90.47	127.20	14.01	9.97	100.00
Less HO _{1/2} + CO ₂ -----								36.39	4.01		
O-----								90.81	10.00		
											Total
V _e -----	20.45	18.67	18.12	20.01	20.31	23.90	21.00				
Volume proportions-----	10.8	58.3	57.8	38.0	14.2	2.2	1,899.9				2,081.2
Volume percent-----	.52	2.80	2.78	1.83	.68	.10	91.29				100.00

C. CHLORITE FORMULA

[Formula values: $n=5.97$, $p=1.29$, $2(n-2)=7.94$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 52.—Calculations upon analysis of blackwall chlorite rock, sample Vt.-118, Mad River

[Analysis 32, table 3. Index of chlorite: $\beta=1.591$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
SiO ₂ -----	31. 17	0. 51898	29. 62	59. 24	29. 37
AlO _{3/2} -----	14. 67	. 28782	16. 43	24. 65	16. 29
FeO _{3/2} -----	2. 04	. 02555	1. 46	2. 19	1. 45
FeO-----	7. 63	. 10619	6. 06	6. 06	6. 01
MgO-----	27. 79	. 68924	39. 34	39. 34	39. 00
CaO-----	2. 22	. 03959	2. 26	2. 26	2. 24
NaO _{1/2} -----	1. 04	. 03355	1. 92	. 96	1. 90
KO _{1/2} -----	. 20	. 00425	. 24	. 12	. 24
HO _{1/2} -----	. 00				
HO _{1/2} +-----	11. 02	1. 22336	69. 82	34. 91	69. 22
TiO ₂ -----	. 86	. 01076	. 61	1. 22	. 60
PO _{5/2} -----	. 16	. 00225	. 13	. 33	. 13
MnO-----	. 13	. 00183	. 10	. 10	. 10
CO ₂ -----	1. 41	. 03204	1. 83	3. 66	1. 81
Total-----	100. 34	2. 97541	169. 82	175. 04	
Less HO _{1/2} -----		1. 22336	69. 82	34. 91	
Total-----		1. 75205	100. 00	140. 13	
Less HO _{1/2} -----				34. 91	
O-----				105. 22	
Oeq-----					173. 53
Cations-----					99. 14
O-----					104. 32
F_{rk} (cell factor) = V_{MSC}/Σ volume proportions-----					0. 9914

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS

1. Na and K assumed to be in chlorite

	Calcite	Apatite	Sphene	Chlorite				Cation totals
				Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----			0. 61	29. 01	58. 02	6. 04	3. 02	29. 62
AlO _{3/2} -----				16. 43	24. 65	2. 56	1. 71	16. 43
FeO _{3/2} -----				1. 46	2. 19	. 23	. 15	1. 46
FeO-----	0. 10			5. 96	5. 96	. 62	. 62	6. 06
MgO-----	. 29			39. 05	39. 05	4. 06	4. 06	39. 34
CaO-----	1. 43	0. 22	. 61					2. 26
NaO _{1/2} -----				1. 92	. 96	. 10	. 20	1. 92
KO _{1/2} -----				. 24	. 12	. 01	. 02	. 24
HO _{1/2} -----								
HO _{1/2} +-----				69. 82	34. 91	3. 63	7. 26	69. 82
TiO ₂ -----			. 61					. 61
PO _{5/2} -----		. 13						. 13
MnO-----	. 01			. 09	. 09	. 01	. 01	. 10
CO ₂ -----	1. 83							1. 83
Total-----	3. 66	0. 35	1. 83	163. 98	165. 95	17. 26	17. 05	169. 82
Less HO _{1/2} -----				69. 82	34. 91	3. 63	7. 26	69. 82
Total-----	3. 66	0. 35	1. 83	94. 16	131. 04	13. 63	9. 79	100. 00
Less HO _{1/2} -----					34. 91	3. 63		
O-----					96. 13	10. 00		
Total-----								
V _e -----	17. 45	20. 45	18. 67	21. 00				
Volume proportions-----	63. 9	7. 2	34. 2	1, 977. 4				2, 082. 7
Volume percent-----	3. 07	. 35	1. 64	94. 94				100. 00

TABLE 52.—Calculations upon analysis of blackwall chlorite rock, sample Vt.-118, Mad River—Continued

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS—Continued

2. Na and K assumed to be in albite and muscovite

	Calcite	Apatite	Sphene	Albite	Muscovite	Chlorite				Cation totals
						Equivalent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂			0.61	5.76	0.72	22.53	45.06	5.75	2.88	29.62
AlO _{3/2}				1.92	.72	13.79	20.69	2.64	1.76	16.43
FeO _{3/2}						1.46	2.19	.28	.19	1.46
FeO.....	0.10					5.96	5.96	.76	.76	6.06
MgO.....	.29					39.05	39.05	4.98	4.98	39.34
CaO.....	1.43	0.22	.61							2.26
NaO _{1/2}				1.92						1.92
KO _{1/2}					.24					.24
HO _{1/2}										
HO _{1/2} +.....					.48	69.34	34.67	4.42	8.84	69.82
TiO ₂			.61							.61
PO _{5/2}		.13								.13
MnO.....	.01					.09	.09	.01	.01	.10
CO ₂	1.83									1.83
Total.....	3.66	.35	1.83	9.60	2.16	152.22	147.71	18.84	19.42	169.82
Less HO _{1/2}					.48	69.34	34.67	4.42	8.84	69.82
Total.....	3.66	.35	1.83	9.60	1.68	82.88	113.04	14.42	10.58	100.00
Less HO _{1/2}							34.67	4.42		
O.....							78.37	10.00		
										Total
V.....	17.45	20.45	18.67	20.01	20.31	22.31				
Volume proportions.....	63.9	7.2	34.2	192.1	34.1	1,849.1				2,180.6
Volume percent.....	2.93	.33	1.57	8.81	1.56	84.80				100.00

C. CHLORITE FORMULA

1. Na and K assumed to be in chlorite

[Formula values: $n=6.01$, $p=0.98$, $2(n-2)=8.02$]

2. Na and K assumed to be in albite and muscovite

[Formula values: $n=6.58$, $p=1.12$, $2(n-2)=9.16$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

APPENDIX J. SEDIMENTARY CARBONATE ROCK

The calculations in table 53 require little explanation. They are based upon a rock analysis of impure bedded carbonate rock. Computation of the modified standard cell is based upon measured rock density and follows pro-

cedures described fully in appendix B. The calculated mode is based upon thin-section determinations, and follows procedures fully described in the sample calculation in appendix B. Calculation of the carbonate formula has been described in appendix C.

TABLE 53.—Calculations upon analysis of bedded carbonate rock, sample MR-3, Mad River

[Analysis 30, table 3. Index of carbonate: $\omega = 1.689$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	6.0	6.0	0.09990	4.82	9.64	6.1
AlO _{3/2} -----	.9	.9	.01766	.85	1.28	1.1
Total Fe as FeO _{3/2} -----	5.6					
MgO-----	18.2	18.2	.45139	21.78	21.78	27.4
CaO-----	27.4	27.4	.48859	23.57	23.57	29.6
NaO _{1/2} -----	.16	.16	.00516	.25	.12	.31
KO _{1/2} -----	.08	.08	.00170	.08	.04	.10
TiO ₂ -----	.02	.02	.00025	.01	.02	.01
PO _{5/2} -----	.14	.14	.00197	.10	.25	.13
MnO-----	.10	.10	.00141	.07	.07	.09
Ignition loss-----	41.3					
Sum-----	100					
FeO-----	4.6	4.6	.06402	3.09	3.09	3.9
FeO _{3/2} -----	.49	.49	.00614	.30	.45	.38
Gain from oxidation of FeO-----	.5					
Corrected ignition loss-----	41.8					
C (free)-----	.02	.02	.00167	.08	.04	.03
HO _{1/2} + est. ¹ -----		.34	.03812	1.84	.92	2.3
CO ₂ est. ² -----		41.05	.93274	45.00	90.00	56.6
S est. ³ -----		.39	.01228	.59	.59	.74
Total-----		99.89			151.86	
Less O for S-----		.15			.44	
Total-----		99.74			151.42	
Less HO _{1/2} + S + C ⁴ -----			2.12300	102.43	1.55	
Total-----			.05040	2.43		
Less HO _{1/2} + CO ₂ -----					149.87	
O-----			2.07260	100.00	90.92	
					58.95	
Oeq-----						190.4
Cations-----						125.7
O-----						74.1
W ₁₀₀ -----						4,813.1
Density-----						2.93
V ₁₀₀ -----						1,642.7
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----						1.2570

¹ Based on assumption that one-fourth of the SiO₂ is in quartz, the rest in talc; therefore equivalent molecular numbers of HO_{1/2} = (3/8SiO₂ + 1/3PO_{5/2}).

² CO₂ (weight percent) = corrected ignition loss - (HO_{1/2} + S + C).

³ S (molecular percent) = 2 FeO_{3/2}.

⁴ C is included in the calculations only in "Oeq" columns.

TABLE 53.—Calculations upon analysis of bedded carbonate rock, sample MR-3, Mad River—Continued

B. CALCULATED MODE AND CARBONATE FORMULA NUMBERS

	Quartz	Talc	Apatite	Pyrite	Graphite	Other	Carbonate				Cation totals
							Equivalent molecular percent	Formula numbers	Weight proportions	Weight percent	
SiO ₂ -----	1. 20	3. 62	-----	-----	-----	-----	-----	-----	-----	-----	4. 82
AlO _{3/2} -----	-----	-----	-----	-----	-----	0. 85	-----	-----	-----	-----	. 85
MgO-----	-----	2. 57	-----	-----	-----	-----	19. 21	0. 424	774. 5	18. 1	21. 78
CaO-----	-----	-----	0. 17	-----	-----	-----	23. 40	. 516	1, 312. 3	30. 6	23. 57
NaO _{1/2} -----	-----	-----	-----	-----	-----	. 25	-----	-----	-----	-----	. 25
KO _{1/2} -----	-----	-----	-----	-----	-----	. 08	-----	-----	-----	-----	. 08
TiO ₂ -----	-----	-----	-----	-----	-----	. 01	-----	-----	-----	-----	. 01
PO _{5/2} -----	-----	-----	. 10	-----	-----	-----	-----	-----	-----	-----	. 10
MnO-----	-----	-----	-----	-----	-----	-----	. 07	. 002	5. 0	. 12	. 07
FeO-----	-----	. 15	-----	-----	-----	-----	2. 94	. 065	211. 2	4. 9	3. 09
FeO _{3/2} -----	-----	-----	-----	. 30	-----	-----	-----	-----	-----	-----	. 30
C (free)-----	-----	-----	-----	-----	0. 08	-----	-----	-----	-----	-----	. 08
HO _{1/2} + est-----	-----	1. 81	. 03	-----	-----	-----	-----	-----	-----	-----	1. 84
CO ₂ est-----	-----	-----	-----	-----	-----	-----	45. 00	. 993	1, 980. 5	46. 3	45. 00
S est-----	-----	-----	-----	0. 59	-----	-----	-----	-----	-----	-----	. 59
Total-----	1. 20	8. 15	0. 30	0. 89	0. 08	1. 19	90. 62	2. 000	4, 283. 5	100. 0	102. 43
Less HO _{1/2} +S+C-----	-----	1. 81	. 03	. 59	-----	-----	-----	-----	-----	-----	2. 43
Total-----	1. 20	6. 34	0. 27	0. 30	0. 08	1. 19	90. 62	-----	-----	-----	100. 00
											Total
V ₂ -----	22. 63	19. 21	20. 45	23. 90	5. 34	20. 00	16. 18	-----	-----	-----	-----
Volume proportions-----	27. 2	121. 8	5. 5	7. 2	. 4	23. 8	1, 466. 2	-----	-----	-----	1, 652. 1
Volume percent-----	1. 65	7. 37	. 33	. 44	. 03	1. 44	88. 74	-----	-----	-----	100. 00

C. CARBONATE FORMULA

D. ROCK FORMULA, MODIFIED STANDARD CELL

APPENDIX K. SCHIST AND ALBITE PORPHYROBLAST ROCK

The calculations in tables 54 to 57 are of schist and albite porphyroblast rock. The density of specimen W-DDH-11-60 (table 54) was not determined, and the modified standard cell was computed from the calculated mode; computations for the others were based upon measured rock densities. Computations of the mineral mode were based, for most, on measured modes,

and follow procedures described fully in appendix B and followed in the rest of the appendixes. Computation of mineral formulas from such rock analyses is generally unsatisfactory, as is demonstrated in tables 54 and 57, where attempts to calculate the formula of chlorite—which in these tables makes up only about 8 and 12 percent, respectively, of the rocks—yielded formulas obviously in error.

TABLE 54.—*Calculations upon analysis of schist, sample W-DDH-11-60, Waterbury mine*

[Analysis 14, table 3]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent	Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
SiO ₂ -----	65. 60	1. 09224	64. 27	128. 54	62. 79
AlO _{3/2} -----	14. 77	. 28978	17. 05	25. 58	16. 66
FeO _{3/2} -----	5. 83	. 07301	4. 30	6. 45	4. 20
FeO-----	1. 32	. 01837	1. 08	1. 08	1. 06
MgO-----	2. 58	. 06399	3. 76	3. 76	3. 67
CaO-----	. 51	. 00909	. 54	. 54	. 53
NaO _{1/2} -----	1. 72	. 05549	3. 26	1. 63	3. 19
KO _{1/2} -----	3. 69	. 07835	4. 61	2. 30	4. 50
HO _{1/2} -----	. 00				
HO _{1/2} +-----	2. 47	. 27420	16. 13	8. 07	15. 76
TiO ₂ -----	. 82	. 01026	. 60	1. 20	. 59
CO ₂ -----	. 07	. 00159	. 09	. 18	. 09
PO _{5/2} -----	. 09	. 00127	. 08	. 20	. 08
MnO-----	. 43	. 00606	. 36	. 36	. 35
Total-----	99. 90	1. 97370	116. 13	179. 89	
Less HO _{1/2} -----		. 27420	16. 13	8. 07	
Total-----		1. 69950	100. 00	171. 82	
Less HO _{1/2} +CO ₂ -----				8. 25	
O-----				163. 57	
Oeq-----					175. 75
Cations-----					97. 70
O-----					159. 81
F_{rk} (cell factor) = V_{MSC}/Σ volume proportions-----					0. 9770

TABLE 54.—Calculations upon analysis of schist, sample W-DDH-11-60, Waterbury mine—Continued

B. CALCULATED MODES AND CHLORITE FORMULA NUMBERS

	Carbon- ate	Apatite	Sphene	Ilmen- ite	Albite	Muscov- ite	Biotite	Quartz	Other	Chlorite				Cation totals
										Equi- valent molec- ular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----			0.32		9.78	12.33	1.45	37.76		2.63	5.26	6.76	3.38	64.27
AlO _{3/2} -----					3.26	12.33	.50			.96	1.44	1.85	1.23	17.05
FeO _{3/2} -----							.10		3.50	.70	1.05	1.35	.90	4.30
FeO-----				0.28			.73			.07	.07	.09	.09	1.08
MnO-----							.72			3.04	3.04	3.91	3.91	3.76
CaO-----	0.09	0.13	.32											.54
NaO _{1/2} -----					3.26									3.26
KO _{1/2} -----						4.11	.50							4.61
HO _{1/2} -----														
HO _{1/2} +-----		.03				8.22	1.00			6.88	3.44	4.42	8.84	16.13
TiO ₂ -----			.32	.28										.60
CO ₂ -----	.09													.09
PO _{5/2} -----		.08												.08
MnO-----										.36	.36	.46	.46	.36
Total-----	0.18	0.24	0.96	0.56	16.30	36.99	5.00	37.76	3.50	14.64	14.66	18.84	18.81	116.13
Less HO _{1/2} -----		.03				8.22	1.00			6.88	3.44		8.84	16.13
Total-----	0.18	0.21	0.96	0.56	16.30	28.77	4.00	37.76	3.50	7.76	11.22		9.97	100.00
Less HO _{1/2} +CO ₂ -----											3.44			
O-----											7.78			
														Total
V-----	18.42	20.45	18.67	16.14	20.01	20.31	18.88	22.63	20.00	21.70				
Volume proportions-----	3.32	4.29	17.92	9.04	326.16	584.32	75.52	854.51	70.00	168.39				2,113.5
Volume percent-----	.16	.20	.85	.43	15.43	27.65	3.57	40.43	3.31	7.97				100.00

C. CHLORITE FORMULA

[Formula values: $n=5.97$, $p=0.62$, $2(n-2)=7.94$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 55.—*Calculations upon analysis of albite porphyroblast rock, sample W-DDH-11-116, Waterbury mine*

[Analysis 24, table 3]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
	Reported	Modified				
SiO ₂	60. 4	60. 4	1. 00566	55. 00	110. 00	56. 6
AlO _{3/2}	17. 0	17. 0	. 33353	18. 24	27. 36	18. 8
Total Fe as FeO _{3/2}	8. 0					
MgO.....	3. 1	3. 1	. 07688	4. 21	4. 21	4. 3
CaO.....	. 68	. 68	. 01213	. 66	. 66	. 68
NaO _{1/2}	7. 2	7. 2	. 23228	12. 70	6. 35	13. 1
KO _{1/2}	2. 2	2. 2	. 04671	2. 56	1. 28	2. 6
TiO ₂	. 92	. 92	. 01151	. 63	1. 26	. 65
PO _{5/2}	. 12	. 12	. 00169	. 09	. 23	. 09
MnO.....	. 52	. 52	. 00733	. 40	. 40	. 41
Ignition loss.....	1. 1					
Sum.....	101					
FeO.....	6. 0	6. 0	. 08351	4. 57	4. 57	4. 7
FeO _{3/2}	1. 3	1. 3	. 01628	. 89	1. 34	. 92
Gain from oxidation of FeO.....	. 7					
Corrected ignition loss.....	1. 8					
C.....	. 01	. 01	. 00083	. 05	. 02	. 05
S.....	< . 05	< . 05	< . 00156	< . 09	< . 09	< . 09
HO _{1/2} + est. ¹		1. 8	. 19982	10. 93	5. 47	11. 2
CO ₂ est.....		. 00	. 00000	. 00	. 00	. 00
Total.....		101. 25			163. 15	
Less O for S.....		. 60			. 00	
Total.....		101. 25	2. 02816	110. 93	163. 15	
Less HO _{1/2} + S + C ²			. 19982	10. 93	5. 49	
Total.....			1. 82834	100. 00	157. 66	
Less HO _{1/2} + CO ₂					5. 47	
O.....					152. 19	
Oeq.....						167. 9
Cations.....						102. 9
O.....						156. 6
W ₁₀₀						5, 537. 8
Density.....						2. 76
V ₁₀₀						2, 006. 4
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀						1. 0291

¹ Equals corrected ignition loss.² C is included in the calculation only in the "Oeq" column.

TABLE 55.—Calculations upon analysis of albite porphyroblast rock, sample W-DDH-11-116, Waterbury mine—Continued

B. CALCULATED MODE

	Albite	Chlorite	Muscovite	Biotite	Quartz	Apatite	Sphene	Ilmenite	Clinozolsite	Graphite	Cation total
SiO ₂ -----	38.10	1.95	2.31	5.37	6.75	-----	0.48	-----	0.04	-----	55.00
AlO _{3/2} -----	12.70	1.85	2.31	1.35	-----	-----	-----	-----	.03	-----	18.24
MgO-----	-----	1.76	-----	2.45	-----	-----	-----	-----	-----	-----	4.21
CaO-----	-----	-----	-----	-----	-----	0.15	.48	-----	.03	-----	.66
NaO _{1/2} -----	12.70	-----	-----	-----	-----	-----	-----	-----	-----	-----	12.70
KO _{1/2} -----	-----	-----	.77	1.79	-----	-----	-----	-----	-----	-----	2.56
TiO ₂ -----	-----	-----	-----	-----	-----	-----	.48	0.15	-----	-----	.63
PO _{5/2} -----	-----	-----	-----	-----	-----	.09	-----	-----	-----	-----	.09
MnO-----	-----	.10	-----	.30	-----	-----	-----	-----	-----	-----	.40
FeO-----	-----	1.80	-----	2.62	-----	-----	-----	.15	-----	-----	4.57
FeO _{3/2} -----	-----	.38	-----	.50	-----	-----	-----	-----	.01	-----	.89
C-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	0.05	.05
S-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
HO _{1/2} + est-----	-----	5.77	1.54	3.58	-----	.03	-----	-----	.01	-----	10.93
CO ₂ est-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total-----	63.50	13.61	6.93	17.96	6.75	0.27	1.44	0.30	0.12	0.05	110.93
Less HO _{1/2} +S+C-----	-----	5.77	1.54	3.58	-----	.03	-----	-----	.01	-----	10.93
Total-----	63.50	7.84	5.39	14.38	6.75	0.24	1.44	0.30	0.11	0.05	100.00
											Total
V _e -----	20.01	21.70	20.31	18.88	22.63	20.45	18.67	16.14	17.00	5.34	-----
Volume proportions-----	1,270.6	170.1	109.5	271.5	152.8	4.9	26.9	4.8	1.9	.3	2,013.3
Volume percent-----	63.11	8.45	5.44	13.49	7.59	.24	1.34	.24	.09	.01	100.00

C. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[K_{2.6}Na_{13.1}Ca_{.68}Mg_{4.3}Fe^{+2}_{4.7}Mn_{.41}Al_{18.8}Fe^{+3}_{.92}Ti_{.65}Si_{56.6}P_{.09}S_{<.09}C_{.05}O_{156.6}(OH)_{11.2}(CO_2)_{.00} \right] \begin{matrix} \text{Cations}=102.9 \\ \text{Oeq}=167.9 \end{matrix}$$

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

TABLE 56.—Calculations upon analysis of schist, sample B-DDH-11-73, Barnes Hill

[Analysis 27, table 3]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula num- bers in MSC
	Reported	Modified				
SiO ₂	58.0	58.0	0.96570	55.62	101.24	56.1
AlO _{3/2}	20.4	20.4	.40024	23.05	34.58	23.2
Total Fe as FeO _{3/2}	8.4					
MgO.....	2.6	2.6	.06448	3.71	3.71	3.7
CaO.....	.78	.78	.01391	.80	.80	.81
NaO _{1/2}	2.9	2.9	.09356	5.39	2.70	5.4
KO _{1/2}	3.4	3.4	.07219	4.16	2.08	4.2
TiO ₂	.98	.98	.01227	.71	1.42	.72
PO _{5/2}	.13	.13	.00183	.10	.25	.10
MnO.....	.20	.20	.00282	.16	.16	.16
Ignition loss.....	3.4					
Sum.....	101					
FeO.....	6.0	6.0	.08351	4.81	4.81	4.8
FeO _{3/2}	1.7	1.7	.02129	1.23	1.85	1.2
Gain from oxidation of FeO.....	.7					
Corrected ignition loss.....	4.1					
S.....	.50	.50	.01560	.90	.90	.91
HO _{1/2} + est. ¹		3.4	.37744	21.74	10.87	21.9
CO ₂ est. ²		.2	.00454	.26	.52	.26
Total.....		101.19			165.89	
Less O for S.....		.19			.68	
Total.....		101.00	2.12938	122.64	165.21	
Less HO _{1/2} + S.....			.39304	22.64	11.77	
Total.....			1.73634	100.00	153.44	
Less HO _{1/2} + CO ₂					11.39	
O.....					142.05	
Oeq.....						166.5
Cations.....						100.8
O.....						143.2
W ₁₀₀						5,816.8
Density.....						2.84
V ₁₀₀						2,048.2
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀						1.0081

¹ Equals corrected ignition loss less weight percent S and CO₂.² Based on thin section determination of carbonate content.

TABLE 56.—Calculations upon analysis of schist, sample B—DDH-11-78, Barnes Hill—Continued

B. CALCULATED MODE

	Apatite	Sphene	Ilmenite	Carbonate	Garnet	Pyrite	Albite	Muscovite	Chlorite	Quartz	Cation totals
SiO ₂ -----		0.37			0.30		16.17	12.48	5.17	21.13	55.62
AlO _{3/2} -----					.20		5.39	12.48	4.98		23.05
MgO-----					.02				3.69		3.71
CaO-----	0.17	.37		0.26							.80
NaO _{1/2} -----							5.39				5.39
KO _{1/2} -----								4.16			4.16
TiO ₂ -----		.37	0.34								.71
PO _{5/2} -----	.10										.10
MnO-----					.03				.13		.16
FeO-----					.25				4.56		4.81
FeO _{3/2} -----			.34			0.45			.44		1.23
S-----						.90					.90
HO _{1/2} + est-----	.03							8.32	13.39		21.74
CO ₂ est-----				.26							.26
Total-----	0.30	1.11	0.68	0.52	0.80	1.35	26.95	37.44	32.36	21.13	122.64
Less HO _{1/2} +S-----	.03					.90		8.32	13.39		22.64
Total-----	0.27	1.11	0.68	0.52	0.80	0.45	26.95	29.12	18.97	21.13	100.00
											Total
V-----	20.45	18.67	16.14	18.42	14.44	23.90	20.01	20.31	21.71	22.63	
Volume proportions-----	5.5	20.7	11.0	9.6	11.6	10.8	539.3	591.4	411.8	478.2	2,089.9
Volume percent-----	.26	.99	.53	.46	.56	.52	25.80	28.30	19.70	22.88	100.00

C. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 57.—*Calculations upon analysis of schist, sample B-DDH-8-372, Barnes Hill*[Analysis 29, table 3. Index of chlorite: $\beta=1.597$]

A. CALCULATION OF MODIFIED STANDARD CELL

	Weight percent		Equivalent molecular numbers	Equivalent molecular percent	Oeq	Formula numbers in MSC
	Reported	Modified				
SiO ₂ -----	66. 4	66. 4	1. 10556	64. 81	129. 62	63. 9
AlO _{3/2} -----	16. 7	16. 7	. 32764	19. 21	28. 82	18. 9
Total Fe as FeO _{3/2} -----	6. 4					
MgO-----	1. 4	1. 4	. 03472	2. 03	2. 03	2. 0
CaO-----	. 80	. 80	. 01427	. 84	. 84	. 83
NaO _{1/2} -----	1. 8	1. 8	. 05807	3. 40	1. 70	3. 4
KO _{1/2} -----	3. 4	3. 4	. 07219	4. 23	2. 12	4. 2
TiO ₂ -----	. 80	. 80	. 01001	. 59	1. 18	. 58
PO _{5/2} -----	. 10	. 10	. 00141	. 08	. 20	. 08
MnO-----	. 16	. 16	. 00226	. 13	. 13	. 13
Ignition loss-----	2. 4					
Sum-----	100					
FeO-----	4. 2	4. 2	. 05846	3. 43	3. 43	3. 4
FeO _{3/2} -----	1. 7	1. 7	. 02129	1. 25	1. 88	1. 2
Gain from oxidation of FeO-----	. 5					
Corrected ignition loss-----	2. 9					
HO _{1/2} + est. ¹ -----		2. 9	. 32194	18. 87	9. 43	18. 6
CO ₂ est-----		. 00	. 00000	. 00	. 00	. 00
Total-----		100. 36	2. 02782	118. 87	181. 38	
Less HO _{1/2} -----			. 32194	18. 87	9. 43	
Total-----			1. 70588	100. 00	171. 95	
Less HO _{1/2} + CO ₂ -----					9. 43	
O-----					162. 52	
Oeq-----						178. 9
Cations-----						98. 6
O-----						160. 3
W ₁₀₀ -----						5, 883. 2
Density-----						2. 81
V ₁₀₀ -----						2, 093. 7
F _{rk} (cell factor) = V _{MSC} /V ₁₀₀ -----						0. 9862

¹ Equals corrected ignition loss.

TABLE 57.—Calculations upon analysis of schist, sample B-DDH-8-372, Barnes Hill—Continued

B. CALCULATED MODE AND CHLORITE FORMULA NUMBERS

	Apatite	Spene	Magnetite	Epidote	Albite	Muscovite	Quartz	Chlorite				Cation total
								Equiva- lent molecular percent	Oeq	O=10	Formula numbers	
SiO ₂ -----	-----	0. 59	-----	0. 18	10. 20	12. 69	38. 06	3. 09	6. 18	5. 43	2. 72	64. 81
AlO _{3/2} -----	-----	-----	-----	. 14	3. 40	12. 69	-----	2. 98	4. 47	3. 93	2. 62	19. 21
MgO-----	-----	-----	-----	-----	-----	-----	-----	2. 03	2. 03	1. 78	1. 78	2. 03
CaO-----	0. 13	. 59	-----	. 12	-----	-----	-----	-----	-----	-----	-----	. 84
NaO _{1/2} -----	-----	-----	-----	-----	3. 40	-----	-----	-----	-----	-----	-----	3. 40
KO _{1/2} -----	-----	-----	-----	-----	-----	4. 23	-----	-----	-----	-----	-----	4. 23
TiO ₂ -----	-----	. 59	-----	-----	-----	-----	-----	-----	-----	-----	-----	. 59
PO _{5/2} -----	. 08	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	. 08
MnO-----	-----	-----	-----	-----	-----	-----	-----	. 13	. 13	. 11	. 11	. 13
FeO-----	-----	-----	0. 38	-----	-----	-----	-----	3. 05	3. 05	2. 68	2. 68	3. 43
FeO _{3/2} -----	-----	-----	. 76	. 04	-----	-----	-----	. 45	. 68	. 60	. 40	1. 25
HO _{1/2} + est-----	. 03	-----	-----	. 06	-----	8. 46	-----	10. 32	5. 16	4. 53	9. 06	18. 87
CO ₂ est-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total-----	. 24	1. 77	1. 14	. 48	17. 00	38. 07	38. 06	22. 05	21. 70	19. 06	-----	118. 87
Less HO _{1/2} -----	. 03	-----	-----	. 06	-----	8. 46	-----	10. 32	5. 16	4. 53	-----	18. 87
Total-----	. 21	1. 77	1. 14	. 42	17. 00	29. 61	38. 06	11. 73	16. 54	14. 53	-----	100. 00
Less HO _{1/2} +CO ₂ -----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
V-----	20. 45	18. 67	14. 84	17. 34	20. 01	20. 31	22. 63	21. 00	-----	-----	-----	Total
Volume proportions-----	4. 3	33. 0	16. 9	7. 3	340. 2	601. 4	861. 3	246. 3	-----	-----	-----	2, 110. 7
Volume percent-----	. 20	1. 56	. 80	. 35	16. 12	28. 49	40. 81	11. 67	-----	-----	-----	100. 00

C. CHLORITE FORMULA

[Formula values: $n=6.31$; $p=1.28$; $2(n-2)=8.62$]

D. ROCK FORMULA, MODIFIED STANDARD CELL

APPENDIX L. CALCULATED ROCK ANALYSES

In this appendix are assembled all the calculated ideal rock analyses (tables 58 to 67) used in figures 24 to 33 in the section on "Mechanism of steatitization." The calculations are based upon assumed volume percentages of minerals, and assumed mineral compositions. The assumed mineral mode, in each case, is based upon many actual modes of similar rock and upon other

available information, and the mineral compositions are based upon all information available (see appropriate sections under "Petrography") upon the composition of the given mineral in similar rocks from the same localities. Calculation of a chemical analysis from the mode is essentially the reverse of calculating the mode from an analysis. Using table 58 as an example, the procedure is as follows:

TABLE 58.—*Calculated analysis of nonalbitic schist, CA-1*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Muscovite	Quartz	Sphene	Ilmenite	Apatite	Calcite	Pyrite
Volume percent.....	45.77	29.79	1.96	0.50	0.51	0.49	0.49
V_{a}	20.31	22.63	18.67	16.14	20.45	18.42	23.90
Equivalent molecular numbers.....	2.2536	1.3164	.1050	.0310	.0249	.0266	.0205
Equivalent molecular percent.....	46.27	27.03	2.16	.64	.51	.54	.42
SiO ₂	19.83	27.03	0.72				
AlO _{3/2}	19.83						
FeO _{3/2}							0.42
FeO.....				.32			
MgO.....							
CaO.....			.72		.32	.27	
NaO _{1/2}							
KO _{1/2}	6.61						
HO _{1/2} +.....	13.22				.06		
TiO ₂			.72	.32			
CO ₂						.27	
PO _{4/2}					.19		
S.....							.84
C.....							
Sum.....							
Less O for S.....							
Total.....	59.49	27.03	2.16	0.64	0.57	0.54	1.26
Less HO _{1/2} +S.....	13.22				.06		.84
Total.....	46.27	27.03	2.16	0.64	0.51	0.54	0.42
Less HO _{1/2} +CO ₂ +C.....							
O.....							
Oeq.....							
Cations.....							
O.....							
W_{100}							
Density (calculated).....							
V_{100}							
$F_{rk} = V_{MSC}/V_{100}$							

TABLE 58.—*Calculated analysis of nonalbitic schist, CA-1—Continued.*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES—Continued

	Graphite	Chlorite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent	0.99	19.50	100.00				
V _s	5.34	21.51					
Equivalent molecular numbers	.1854	.9066	4.8700				
Equivalent molecular percent	3.82	18.61	100.00				
SiO ₂		4.84	52.42	104.84	52.71	3,148.3	54.86
AlO _{3/2}		4.47	24.30	36.45	24.44	1,238.6	21.58
FeO _{3/2}		.74	1.16	1.74	1.17	92.6	1.61
FeO		2.59	2.91	2.91	2.93	209.1	3.64
MgO		5.97	5.97	5.97	6.00	240.7	4.19
CaO			1.31	1.31	1.32	73.5	1.28
NaO _{1/2}			.00	.00	.00	.0	.00
KO _{1/2}			6.61	3.31	6.65	311.3	5.43
HO _{1/2} +		14.89	28.17	14.09	28.33	253.8	4.42
TiO ₂			1.04	2.08	1.05	83.1	1.45
CO ₂			.27	.54	.27	11.9	.21
PO _{3/2}			.19	.48	.19	13.5	.24
S			.84	.84	.84	26.9	.47
C	3.82		3.82	1.91	3.84	45.9	.80
Sum				176.47		5,749.2	100.18
Less O for S				.63		10.1	.18
Total	3.82	33.50	129.01	175.84		5,739.1	100.0
Less HO _{1/2} +S		14.89	29.01	14.93			
Total	3.82	18.61	100.00	160.91			
Less HO _{1/2} +CO ₂ +C				16.54			
O				144.37			
Oeq					176.82		
Cations					100.56		
O					145.18		
W ₁₀₀							5,739.1
Density (calculated)							2.795
V ₁₀₀							2,053.3
F _{rk} = V _{MSC} /V ₁₀₀							1.0056

B. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[K_{.65} Na_{.00} Ca_{1.32} Mg_{6.00} Fe^{+2}_{2.93} Al_{24.44} Fe^{+3}_{1.17} Ti_{1.05} Si_{52.71} P_{.19} S_{.84} C_{3.84} O_{145.18} (OH)_{28.33} (CO_2)_{.27} \right] \begin{matrix} \text{Cations} = 100.56 \\ \text{Oeq} = 176.82 \end{matrix}$$

TALC-BEARING ROCKS IN NORTH-CENTRAL VERMONT

TABLE 59.—*Calculated analysis of talc-carbonate rock, CA-2*

[After samples W-89 and W-71, analyses 22 and 1, table 3]

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Samples W-89 and W-71			Sample CA-2								
	Talc-carbonate rock (W-89)	Carbonate ¹ (W-71)	Total	Talc	Carbonate	Pyrrhotite	Apatite	Other	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent	66.00	34.00	100.00									
V _e	19.17	13.91										
Equivalent molecular numbers	3.44288	2.44428	5.88716									
Equivalent molecular percent	58.48	41.52	100.00									
Density	2.88	3.24										
SiO ₂	31.55		31.55	31.55					63.10	38.34	1,894.9	37.17
AlO _{3/2}	1.01		1.01	1.01					1.52	1.23	51.5	1.01
FeO _{3/2}	.73		.73	.01		0.72			1.10	.89	58.3	1.14
FeO	1.83	3.40	5.23	1.79	3.44				5.23	6.36	375.8	7.37
MgO	22.78	16.95	39.73	22.63	17.10				39.73	48.28	1,601.9	31.43
CaO	.09	.13	.22		.20		0.02		.22	.27	12.3	.24
NaO _{1/2}	.12		.12					0.12	.06	.15	3.7	.07
KO _{1/2}	.05		.05					.05	.03	.06	2.4	.05
HO _{1/2} +	15.77		15.77	15.77					7.88	19.16	142.1	2.79
TiO ₂	.01		.01	.01					.02	.01	.8	.02
CO ₂	.28	20.76	21.04		21.04				42.08	25.57	92.6	18.17
PO _{5/2}	.01		.01				.01		.03	.01	.7	.01
S	.72		.72			.72			.72	.87	23.1	.45
MnO	.03	.27	.30		.30				.30	.36	21.3	.42
Sum									162.02		5,114.8	100.34
O for S									1.08		17.3	.34
Total	74.98	41.51	116.49	72.77	42.08	1.44	0.03	0.17	160.94		5,097.5	100.00
Less HO _{1/2} +S	16.49		16.49	15.77		.72			8.60			
Total	58.49	41.51	100.00	57.00	42.08	0.72	0.03	0.17	152.34			
Less HO _{1/2} +CO ₂									49.96			
O									102.38			
V _e				19.21	13.91	18.43	20.45	20.00				
Volume proportions			1,697.6	1,095.0	585.3	13.3	.6	3.4				
Volume percent			100.00	64.50	34.48	.78	.04	.20				
Oeq										195.57		
Cations										121.52		
O										124.41		
W ₁₀₀												5,097.5
Density												3.000
V ₁₀₀												1,699.2
F _{rk} = V _{MSC} /V ₁₀₀												1.2152

¹ Assumed composition: (Ca_{.006}Mg_{.316}Fe⁺²_{.144}Mn_{.018})CO₃.

B. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[\text{K}_{.06}\text{Na}_{.15}\text{Ca}_{.27}\text{Mg}_{48.23}\text{Fe}^{+2}_{.36}\text{Mn}_{.36}\text{Al}_{1.23}\text{Fe}^{+3}_{.89}\text{Ti}_{.01}\text{Si}_{38.34}\text{P}_{.01}\text{S}_{.87}\text{O}_{124.41}(\text{OH})_{19.16}(\text{CO}_2)_{25.57} \right] \begin{matrix} \text{Cations} = 121.52 \\ \text{Oeq} = 195.57 \end{matrix}$$

TABLE 60.—*Calculated analysis of steatite, CA-3*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Talc	Apatite	Magnetite	Pyrite	Other ¹	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	99.90	0.03	0.02	0.01	0.04	100.00				
V.....	19.21	20.45	14.84	23.90	20.00					
Equivalent molecular numbers.....	5.20042	.00147	.00135	.00042	.00200	5.20566				
Equivalent molecular percent.....	99.900	.028	.026	.008	.038	100.000				
SiO ₂	56.50					56.50	113.00	60.29	3,393.4	62.16
AlO _{3/2}	.86					.86	1.29	.92	43.8	.80
FeO _{3/2}			0.017	0.008		.03	.05	.03	2.4	.04
FeO.....	.78		.009			.79	.79	.84	56.8	1.04
MgO.....	41.23					41.23	41.23	43.99	1,662.4	30.45
CaO.....		0.018				.02	.02	.02	1.1	.02
NaO _{1/2}						.00	.00	.00	.0	.00
KO _{1/2}					0.038	.04	.02	.04	1.9	.04
HO _{1/2} +.....	28.53	.004				28.53	14.26	30.44	257.0	4.71
TiO ₂	.01					.01	.02	.01	.8	.02
CO ₂						.00	.00	.00	.0	.00
PO _{5/2}		.010				.01	.03	.01	.7	.01
S.....				.016		.02	.02	.02	.6	.01
CrO _{3/2}	.23					.23	.35	.25	17.5	.32
NiO.....	.14					.14	.14	.15	10.5	.19
MnO.....	.14					.14	.14	.15	9.9	.18
CoO.....	.01					.01	.01	.01	.7	.01
Sum.....							171.37		5,459.5	100.00
O for S.....							.02		.2	.00
Total.....	128.43	0.032	0.026	0.024	0.038	128.56	171.35		5,459.3	100.00
Less HO _{1/2} +S.....	28.53	.004		.016		28.56	14.28			
Total.....	99.90	0.028	0.026	0.008	0.038	100.00	157.07			
Less HO _{1/2}							14.26			
O.....							142.81			
Oeq.....								182.83		
Cations.....								106.70		
O.....								152.38		
W ₁₀₀										5,459.3
Density.....										2.821
V ₁₀₀										1,935.2
F _{rk} =V _{MSC} /V ₁₀₀										1.0670

¹ Equal KO_{1/2}, which is present in ultramafic rocks in about 0.04 percent, but in what mineral is not known.

B. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 61.—*Calculated analysis of talc-carbonate rock, CA-4.*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Stentite and carbonate			Talc-carbonate rock, CA-4:								
	Stentite CA-3	Carbonate ¹	Total	Talc	Carbon- ate	Pyrrho- tite	Apatite	Other	Oeq.	Formula numbers in MSC	Weight pro- portions	Weight percent
Volume percent	60.00	40.00	100.00									
V	19.35	13.72										
Equivalent molecular numbers	3.10078	2.91545	6.01623									
Equivalent molecular percent	51.54	48.46	100.00									
Density	2.821	3.10										
SiO ₂	29.12		29.12	29.12					58.24	36.13	1,748.9	35.83
AlO _{3/2}	.44		.44	.44					.66	.55	22.4	.46
FeO _{3/2}	.02		.02	.01		0.01			.03	.02	1.6	.03
FeO	.41	0.56	.97	.41	0.56				.97	1.20	69.7	1.43
MgO	21.25	23.47	44.72	21.25	23.47				44.72	55.49	1,803.1	36.94
CaO	.01		.01				0.01		.01	.01	.6	.01
NaO _{1/2}			.00						.00	.00	.0	.00
KO _{1/2}	.02		.02					0.02	.01	.02	.9	.02
H ₂ O _{1/2} +	14.70		14.70	14.70					7.35	18.24	132.4	2.71
TiO ₂	.01		.01	.01					.02	.01	.8	.02
CO ₂		24.23	24.23		24.23				48.46	30.06	1,066.4	21.85
PO _{5/2}	.01		.01				.01		.03	.01	.7	.01
S	.01		.01			.01			.01	.01	.3	.01
CrO _{3/2}	.12		.12	.12					.18	.15	9.1	.19
NiO	.07	.06	.13	.07	.06				.13	.16	9.7	.20
MnO	.05	.14	.19	.05	.14				.19	.24	13.5	.28
ClO	.01	.00	.01	.01					.01	.01	.7	.01
Sum									161.02		4,880.8	100.00
Less O for S									.01		.1	.00
Total	66.25	48.46	114.71	66.19	48.46	0.02	0.02	0.02	161.01		4,880.7	100.00
Less H ₂ O _{1/2} + S	14.71		14.71	14.70		.01			7.36			
Total	51.54	48.46	100.00	51.49	48.46	0.01	0.02	0.02	153.65			
Less H ₂ O _{1/2} + CO ₂									55.81			
O									97.84			
V				19.35	13.72	23.90	20.45	20.00				
Volume proportions			1,662.25	996.33	664.87	.24	.41	.40				
Volume percent			100.00	59.94	40.00	.01	.03	.02				
Oeq									199.78			
Cations									124.08			
O									121.40			

W_{100}	4,880.7
Density	2.933
V_{100}	1,664.1
$F_{1.1} = V_{MSC}/V_{100}$	1.2408

¹ Assumed composition: (Mg_{0.007}Fe⁺²_{0.021}Mn_{0.003}Ni_{0.022}Cr_{0.0004})CO₂

B. ROCK FORMULA, MODIFIED STANDARD CELL

$[K_{.02}Na_{.06}Ca_{.01}Mg_{55.40}Fe^{+2}_{1.20}Mn_{.24}Ni_{.16}Co_{.01}Al_{.55}Fe^{+3}_{.02}Cr_{.15}Ti_{.01}Si_{66.13}P_{.01}S_{.01}O_{121.40}(OH)_{18.24}(CO_2)_{30.06}]$	Cations=124.08
	Oeq=199.78

TABLE 62.—*Calculated analysis of graphitic albite schist, CA-5, after W-DDH-11-60*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Quartz	Saiteite	Albite	Chlorite	Biotite	Garnet	Carbonate	Apatite	Epidote
Volume percent.....	39.60	27.65	15.43	7.97	3.57	2.00	0.20	0.30	0.20
V_c	22.63	20.31	20.01	21.63	18.88	14.40	18.42	20.45	17.34
Equivalent molecular numbers.....	1.7499	1.3614	.7711	.3685	.1891	.1389	.0109	.0147	.0115
Equivalent molecular percent.....	35.13	27.33	15.48	7.40	3.80	2.79	.22	.29	.23
Density.....	2.654	2.80	2.62	2.967	3.12	4.25	2.717	3.18	3.0
SiO ₂	35.13	11.71	9.29	2.00	1.28	1.05			0.09
AlO _{3/2}		11.71	3.09	1.85	.70	.70			.07
FeO _{3/2}				.08	.05				.02
FeO.....				1.80	.70	.89			
MgO.....				1.54	.52	.08			
CaO.....						.02	0.11	0.18	.05
NaO _{1/2}			3.10						
KO _{1/2}		3.91			.48				
HO _{1/2} +.....		7.81		5.92	.95			.04	.03
TiO ₂									
CO ₂							.11		
PO _{5/2}								.11	
S.....									
CrO _{3/2}					.01	.01			
NiO.....				.02					
MnO.....				.10	.06	.04			
CoO.....				.01					
AsO _{3/2}									
C.....									
Sum.....									
O for S and As.....									
Total.....	35.13	35.14	15.48	13.32	4.75	2.79	0.22	0.33	0.26
Less HO _{1/2} +S+ As.....		7.81		5.92	.95			.04	.03
Total.....	35.13	27.33	15.48	7.40	3.80	2.79	0.22	0.29	0.23

TABLE 62.—*Calculated analysis of graphitic albitic schist, CA-5, after W-DDH-11-60—Continued*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES—Continued

	Sphene	Ilmenite	Pyrite	Graphite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	0.85	0.43	0.30	1.50	100.00				
V.....	18.67	16.14	23.90	5.34					
Equivalent molecular numbers.....	.0455	.0266	.0126	.2809	4.9816				
Equivalent molecular percent.....	.91	.53	.25	5.64	100.00				
Density.....	3.50	4.70	5.02	2.25					
SiO ₂	0.31				60.86	121.72	62.61	3,655.25	65.44
AlO _{3/2}					18.12	27.18	18.64	923.58	16.53
FeO _{3/2}			0.25		.40	.60	.41	31.94	.57
FeO.....		0.26			3.65	3.65	3.75	262.25	4.69
MgO.....					2.14	2.14	2.20	86.28	1.54
CaO.....	.30				.66	.66	.68	37.01	.66
NaO _{1/2}					3.10	1.55	3.19	96.09	1.72
KO _{1/2}					4.39	2.20	4.52	206.75	3.70
HO _{1/2} +					14.75	7.37	15.17	132.87	2.38
TiO ₂	.30	.27			.57	1.14	.59	45.54	.82
CO ₂					.11	.22	.11	4.84	.09
PO _{5/2}					.11	.28	.11	7.81	.14
S.....			.50		.50	.50	.51	16.03	.29
CrO _{3/2}					.02	.03	.02	1.52	.03
NiO.....					.02	.02	.02	1.49	.03
MnO.....					.20	.20	.21	14.19	.25
CoO.....					.01	.01	.01	.75	.01
AsO _{3/2}					.00	.00	.00	.00	.00
C.....				5.64	5.64	2.82	5.80	67.74	1.21
Sum.....						172.29		5,591.93	100.10
O for S and As.....						.38		6.00	.11
Total.....	0.91	0.53	0.75	5.64	115.25	171.91		5,585.93	99.99
Less HO _{1/2} + S + As.....			.50		15.25	7.87			
Total.....	0.91	0.53	0.25	5.64	100.00	164.04			
Less HO _{1/2} + CO ₂ + C.....						10.41			
O.....						153.63			
Oeq.....							176.84		
Cations.....							102.87		
O.....							158.04		
W ₁₀₀									5,585.93
Density.....									2.783
V ₁₀₀									2,007.2
F _{rk} = V _{MSC} /V ₁₀₀									1.0287

B. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[K_{4.52} Na_{2.19} Ca_{.68} Mg_{2.20} Fe^{+2}_{3.75} Mn_{.21} Ni_{.02} Co_{.01} Al_{18.64} Fe^{+3}_{.41} Cr_{.02} Ti_{.59} Si_{62.61} P_{.11} S_{.51} As_{.06} C_{5.80} O_{158.04} (OH)_{15.17} (CO_2)_{.11} \right] \begin{matrix} \text{Cations} = 102.87 \\ \text{Oeq} = 176.84 \end{matrix}$$

TABLE 63.—*Calculated analysis of albite porphyroblast rock, CA-6*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Quartz	Sericite	Albite	Chlorite	Biotite	Garnet	Carbonate	Apatite	Epidote	Sphene
Volume percent.....	8.08	4.95	62.45	6.05	12.90	0.96	0.14	0.30	0.10	0.88
V_e	22.63	20.31	20.01	21.63	18.88	14.40	18.42	20.45	17.34	18.67
Equivalent molecular numbers.....	.3570	.2437	3.1209	.2797	.6833	.0667	.0776	.0147	.0058	.0471
Equivalent molecular percent.....	6.70	4.57	58.54	5.25	12.82	1.25	.14	.28	.11	.88
Density.....	2.654	2.80	2.62	2.967	3.12	4.25	2.717	3.18	3.40	3.50
SiO ₂	6.70	1.96	35.12	1.42	4.32	0.47	-----	-----	0.04	0.29
AlO _{3/2}	-----	1.96	11.71	1.32	2.46	.31	-----	-----	.03	-----
FeO _{3/2}	-----	-----	-----	.06	.08	-----	-----	-----	.01	-----
FeO.....	-----	-----	-----	1.26	2.48	.43	-----	-----	-----	-----
MgO.....	-----	-----	-----	1.08	1.76	.02	-----	-----	-----	-----
CaO.....	-----	-----	-----	-----	-----	-----	0.07	0.18	.03	.29
NaO _{1/2}	-----	-----	11.71	-----	-----	-----	-----	-----	-----	-----
KO _{1/2}	-----	.65	-----	-----	1.60	-----	-----	-----	-----	-----
HO _{1/2} +.....	-----	1.31	-----	4.18	3.20	-----	-----	.04	.01	-----
TiO ₂	-----	-----	-----	-----	-----	-----	-----	-----	-----	.30
CO ₂	-----	-----	-----	-----	-----	-----	.07	-----	-----	-----
PO _{5/2}	-----	-----	-----	-----	-----	-----	-----	.10	-----	-----
S.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
CrO _{3/2}	-----	-----	-----	-----	.02	-----	-----	-----	-----	-----
NiO.....	-----	-----	-----	.02	-----	-----	-----	-----	-----	-----
MnO.....	-----	-----	-----	.08	.10	.02	-----	-----	-----	-----
CoO.....	-----	-----	-----	.01	-----	-----	-----	-----	-----	-----
AsO _{3/2}	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
C.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Sum.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
O for S and As.....	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Total.....	6.70	5.88	58.54	9.43	16.02	1.25	0.14	0.32	0.12	0.88
Less HO _{1/2} +S+As.....	-----	1.31	-----	4.18	3.20	-----	-----	.04	.01	-----
Total.....	6.70	4.57	58.54	5.25	12.82	1.25	0.14	0.28	0.11	0.88

TABLE 63.—*Calculated analysis of albite porphyroblast rock, CA-6—Continued*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES—Continued

	Rutile	Ilmenite	Pyrite	Graphite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	0.02	0.37	0.30	2.50	100.00				
V.....	19.02	16.14	23.90	5.34					
Equivalent molecular numbers.....	.0011	.0229	.0125	.4682	5.3312				
Equivalent molecular percent.....	.02	.43	.23	8.78	100.00				
Density.....	4.20	4.70	5.02	2.25					
SiO ₂					50.32	100.64	55.41	3,022.22	58.63
AlO _{3/2}					17.79	26.69	19.59	906.76	17.59
FeO _{3/2}			0.23		.38	.59	.42	30.34	.59
FeO.....		0.21			4.38	4.38	4.32	314.70	6.10
MgO.....					2.86	2.86	3.15	115.32	2.24
CaO.....					.57	.57	.63	31.97	.62
NaO _{1/2}					11.71	5.85	12.39	362.97	7.04
KO _{1/2}					2.25	1.12	2.48	105.97	2.05
H ₂ O _{1/2}					8.74	4.37	9.62	78.73	1.53
ThO ₂	0.02	.22			.54	1.08	.59	48.15	.84
CO ₂					.07	.14	.08	3.08	.06
PO _{5/2}					.10	.25	.11	7.10	.14
S.....			.45		.46	.45	.51	14.75	.29
CrO _{3/2}					.02	.03	.02	1.52	.03
NiO.....					.02	.02	.02	1.49	.03
MnO.....					.20	.20	.22	14.19	.28
CuO.....					.01	.01	.01	.75	.01
AsO _{3/2}					.00	.00	.00	.00	.00
C.....				8.78	8.78	4.39	9.67	105.45	2.04
Sum.....						153.65		5,160.46	100.11
O for S and As.....						.35		5.52	.11
Total.....	0.02	0.43	0.69	8.78	109.20	153.30		5,154.94	100.00
Less HO _{1/2} + S + As.....			.46		9.20	4.83			
Total.....	0.02	0.43	0.23	8.78	100.00	148.47			
Less HO _{1/2} + CO ₂ + C.....						8.90			
O.....						139.57			
Oeq.....							168.80		
Cations.....							110.11		
O.....							153.68		
W ₁₀₀									5,155.56
Density.....									2.749
V ₁₀₀									1,875.2
F _{rk} = V _{MSC} /V ₁₀₀									1.1011

B. ROCK FORMULA, MODIFIED STANDARD CELL

$\left[K_{2.48}Na_{12.89}Ca_{.63}Mg_{.15}Fe^{+2}_{4.82}Mn_{.22}Ni_{.02}Co_{.01}Al_{19.59}Fe^{+3}_{.42}Cr_{.02}Ti_{.59}Si_{55.41}P_{.11}S_{.51}As_{.00}C_{9.27}O_{153.68}(OH)_{9.62}(CO_2)_{.08} \right]$	Cations=110.11
	Oeq=168.80

TABLE 64.—*Calculated analysis of blackwall chlorite rock, CA-7*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Chlorite	Sphene	Rutile	Pyrite	Apatite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	97.18	2.19	0.10	0.30	0.23	100.00				
V_c	21.00	18.67	19.02	23.90	20.45					
Equivalent molecular numbers.....	4.6276	.1173	.0053	.0126	.0112	4.7740				
Equivalent molecular percent.....	96.93	2.46	.11	.26	.24	100.00				
Density.....	2.831	3.50	4.20	5.02	3.18					
SiO ₂	26.17	0.82				26.99	53.98	26.60	1,621.02	27.11
AlO _{3/2}	25.04					25.04	37.56	24.68	1,276.29	21.35
FeO _{3/2}	.14			0.26		.40	.60	.39	31.94	.53
FeO.....	11.38					11.38	11.38	11.22	817.65	13.67
MgO.....	33.90					33.90	33.90	33.41	1,366.85	22.86
CaO.....		.82			0.15	.97	.97	.96	54.40	.91
NaO _{1/2}	.01					.01	.01	.01	.31	.01
KO _{1/2}	.02					.02	.01	.02	.94	.02
HO _{1/2} +.....	77.54				.03	77.57	38.78	76.45	698.75	11.69
TiO ₂	.01	.82	0.11			.94	1.88	.93	75.11	1.26
CO ₂						.00	.00	.00	.00	.00
PO _{5/2}					.09	.09	.23	.09	6.39	.11
S.....				.52		.52	.52	.51	16.67	.28
CrO _{3/2}	.02					.02	.03	.02	1.52	.02
NiO.....	.02					.02	.02	.02	1.49	.02
MnO.....	.21					.21	.21	.21	14.90	.25
CoO.....	.01					.01	.01	.01	.75	.01
AsO _{3/2}						.00	.00	.00	.00	.00
C.....						.00	.00	.00	.00	.00
Sum.....							180.09		5,984.98	100.10
O for S and As.....							.39		6.23	.10
Total.....	174.47	2.46	0.11	0.78	0.27	178.09	179.70		5,978.75	100.00
HO _{1/2} +S+As.....	77.54			.52	.03	78.09	39.30			
Total.....	96.93	2.46	0.11	0.26	0.24	100.00	140.40			
Less HO _{1/2} +CO ₂ +C.....							38.78			
O.....							101.62			
Oeq.....								177.31		
Cations.....								98.56		
O.....								100.16		
W_{100}									5,978.75	
Density.....									2.854	
V_{100}									2,094.86	
$F_{rk} = V_{MSC}/V_{100}$									0.9856	

B. ROCK FORMULA, MODIFIED STANDARD CELL

TABLE 65.—*Calculated analysis of steatite, CA-8*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Talc	Magnetite	Pyrite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	99.92	0.02	0.06	100.00				
V.....	19.58	14.84	23.90					
Equivalent molecular numbers.....	5.1032	.0013	.0025	5.1070				
Equivalent molecular percent.....	99.92	.03	.05	100.00				
Density.....	2.835	5.20	5.02					
SiO ₂	56.50			56.50	113.00	60.04	3,393.39	61.56
AlO _{3/2}	.85			.85	1.28	.90	43.32	.79
FeO _{3/2}	.11	0.02	0.05	.18	.24	.19	14.37	.26
FeO.....	2.31	.01		2.32	2.32	2.47	166.69	3.02
MgO.....	39.68			39.68	39.68	42.17	1,599.90	29.03
CaO.....				.00	.00	.00	.00	.00
NaO _{1/2}				.00	.00	.00	.00	.00
KO _{1/2}				.00	.00	.00	.00	.00
HO _{1/2} +.....	28.54			28.54	14.27	30.33	257.09	4.66
TiO ₂	.015			.015	.03	.00	1.20	.02
CO ₂				.00	.00	.00	.00	.00
PO _{5/2}	.02			.02	.05	.02	1.42	.03
S.....			.10	.10	.10	.11	3.21	.06
CrO _{3/2}	.19			.19	.29	.20	14.44	.26
NiO.....	.16			.16	.16	.17	11.95	.22
MnO.....	.07			.07	.07	.07	4.97	.09
CoO.....	.015			.015	.02	.02	1.12	.02
AsO _{3/2}			.0023	.0023	.00	.002	.23	.004
C.....				.00	.00	.00	.00	.00
Sum.....					171.51		5,513.30	100.02
O for S and As.....					.08		1.20	.02
Total.....	128.46	0.03	0.15	128.64	171.43		5,512.10	100.00
Less HO _{1/2} + S + As.....	28.54		.10	28.64	14.37			
Total.....	99.92	0.03	0.05	100.00	157.06			
Less HO _{1/2} + CO ₂ + C.....					14.27			
O.....					142.79			
Oeq.....						182.18		
Cations.....						106.27		
O.....						151.74		
W ₁₀₀								5,512.36
Density.....								2.837
V ₁₀₀								1,943.02
F _{rk} = V _{MSC} /V ₁₀₀								1.0627

B. ROCK FORMULA, MODIFIED STANDARD CELL

[K _{.00} Na _{.00} Ca _{.00} Mg _{42.17} Fe ⁺² _{2.47} Mn _{.07} Ni _{.16} Co _{.02} Al _{.90} Fe ⁺³ _{.19} Cr _{.20} Ti _{.02} Si _{60.04} P _{.02} S _{.11} As _{.002} C _{.00} O _{151.74} (OH) _{30.33} (CO ₂) _{.00}]	Cations=106.27
	Oeq=182.18

TABLE 66.—*Calculated analysis of talc-carbonate rock, CA-9*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Talc	Carbonate	Magnetite	Pyrrhotite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	61. 55	38. 32	0. 03	0. 10	100. 00				
V_e	19. 58	13. 91	14. 84	18. 43					
Equivalent molecular numbers.....	3. 1435	2. 7549	. 0020	. 0054	5. 9058				
Equivalent molecular percent.....	53. 23	46. 65	. 03	. 09	100. 00				
Density.....	2. 83	3. 21	5. 20	4. 77					
SiO ₂	30. 08				30. 08	60. 16	36. 83	1, 806. 60	35. 98
AlO _{3/2}	. 42				. 42	. 63	. 51	21. 41	. 43
FeO _{3/2}	. 30		0. 02	0. 09	. 41	. 61	. 50	32. 74	. 65
FeO.....	1. 00	3. 15	. 01		4. 16	4. 16	5. 13	298. 90	5. 96
MgO.....	21. 17	19. 86			41. 03	41. 03	50. 24	1, 654. 33	32. 95
CaO.....					. 00	. 00	. 00	. 00	. 00
NaO _{1/2}					. 00	. 00	. 00	. 00	. 00
KO _{1/2}					. 00	. 00	. 00	. 00	. 00
HO _{1/2} +.....	15. 20				15. 20	7. 60	18. 61	136. 92	2. 73
TiO ₂	. 01				. 01	. 02	. 01	. 80	. 02
CO ₂		23. 32			23. 32	46. 64	28. 56	1, 026. 31	20. 45
PO _{5/2}	. 01				. 01	. 03	. 01	. 71	. 01
S.....				. 09	. 09	. 09	. 11	2. 89	. 06
CrO _{3/2}	. 10	. 02			. 12	. 18	. 12	9. 12	. 18
NiO ₂	. 12	. 02			. 14	. 14	. 17	10. 46	. 21
MnO.....	. 02	. 27			. 29	. 29	. 36	20. 57	. 41
CoO.....		. 01			. 01	. 01	. 01	. 75	. 01
AsO _{3/2}				. 0023	. 0023	. 00	. 003	. 23	. 0046
C.....					. 00	. 00	. 00	. 00	. 00
Sum.....						161. 59		5, 022. 74	100. 05
Less O for S and As.....						. 14		2. 16	. 05
Total.....	68. 43	46. 65	0. 03	0. 18	115. 29	161. 45		5, 020. 58	100. 00
Less HO _{1/2} +S+As.....	15. 20			. 09	15. 29	7. 69			
Total.....	53. 23	46. 65	0. 03	0. 09	100. 00	153. 76			
Less HO _{1/2} +CO ₂ +C.....						54. 24			
O.....						99. 52			
Oeq.....							197. 71		
Cations.....							122. 45		
O.....							121. 87		
W_{100}									5, 020. 58
Density.....									2. 978
V_{100}									1, 685. 9
$F_{rk} = V_{MSC}/V_{100}$									1. 2247

B. ROCK FORMULA, MODIFIED STANDARD CELL

$$\left[K_{.00}Na_{.00}Ca_{.00}Mg_{50.24}Fe^{+2}_{5.13}Mn_{.36}Ni_{.17}Co_{.01}Al_{.51}Fe^{+3}_{.50}Cr_{.12}Ti_{.01}Si_{36.83}P_{.01}S_{.11}As_{.003}C_{.00}O_{121.87}(OH)_{18.61}(CO_2)_{28.56} \right] \begin{matrix} \text{Cations} = 122.46 \\ \text{Oeq} = 197.71 \end{matrix}$$

TABLE 67.—*Calculated analysis of serpentinite, CA-10*

A. CALCULATION OF FORMULA NUMBERS AND WEIGHT PERCENTAGES

	Serpentine	Magnetite	Pyrrhotite	Total	Oeq	Formula numbers in MSC	Weight proportions	Weight percent
Volume percent.....	97.34	2.56	0.10					
V_e	21.81	14.70	18.43					
Equivalent molecular numbers.....	4.4631	.1741	.0054	4.6426				
Equivalent molecular percent.....	96.13	3.75	.12					
Density.....	2.61	4.94	4.77					
SiO ₂	38.43			38.43	76.86	36.83	2,308.11	40.09
AlO _{3/2}	1.49	0.18		1.67	2.51	1.60	85.12	1.48
FeO _{3/2}	.04	1.98	0.12	2.14	3.21	2.05	170.88	2.97
FeO.....	3.83	.87		4.70	4.70	4.50	337.70	5.87
MgO.....	52.09	.34		52.43	52.43	50.24	2,113.98	36.72
CaO.....				.00	.00	.00	.00	.00
NaO _{1/2}				.00	.00	.00	.00	.00
KO _{1/2}				.00	.00	.00	.00	.00
HO _{1/2} +.....	76.90			76.90	38.45	73.69	692.72	12.03
TiO ₂	.01			.01	.02	.01	.80	.01
CO ₂				.00	.00	.00	.00	.00
PO _{5/2}	.02			.02	.05	.02	1.42	.02
S.....			.12	.12	.12	.11	3.85	.07
CrO _{3/2}	.01	.34		.35	.53	.34	26.60	.46
NiO.....	.18			.18	.18	.17	13.44	.23
MnO.....	.02	.04		.06	.06	.06	4.26	.07
CoO.....	.01			.01	.01	.01	.75	.01
AsO _{3/2}			.0023	.0023	.00	.002	.23	.003
C.....				.00	.00	.00	.00	.00
Sum.....					179.13		5,759.86	100.05
Less O for S and As.....					.18		2.88	.05
Total.....	173.03	3.75	0.24	177.02	178.95		5,756.98	100.00
Less HO _{1/2} +S+As.....	76.90		.12	77.02	38.57			
Total.....	96.13	3.75	0.12	100.00	140.38			
Less HO _{1/2} +CO ₂ +C.....					38.45			
O.....					101.93			
Oeq.....						171.49		
Cations.....						95.83		
O.....						97.68		
W_{100}								5,756.98
Density.....								2.672
V_{100}								2,154.56
$F_{rk} = V_{MSC}/V_{100}$								0.9583

B. ROCK FORMULA, MODIFIED STANDARD CELL

$[K_{.00}Na_{.00}Ca_{.00}Mg_{.50.24}Fe^{+2}_{4.50}Mn_{.06}Ni_{.17}Co_{.01}Al_{1.60}Fe^{+3}_{2.05}Cr_{.34}Ti_{.01}Si_{36.83}P_{.02}S_{.11}As_{.002}C_{.00}O_{97.68}(OH)_{73.69}(CO_2)_{.00}]$	Cations=95.83
	Oeq=171.49

The volume percentage of each mineral ("Volume percent" stub entry) is divided by the equivalent volume (" V_e " entry) appropriate to the assumed composition of each mineral. The quotients ("Equivalent molecular numbers" entry) are reduced to equivalent molecular percent by dividing by the sum of the quotients. The total equivalent molecular percentage of each mineral is then apportioned among the oxides in accordance with the assumed composition. For example, muscovite constitutes 46.27 equivalent molecular percent of the rock and has the formula $KAl_3Si_3O_{10}(OH)_2$, for which the metal ions total 7. Therefore, for SiO₂ under the muscovite column we write the product of 3/7

$\times 46.27 = 19.83$; for KO_{1/2} write $1/7 \times 46.27 = 6.61$; for AlO_{3/2} write $3/7 \times 46.27 = 19.83$; and for OH, $2/7 \times 46.27 = 13.22$. The remaining minerals are treated analogously. The totals for each oxide in all the minerals then yield the calculated chemical analysis in equivalent molecular percent.

These data are readily converted to the modified standard cell formula by procedures described in appendix B. The figures in the "Weight proportions" column, which represent a step in the calculation of the modified standard cell, are reduced to a total of 100 to obtain the calculated analysis in terms of weight percent. The density is calculated either by dividing the

total in "Weight proportions" column by the sum of the products obtained by multiplying the "Equivalent molecular percent" and " V_e " entries for each mineral; or, by a weighted average, by summing the products of the volume percentage and the density of each mineral or rock component and dividing by 100—whichever is appropriate.

REFERENCES CITED

- Albee, A. L., 1957, Bedrock geology of the Hyde Park quadrangle, Vermont: U.S. Geol. Survey Geol. Quadrangle Map, GQ-102.
- Axelrod, J. M., and Grimaldi, F. S., 1949, Muscovite with small optic axial angle: *Am. Mineralogist*, v. 34, nos. 7 and 8, p. 559-572.
- Bain, G. W., 1932, Chrysotile asbestos: II, chrysotile solutions: *Econ. Geology*, v. 27, p. 281-296.
- 1934, Serpentinization: origin of certain asbestos, talc and soapstone deposits: *Econ. Geology*, v. 29, p. 397-400.
- 1936, Serpentinization of Vermont ultrabasics: *Geol. Soc. America Bull.*, v. 47, p. 1961-1979.
- Barth, T. F. W., 1936, Structural and petrologic studies in Dutchess County, New York; Part II: Petrology and metamorphism of the Paleozoic rocks: *Geol. Soc. America Bull.*, v. 47, p. 775-850.
- 1948, Oxygen in rocks: a basis for petrographic calculations: *Jour. Geology*, v. 56, no. 1, p. 50-60.
- 1949, The use of oxygen as a reference substance in petrographic calculations: a supplement and a reply: *Jour. Geology*, v. 57, no. 4, p. 425-427.
- 1952, *Theoretical petrology*: 387 p., New York, John Wiley and Sons, Inc.; London, Chapman & Hall, Ltd.
- 1955, Presentation of rock analyses: *Jour. Geology*, v. 63, p. 348-363.
- Bates, T. F., and Mink, J. F., 1950, Morphology and structure of the serpentine minerals antigorite and chrysotile [abs.]: *Geol. Soc. America Bull.*, v. 61, no. 12, pt. 2, p. 1442-1443.
- Benson, W. N., 1918, The origin of serpentine, a historical and comparative study: *Am. Jour. Sci.*, 4th ser., v. 46, p. 693-731.
- 1926, The tectonic conditions accompanying the intrusion of basic and ultrabasic igneous rocks: *Nat. Acad. Sci.*, v. 19, Mem. 1, 90 p.
- Berman, Harry, 1937, Constitution and classification of the natural silicates: *Am. Mineralogist*, v. 22 (Palache volume), p. 342-408.
- Billings, M. P., 1937, Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: *Geol. Soc. America Bull.*, v. 48, p. 463-566.
- 1942, *Structural geology*: 473 p., New York, Prentice-Hall, Inc.
- Billings, M. P., and Chidester, A. H., 1948a, Geologic maps of the Barnes Hill talc prospect, Waterbury, Vermont, Hammondsville talc quarry, Reading, Vermont, and Vermont Talc Company quarry, Windham, Vermont: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Map 3-224.
- 1948b, Geologic maps and structure sections of the Eastern Magnesia Talc Company Waterbury mine, Moretown, Vermont: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Map 3-225.
- 1949, Geologic maps and structure sections of the Carleton talc quarry, Chester, Vermont, Rousseau talc prospect, Cambridge, Vermont, and Mad River talc mine, Fayston, Vermont: U.S. Geol. Survey Strategic Minerals Inv. Prelim. Map 3-227.
- Billings, M. P., Rodgers, John, and Thompson, J. B., Jr., 1952, Geology of the Appalachian Highlands of east-central New York, southern Vermont, and southern New Hampshire: *Geol. Soc. America Guidebook for Field Trips*, 65th Annual Meeting, 48 p.
- Billings, M. P., and White, W. S., 1950, Metamorphosed mafic dikes of the Woodsville quadrangle, Vermont and New Hampshire: *Am. Mineralogist*, v. 35, p. 629-643.
- Booth, V. H., 1950, Stratigraphy and structure of the Oak Hill succession in Vermont: *Geol. Soc. America Bull.*, v. 61, p. 1131-1168.
- Boucot, A. J., Harner, R. S., MacDonald, G., and Milton, C., 1953, Age of the Bernardston formation [abs.]: *Geol. Soc. America Bull.*, v. 64, p. 1397-1398.
- Bowen, N. L., 1915, The later stages of the evolution of the igneous rocks: *Jour. Geology*, v. 23, no. 8, Suppl., 91 p.
- 1917, The problem of the anorthosites: *Jour. Geology*, v. 25, p. 209-243.
- 1927, The origin of ultramafic and related rocks: *Am. Jour. Sci.*, 5th ser., v. 14, p. 89-108.
- 1947, *Magma*: *Geol. Soc. America Bull.*, v. 58, p. 263-279.
- Bowen, N. L., and Schairer, J. F., 1936, The problem of the intrusion of dunite in the light of the olivine diagram: *Internat. Geol. Cong.*, 16th, Washington, 1933, Rept. v. 1, p. 391-396.
- Bowen, N. L., and Tuttle, O. F., 1949, The system $MgO-SiO_2-H_2O$: *Geol. Soc. America Bull.*, v. 60, p. 439-460.
- Brace, W. F., 1953, The geology of the Rutland area, Vermont: *Vermont Geol. Survey Bull.* 6, 120 p.
- Brindley, G. W., 1951, The kaolin minerals, in Brindley, G. W. and others, 1951, p. 32-75.
- 1954, The structural formula of an antigorite from Venezuela: *Am. Mineralogist*, v. 39, p. 391-393.
- Brindley, G. W., and Robinson, K., 1951, The chlorite minerals, in Brindley, G. W. and others, 1951, p. 173-198.
- Brindley, G. W., and others, 1951, X-ray identification and crystal structures of clay minerals: London, England, The Mineralog. Soc.
- Buddington, A. F., 1943, Some petrological concepts and the interior of the earth: *Am. Mineralogist*, v. 28, p. 119-140.
- Burfoot, J. D., Jr., 1930, The origin of the talc and soapstone deposits of Virginia: *Econ. Geology*, v. 25, p. 805-826.
- Cady, W. M., 1945, Stratigraphy and structure of west-central Vermont: *Geol. Soc. America Bull.*, v. 56, p. 515-588.
- 1956, Bedrock geology of the Montpelier quadrangle, Vermont: U.S. Geol. Survey Geol. Quadrangle Map, GQ-79.
- Cady, W. M., Albee, A. L., and Chidester, A. H., 1962?, Bedrock geology and asbestos deposits, Missisquoi Valley, Vermont: U.S. Geol. Survey Bull. 1122-B (in press).
- Chapman, R. W., 1954, Criteria for the mode of emplacement of the alkaline stock at Mount Monadnock, Vermont: *Geol. Soc. America Bull.*, v. 65, p. 97-114.
- Chayes, F., 1949, A simple point counter for thin section analysis: *Am. Mineralogist*, v. 34, p. 1-11.
- 1953, In defense of the second decimal: *Am. Mineralogist*, v. 38, p. 784-793.
- Chidester, A. H., 1951, Diamond drill exploration of the Rousseau talc prospect, Cambridge, Vermont, and the Barnes Hill talc prospect, Waterbury, Vermont: U.S. Geol. Survey open-file report, 25 p.

- Chidester, A. H., 1953, Geology of the talc deposits, Sterling Pond area, Stowe, Vermont: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-11.
- Chidester, A. H., Billings, M. P., and Cady, W. M., 1951, Talc investigations in Vermont, preliminary report: U.S. Geol. Survey Circ. 95, 33 p.
- Chidester, A. H., Stewart, G. W., and Morris, D., 1952, Geologic map of the Barnes Hill talc prospect, Waterbury, Vermont: U.S. Geol. Survey Mineral Inv. Field Studies Map MF-7.
- Clemmer, J. B., and Cooke, S. R. B., 1936, Flotation of Vermont talc-magnesite ores: U.S. Bur. of Mines Rept. of Inv. 3314, 12 p.
- Cooke, H. C., 1937, Thetford, Disraeli, and eastern half of Warwick map-areas, Quebec; with chapters on the Beauceville, St. Francis, and Lake Aylmer series by Thomas Henry Clark: Canada Geol. Survey Mem. 211, 160 p.
- Dale, T. N., 1898, The slate belt of eastern New York and western Vermont: U.S. Geol. Survey 19th Ann. Rept., pt. 3, p. 153-307.
- Dennen, W. H., Ahrens, L. H., and Fairbairn, H. W., 1951, Spectrochemical analysis of major constituent elements in minerals and rocks: in Fairbairn and others, A cooperative investigation of precision and accuracy in chemical, spectrochemical, and modal analysis of silicate rocks: U.S. Geol. Survey Bull. 980, p. 25-52.
- Doll, C. G., 1951, Geology of the Memphremagog quadrangle and the south-eastern portion of the Irasburg quadrangle, Vermont: Vermont State Geol. Survey Bull. 3, 113 p.
- DuMond, J. W. M., and Cohen, E. R., 1953, Least-squares adjustment of the atomic constants, 1952: Rev. Mod. Physics, v. 25, p. 691-708.
- Du Rietz, Torsten, 1935, Peridotites, serpentines, and soapstones of northern Sweden: Geol. fören. Stockholm Förh. band 57, heft 2, no. 401, p. 133-260.
- Engel, A. E. J., 1949, Talc and ground soapstone: Industrial Minerals and Rocks: p. 1018-1041, Am. Inst. Min. Met. Eng.
- Eskola, Pentti, 1932, On the principles of metamorphic differentiation: Comm. geol. Finlande Bull. 97, p. 68-77.
- 1954, A proposal for the presentation of rock analyses in ionic percentage: Ann. Acad. Sci. Fennicae, ser. A, III Geol. Geogr., no. 38, 15p.
- Fairbairn, H. W., 1949, Structural petrology of deformed rocks: 344 p., Cambridge, Mass., Addison-Wesley Press Inc.
- Foslie, S., 1945, Hastingsites and amphiboles from the epidote-amphibolite facies: Norsk. geol. tidsskr., v. 25, p. 74-98.
- Fowler, Phillip, 1950, Stratigraphy and structure of the Castleton area, Vermont: Vermont Geol. Survey Bull. 2, 83 p.
- Gillson, J. L., 1927, Origin of the Vermont talc deposits: Econ. Geology, v. 22, p. 246-287.
- Goddard, E. N., and others, 1948, Rock-color chart: Washington, D. C., National Research Council.
- Graham, R. P. D., 1917, Origin of massive serpentine and chrysotile asbestos, Black Lake-Thetford area, Quebec: Econ. Geology, v. 12, p. 154-202.
- Gruner, J. W., 1937, Notes on the structure of serpentines: Am. Mineralogist, v. 2, p. 97-103.
- Hadley, J. B., 1942, Stratigraphy, structure, and petrology of the Mt. Cube area, New Hampshire: Geol. Soc. America Bull., v. 53, p. 113-176.
- 1950, Geology of the Bradford-Thetford area, Orange County, Vermont: Vermont Geol. Survey Bull. 1, 36 p.
- Herz, N., 1955, Alternative to the "Taconic overthrust" hypothesis in western Massachusetts: Geol. Soc. America Bull. v. 66, p. 1714.
- Hess, H. H., 1933a, Hydrothermal metamorphism of an ultrabasic intrusive at Schuyler, Virginia: Am. Jour. Sci., 5th ser., v. 26, p. 377-408.
- 1933b, The problem of serpentinization and the origin of certain chrysotile asbestos, talc and soapstone deposits: Econ. Geology, v. 28, p. 634-675.
- 1938, A primary peridotite magma: Am. Jour. Sci., 5th ser., v. 35, p. 321-344.
- Hess, H. H., Smith, R. J., and Dengo, G., 1952, Antigorite from the vicinity of Caracas, Venezuela: Am. Mineralogist, v. 37, p. 68-75.
- Hey, M. H., 1954, A new review of the chlorites: Mineralog. Mag., v. 30, no. 224, p. 277-292.
- Hitchcock, C. H., 1878, Atlas accompanying the report on the geology of New Hampshire: New York.
- Hitchcock, Edward, Hitchcock, Edward, Jr., Hager, A. D., and Hitchcock, C. H. 1861, Report on the geology of Vermont: 2 vols., 988 p., Claremont, N. H., Claremont Mfg. Co.
- Jacobs, E. C., 1914, Talc, and the talc deposits of Vermont: Vermont State Geologist 9th bienn. rept. 1913-14, p. 382-429.
- 1916, The talc and verde antique deposits of Vermont: Vermont State Geologist 10th bienn. rept. 1915-16, p. 232-280.
- Johannsen, A. J., 1939a, A descriptive petrography of the igneous rocks, v. 1: 318 p., Chicago, Univ. Chicago Press.
- 1939b, A descriptive petrography of the igneous rocks, v. 4, 523 p.: Chicago, Univ. Chicago Press.
- Keith, Arthur, 1932, Stratigraphy and structure of northwestern Vermont: Washington Acad. Sci. Jour., v. 2, p. 393-406.
- Keith, S. B., and Bain, G. W., 1932, Chrysotile asbestos: I, Chrysotile veins: Econ. Geology, v. 27, p. 169-188.
- Korzhinsky, D. S., 1950, Phase rule and geochemical mobility of elements: Internat. Geol. Cong., 18th, Great Britain, Rept., pt. 2, p. 50-65.
- Kracek, F. C., 1942, Melting and transformation temperatures of mineral and allied substances, in Francis Birch and others, Handbook of physical constants, p. 139-174: Geol. Soc. America Special Paper No. 36.
- Lovering, T. S., 1949, Rock alteration as a guide to ore—East Tintic district, Utah: Econ. Geology Mon. 1, 65 p.
- Lyons, J. B., 1955, Geology of the Hanover quadrangle, New Hampshire-Vermont: Geol. Soc. America Bull., v. 66, p. 105-146.
- MacFadyen, J. A., Jr., 1956, Geology of the Bennington quadrangle, Vermont: Vermont Geol. Survey Bull. 7, 72 p.
- Nagy, B., 1953, The textural pattern of the serpentines: Econ. Geology, v. 48, p. 591-597.
- Nagy, B., and Bates, T. F., 1952a, Mineralogy of the serpentine group (abs.): Geol. Soc. America Bull., v. 63, p. 1285.
- 1952, Stability of chrysotile asbestos: Am. Mineralogist, v. 37, p. 1055-1058.
- Nagy, B., and Faust, G. T., 1956, Serpentines: natural mixtures of chrysotile and antigorite: Am. Mineralogist, v. 41, p. 817-838.
- Nanz, R. H., Jr., 1953, Chemical composition of Precambrian slates with notes on the geochemical evolution of lutites: Jour. Geology, v. 61, p. 51-64.
- Nemecz, Erno, 1958, A Perkpai szerpentin ásványtani és geokémiai vizsgálata: Földtani Közlemény K. 86, f. 4, p. 424-434.

- Niggli, P., 1936, Über Molekularnormen zur Gesteinsberechnungen: Schweizer. min. pet. Mitt., v. 16, p. 295-317.
- 1954, Rocks and mineral deposits: 559 p., San Francisco, W. H. Freeman and Co.
- Osberg, P. H., 1952, The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vermont: Vermont Geol. Survey Bull. 5, 127 p.
- Perry, E. L., 1927, Summary report on the geology of Plymouth and Bridgewater, Vermont: Vermont State Geologist 15th bienn. rept. 1925-26, p. 160-162.
- 1929?, The geology of Bridgewater and Plymouth townships, Vermont: Vermont State Geologist 16th bienn. rept. 1927-28, p. 1-64.
- Pettijohn, F. J., 1949, Sedimentary rocks: 526 p., Harper & Brothers, New York.
- Phillips, A. H., and Hess, H. H., 1936, Metamorphic differentiation at contacts between serpentinite and siliceous country rocks: Am. Mineralogist, v. 21, p. 333-362.
- Poldervaart, Arie, 1953, Petrological calculations in metasomatic processes: Am. Jour. Sci., v. 251, p. 481-504.
- Prindle, L. M., and Knopf, E. B., 1932, Geology of the Taconic quadrangle: Am. Jour. Sci., 5th ser., v. 29, p. 257-302.
- Ramberg, Hans, 1945, Petrological significance of sub-solidus phase transitions in mixed crystals: Norsk geol. tidsskr., v. 24, p. 42-74.
- 1952, The origin of metamorphic and metasomatic rocks: 317 p., Chicago, Univ. Chicago Press.
- Read, H. H., 1934, On zoned associations of antigorite, talc, actinolite, chlorite, and biotite in Unst, Shetland Islands: Mineralog. Mag., v. 23, no. 145, p. 519-540.
- Roy, D. M., and Roy, Rustum, 1952, Studies in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ [abs.]: Geol. Soc. America Bull., v. 63, p. 1293-1294.
- 1953, Synthesis, stability, and properties of layer silicate structures. I. Serpentine-kaolinite family [abs.]: Geol. Soc. America Bull., v. 64, p. 1468-1469.
- 1955, Synthesis and stability of minerals in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$: Am. Mineralogist, v. 40, p. 147-178.
- Ryan, C. W., 1929, Soapstone mining in Virginia: Am. Inst. Min. Met. Eng. Tech. Pub. 160.
- Selfridge, G. C., Jr., 1936, An X-ray and optical investigation of the serpentinite minerals: Am. Mineralogist, v. 21, p. 463-503.
- Shapiro, Leonard, and Brannock, W. W., 1952, Rapid analysis of silicate rocks: U.S. Geol. Survey Circ. 165.
- Shaw, A. B., 1949, Stratigraphy and structure of the St. Albans area, Vermont: Ph. D. dissertation, Harvard University.
- Smith, J. V., and Yoder, H. S., 1953, Theoretical and X-ray study of the mica polymorphs [abs.]: Geol. Soc. America Bull., v. 64, p. 1475.
- Sosman, R. B., 1938, Evidence on the intrusion-temperature of peridotites: Am. Jour. Sci., 5th ser., v. 35A, p. 353-359.
- Stone, S. W., 1951, Structure and stratigraphy of the Milton area, Vermont: Ph. D. dissertation, Harvard University.
- Thayer, T. P., 1956, The geology and mineralogy of chromite, in Udy, M. J., Chemistry of chromium and its compounds, p. 14-52: New York; Reinhold; London, Chapman and Hall.
- Thomas, R. G., 1951, An example of re-intrusion of serpentinite: Am. Geophys. Union Trans., v. 32, p. 462-465.
- Thompson, J. B., 1952, Southern Vermont, in Billings, M. P., Rodgers, John, and Thompson, J. B., Geology of the Appalachian highlands of east-central New York, southern Vermont, and southern New Hampshire: Geol. Soc. America Guidebook for Field Trips, 65th Ann. Meeting, p. 14-23.
- 1955, The thermodynamic basis for the mineral facies concept: Am. Jour. Sci., v. 253, p. 65-103.
- Turner, F. J., 1948a, Mineralogical and structural evolution of the metamorphic rocks: Geol. Soc. America Mem. 30, 342 p.
- 1948b, Review of current hypotheses of origin and tectonic significance of schistosity (foliation) in metamorphic rocks: Am. Geophys. Union Trans., v. 29, p. 558-564.
- U.S. Bureau of Mines, 1944, Mad River tale mine, Washington County, Vt.: War Minerals Rept. 222.
- Vogt, J. H. L., 1921, The physical chemistry of the crystallization and magmatic differentiation of igneous rocks: Jour. Geology, v. 29, p. 522-539.
- 1924, Vidensk. selsk. Kristiania Skr., I, Mat.-naturw. Kl., no. 15, p. 97.
- Weaver, J. D., 1953, "Taconic allochthone" in Copake area, New York: Geol. Soc. America Bull., v. 64, p. 1489.
- Weinschenk, E., 1891, Serpentin aus dem ostlichen Centralalpen: Habilitationsschrift Munich.
- 1894, Bayer. Akad. Wiss., Abh. 1 Cl., 18, p. 653-713.
- White, W. S., 1949, Cleavage in east-central Vermont: Am. Geophys. Union Trans., v. 30, p. 587-594.
- White, W. S., and Billings, M. P., 1951, Geology of the Woodsville quadrangle, Vermont-New Hampshire: Geol. Soc. America Bull., v. 62, p. 647-696.
- White, W. S., and Jahns, R. H., 1950, Structure of central and east-central Vermont: Jour. Geology, v. 58, p. 179-220.
- Whittaker, E. J. W., and Zussman, J., 1956, The characterization of serpentine minerals by X-ray diffraction: Mineralog. Mag., v. 31, no. 233, p. 107-126.
- Wigglesworth, Edward, 1916, The serpentines of Vermont: Vermont State Geologist 10th bienn. rept. 1915-16, p. 281-292.
- Winchell, A. N., and Winchell, Horace, 1951, Elements of optical mineralogy, part II: 551 p., New York, John Wiley and Sons, Inc.
- Wing, Augustus, 1867, Letter to James Hall, in Cady, W. M., 1945, Stratigraphy and structure of west-central Vermont: Geol. Soc. America Bull., v. 56, p. 550.
- Wiseman, J. D. H., 1934, The central and southwest Highland epidiorites: a study in progressive metamorphism: Geol. Soc. London Quart. Jour., v. 90, p. 354-417.
- Yoder, H. S., 1952, The $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ system and the related metamorphic facies: Am. Mineralogist, Bowen vol., p. 569-627.
- Zen, E-an, 1956, Correlation of chemical composition and physical properties of dolomite: Am. Jour. Sci., v. 254, p. 51-60.