THE GEOLOGY OF THE HARDWICK AREA, VERMONT

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ABSTRACT

Metamorphosed Upper Cambrian (?), Ordovician, Silurian and probable Devonian sedimentary and intermediate to basic igneous rocks have been deformed in at least two stages and subsequently cut and locally metamorphosed by Devonian granodiorites. The principal stages of deformation seem related to the development of the Green Mountain anticlinorium and the Willoughby arch. Each of these large-scale structural features has related smaller scale linear and planar fabric elements. Criteria are given that are useful in assigning the small-scale fabric features to either the development of the Green Mountain anticlinorium or the formation of the Willoughby arch. Vertical movement appears to have played a conspicuous role in the formation of both the Green Mountain anticlinorium and the Willoughby arch.

A new fossil locality in the Shaw Mountain Formation has yielded corals, brachiopods, bryozoans, and echinodermata debris. These fossils have made possible a more positive age determination for the Shaw Mountain Formation.

INTRODUCTION

Location

The Hardwick quadrangle is situated between latitudes 44°30′ and 44°45′ north and longitudes 72°15′ and 72°30′ west. Its northern limit is less than 20 miles from the Canadian border. The area is served by Vermont highway 15 (east to west) and Vermont highways 14 and 16 (north and south)[1]. Railroad freight traffic is maintained by the St. Johnsbury and Lamoille County Railroad. The old Boston stage road originally passed through the village of Greensboro. Remnants of this

[1]On the topographic base of Plate 1, Route 14 has the old designation 12 south of Hardwick and 12B north of Hardwick. Route 16 is that part of former Route 12 which is north of Hardwick.

stage road may be followed through the swamps of Skunk Hollow north of Long Pond in the north-central 1/9 of the quadrangle.

Geological Setting

The Hardwick area lies in a zone of Paleozoic rocks occupying an apparently homoclinal structure between the Green Mountain anticlinorium and the Gaspé-Connecticut Valley synclinorium. From west to east the rocks range in age from Cambrian or Ordovician to probable Devonian. A number of granodioritic plutons in the eastern part of the area belong to a belt of plutons extending from Massachusetts into the Eastern Townships of Quebec. These plutons are related to a structural arch within the Gaspé-Connecticut Valley synclinorium.

Tectonic features in the Hardwick quadrangle are outlined on Plate 2 (in pocket). At the time of mapping the geology of the surrounding areas was known, as detailed below.

Previous Work

Early work in the region, on a reconnaissance scale, was carried out by Adams (1845), Hitchcock (1861), and Richardson (1902 and 1906). Detailed published work in adjacent areas is by Doll (1951), Cady (1956), Dennis (1956), Albee (1957), Hall (1959), Konig (1961) and Cady and others (1963). The distribution of adjacent quadrangles is shown in Figure 1.

Method

Field work was carried out principally in the summer of 1959. Konig mapped the Northfield Formation and rocks to the west, and the area south of Caspian Lake. Dennis mapped the post-Northfield metasedimentary rocks to the east and plutons in the area north of Caspian Lake. The area northwest of the Missisquoi Formation had been mapped previously by Cady and others (1963). Further, in this report, the section on igneous and metamorphic rocks is by Konig and that on structural geology by Dennis; however, both authors have contributed to and criticized each other's section. In the stratigraphic part of the text each author is responsible for the area he has mapped.

Acknowledgments

The writers are indebted to Charles G. Doll, State Geologist, who supported the work, and Wallace M. Cady, U. S. Geological Survey who gave much valuable help and advice. Both Doll and Cady had

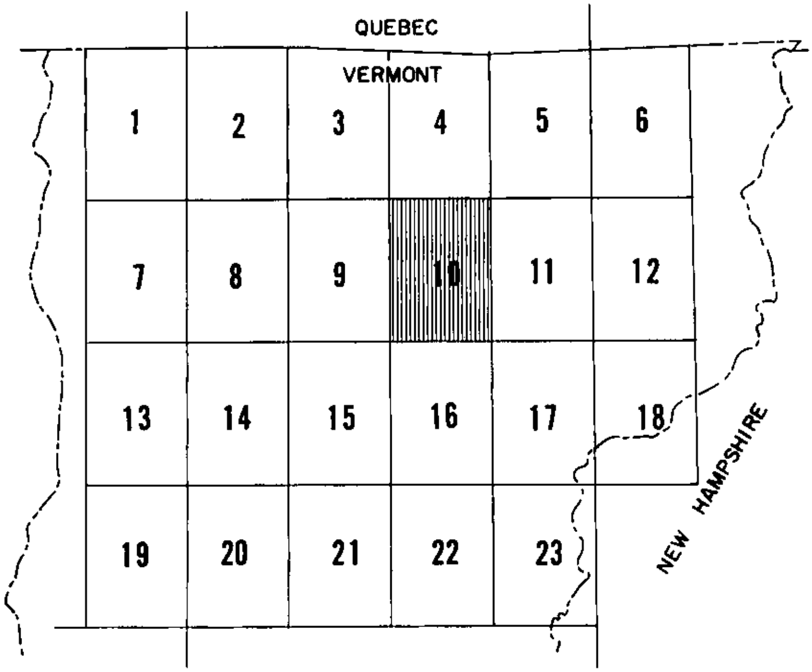


Figure 1. Index map of northern Vermont showing the location of the present area of study (ruled). The quadrangles are numbered as follows:

1. St. Albans
2. Enosburg Falls
3. Jay Peak
4. Irasburg
5. Memphremagog
6. Island Pond
7. Milton
8. Mt. Mansfield
9. Hyde Park
10. Hardwick
11. Lyndonville
12. Burke
13. Burlington
14. Camels Hump
15. Montpelier
16. Plainfield
17. St. Johnsbury
18. Littleton
19. Middlebury
20. Lincoln Mtn.
21. Barre
22. East Barre
23. Woodsville

worked in nearby areas and were able to give guidance on a number of perplexing problems. The geology of a considerable part of the northwestern ninth of the quadrangle had been completed previously by Cady, Albee, and Chidester. Much of this information was made available to the writers and has been included in the present report.

David Wichman, of Cornell University, served as a field assistant during the summer of 1959. Additional field assistance by Paul Rockman, Gerald Nalewaik, Stephen Clement, and Maurice Brouha is greatly appreciated.

The writers further acknowledge the efficient help of Rosemary Donica and Minniebel Richardson with the typing and Pamela White with the drafting. Much of the office and laboratory work was made possible through grants from Texas Technological College and the University of Arkansas.

Physiography

The area is hilly, with local relief exceeding 1300 feet in the vicinity of the Lowell Mountains. The lowest elevations (600–700 feet) occur along the Lamoille River in Wolcott township. The highest elevation is in the Lowell Mountains at Bigelow "Basin" (2627 feet). A good correlation exists between geologic structure and topography. This correlation is due largely to differential stream and glacial erosion.

One of the more striking topographic features in the Hardwick quadrangle is the Alder Brook-Black River (western branch) valley which extends from the village of Hardwick northward through the village of Albany. The trend of this valley is essentially parallel to the strike of the underlying rock units (Pl. 1, in pocket). Along the Black River the valley is carved in a relatively nonresistant recrystallized limestone which comprises the lower part of the Ayers Cliff Member of the Waits River Formation. This nonresistant horizon is very poorly exposed in the present area of study due to extensive alluviation within the valley. Consequently the nature of this horizon has been inferred largely from observations made outside the Hardwick quadrangle. The Ayers Cliff Member becomes progressively thinner from north to south until in the vicinity of Eligo Pond it wedges out completely. As the Ayers Cliff Member thins, the associated valley becomes narrower, less alluviated and eventually passes into a narrow U-shaped valley containing little alluvial material.

The higher hills in the eastern part of the area are underlain by more resistant siliceous rock units in the Waits River Formation and by bodies of granodiorite emplaced in the Waits River Formation. A second area of considerable relief, the Lowell Mountains, is located in the northwestern ninth of the quadrangle. The relief in this area seems to be controlled by the quartz-rich phyllites and the massive greenstones of the Stowe Formation.

Glacial and fluvial geomorphic features are abundant in the Hardwick quadrangle. The Hosmer Ponds and various smaller ponds and swamps scattered throughout the area are largely the result of glaciation. Other glacial features include striations on bedrock, small erratic boulders largely of local origin, and *roches moutonnées*. One of the best developed *roches moutonnées* is Paddock Hill, located approximately one mile northeast of Long Pond in the east-central ninth of the quadrangle. Alluvial terraces along the west branch of the Black River are of fluvial or glacio-fluvial origin.

STRATIGRAPHY

Introduction

Metasedimentary rocks in the Hardwick quadrangle range from Ordovician to lower Devonian (?), and include the Stowe, Missisquoi, Shaw Mountain, Northfield, and Waits River formations. A generalized stratigraphic section for the Hardwick quadrangle and vicinity is given in Table 1.

Stowe Formation

General Statement

The Stowe Formation, as well as parts of the overlying Umbrella Hill Member of the Missisquoi Formation, has been mapped in detail by Cady and others (1963) and the results of their work have been included, with slight modifications, in the geologic map (Pl. 1, in pocket). Several minor changes in the position of the formation contacts have been made in accordance with revised topographic control available in 1959.

The Stowe Formation (Cady, 1956) is composed primarily of schist and thick interbeds of greenstone and amphibolite at its type locality in the southeastern part of Stowe township and adjoining areas. Elsewhere in Vermont rocks which are now referred to the Stowe Formation include the Bethel Schist (Richardson, 1924) and the lower part of what has been called the arenites of the Braintree-Northfield Range by Currier and Jahns (1941), and White and Jahns (1950).

Distribution

The Stowe Formation is exposed in the northwestern ninth of the Hardwick quadrangle from the Lowell Mountains northwestward. Its western contact is outside the quadrangle. Thus, only the upper part of the formation is exposed in the present area of study. The formation has been mapped northeastward into the Irasburg quadrangle by Doll and southwestward through the Hyde Park and Montpelier quad-

STRATIGRAPHIC SEQUENCE					REMARKS
DEVONIAN	Lower ----- ?	ST. FRANCIS GROUP		Gile Mountain Fm. equals Westmore Fm.	Not present in mapped area.
					Fossils (Doll, 1943)
DEVONIAN	Lower	ST. FRANCIS GROUP	WAITS RIVER Fm.	Barton River Mem.	Fossils (Cady, 1950)
DEVONIAN	Lower	ST. FRANCIS GROUP	WAITS RIVER Fm.	Ayers Cliff Mem.	Contains Irasburg congl. (Doll, 1951).
SILURIAN	Upper	ST. FRANCIS GROUP		Northfield Fm.	
SILURIAN	Upper			Shaw Mtn. Fm.	Fossils (this report).
					Unconformity
SILURIAN	Middle				
SILURIAN	Lower				
ORDOVICIAN	Upper				
ORDOVICIAN	Middle	MISSISQUOI Fm.		Moretown Mem.	Greenstone abundant in upper part.
ORDOVICIAN	Middle	MISSISQUOI Fm.		Umbrella Hill Mem.	
					Unconformity (?)
ORDOVICIAN	Lower			Stowe Fm.	Lower part of formation not present in mapped area.

Table 1. Stratigraphic section for Hardwick quadrangle and vicinity.

rangles by Albee (1957) and Cady (1956), respectively; and into the Rochester and East Middlebury areas by Osberg (1952).

Lithologic Detail

The Stowe Formation is composed dominantly of three distinct rock types: 1) sericite-quartz-chlorite-albite schist, 2) greenstone, and 3) carbonaceous quartz-sericite-chlorite schist and phyllite. Since these rocks were not studied in detail they are considered only briefly here and the reader is referred to Cady and others (*op. cit.*) for more detailed information.

Sericite-quartz-chlorite-albite schist: Sericite-quartz-chlorite-albite schist is well exposed in the vicinity of Mt. Norris and at higher elevations in the Lowell Mountains (Pl. 1, in pocket). This rock is silvery-green and is composed principally of quartz, sericite and chlorite, and lesser amounts of porphyroblastic albite. Accessory amounts of magnetite, ilmenite, tourmaline, zircon, carbonate, and epidote are common. Numerous lenticles of granular white quartz, which are generally parallel to schistosity are characteristic of this schist. These quartz lenticles appear to be the result largely of metamorphic segregation, the quartz being derived from adjacent quartz-rich rocks (Albee, 1957). These quartz lenticles are often parallel to the schistosity, but cross-cutting relationships have been observed.

Bedded greenstone: Greenstone in the Stowe Formation is generally greenish-gray and conspicuously massive in comparison to the adjacent metasediments. Because of these characteristics the greenstone is easily traced in the field and serves as an excellent marker horizon for distinguishing relatively large-scale structural features. Detailed megascopic and microscopic examination of these rocks indicates the presence of poorly developed bedding. The position of the bedding planes is indicated by a change in mineral composition and/or grain size. Upon weathering carbonate minerals, which are frequently confined to distinct horizons in the rocks, are leached producing numerous small cavities. The position of these pitted horizons is commonly emphasized by the presence of brown iron oxide stains. The source of the iron producing these stains is believed to be the carbonate minerals. Bedding may be observed in many of the greenstones, suggesting that most of the greenstones may represent metamorphosed volcanic debris, perhaps contaminated by terrigenous sedimentation.

In thin section the bedded greenstones usually contain essential chlorite and albite and accessory epidote, quartz, magnetite, carbonate, leucoxene, apatite and sphene (?). The albite is usually metamorphic and seldom shows any twinning or secondary alteration to sericite or calcite. As the chlorite content increases the greenstone generally acquires a schistosity. Because the chlorite content of these rocks is variable, the greenstones may vary from relatively massive, with low chlorite content, to relatively schistose when the chlorite content is high in comparison to the other minerals present.

Carbonaceous quartz-sericite-chlorite schist and phyllite: Carbonaceous quartz-sericite-chlorite schist and phyllite is well exposed near the axial region of the Lowell Mountain syncline in the Lowell Mountains (Pl. 1, in pocket). These rock types are usually fine grained, well foliated and contain essential quartz, chlorite and sericite. Albite, if present, occurs in accessory amounts.

Age

The Stowe Formation underlies the Umbrella Hill Member of the Missisquoi Formation which is considered to be Middle Ordovician (Cady, 1960), and overlies the Ottauquechee Formation which is Middle Cambrian (Cady, 1960). Thus the Stowe Formation is assigned to late Cambrian (?) or Early (?) Ordovician (Cady, 1960). No additional information regarding the age of the Stowe Formation was discovered during the present investigation.

Missisquoi Formation

General Statement

The Missiquoi Formation has been divided into the Moretown and Umbrella Hill Members in north-central Vermont (Cady and others, in press). In the Hardwick quadrangle both of these members are present along with a third definable unit in which greenstone is abundant. The unit in which greenstone is abundant is generally confined to the upper part of the Moretown Member. The Missisquoi Formation of this report, includes the Moretown Formation of Osberg, (1952) and Cady, (1956) and the Umbrella Hill Formation of Albee, (1957). These units have now been relegated to member status within the Missisquoi Formation.

Distribution

The Umbrella Hill Member of the Missisquoi Formation has been traced in detail from the vicinity of Mud Pond in the east-central ninth of the Hyde Park quadrangle northeastward to the western edge of the Hardwick quadrangle (Albee, 1957). More recent work by Cady and others (1963) and the writers has extended this unit through the northwestern corner of the Hardwick quadrangle into the Irasburg quadrangle. The Umbrella Hill Member dies out to the north in the Irasburg quadrangle as well as to the south in the Hyde Park quadrangle, giving the unit a total strike length of approximately 20 miles. Easily accessible exposures of the Umbrella Hill Member may be seen adjacent to the road between Craftsbury (Hardwick quadrangle) and Eden (Hyde Park quadrangle) at an elevation of approximately 1860 feet (Pl. 1, in pocket).

The Moretown Member of the Missisquoi Formation has been traced in a northeasterly direction throughout much of central and northern Vermont. This unit is well exposed in the Montpelier quadrangle (Cady, 1956), in the Plainfield quadrangle (Konig, 1961) as well as in the present area of study. In all of these areas the Moretown Member is composed of very similar rock types which are readily identified in the field. Easily accessible exposures of this unit may be seen along Highway 15 between the town of Hardwick and the western border of the Hardwick quadrangle.

Umbrella Hill Member

The dominant rock type in the Umbrella Hill Member of the Missisquoi Formation in the Hardwick quadrangle is a massive conglomerate containing pebbles of milky quartz, ferruginous and carbonaceous slate and phyllite, and calcareous metaquartzite. Small masses of serpentinite up to 10 millimeters in diameter have been observed locally in the conglomerate. The above material is embedded in a quartz-sericite-chloritoid phyllite matrix containing accessory magnetite, leucoxene, hematite, apatite, zircon, rutile (?) and sphene (?). Chloritoid occurs as randomly oriented 1–5 millimeter long dark gray to black grains that are most abundant in and adjacent to iron-rich slate and phyllite fragments. The chloritoid shows no apparent orientation and is not cut by secondary foliation, as are many of the pebbles; therefore it probably developed after the last stage of deformation in the northwestern part of the quadrangle.

Quartz-sericite-chloritoid slate and phyllite may be found interbedded with conglomerate. This rock type is poorly exposed and was only observed locally in the northwestern ninth of the quadrangle. Representative exposures of the quartz-sericite-chloritoid slate and phyllite may be seen in the Hyde Park quadrangle on the western slopes of Umbrella Hill (Albee, 1957).

Moretown Member

The Moretown Member of the Missisquoi Formation is composed dominantly of quartz-sericite-albite-chlorite granulite. This rock is commonly referred to as the "pinstripe" by geologists familiar with the Moretown Member because it contains alternating thin light gray and greenish layers. The light gray layers are composed mainly of untwinned albite and quartz as well as lesser amounts of sericite and chlorite. These layers, which are commonly subparallel to bedding, are generally 1–4 millimeters wide. The greenish layers are usually thinner than the light gray layers and are composed mainly of sericite, chlorite (pennine and clinochlore) and lesser amounts of quartz, iron ore and locally albite. Albite, which is present in accessory amounts in both the light gray and greenish layers contains only minor amounts of sericite and calcite as inclusions. Albite is distinguished from quartz with some difficulty in the finer grained rocks.

Interbedded and locally intragradational with the granulite (pinstripe) is sericitic and chloritic metaquartzite and carbonaceous quartz-sericite-chlorite phyllite and slate. These rock types have been observed throughout the entire Moretown Member.

Greenstone: The term greenstone is used in this report for medium gray to greenish gray rocks which are oriented parallel or subparallel to adjacent bedding planes. Poorly defined bedding planes are discernible in some greenstones whereas others contain no visible bedding. Unbedded greenstone locally contains features which are suggestive of deformed pillow structures, but none of these features are well enough defined to verify this conclusion. Even though these rocks have been metamorphosed and deformed to the same degree as the adjacent metasedimentary rocks they are easily recognized in the field by their color, massive appearance because of weakly developed secondary foliation, and superior resistance to erosion.

Greenstone has been observed throughout the entire Moretown Member of the Missisquoi Formation in the northern part of the quadrangle, but it is most abundant in the upper third of the member in the southern part of the quadrangle. Farther south in the Plainfield quadrangle (Konig, 1961) and in the Montpelier quadrangle (Cady, 1956) it has been possible to distinguish the upper part of the Moretown Member from the lower part by the relative abundance of greenstone. That part of the Moretown Member in which greenstone is abundant is not clearly defined in the present area of study, but it is shown separately on Plate 1 (in pocket).

Most greenstone observed in the Hardwick quadrangle is greenish gray and contains megascopically discernible grains of quartz, feldspar, epidote, carbonate (ankerite ?) and biotite. Upon weathering the carbonate minerals are leached producing a pitted surface which locally is stained brown by iron oxide. Occasionally the carbonate minerals and/or pitted areas are oriented so as to produce distorted plannar surfaces. These planar surfaces may reflect relict bedding developed in sedimentary rocks that have been contaminated by considerable amounts of clastic volcanic debris.

In thin section the majority of greenstone is composed of essential quartz, albite, chlorite and epidote and accessory carbonate, muscovite, biotite, iron ore, zircon, tourmaline, and apatite, and locally oligoclase. This mineral suite is nearly identical with the mineral suites reported by Konig (*op. cit.*) for six holocrystalline greenstones in the Plainfield quadrangle. Inasmuch as the greenstones in the Plainfield quadrangle and in the present area of study have undergone approximately the same degree of metamorphism and have essentially the same mineral composition it is assumed that they were originally very similar in composition. The absence of bedding planes in these rocks, combined with the abovementioned mineral suite suggests that these greenstones represent metamorphosed intermediate to basic igneous rock. Locally the greenstones are associated with relatively pure white recrystallized limestone. This limestone appears to be present only in the immediate vicinity of the greenstone.

Age

The Moretown Member of the Missisquoi Formation correlates stratigraphically with the Beauceville Formation in Quebec (Cady, 1960), which has yielded late Middle Ordovician (Trenton) fossils (Cooke, 1950; Fortier, 1956, Ph. D. thesis, Stanford Univ.). Therefore the Moretown Member of the Missisquoi Formation is very probably late Middle Ordovician.

The Umbrella Hill Member of the Missisquoi Formation lies stratigraphically below the Moretown Member and above the Stowe Formation. Inasmuch as the Moretown Member is here considered to be late Middle Ordovician and the upper part of the Stowe Formation is considered to be Lower Ordovician, the Umbrella Hill Member is probably Middle Ordovician.

Shaw Mountain Formation

General Statement

The type locality for the Shaw Mountain Formation (Currier and Johns, 1951) is near the base of the north slope of Shaw Mountain, 2 miles south-southeast of Northfield in the Barre quadrangle. In this area the formation is composed of three distinct lithologies. The oldest or basal rock type is a white to pinkish-brown, massively bedded quartz conglomerate containing numerous pebbles of quartzite, phyllite, slate, greenstone, rhyolite and jasperoid. Stratigraphically above this unit is a thin-bedded soda rhyolite tuff and a crystalline crinoidal limestone containing numerous interbeds of tuff. North of the type locality in the Plainfield and Hardwick quadrangles the formation is composed principally of crystalline limestone, calcareous metaquartzite, phyllite, greenstone and lesser amounts of recrystallized calcareous quartz conglomerate.

Distribution

The Shaw Mountain Formation has been mapped in detail from the vicinity of Bethel (Randolph quadrangle) northward to the Canadian border, for a total strike distance of approximately 80 miles. In the Hardwick quadrangle and elsewhere the formation is exposed as a series of discontinuous masses ranging from a few inches to several hundreds of feet in thickness and from a few feet to several miles in strike length.

Lithologic Detail

In the present area of study the Shaw Mountain Formation is composed principally of light tan crystalline limestone and calcareous metaquartzite and medium to dark gray slate and phyllite. Locally, however, massive greenstone, calcareous quartz conglomerate and medium gray crystalline limestone are exposed. The latter limestone is frequently fossiliferous and occurs as lenticular masses ranging from a fraction of an inch to several feet in thickness. Corals, bryozoans, brachiopods and echinodermata debris have been obtained from this rock type. They are described below.

The Shaw Mountain Formation is well exposed approximately 2½ miles due east of Great Hosmer Pond located in the north-central ninth of the quadrangle (Pl. 1, in pocket). All the rock types listed above crop out in this area, including several lenticular bodies of fossiliferous medium gray crystalline limestone. Greenstone is abundant near the contact of the Shaw Mountain and Northfield formations. This greenstone probably represents metamorphosed sills and dikes of intermediate to basic igneous rock. A carbonaté mineral, ankerite, is abundant in these rocks and is thought to have been partly derived from the breakdown of originally calcic plagioclase feldspar to albite during metamorphism.

AGE

A new fossil locality 2 miles S. 37° W. of the center of the village of Albany on an east-facing hill slope, 0.25 miles north of the Seaver Branch of the Black River (Pl. 1, in pocket) has yielded corals, bryozoans, brachiopods and echinodermata debris. The fossils were collected from a lense of light- to medium-gray, medium-grained, incompletely recrystallized quartz-bearing limestone located near the middle of the Shaw Mountain Formation. This limestone lens has been completely destroyed in obtaining the above-mentioned fossils.

Although the fossils are few and poorly preserved, they permit a more specific age determination than post-Middle Ordovician (Currier and Johns, 1941) for the Shaw Mountain Formation. One sample of medium gray rock contained brachiopods, corals and bryozoans. Two brachipood specimens, one a brachial valve and one a pedicle valve, were identified by A. J. Boucot, then of Massachusetts Institute of Technology (written comm., 1960) as a strongly plicated form of the genus Howellella. According to Boucot, "Howellellids of this type have been found elsewhere in strata of upper Llandoverian to Lower Gedinnian age." In the northern Appalachians it occurs in the Fitch Formation of New Hampshire and in the Lake Aylmer Formation in Quebec. Both of these formations are of Ludlovian age.

Favositoid and amplexoid corals as well as small fragments of branching bryozoa (trepostomes), all obtained from the same horizon as the howellellids, were studied by W. A. Oliver of the U. S. Geological Survey (written comm., 1960), and are considered to be of probable Silurian or Devonian age. A second sample of lighter colored rock from the same locality yielded only crinoidal debris. Its large crinoid columnal plates indicate only a post-Early Ordovician age for the Shaw Mountain Formation (R. B. Neuman, U. S. Geological Survey, written comm., 1961).

On the basis of available paleontologic data it may be concluded that the Shaw Mountain Formation represents some part of the Silurian to Lower Devonian interval, and very possibly is Upper Silurian in the present area of study.

Northfield Formation

General Statement

The Northfield Formation is named for rocks which crop out in the center of an old slate quarrying district in the vicinity of Northfield, Vermont, in the Barre quadrangle (Currier and Jahns, 1941). In this area the formation is composed dominantly of light- to dark-gray slate as well as lesser amounts of crystalline and dolomitic limestone, soda rhyolite, siliceous nodular zones, tuffaceous beds, and a basal conglomerate which is well exposed in Shaw Brook south of the town of Northfield. The light- to dark-gray slate is not only the dominant lithology but is also the most persistent lithology parallel to the strike of the formation.

Distribution

The Northfield Formation has been mapped almost continuously from Braintree Hill in the Randolph quadrangle northeastward to the southern shore of Lake Memphremagog in the Memphremagog quadrangle. Thus the formation is exposed for a strike distance of approximately 70 miles in Vermont.

In the Hardwick quadrangle the formation is exposed more or less continuously on the western slopes of the Black River valley to the north and on the western slopes of the valley occupied by Hardwick Lake and Eligo Pond to the south. Although the Northfield Formation is not exceptionally well exposed in these areas it is possible to study nearly complete stratigraphic sections locally. For example, good exposures may be seen, 1) along the lower slopes of Buffalo Mountain west of Hardwick, 2) along Route 14 (shown as Route 12 on Pl. 1) about 1 mile south of Craftsbury, and 3) in the vicinity of Albany in the northern part of the quadrangle. These three localities represent the general lithologic features of the formation throughout the present area of study.

Lithologic Detail

In the Hardwick quadrangle the Northfield Formation is composed of carbonaceous slate and phyllite and lesser amounts of bluish-gray impure crystalline limestone. The slate and phyllite make up more than 95 per cent of the formation in the southern two-thirds of the quadrangle. In the northern third of the quadrangle the slate and phyllite are gradually replaced by a highly impure crystalline limestone so that locally as much as 40 per cent impure crystalline limestone may be present in the formation. As the impure crystalline limestone content increases, the apparent thickness of the formation increases. It has been observed, however, that even where the impure crystalline limestone content reaches a maximum it is confined to the top two-thirds of the formation, leaving the bottom third of the formation composed principally of carbonaceous slate and phyllite.

Carbonaceous slate and phyllite: Carbonaceous slate and phyllite are composed principally of sericite, chlorite and quartz and lesser amounts of graphite, ilmenite and pyrite. Graphite and ilmenite, although present in amounts not exceeding 5 per cent of the total, are sufficiently abundant to color the rock dark gray to black. Pyrite, when present, is usually in the form of conspicuous euhedral crystals. Upon weathering the pyrite decomposes to produce a reddish brown stain surrounding the crystal.

Impure crystalline limestone: Bluish-gray impure crystalline limestone, which is present in minor amounts in the southern two-thirds of the quadrangle and becomes increasingly abundant in the northern third of the quadrangle is usually detected with some difficulty. The difficulty in recognizing this limestone is connected with the susceptibility of the rock to chemical weathering. Chemical weathering leaches the exposed surfaces of the limestone, removing calcium carbonate and leaving the more stable rock constituents behind in the form of a skeletal mass. This weathered zone frequently attains a thickness of several inches and locally may penetrate the rock to a depth of one foot. Usually the more highly foliated rocks undergo the greatest degree of leaching. This leaching is particularly pronounced in the northern third of the mapped area where the Northfield Formation thickens (Pl. 1, in pocket).

Age

Due to the lack of paleontologic evidence, particularly in the rocks immediately above the Northfield formation, it is not possible to assign the formation definitely to either the Silurian or the Devonian. However, inasmuch as the Shaw Mountain Formation, which immediately underlies the Northfield Formation, contains a fauna which ranges from the Silurian to the lower Devonian and very probably is Upper Silurian, it is concluded tentatively that the Northfield Formation also is Upper Silurian in the present area of study.

Waits River Formation

General Statement

The Waits River Formation of this report was first named the Waits River limestone by Richardson in 1906 and included a thick sequence of limestones and schists in eastern Vermont. Previous stratigraphic nomenclature and interpretation of this formation have been traced by Dennis (1956) and its present correlation and stratigraphic relationships have been thoroughly dealt with by Cady (1960). The reader is referred to these two accounts for additional detail.

Doll (1951) split the Waits River into the lower Ayers Cliff Formation and the upper Barton River Formation. Dennis (1956) and later workers have classified these two units as members of the Waits River Formation. In view of the limited distribution of the Ayers Cliff member, the name Barton River is synonymous with Waits River south of Eligo Pond, i.e. for most of the extent of the Waits River Formation. Murthy (1957 and 1958), in an interesting interpretation, differentiated stratigraphically between an older Barton River Formation (western outcrop belt) and a younger Waits River Formation (eastern outcrop belt). This interpretation has not found general acceptance. A discussion is given in Eric and Dennis (1958), and by White (1959), Dennis (1959) and Murthy (1959, (a) and (b)).

Distribution

The name Waits River Formation is applied to the lower part of presumed Devonian rocks within the Gaspé-Connecticut valley synclinorium in Vermont. Correlatives have been traced into Gaspé (Logan, 1863; Cady, 1960) and Massachusetts (Hunt, 1854; Boucot *et al.*, 1953). The Waits River Formation normally occurs as a seemingly homoclinal sequence between the underlying Northfield Formation and the overlying Gile Mountain Formation. Between latitudes 44°45′ and 43°45′, however this unit is repeated to the west of the principal outcrop belt in an anticlinal structure, the Willoughby arch (Doll, 1944; White and Jahns, 1950; Dennis, 1956; Hall, 1959; Konig, 1961).

Intense minor folding makes an estimate of the thickness of the formation extremely difficult. The present writers believe that the outcrop width of the Waits River Formation in the Hardwick quadrangle is a multiple of its actual thickness, even though most measured dips of beds are steep. The base of the overlying Gile Mountain Formation practically coincides with the quadrangle boundary near Greensboro

Bend in the southwestern ninth of the quadrangle. In the northwestern and east-central part of the Hardwick quadrangle the high ground included in the Waits River Formation is underlain by a lithology which locally resembles that of the overlying Gile Mountain Formation: Siliceous schists, metaquartzites and some recrystallized limestones. Section AA′ on Plate 1 (in pocket) could accommodate these patches as Gile Mountain, especially on Sharps Hill. However, the irregular and limited distribution of these Gile Mountain-like patches, and the normally gradational nature of the Waits River-Gile Mountain contact would make a definite delineation and correlation with the Gile Mountain hazardous. More detailed mapping will be required. Fortunately, these controversial areas are of minor importance in the overall stratigraphic and structural interpretation.

Canadian geologists and Dennis (1956) have grouped the Silurian and Devonian rocks of the Gaspé-Connecticut River synclinorium in a comprehensive unit, the St. Francis group. This grouping is convenient because contacts between the individual stratigraphic units within the group are gradational and because of the recurrence throughout of similar lithologies, in varying proportions. A basal, partially conglomeratic unit (Shaw Mountain Formation in Vermont) is usually excluded from the group.

Age

The age of the Waits River formation has been discussed by Dennis (1956) and Cady (1960). There has been some controversy as to age in the past, but since 1956 most workers accept Devonian age for most or all of the Waits River Formation.

Lithologic Detail

Definition of formations within the St. Francis group hinges on the relative proportion of three key lithologies found throughout the group. There are, of course, variations within each lithology from the bottom to the top of the group, and some of these variations may be significant. The three key lithologies found throughout the group are:

1. Siliceous limestone
2. Impure quartzite
3. Argillaceous phyllite and schist

1. *Siliceous limestone.* This rock type is typically fine grained and bluish-gray when fresh. Upon weathering the siliceous limestone ranges from gray to rusty brown, with the rusty brown color increasing with

increasing pyrite content. It consists of recrystallized calcite and quartz grains, averaging 0.02 — 0.05 mm in diameter and variable amounts of disseminated carbon. This rock should properly be called a marble. Normally the siliceous limestone is remarkably free of argillaceous and magnesium impurities; where present these impurities have been recrystalized to sericite, tremolite and phlogopite. Some of the more impure carbonate lithologies contain much calcic amphibole. Locally the amphibole-bearing limestone appears to be almost a mono-mineralic amphibolite, but close examination invariably shows the presence of a considerable amount of calcite matrix. White and Jahns (1950) state that they have found gradations between pure calcarenites and argillaceous rocks but in the Hardwick area the writers have found no gradation: the calcareous layers may be more or less impure; the argillaceous layers may be locally calcareous, but contacts between the two are invariably sharp.

The limestone beds vary in width from little more than an inch, forming septa between argillite beds, to cliffs exposing thicknesses of over 50 feet. In Glover township, in the eastern part of the quadrangle, some areas within the Barton River Member contain over 90 per cent limestone.

Many of the limestones contain 2–3 mm thick laminae composed of fine-grained siliceous and/or calcareous matter. These laminae are parallel to sub-parallel to the contacts of the limestones with adjacent argillites and they sometimes outline intense internal deformation.

2. *Impure quartzite.* Impure quartzites are not abundant in the Waits River Formation. Essentially, there appear to be two types of impure quartzite: a tough bluish silty rock which often weathers like siliceous varieties of the limestone (in some exposures it can be mistaken for the latter in the absence of further tests), and a whitish rock which can be observed to grade into a more argillaceous lithology. Both are more typical of the overlying Gile Mountain Formation.

3. *Argillaceous schist and phyllite.* Argillite beds vary in composition, and their variety is accentuated by metamorphism. The following lithologies are characteristic:

a) a dark, almost black dense graphitic schist containing pyrrhotite aligned in grains parallel to the bedding; the rusty weathering of this rock is very characteristic.

b) a gray brittle quartz-sericite--biotite schist containing varying amounts of carbon and, sometimes, sulphides. This rock also frequently weathers rusty brown due to the presence of sulphides.

It is normally better foliated than the graphitic variety, but gradational types between the two are common.

In general, rusty weathering of argillaceous lithologies is typical of the Waits River Formation, whereas it is rare in the Gile Mountain Formation. However, this difference is merely indicative, not diagnostic. It points up a change in available iron content, particularly iron sulphide, in the rock.

Ayers Cliff Member

The type section from which this member received its name is in a series of road cuts beginning half a mile west of the village of Ayers Cliff, Quebec (Doll, 1951, p. 22). Good exposures of the Ayers Cliff Member in the Hardwick quadrangle are along the road from Page Pond to Albany. The member wedges out in the vicinity of Eligo Pond. The gradational contact between the Ayers Cliff and the overlying Barton River Member would seem to indicate that the disappearance southward of the Ayers Cliff is due to facies change rather than nondeposition. The extent of the Ayers Cliff in Canada is not known, because the St. Francis group has not yet been adequately subdivided in southern Quebec.

The Ayers Cliff Member is composed predominantly of calcareous units that are present in varying proportions in all members of the Waits River Formation (lithology 1 above). The member is generally more thinly bedded than the Barton River Member and contains more pyrite cubes. Beds of phyllite and slate are subordinate, but increase in relative abundance towards the gradational upper and lower contacts with the Barton River Member of the Waits River Formation and the Northfield Formation, respectively.

An unusual characteristic of the Ayers Cliff Member is provided by the sporadic occurrence within it of pebbles and boulders of highly variable size, lithology and concentration. This conglomeratic facies is most common near the contact with the Barton River Member, but it occurs sporadically throughout the Ayers Cliff Member east of the western branch of the Black River. Richardson (1906) and Doll (1951) interpreted this conglomerate as a stratigraphic unit, the Irasburg conglomerate. Detailed studies in the Hardwick quadrangle seem to indicate that the pebbles are a sporadic facies within the Ayers Cliff Member. This facies is well exposed along the road from Page Pond to Albany. The pebbles are never closely concentrated, but appear to be "swimming" far apart in the limestone matrix. Apart from the limy matrix, the mode of occurrence of the pebbles resembles the Tertiary Wildflysch facies of the Central Alps. Deposition in a dense medium (turbidite deposition) seems indicated.

Several of these pebbles and boulders have been studied microscopically in order to determine structural, textural and mineralogical relationships. As a result of this study a number of pebbles and boulders were identified. Dark gray, fine-grained pebbles and boulders examined contained a mineral suite suggestive of amygdaloidal sodaclase andesite and albitite. Amydaloidal sodaclase andesite has essential plagioclase feldspar (albite-oligoclase) and chlorite (pennine) and accessory zeolites (metascolecite), pyrite, hematite, apatite and quartz. The majority of the chlorite, quartz and zeolites occur as spherical masses scattered randomly throughout the rock. The central part of some of these spherical masses contains mostly chlorite, which in turn is enveloped by quartz and zeolites. Mafic minerals and plagioclase feldspar encircle the inner zones with the plagioclase feldspar crystals aligned subparallel to the quartz-zeolite layer. Other dark gray, fine-grained pebbles and boulders are composed principally of a felted mass of albite (about 85%) and opaque minerals (about 10%) and accessory pyrite, calcite, quartz, apatite, zircon and pale green chlorite. Rocks of this composition have no visible preferred orientation and are called albitites in this report. Light gray, medium- and fine-grained pebbles and boulders generally contain more than 70 per cent quartz and minor amounts of opaque minerals, muscovite (including sericite) and chlorite. These rocks are metaquartzites and locally may represent metamorphosed chert. Other compositions of pebbles and boulders were observed in the field but were not studied microscopically. These rocks appeared to represent deformed slate and phyllite fragments.

Barton River Member

The Barton River Member consists of intercalated impure calcareous rocks ranging from limy quartzites to limestones, amphibole-bearing layers, slates, phyllites, quartzites and schist. These rocks are gray to black, with the calcareous members containing thin, porcelainized layers parallel with the bedding. Brown iron stain is a characteristic coating, particularly of the slates and phyllites (Doll, 1951, p. 25).

The type locality of the Barton River member is within the Newport city limits in a low cut along U. S. Route 5 north of the center of the city, and on the south flank of Shattuck Hill (Doll, 1951, p. 25 and Pl. 1.). These rocks are similar to those of Richardson's (1906) type area for the Waits River limestone in the Washington-Waits River area of Central Vermont. As mentioned before, the names Waits River and Barton River refer to the same rock unit south of the latitude of Eligo Pond.

The relative proportions of siliceous recrystallized limestone, phyllite and quartzite vary within the formation. The lower contact with the Ayers Cliff Member is drawn where the proportion of recrystallized limestone appears to exceed 75 per cent; additional field criteria include the appearance of numerous pebbles and boulders and thinner bedding with greater fissility below the Barton River Member. Where the Barton River Member is in direct contact with the Northfield Formation less than 25 per cent of recrystallized limestone in an outcrop is taken to indicate the Northfield. These are "rule of thumb" field criteria, necessary to establish a generally agreed trace for gradational contacts. Individual field geologists often develop their own criteria which, in practice, agree well with those listed above.

As mentioned before, some of the high ground within the area included in the Barton River Member of plate 1 is underlain by quartzites and phyllites, with very subordinate recrystallized limestone. This assemblage is characteristic of the overlying Gile Mountain Formation. In view of the great outcrop width of the Waits River Formation in the Hardwick area, it is possible that some of these high areas represent outliers of the Gile Mountain Formation. More detailed mapping will be necessary in order to confirm or reject this possibility.

Near Greensboro Bend, the Waits River-Gile Mountain contact in the Lyndonville quadrangle (Dennis, 1956, Pl. 1) has to be drawn very close to the quadrangle border. Because the critical area is covered by a thick glacial deposit, it is not possible to decide whether or not the Gile Mountain Formation extends into the Hardwick quadrangle. In any case, no confirmed Gile Mountain crops out within this quadrangle.

INTRUSIVE IGNEOUS ROCKS

Introduction

Intrusive igneous rocks exposed in the Hardwick quadrangle occur as stocks, sills and dikes which range in composition from acidic to ultrabasic. The larger intrusive masses generally are composed of granodiorite and closely related rocks, whereas the sills and dikes are usually granites or lamprophyres. Many of the smaller dikes and sills do not appear on Plate 1 (in pocket) due to their size and the scale of the map used in this report. Several of the more prominent and/or unique rock types have been examined in detail and the data presented below.

Granodiorite Stocks

Granodiorite is exposed in two distinct areas in the Hardwick quadrangle. The principal occurrence is in the east-central ninth of the quadrangle (Pl. 1, in pocket). These rocks are light gray, medium grained and composed of approximately 50 per cent plagioclase feldspar, 20 per cent potash feldspar, 20 per cent quartz, 6 per cent biotite, 3 per cent muscovite and lesser amounts of sphene, zircon, zoisite and allanite. Plagioclase feldspar is usually zoned, twinned, somewhat altered to sericite along cleavage traces and has the composition of oligoclase. Myrmekite is developed occasionally when oligoclase and potash feldspar come in contact. Potash feldspar is fresh and usually displays the gridiron structure that is typical of microcline. Some microcline is perthitic.

A second area of granodiorite is located along the southern border of the south-central ninth of the quadrangle. This rock body extends into the Plainfield quadrangle for approximately half a mile and is similar in appearance to other granodiorite plutons previously described there (Konig, 1961). Examination of several thin sections of this rock mass show it to be composed of approximately 60 per cent oligoclase, 24 per cent quartz, 8 per cent microline, 6 per cent biotite, 3 per cent muscovite (including sericite) and lesser amounts of epidote, apatite and zircon.

Comparison of the granodioritic rocks taken from both granodiorite localities in the Hardwick quadrangle showed them to be related in texture and mineral composition. Similar appearing granodiorites in the Plainfield quadrangle (Konig,*op. cit.*) contain a lower percentage of plagioclase feldspar and a higher percentage of potash feldspar than the granodiorites in the Hardwick quadrangle. However, inasmuch as all these geographically related granodiorites are similar in texture and mineral composition, minor differences in mineral percentage is not considered sufficient to regard these rocks as not being comagmatic.

Orbicular Granodiorite

General statement: An elliptical mass of igneous rock, of a type variously called concretionary granite, pudding granite, variolitic granite, orbicular granite and orbicular granodiorite, crops out in the central ninth of the Hardwick quadrangle in the vicinity of the village of Craftsbury. The rock mass has been mapped as ¾ of a mile long and ⅛ of a mile wide (Pl. 1, in pocket), but due to inadequate exposures these dimensions may be in error. Easily accessible exposures of orbicular granodiorite occur on either side of the bridge crossing the Black River at the downstream end of the small pond located on the northwestern edge of the village of Craftsbury. Other masses of this rock are found on the adjacent valley flats, particularly on the south side of the abovementioned bridge over the Black River. Most of the unconsolidated material on the valley flats has been transported by stream and glacial activity.

Previous work: The orbicular granodiorite near Craftsbury, Vermont, was reported by both Hitchcock and Hall in 1861. Hitchcock described the rock as syenitic in appearance and containing numerous wrinkled spherical masses composed of biotite and lesser amounts of granular quartz and probably some feldspar. Several years later Hawes (1878) and Kroustschoff (1886) further described this locality. Hawes concluded that the varioles (orbicles of this report) contained cores consisting of round mica-poor fragments similar in composition to the host rock. According to Hawes these cores are surrounded by quartz, mica, calcite and feldspar, with the mica arranged in numerous concentric zones about the cores. McCormick (1886) restudied the orbicular granodiorite and concluded that the rock mass was composed of quartz, feldspar and mica, which he asserted were the usual ingredients of a true granite. McCormick also stated that the orbicules are composed of concentric layers of biotite and irregularly distributed quartz and do not represent micaceous rolls or concretions but are merely biotite segregations from the original granite mass. The wrinkles found on the surface of the orbicles are attributed by McCormick to the contraction of the rock mass as it crystallized around the earlier formed orbicules. Kroustschoff described the Craftsbury "granite" again in 1894 stating that the biotite "nodules" contained over twice as much primary calcite as does the "granite" host rock and that the "nodules" are primary concretionary forms that developed in the "normal" rock. Rosenbusch (1907) apparently could not find either the calcite or the cores reported by earlier workers, but concluded that there was an intimate relationship between the orbicules and the oldest basic segregations of the rock mass. Two years later Dale (1909) briefly considered the "nodular" granite of Craftsbury and related it to a similar appearing rock mass which crops out near the town of Bethel in central Vermont.

More recently Johannsen (1932) considered the subject of orbicular granodiorite and reviewed some of the more pertinent literature regarding the occurrence of this rock type at Kangasniemi, Finland, as well as at Bethel and Craftsbury, Vermont. Johannsen reported that a study of the groundmass in his own specimen from Craftsbury indicates that it is composed of 33 per cent quartz, 49 per cent oligoclase, 8 per cent biotite, 4 per cent muscovite, 3 per cent microperthite, 1 per cent microcline and accessory apatite and magnetite as well as minor amounts of secondary white mica, kaolin, magnetite, chlorite, and calcite.

Present study: The orbicular granodiorite exposed near Craftsbury, Vermont, is a medium-grained, medium gray rock containing megascopically discernible quartz, feldspar, biotite and epidote. The biotite may occur as disseminated grains or in concentric layers in the form of spheroidal and ellipsoidal orbicules with diameters ranging from a fraction of an inch up to several inches or more (Pl. 3). The basal cleavage of the disseminated biotite and the flatter parts of the ellipsoidal orbicules are subparallel. This subparallel arrangement locally produces a conspicuous, steeply inclined planar flow structure in the rock, particularly near the western margin of the pluton.

Several thin sections of orbicular granodiorite were prepared, both of the groundmass and of the orbicules within the groundmass. Examination of thin sections from the groundmass showed that it is hypidiomorphic-granular and composed of approximately 49 per cent oligoclase (including minor albite), 27 per cent quartz, 12 per cent biotite, 5 per cent potash feldspar (including microperthite), 5 per cent muscovite (including sericite), and accessory apatite, zircon, epidote, magnetite, leucoxene, sphene, calcite, kaolin and chlorite. Plagioclase feldspar occurs as conspicuous subhedral grains, many of which contain inclusions of secondary sericite and kaolin. Potash feldspar is distinguished from the plagioclase feldspar by its deficiency in included muscovite and kaolin, the presence of minor perthite, and frequent polysynthetic twinning (gridiron structure). Both the plagioclase and potash feldspar have an average diameter of 2 millimeters and are found scattered randomly throughout the groundmass. Biotite occurs as discrete pleochroic grains with X = brownish-green, Y = light yellow-brown and Z = dark brown. There is no distortion or warping apparent within individual biotite grains. Muscovite occurs in two principal habits in the groundmass. The first and most abundant occurrence of muscovite is as small (generally less than ¼ mm. in diameter) subhedral and anhedral grains contained in the plagioclase feldspar. The muscovite of this habit probably has been derived from the decomposition of plagioclase feldspar and therefore should be added to the total plagioclase content of the rock for the purpose of classification. The second occurrence of muscovite is in the form of discrete grains with diameters ranging from a fraction of a millimeter to 3 millimeters. These grains are generally subhedral,

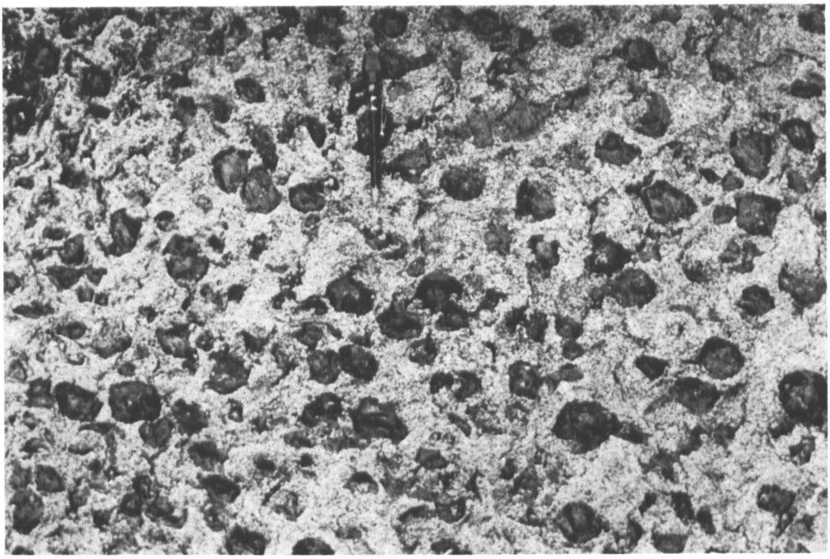


Plate 3. Orbicular granodiorite at Craftsbury, Vermont, showing orbicules (black) embedded in light gray groundmass.

show little or no preferred orientation within the sections examined and are not associated necessarily with feldspar.

Minerals making up less than 5 per cent of the groundmass are referred to as accessory minerals in this report. The most abundant accessory minerals are epidote and sphene. Epidote occurs as weakly pleochroic, euhedral and subhedral grains having a diameter of less than ½ millimeter. The epidote is randomly scattered throughout the rock. Sphene occurs as light brown, weakly pleochroic, anhedral and subhedral masses which are slightly altered to leucoxene near the grain boundaries and along cleavage traces. This alteration was not observed in all of the sphene studied. There is a conspicuous association of sphene and biotite, with the sphene usually occurring immediately adjacent to the biotite or as inclusions within biotite. An increase in biotite content generally is accompanied by an increase in sphene content. Other accessory minerals of lesser importance in the groundmass, as listed in order of decreasing abundance, include apatite, titaniferous magnetite, leucoxene, kaolin, zircon, chlorite and calcite. Kaolin is an alteration product of plagioclase feldspar.

Nine thin sections cut through orbicules of various diameters show that the orbicules are composed principally of the same minerals as the groundmass. Most of the orbicules examined contained a conspicuous central portion or core which ranged in diameter from 2 to 15 millimeters. This core is composed mainly of oligoclase, which has been largely altered to sericite, kaolin, and quartz. Associated with the oligoclase and quartz are accessory biotite, titaniferous magnetite, leucoxene, chlorite, sphene, apatite, pyrite, hematite and epidote. Magnetite, pyrite, hematite and chlorite are considerably more abundant in the core than elsewhere in the orbicule. Immediately surrounding the core is a shell composed principally of biotite, quartz, and oligoclase. The sections examined showed no orderly distribution of these minerals within the shell. In passing from the shell of the orbicule into the groundmass, or from the shell to the core, the principal difference noted is in the relative abundance of minerals which are usually present in both the core and the groundmass. Examination of all thin sections prepared showed consistently that the shell is composed of approximately 75 per cent biotite, 15 per cent quartz, 8 per cent oligoclase and 2 per cent muscovite. The remaining 5 per cent of the shell is composed of sphene, potash feldspar, epidote, reddish brown rutile, zircon, apatite and leucoxene. Sphene is closely associated with biotite and may be present in amounts up to 4 per cent in the shell. The oligoclase is partly altered to sericite and kaolin, but not nearly to the extent that alteration has taken place in the core. Muscovite occurs as distinct laths up to 2 millimeters in length which usually are oriented at a high angle to the biotite laths.

Crinkles are small folds which are present on the surface of the orbicules; they may be traced into the shell of the orbicule and frequently die out before reaching the core. Small folds or crinkles which are clearly related to protuberances of the core may die out before passing entirely through the shell. The biotite clearly outlines every fold in the orbicule, but not a single grain of biotite was observed to be warped or folded. The biotite outlines the fold pattern by a gradual, or sometimes a rather abrupt, change in the orientation of individual grains.

Conclusion: Several important relationships have been brought out in the above discussion which must be included in any theory concerning the origin of the orbicular granodiorite at Craftsbury, Vermont.

1. Most orbicules have a conspicuous core which is poor in mica and rich in quartz, plagioclase feldspar, magnetite, and chlorite.
2. Plagioclase feldspar in the core of the orbicules is more extensively altered to sericite and kaolin than plagioclase feldspar observed in the shell of the orbicule or in the groundmass.

3. Potash feldspar (dominantly microcline) is found almost entirely in the groundmass.
4. The exterior of the orbicule is usually wrinkled or folded and this folding is present within the shell of the orbicule and is clearly outlined by undistorted biotite grains.
5. The wrinkles or folds associated with the orbicule do not necessarily penetrate the entire thickness of the shell.
6. Discrete grains of muscovite are present in the shell of the orbicule; they show cross-cutting relationships with biotite which outlines the fold or wrinkle. Some plagioclase feldspar and quartz also show this cross-cutting relationship.

In consideration of the above relationships it is concluded that the shell of the orbicules in the Craftsbury granodiorite developed around a core composed of early crystallization products of the magma. This relationship is assumed because of the nature of the plagioclase feldspar found both in the core and in the shell of the orbicules. The plagioclase feldspar in the core is badly decomposed to sericite and kaolin, whereas in the shell this decomposition is poorly developed. Even though the plagioclase feldspar in both areas is oligoclase, the oligoclase in the core may be more calcic and therefore more susceptible to decomposition under pressure-temperature conditions which prevailed during the later crystallization of the shell. Biotite, some quartz, plagioclase feldspar, and possibly sphene and rutile crystallized somewhat later around the core. Movement within the partially crystallized magma produced the small wrinkles or folds observed both on and within the shell of the orbicules without bending or warping the minerals already crystallized. This requires the presence of some interstitial liquid in the shell developing about the core. Crystallization continued until the melt within the shell was used up at which time intergranular movement within the shell ceased. The cross-cutting muscovite, plagioclase feldspar and quartz represent the final crystallization products within the shell of the orbicule. Crystallization of the groundmass was largely penecontemporaneous with crystallization of cross-cutting minerals in the shell of the orbicule and produced additional plagioclase and potash feldspar, quartz, muscovite and other accessory minerals.

Granite Sills and Dikes

Granite sills and dikes are exposed locally in rocks of Ordovician, Silurian and Devonian age. They are most numerous, however, in the Devonian rocks of the Waits River Formation, particularly in the east-central part of the area, near the mapped larger bodies of granodiorite (see Pl. 1). These dike rocks range from light- to medium-gray, fine- to medium-grained and have a mineral composition which is usually equivalent to a granite.

An interesting dike is well exposed along Route 14 approximately one mile south of the town of Craftsbury in the central ninth of the quadrangle. The dike rock is light gray and fine grained and contains megascopically discernible grains of quartz, feldspar, chlorite and a light brown carbonate mineral. Upon weathering the carbonate mineral is largely dissolved, leaving the exposed surface finely pitted and incompletely coated by a light brown iron oxide residue.

This section study showed the dike rock to be composed of approximately 41 per cent calcic albite, 34 per cent quartz, 12 per cent ankerite (?), 10 per cent muscovite (including sericite), 1 per cent chlorite (penninite) and trace amounts of leucoxene, apatite, magnetite, hematite and rutile. This rock is classified as a carbonate-bearing, leuco-sodaclasetonalite-aplite (Johannsen, 1932).

Basic Dikes

Steeply inclined unmetamorphosed basic dikes, ranging from 2–10 feet in thickness are exposed in the Moretown Member of the Missisquoi Formation and in the Ayers Cliff member of the Waits River Formation. These dikes are dark gray and are usually porphyritic to sub-porphyritic, with phenocrysts of hornblende and, frequently, augite surrounded by an aphanitic groundmass. Weathering locally produces a reddish brown rind which attains a maximum thickness of about ¼ inch.

In thin section the basic dikes are holocrystalline and composed of phenocrysts of brown hornblende and frequently pale green augite. Both augite and hornblende may be zoned. Other minerals identified in the basic dikes include plagioclase feldspar, chlorite, magnetite, hematite, calcite, and apatite. Chlorite, hematite, calcite and some magnetite have developed from the chemical breakdown of pre-existing high temperature minerals in the dike rock.

Most of the basic dike rocks in the Hardwick quadrangle contain a mineral suite which is suggestive of a lamprophyre of spessartite-kersantite composition. Similar rock types have been reported in the East Barre quadrangle by Murthy (1957), in the St. Johnsbury quadrangle by Hall (1960) and in the Plainfield quadrangle by Konig (1961), in the Milton quadrangle by Stone and Dennis (in press) and in the

Burke quadrangle by Woodland (1962). These unmetamorphosed mafic dikes may be related to the White Mountain plutonic-volcanic series (Billings, 1956). Lead-alpha radiometric measurements of selected rocks of this series give a mean age of 186 ± 14 million years (Lyons and others, 1957). This would indicate a late Triassic age (Kulp, 1961).

Recently Woodland (1962) has made a detailed study of related lamprophyres in the Burke area. Woodland suggests that the lamprophyres may be more closely related to the Monteregian intrusives than to the White Mountain plutonic-volcanic series. The Monteregian rocks are considered to be Jurassic, possibly early Cretaceous (Larochelle, 1962, p. 40).

STRUCTURAL GEOLOGY

Introduction and Structural Setting

The Hardwick quadrangle covers an area located between two major tectonic features: the Green Mountain anticlinorium to the west and the Gaspé-Connecticut valley synclinorium to the east. In Vermont the core of this synclinorium is complicated by the presence of a structural high, the Willoughby arch.

Superficially, this location with respect to the adjoining features would indicate an almost straightforward homoclinal structure for the Hardwick area. Detailed mapping by the present authors, as well as by workers in adjoining areas, and the gradual resolution of the major stratigraphic problems in recent years have revealed important complications.

Major Structural Features

Terminology

Because there is still insufficient agreement concerning the terminology of structural geology, and in order to avoid misunderstandings, definitions and explanations of a few tectonic terms used in this bulletin may be useful.

Anticline: This term is used in its stratigraphic sense: a fold in which the oldest rocks are at the core.

Arch: An anticline developed directly and predominantly by presumed vertical movement.

Dome: A short arch; length usually no more than 3 times its width.

Lowell Mountain Anticline

This is the easternmost constituent anticline of the Green Mountain anticlinorium. The structure lies along the trend of the Worcester Mountain anticline (Cady, 1956). Anticlinal structure is confirmed by the periclinal structure of the younger carbonaceous lithology and of the underlying greenstone of the Stowe Formation around older Stowe lithology. Also, in the Irasburg quadrangle to the north, the Stowe is in the core of an anticline in the younger Missisquoi Formation.

The attitude of the bedding in the Stowe Formation is rarely discernible, but where it can be identified it usually dips at low angles; this is compatible with its position at the crest of an anticline.

Craftsbury homocline: This "homocline" is probably a rather complicated structure. Only the straight sequential relationship of the stratigraphic units in the area indicates homoclinal structure. Local exposures give every indication that abundant and intense minor folding may repeat parts of the Waits River Formation many times. And, as noted under Stratigraphy, the possible presence of Gile Mountain lithology on high ground within the Waits River outcrop belt may represent outliers of Gile Mountain Formation. Thus, on cross-section AA′ (Pl. 1, in pocket), the top of Sharps Hill may be underlain by a part of the Gile Mountain Formation; in fact, this might make for a more acceptable interpretation of the cross-section. However, such an interpretation would not be altogether justifiable in the light of presently available evidence, and the writers prefer not to introduce another formation within the quadrangle, unless its presence is inferred from better evidence than informed speculation.

Brownington syncline: The rocks of the eastern part of the quadrangle are part of the west limb of the Brownington syncline; the core of this syncline does not crop out within the quadrangle. Full discussions of the structural and stratigraphic relationships of the Brownington syncline are given by Doll (1951) and Dennis (1956). Notwithstanding some recent controversy (Murthy, 1957, 1958, 1959 (a) and (b); Dennis, 1959; White, 1959), the synclinal nature of this structure is accepted by the present writers.

Willoughby arch: The Willoughby arch is superimposed on the Gaspé-Connecticut Valley synclinorium, and on its constituent Brownington syncline. Evidence for this is found in the pattern of the minor structural features, which is explained in the next section. The crest of the arch is in the adjacent Lyndonville quadrangle (Dennis, 1956). The rocks of

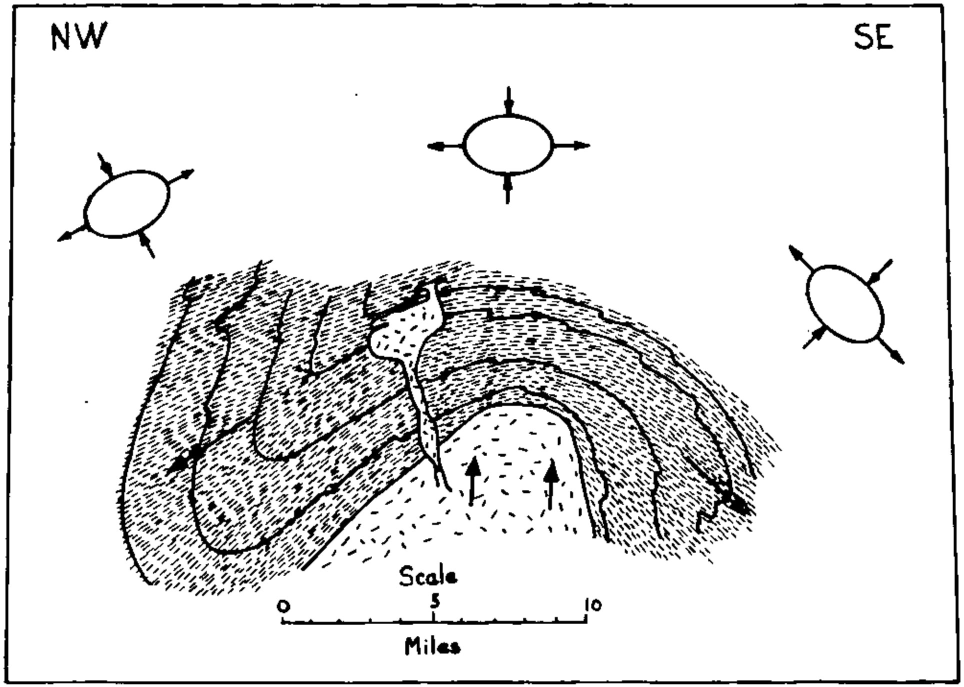


Figure 2. Generalized structural cross-section diagram of the Browington syncline and Willoughby arch in the vicinity of the Hardwick quadrangle. Heavy black lines represent bedding, dashed parallel lines represent s_2 and disoriented hatches represent intrusive igneous rocks.

the eastern part of the Hardwick quadrangle are part of the west flank of the Willoughby arch. As shown below, the arch was formed after the Brownington syncline, and so, in a seeming paradox, the same belt of rocks is *both* west flank of a major syncline *and* west flank of a structural arch (Fig. 2).

Minor Structural Features

Terminology

Cleavage: The term *cleavage* as applied to rocks refers to all types of secondary planar fabric elements (other than coarse schistosity) which impart mechanical anisotropy to the rock without apparent loss of cohesion. *Continuous cleavage* is the result of continuous parallelism of platy minerals throughout the rock, while in *spaced cleavage*[1] planes of discontinuity are spaced at finite intervals, however small. Cleavage planes are thus potential planes of parting. Any actual fracturing along cleavage planes is subsequent and incidental. Spaced cleavage includes slip cleavage (Dale) and fracture cleavage (Leith).

Foliation: Following Fairbairn (1949, p. 5) any planar anisotropy in a rock due to the presence of parallel planar fabric elements is a *foliation.* Foliation may be the result of sedimentary processes, of recrystallization (continuous cleavage, schistosity) or of mechanical deformation (all kinds of cleavage).

Schistosity is foliation by dimensional parallelism of platy minerals, or by orientation of rod-shaped minerals along planes. In the case of fine-grained platy minerals, schistosity is synonymous with continuous cleavage.

Coordinates a,b,c are used to describe the symmetry of rock fabric at a point or within a fabric domain. The most prominent foliation is selected as the plane of *a* and *b*, or the *ab plane.* The most prominent symmetry plane perpendicular to *ab* is selected as the *ac* plane. Thus, *a*, *b*, and *c* are each fully determined. In addition, any set of planes which introduce a mechanical anisotropy into the fabric are known as *s* planes. Usually, stratification is labelled *ss*, and subsequently formed *s*-planes s_1, s_2, s_3, etc., in order of formation. Theoretically, this definition includes fracture planes. It is becoming customary, however, to restrict

[1] Chidester (1962, p.17) proposes classification of cleavages into "spaced" and "continuous." This non-genetic classification has great merit. Chidester uses "schistosity" as a synonym for cleavage as here defined, but agrees (oral communication, 1963) that "cleavage" may be preferable.

the designation "*s*" to closely spaced planar discontinuities such as foliations, cleavages and schistosities.

The kinematic axial cross is used to describe symmetry of *movement*. The plane of movement or gliding is the kinematic *ab* plane, the gliding direction is *a*, and maximum deformation is in the *ac* plane, which is the only plane of deformation in biaxial deformation. The normal to *ac* will then be *b*. In biaxial deformation there is no movement along *b*. *b* may also be an axis of rotation (*B*).

Foliation

At least four different *s*-surfaces have been observed in the Hardwick quadrangle. Primary (bedding) surfaces are designated *ss*, secondary surfaces, according to presumed relative age, s_1, s_2, and s_3. The only safe way to identify bedding in the Hardwick area is by lithologic contrast. Schistosity often simulates bedding to a remarkable extent (Pl. 2, in pocket).

One *s*-surface is present in practically every outcrop of metasedimentary rock; it is a schistosity and it is designated as s_1, because it is always the oldest secondary foliation present. This surface is displaced in many outcrops by either one or two spaced cleavages, s_2 and s_3. The presence of two spaced cleavages seems to be mainly confined to a north-south trending zone about 2–3 miles wide which centers on the Northfield Formation outcrop. The best exposures exhibiting multiple cleavages are along State Route 14 north of Hardwick, which follows the strike of the Northfield Formation. Nevertheless, two slip cleavages may be observed in exposures far distant from the Route 14 zone. Such occurrences are so sporadic that it has not been possible to determine whether they are of local or regional significance. Each set of foliations is associated with genetically related linear structures. Descriptions follow.

(a) *Pre-Silurian rocks.* In this zone the most commonly observed foliation is the schistosity, s_1. Bedding and spaced cleavage are rarely seen in outcrop. s_1 is axial plane cleavage related to minor folds in *ss*, but most commonly s_1 is parallel to *ss:* it is essentially a bedding schistosity, but not a mimetic schistosity.

In its rare occurrences within the Stowe Formation (notably at the top of Mt. Norris), a later spaced cleavage is axial plane cleavage to chevron folds of a type that is common in the Green Mountain anticlinorium (Chidester, 1953; Dennis, 1961). This cleavage is here named "Green Mountain cleavage" until its age relations have been discussed, and a suffix number assigned.

In the Missisquoi Formation s_1 remains a schistosity. This schistosity is often parallel to the bedding and can sometimes be observed to be axial plane cleavage to related minor folds. However, the characteristic "pinstripe" facies of the Moretown Member is characterized by fine layering which usually is *not* bedding, but rather, bedding drawn out parallel to a steep schistosity. This type of layering has been called transposition layering by Knopf and Ingerson (1938, p. 189–190).

Toward the western outcrops of the Missisquoi Formation, a slip cleavage whose style resembles that of Green Mountain cleavage becomes abundant. The resemblance rests in the geometric similarity of the chevron-like minor folds generated, in the rather wide spacing of cleavage planes (about 1/10 to 1/20 inch), and its post-garnet age. A comparison by means of fabric diagrams would be inconclusive because of the wide zone in the Stowe Formation in which no slip cleavage can be observed. This cleavage apparently is absent in the Willoughby arch zone, but has recently been identified by Dennis in the Gile Mountain Formation near Graves School in the Vermont portion of the Littleton quadrangle.

In the easternmost outcrops of the Missisquoi Formation, a second spaced cleavage appears. This will be dealt with in section (b) below.

(b) *Silurian and later rocks.* In these rocks the tectonic style and the rock fabric are dominated by the Willoughby arch to the east. The circumstance that the doming tectonics seem to begin with the Silurian rocks is largely coincidental; indeed, the influence of the doming does extend into the Ordovician Missisquoi Formation, and that of the Green Mountains into the Waits River Formation. The writers believe that this change in tectonic style is brought out by the influence of the marble interbeds in the Waits River Formation. Dennis (1956) has given evidence that the more mobile marbles flowed differentially away from the crest of the Willoughby arch during the latter's formation, and thus profoundly influenced the deformation pattern of the mantling rocks.

The schistosity, s_1, persists in the rocks of the Willoughby arch, and normally remains parallel to the bedding; as in the older rocks, it is the axial plane cleavage to related intrafolial minor folds, and thus is tectonic, and not mimetic. Such minor folds tend to plunge at lower angles than those in the rocks to the west.

As defined above, schistosity is that foliation which is due to the presence of more or less platy minerals. In the post-Silurian rocks the controlling mineral in pelites is sericite; in some quartzites it is biotite.

The foliation of these quartzites is frequently accentuated by quartz layers a few millimeters thick. These features tend to give secondary foliation in quartzite the appearance of bedding. Recrystallized limestones are sometimes foliated by parallelism of micas, but more often the foliation is produced by intimate banding of calcite and quartz layers on a microscopic scale. This is accentuated by a noticeable flattening of quartz and calcite grains parallel to the foliation planes. Narrow stringers of calcite and/or quartz parallel to the foliation are characteristic of the siliceous recrystallized limestones; this gives the foliation of the recrystallized limestones its macroscopic expression. The most striking feature of the recrystallized limestone foliation is that it often delineates considerable deformation within the rock, whereas pelites in contact with the recrystallized limestones show little or no disturbance. Frequently, even with the most intense deformation within the recrystallized limestones, their contacts with other lithologies are undisturbed. More often than not the foliation within the recrystallized limestones is discordant towards their contact with other lithologies. This discordance is usually at a very small angle (2–5 degrees is a common range), but it is persistent. In thick bands of recrystallized limestone, undeformed foliation has the appearance of bedding. s_1 also appears as transposition layering (Knopf and Ingerson, 1938, p. 189–190).

In the lower metamorphic grades, the sericite schistosity of the argillites passes into "slaty cleavage." "Slaty cleavage" here merely refers to schistosity which gives the rock the characteristic appearance and cleavability of slate; structurally it does not differ from the sericite schistosity of the phyllites.

A slip cleavage that is uniquely related to the Willoughby arch has been described by previous workers along that feature, more especially by White (1949) and Dennis (1956). Until the age relations are clarified in a later section, this foliation will be referred to as the "doming cleavage."

The doming cleavage is spaced cleavage in the rocks flanking the Willoughby arch, but it becomes a true schistosity near the crest of the arch, as a result of a higher grade of metamorphism (White, 1949; Dennis, 1956). This zone of higher metamorphism barely reaches the borders of the Hardwick quadrangle.

Figure 2 shows, in cross-section, the geometric pattern of the doming cleavage, together with its kinematic interpretation. The dip of the cleavage is away from the crest on both flanks, and always less steep

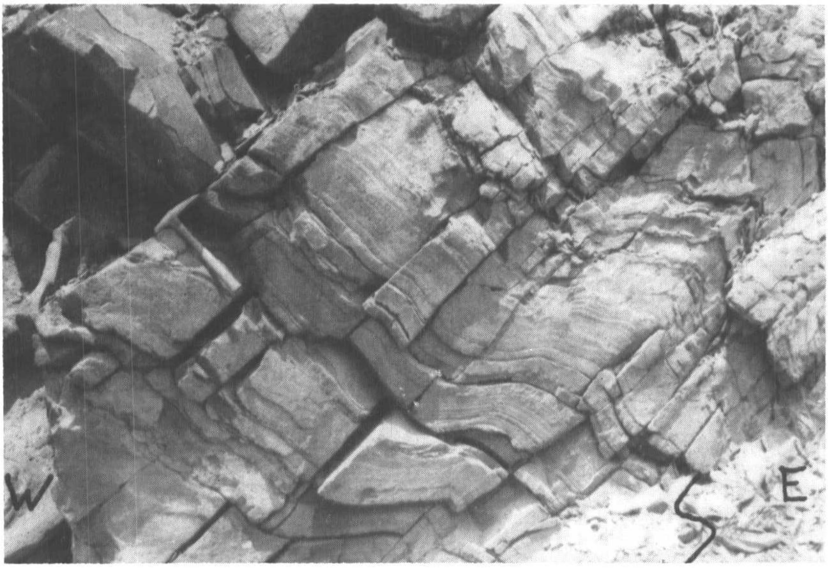


Plate 4. Westward dipping doming cleavage (s_2) in Ayers Cliff member on the road from Albany to South Albany. Pattern of folding in black ink.

than the bedding on either flank (except near the crests of minor folds). Minor folds to which the doming cleavage forms an axial plane cleavage face downdip, away from the crest of the arch (see Fig. 2).

The doming cleavage is developed principally in the phyllites and also in the fine-grained biotite quartzites. This cleavage seems to disappear at the contact of the phyllites and quartzites with the more coarsely recrystallized limestones. Fabric analysis (Dennis, 1956) indicates, however, that the calcite grains of the marbles so reoriented themselves that a preferred glide plane was rotated parallel to the doming cleavage. Thus, kinematically, the same laminar gliding took place in both lithologies, although different mechanisms usually were operative (Pl. 4 and 5).

Beyond the borders of the Hardwick quadrangle, the doming cleavage extends eastward as far as a more easterly outcrop of the Ordovician/ Silurian unconformity (Monroe contact, Eric and Dennis, 1958).

(c) *Age relations of the* s-*surfaces.* Exposures revealing two spaced cleavages are not common. In most cases it is difficult if not impossible in such exposures to differentiate between Green Mountain or doming cleavage with any degree of certainty. Separation by statistical diagrams could not be undertaken, because of insufficiency of suitable read-

Plate 5. Steeply dipping foliation s_1 in Barton River member east of Miles Hill. Note gently dipping bedding crossing the picture from west to east, and deep weathering along both bedding and cleavage planes.

ings available in the central zone of overlap; readings away from the zone of overlap do not help. The most useful criteria for separating doming cleavage from Green Mountain cleavage are related to style: the greater separation between the cleavage planes of the Green Mountain cleavage, the latter's more chevron-like associated folds, and the dip: that of the Green Mountain cleavage usually remains above 60°, that of the doming cleavage is usually less than 60°. Also, the doming cleavage planes are more strictly parallel and individual planes are more persistent. Each one of these criteria taken singly is weak, but taken together they give a certain minimum degree of confidence when attempting to distinguish between the two styles. Only three or four exposures were observed in which such distinction was possible: all were along or close to Route 14. In these exposures Green Mountain cleavage appeared to displace doming cleavage; hence Green Mountain cleavage will be designated s_3, and doming cleavage will be s_2. As a confirmation, it was found that in thin section, garnets in the zone of s_2 are always post-cleavage, whereas those in the zone of s_3 are deformed by the cleavage, or impede cleavage planes, suggesting that they are older than s_3. This relationship assumes that all garnet porphyroblasts in the area are of the same age.

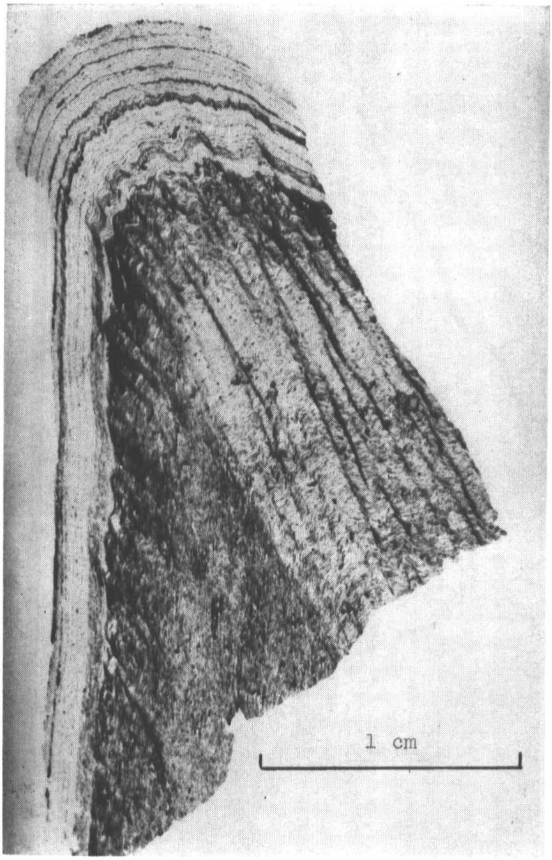


Plate 6. s_3 in hinge of minor fold. Missisquoi Formation, Route 14 west of Hardwick Lake. Quartz-chlorite-sericite-garnet schist. Note metamorphic differentiation parallel to cleavage planes (sericite bands alternate with predominantly granular ones), and deflection of cleavage by garnet.

It has been pointed out elsewhere, however, that garnets may have developed in *two* generations in north-central Vermont: one may be associated with Green Mountain deformation and the other with the development of the Willoughby arch (Konig, 1961). More detailed thin-section coverage is needed to establish the correct relations in north-central Vermont.

s_3 has a fairly consistent strike just east of north, and almost invariably a steep westerly dip. s_2 strikes just north of east in much of the eastern

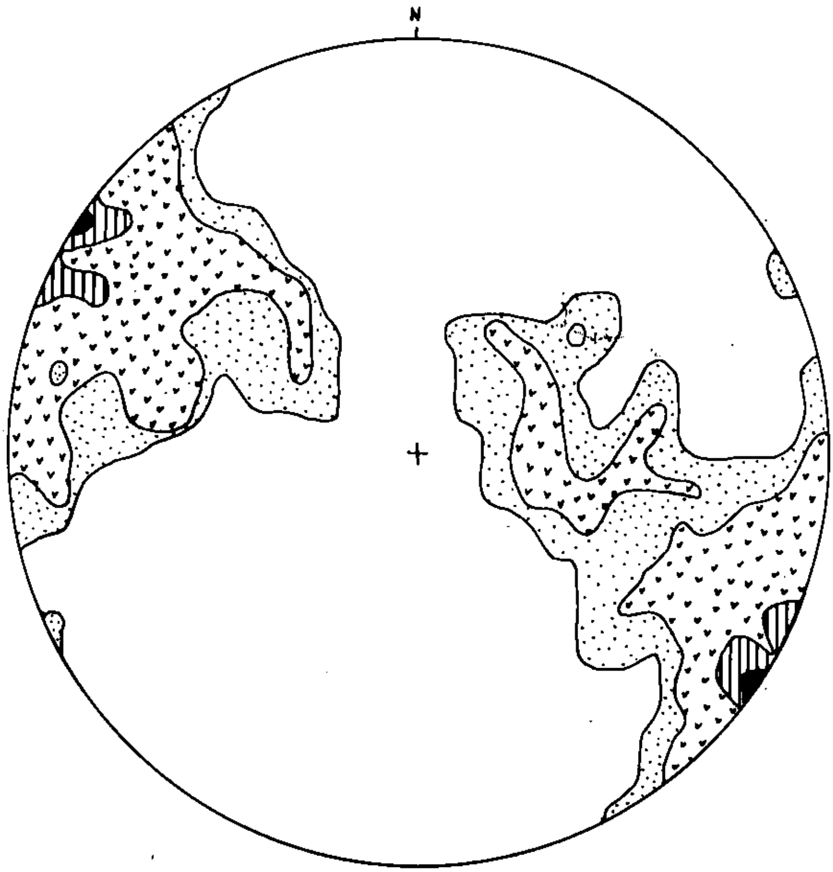


Figure 3. Stereogram of 183 poles of *s*-surfaces (*ss* and s_1) in the northeastern and eastern part of the Hardwick quadrangle. Contours 8, 6, 2, 1 per cent.

part of the area (see Pl. 2), but toward the west it swings around to a more northerly strike closely paralleling that of s_3. Its dip is usually less than 60°, and it flattens toward the east.

Figure 3 is the sterogram of poles of *s*-surfaces in the eastern and northeastern part of the quadrangle. s_1 and *ss* are plotted together, because they were found to lie along the same girdle, with similar distribution. The result is a simple girdle with a concentration in the region of steep dips. In the case of the slip cleavage poles, s_2 and s_3 are not differentiated, because this cannot be done satisfactorily on field evidence alone. In Fig. 4 the poles are believed to represent mainly s_2. The concentration

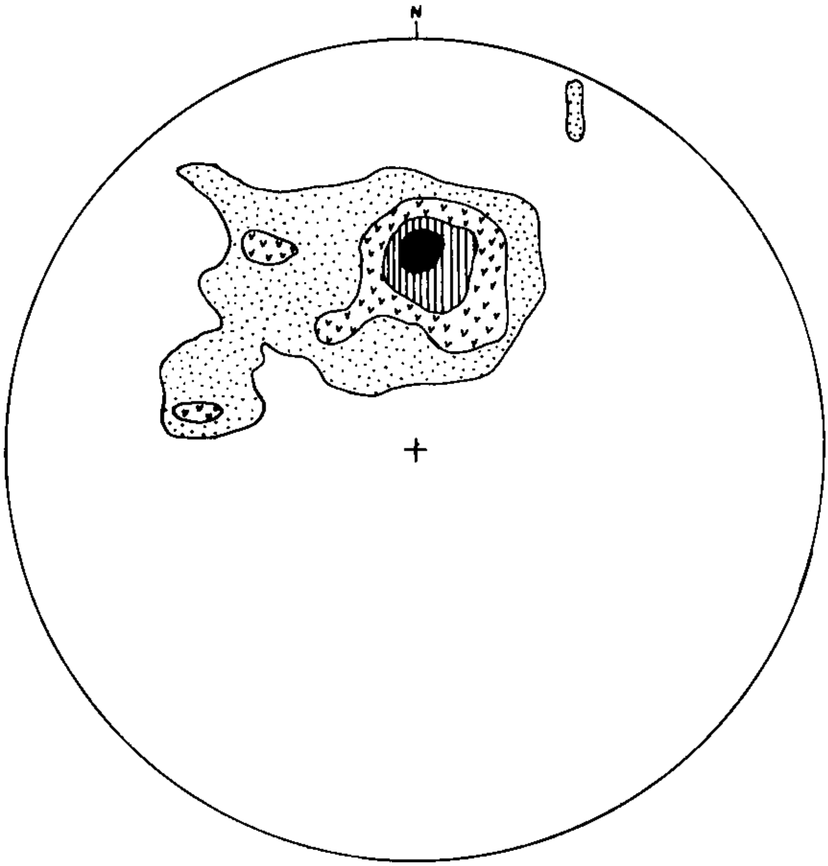


Figure 4. Stereogram of 83 poles of *s*-surfaces (s_2 and s_3) in the northeastern and eastern part of the Hardwick quadrangle. Contours 13, 10, 6, 2 per cent.

of slip cleavage poles in the north-northeasterly segment appears anomalous. However, if s_2 may be taken to represent doming cleavage, then this anomalous trend doubtless reflects a swing in the trend of the Willoughby arch immediately to the southeast of Hardwick. Nevertheless, the widespread occurrence of this anomalous trend (cf. Pl. 2) cannot be satisfactorily explained in this way. It will need further investigation by detailed tectonic analysis.

Although a number of minor folds are clearly formed by s_2, folding is not adequately reflected in Fig. 4; this suggests that, in the Hardwick area, deformation along s_2 is largely homogeneous.

Jointing

Joints are conspicuous in the field as well as on aerial photographs. On aerial photographs fractures show up as small linear depressions and sometimes as more dense lines of vegetation. Comparison of these air photo linears with joint measurements taken in the field indicates that their strikes are essentially parallel, thus validating the correlation between many air photo linears and jointing.

Although a detailed joint study has not been attempted in the Hardwick quadrangle, available field data have been plotted on an equal-area sterographic projection (Fig. 5). Analysis of Fig. 5 indicates that three principal joint sets are developed in the quadrangle. The best developed set strikes N.83°W. Two less well developed sets strike N.51°W. and N.60°E. All have a nearly vertical dip.

Major fold axes trend approximately N.10°E. in the southern third of the quadrangle, N.30°W. in the central third of the quadrangle and N.25°E. in the northern third of the quadrangle (see Pl. 1). Separate joint diagrams were prepared for each of these areas to determine the effect of this variation in strike on the orientation of the three principal joint sets. Comparison of these diagrams showed only minor differences in the joint distribution of each diagram, thus only one diagram may be used to represent the joint pattern in the Hardwick quadrangle (Fig. 5). The absence of any noticeable variation in the joint pattern in the three areas indicates that the jointing postdates the folding. The same relationship has been shown to exist in the Plainfield quadrangle (Konig, 1961).

Joint faces are generally smooth, except for local plumose structure (Hodgson, 1961), and are slightly sinuous along the strike. Nearly all of the rocks in the quadrangle (except the postkinematic plutonic rocks) have been intensely deformed and metamorphosed, but the joints which cut these rocks remain virtually undeformed and transect metamorphic minerals; we therefore conclude that jointing developed late in the deformational history of the area, and post-dates metamorphism.

The three sets of joints brought out by Fig. 5 may reflect compression in approximately a N.80°W.—S.80°E. direction. The N.83°W. joints are probably tension joints; the other two sets, N.51°W. and N.60°E. may represent the associated conjugate shear system (Anderson, 1951).

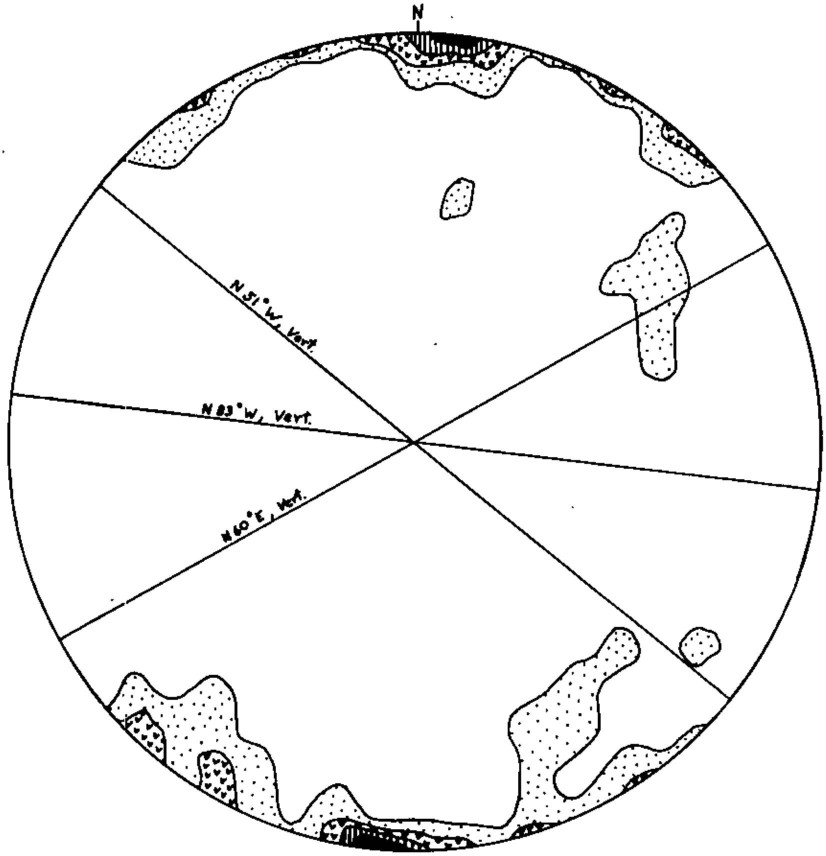


Figure 5. Stereogram of 100 poles of joints in the Hardwick quadrangle. Contours 8½, 6½, 4½, 2½ per cent.

LINEATION

1. *Fold axes.* Few folds associated with s_1 were observed. In the eastern area, their plunge is usually low and their trend north-northeast. Toward the west, their plunge steepens, and is dominantly northerly.

The dominant minor folds in the eastern area are associated with s_2. These face west and downward, away from the crest of the Willoughby arch. Their plunge is usually low, often gently northeast. Corrugations and s_1/s_2 intersections are normally parallel to the axial direction of these folds.

2. *Intersections of s-planes.* Intersections of foliations, and of foliations

and bedding, are nearly always parallel to the minor fold axes, wherever these features occur together. Often these intersections show as small crenulations in the dominant foliation. However, not infrequently there is divergence between intersection lineations and fold axes. Sometimes there are two intersection lineations, revealed by crenulations, due to the presence of multiple sets of s surfaces.

Movement Pattern

Theoretical Premises

All secondary foliation planes in the area are regarded as ab surfaces (cf. Goguel, 1945). This hypothesis is confirmed by the consistent observation that all secondary foliations in the area are parallel to the axial surfaces of related minor folds. The direction perpendicular to fold axes, and appropriate lineations where observable, are taken to indicate the direction of flow within ab. These simple premises lead to a movement picture for each of the secondary foliations.

Movement

(1) *Significance of* s_1. Throughout the area s_1 is normally a bedding schistosity. Hence we must assume widespread stretching and flattening along the bedding. Because s_1 does occur as axial plane cleavage in a number of places, it cannot be due principally to "load" or to mimetic crystallization.

Doming might be a cause of such stretching, but observable doming along the Willoughby arch is far more restricted in extent than s_1. Also, where doming is the cause of stretching, as has been suggested in the case of the Green Mountain anticlinorium (Dennis, 1964), linear features tend to form downdip, perpendicular to b. Features so aligned are not common in the Hardwick area.

In the pelites, s_1 might be interpreted as follows: during compaction and diagenesis of the sediments, vertical load caused thinning of the beds. This is pure flattening without rotation. When the argillaceous rocks came under the influence of regional metamorphism, the clay minerals were transformed into sericite. The resulting volume contraction originated ***within*** the rocks, and this deformation may, particularly in a lithologically heterogeneous succession, cause differential movements along bedding surfaces; this in turn, might lead to local small-scale folding (intrafoliate folds of Turner and Weiss, 1963).

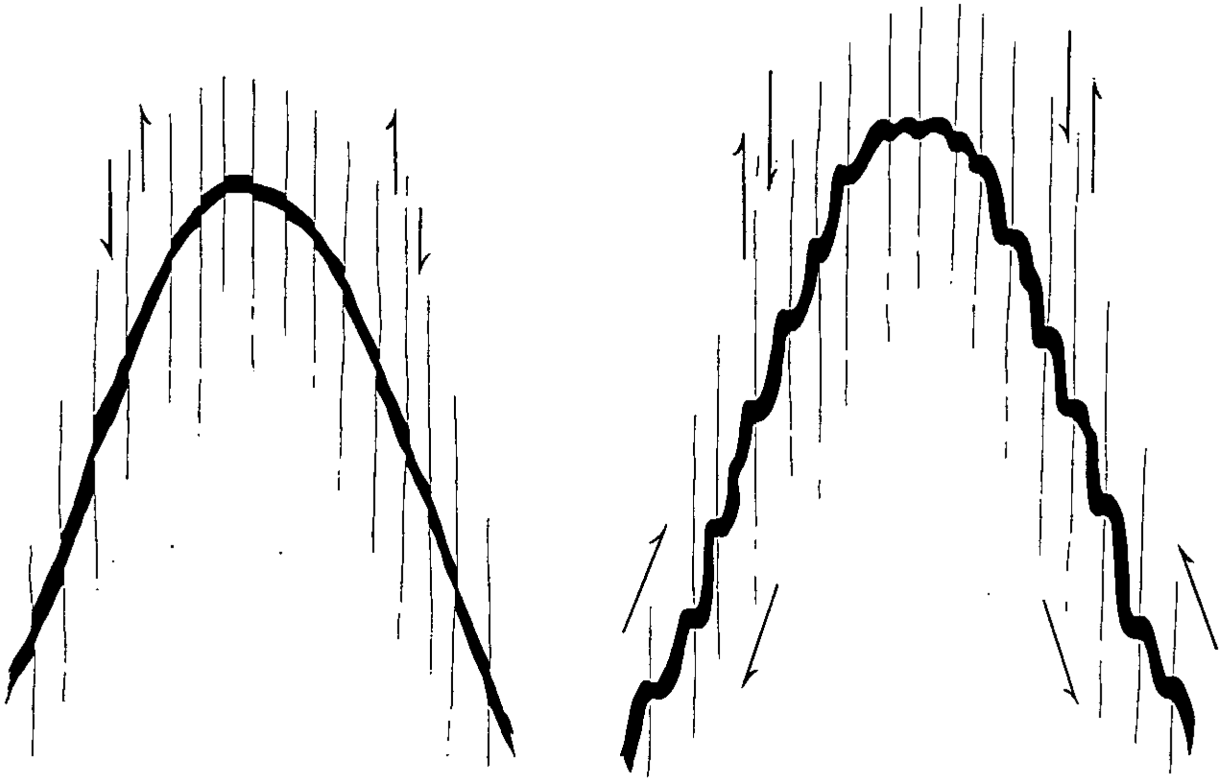
(2) *Significance of* s_2. s_2 appears to be confined to the Gaspé-Con-

necticut Valley synclinorium. Fig. 2 shows its probable genetic relationship to the Willoughby arch: the rocks must have flowed away from the crest of the rising arch, along s_2. The flow sense is given by the s_2-related minor folds which face downward, away from the crest of the arch (Dennis, 1956). Most of the flowage must have taken place in the siliceous recrystallized limestones, for these show intense internal deformation, to an extent rarely seen in the interbedded pelites. This appears to be an example of tectonic selection (Gallwitz, 1956).

s_3 is always very steep, and is related to upright shear folding. This implies an appreciable vertical component of movement. So, whether or not lateral shortening took place while s_3 was formed (there is no unequivocal evidence for this), independent vertical movement must be accounted for.

E. Cloos (1947) has shown, in the classical example of South Mountain, Maryland, that in irrotational flow lateral shortening must take place. Nevertheless, even in this instance Cloos recognized that some of the deformation must have been rotational (shear folding). The typical development of s_3 in the area here considered appears to be predominantly rotational. In the deformation pattern of Fig. 6, pre-existing designs would have been elongated in (rotational) simple shear, i.e. at an acute angle to the s_3 traces. The deformation pattern of s_3 leaves no alternative. The picture is confirmed by the occurrence elsewhere of faulting parallel to s_3. This situation may be explained by assuming active vertically directed differential movement or passive "escape" due to lateral shortening in the crust. Carey (1954; and personal communication, 1959) has shown how typical gneissic basement folds may form as a result of laminar flow, without lateral shortening. The phyllitic basement may deform in a similar manner; but here flowage occurs discontinuously along foliation surfaces. This mechanism has been described by Washburne (1940). Shear and flow folds may develop through heterogeneous differential movement along spaced parallel surfaces. But folding is only an effect of this deformation. There may be no folds at all, because deformation could be homogeneous. In fact, folding often outlines only a fraction of the total deformation that a rock has undergone (cf. Richter, 1959).

It would therefore seem that the deformation pattern in the Hardwick area is an expression of appreciable vertical primary movement. There is no direct evidence for lateral crustal shortening, but there is no evidence that such shortening might not have been a part of the overall deformation, and it might even have been important locally.



a. b.

Figure 6. Diagrammatic cross-sections showing "shear sense" in spaced cleavage. A. Normal shear sense; true shear folding. B. "Reverse" shear sense; hypothetical influence of drag. Probably due to flattening.

METAMORPHISM

General Statement

Bedrock in the Hardwick quadrangle, excluding Devonian plutonic rock, has been metamorphosed at least once and locally twice. The earlier stage of metamorphism was regional in extent, reaching a maximum in the axial region of the Green Mountain anticlinorium (Mt. Mansfield quadrangle) as well as in the Worcester Mountains (Montpelier quadrangle) and in the vicinity of Elmore Mountain (Hyde Park quadrangle). This regional metamorphism generally becomes less intense on both the eastern and western flanks of the Green Mountain anticlinorium. Rocks in the Hardwick quadrangle, which are on the eastern flank of the Green Mountain anticlinorium, have been regionally metamorphosed to the chlorite, biotite and locally garnet zone. The emplacement of Devonian plutonic rock appears to be associated with younger metamorphism on previously regionally metamorphosed rock. This younger metamorphism is best developed in the extreme southeastern part of the Hardwick quadrangle.

Early Metamorphism

Early regional metamorphism is most pronounced near the axial region of the Green Mountain anticlinorium. This metamorphic high (garnet grade) has been outlined by Christman (1959) in the Mount Mansfield quadrangle. Several miles southeast of this area in the Worcester Mountains (Montpelier quadrangle) Cady (1956) has mapped rocks which have been regionally metamorphosed to the garnet grade. In the Hyde Park quadrangle Albee (1957) has mapped garnet and kyanite isograds in the vicinity of Elmore Mountain. These metamorphic highs lie generally west of the present area of study and are associated with structural highs. South, southeast and east of the Hardwick quadrangle high-grade metamorphic rocks have been reported in the Plainfield (Konig, 1961), St. Johnsbury (Hall, 1959) and Lyndonville (Dennis, 1956) quadrangles. This high-grade metamorphism appears to be related to the intrusion of Devonian plutonic rock (Knox Mountain and Woodbury granodiorites) and not directly to the regional metamorphism described earlier. Inasmuch as high-grade metamorphism associated with Devonian plutonic rocks is poorly represented in the Hardwick quadrangle (see Pl. 1) it is not considered in detail.

Bedrock in the Hardwick quadrangle has been metamorphosed, for the most part, to the greenschist facies. Although chlorite, biotite and locally garnet, staurolite and amphiboles are present it has not been possible to establish isograds to represent these different intensities of metamorphism. Exceptions to the above are found in the extreme southeastern part of the quadrangle where the garnet and staurolite isograds have been established, and in the central portion of the quadrangle where the garnet isograde is shown (see Pl. 1). The more centrally located garnet isograd encloses an area of highly deformed rock. This area of deformation and associated metamorphism appears similar to areas located farther west in the Hyde Park quadrangle which have undergone early regional metamorphism.

The majority of the rocks in the present area of study have been metamorphosed to the biotite grade. Consequently argillaceous rocks characteristically contain quartz, muscovite (including sericite), chlorite, biotite and epidote. Locally these rocks contain minor amounts of porphyroblastic garnet, as, for example, those located in the vicinity of Eligo Pond in the central part of the quadrangle. Carbonate lithologies in the biotite zone contain a mineral suite which is controlled by the initial composition of the rock. If the carbonate rock originally contained quartz, calcite and minor amounts of argillaceous and iron oxide material, the resultant metamorphic rock would normally contain quartz and calcite as essential constituents and accessory sericite, chlorite and iron ore. Some of the more impure carbonate lithologies contain one or more of the following: phlogopite, tremolite, epidote, chlorite, quartz and iron ore.

Greenstones in the Moretown Member of the Missisquoi Formation contain a mineral suite which is suggestive of metamorphosed intermediate to basic igneous rocks. A representative mineral suite includes quartz, muscovite (including sericite), chlorite, epidote, albite, carbonate (calcite and/or ankerite) and accessory apatite and zircon. Greenstones in the Stowe Formation contain a similar mineral suite. Both areas of greenstone are confined almost wholly to the biotite zone of metamorphism. A more complete description of early regional metamorphism may be found in Cady (1956), Albee (1957) and Konig (1961).

Later Metamorphism

Later metamorphism is represented principally in the southeastern part of the area by the position of the garnet and staurolite isograds (see Pl. 1). Similar grades of metamorphism have been established in the Plainfield quadrangle to the south (Konig, 1961) and in the St. Johnsbury quadrangle to the southeast (Hall, 1959) and the mineralogy of these rocks described in considerable detail. Additional information regarding these higher grades of metamorphism is given for the adjacent Lyndonville area by Dennis (1956). Since this later grade metamorphism is poorly represented in the Hardwick area, the reader is referred to the above-mentioned reports for more complete treatment.

BIBLIOGRAPHY

ADAMS, C. B., 1845, First annual report on the geology of Vermont: Burlington.

ALBEE, A. L. 1957, Bedrock geology of the Hyde Park quadrangle, Vermont: U. S. Geological Survey Geol. Quad. Map GQ 102.

ANDERSON, E. M., 1951, The dynamics of faulting: Edinburgh, Oliver and Boyd, 191 p.

BILLINGS, M. P., 1956, The geology of New Hampshire, Part II bedrock geology: New Hampshire State Planning and Development Commission, 203 p.

BOUCOT, A. J., HARNER, R. S., MACDONALD, GORDON, MILTON, CHARLES, 1953, Age of the Bernardston formation (Abstract): Geol. Soc. America Bull., v. 64, p. 1397–1398.

CADY, W. M., 1950, Fossil cup corals from the metamorphic rocks of central Vermont: Am. Jour. Sci., v. 248, p. 488–497.

—— 1956, Bedrock geology of the Montpelier quadrangle, Vermont: U. S. Geol. Survey Geol. Quad. Map GQ 79.

—— 1960, Stratigraphic and geotectonic relationships in northern Vermont and southern Quebec: Geol. Soc. America Bull., v. 71, p. 531–576.

CADY, W. M., ALBEE, A. L., CHIDESTER, A. H., 1963, Bedrock geology and asbestos deposits of the upper Missisquoi Valley and vicinity, Vermont: U. S. Geol. Survey Bull. 1122-B., 78 p.

CAREY, S. W., 1953, The rheid concept in geotectonics: Jour. Geol. Soc. Australia, v. 1, p. 76–117.

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.

CHRISTMAN, R. A., 1959, Bedrock geology of the Mt. Mansfield quadrangle, Vermont: Vt. Geol. Survey Bull. 12, 75 p.

CLOOS, E., 1946, Lineation: Geol. Soc. America Mem. 18, 122 p.

—— 1947, Oolite deformation in the South Mountain fold, Maryland: Geol. Soc. America Bull., v. 58, p. 843–918.

COOKE, H. C., 1950, Geology of a southwestern part of the Eastern Townships of Quebec: Geol. Survey Canada Mem. 257, 142 p.

CURRIER, L. W., and JAHNS, R. H., 1941, Ordovician stratigraphy of central Vermont: Geol. Soc. America Bull., v. 52, p. 1487–1512.

DALE, T. N., 1909, The Granites of Vermont: U. S. Geol. Survey Bull. 404, p. 25–26.

DENNIS, J. G., 1956, The geology of the Lyndonville area, Vermont: Vt. Geol. Survey Bull. 8, 98 p.

—— 1959, a revision of the lower Paleozoic stratigraphy in eastern Vermont: a discussion: Jour. Geol., v. 67, p. 583–584.

—— 1961, Zum Gebirgsbau der nördlichen Appalachen: Geol. Rundsch., v. 50, p. 554–577.

—— 1964, Geology of the Enosburg Area, Vermont: Vt. Geol. Surv. Bull. 23, 56 p.

DOLL, C. G., 1943, A brachiopod from mica schist, South Strafford, Vermont: Am. Jour. Sci., v. 241, p. 676–679.

—— 1944, A preliminary report of the geology of the Strafford quadrangle: Vt. State Geol., 24th Biennial Report, 1943–44., p. 14–28.

—— 1951, Geology of the Memphremagog quadrangle and the southeastern portion of the Irasburg quadrangle, Vermont: Vt. Geol. Survey Bull. 3, 113 p.

ERIC, H. H., and DENNIS, J. G., 1958, Geology of the Concord-Waterford area, Vermont: Vt. Geol. Survey Bull. 11, 66 p.

FAIRBAIRN, H. W., 1949, Structural petrology of deformed rocks: Cambridge; Addison-Wesley Press, Inc., 344 p.

GALLWITZ, H., 1956, Über tektonische Selektion: Geotektonisches Symposium zu Ehren von Hans Stille, Stuttgart, p. 20–37.

GOGUEL, J., 1956, Sur l'origine mécanique de la schistosité: Soc. Geol. France Bull., v. 15, p. 509–522.

HALL, REV. S. R., 1861, Report relating to the geology of northern Vermont: Report on the geology of Vermont, v. 2, p. 721.

HALL, L. M., 1959, The geology of St. Johnsbury quadrangle, Vermont and New Hampshire: Vt. Geol. Survey Bull. 13, 105 p.

HAWES, G. W., 1878, Mineralogy and lithology: Geology of New Hampshire, v. 3, part 4, p. 203.

HITCHCOCK, E., 1861, Report on the geology of Vermont: Claremont, New Hampshire, 2 vols., 982 p.

HODGSON, G. W., 1961, Regional study of jointing in Comb Ridge-Navajo Mountain area: Am. Assoc. Petrol. Geologists, v. 45, p. 1–38.

HUNT, T., 1854, On some of the crystalline limestone of North America: Am. Jour. Sci., 2nd ser., v. 18, p. 193–200.

JOHANNSEN, A., 1932, A descriptive petrography of the igneous rocks: Univ. of Chicago Press, v. 2, 428 p.

KAY, G. M., 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

KNOPF, E. B., and INGERSON, E., 1938, Structural petrology: Geol. Soc. America Mem. 6, 270 p.

KONIG, R. H., 1961, Geology of the Plainfield quadrangle, Vermont: Vt. Geol. Survey Bull. 16, 86 p.

KROUSTSCHOFF, K. DE., 1886, Note sur le granite variolitique de Craftsbury en Amérique (Abstract): Am. Nat., v. 20, p. 275–276.

KRYNINE, P. D., 1948, The megascopic study and field classification of sedimentary rocks: Jour. Geol., v. 56, p. 130–165.

KULP, J. L., 1961, Geologic time scale: Science, vol. 133, No. 3459, p. 1105–1114.

LAROCHELLE, A., 1962, Palaeomagnetism of the Monteregian Hills, southeastern Quebec: Geol. Surv. Canada, Bull. 79, 43 p.

LOGAN, W. E., 1863, Geology of Canada: Geol. Survey Canada Prog. Report to 1863, 983 p.

LYONS, J. B., JAFFE, H. W., GOTTFRIED, DAVID, and WARING, C. L., 1957, Lead-alpha ages of some New Hampshire granites: Am. Jour. Sci., v. 255, p. 527–546.

McCORMICK, C., 1886, The inclusions in the granite of Craftsbury, Vermont: Proc. Acad. Nat. Sci., Philadelphia, p. 19–24.

MURTHY, V. R., 1957, Bedrock geology of the East Barre area, Vermont: Vt. Geol. Survey Bull. 10, 121 p.

—— 1958, A revision of the lower Paleozoic stratigraphy in eastern Vermont: Jour. Geology, v. 66, p. 276–287.

—— 1959a, A revision of the lower Paleozoic stratigraphy in Vermont: a reply to discussion by Walter S. White: Journal Geology, v. 67, p. 581–582.

—— 1959b, A revision of the lower Paleozoic stratigraphy in eastern Vermont: a reply to discussion by John G. Dennis: Jour. Geology, v. 67, p. 584.

OSBERG, P. H., 1952, The Green Mountain anticlinorium in the vicinity of Rochester and East Middlebury, Vermont: Vt. Geol. Survey Bull. 5, 127 p.

RICHARDSON, C. H., 1902, The terranes of Orange County, Vermont: Vt. State Geol., 3rd Report, p. 61–101.

—— 1906, The areal and economic geology of northeastern Vermont: Report of the Vt. State Geologist, No. 5, 1905–06, p. 63–115.

—— 1924, The terranes of Bethel, Vermont: Vt. State Geologist 14th bienn. report, 1923–24, p. 77–103.

RICHTER, D., 1959, Tektonisch deformierte Wurzelstubben im Westfal der Plattbergschachte (Niederrhein): N. Jb. Geol. Palaent., Mh. No. 8, p. 367–380.

Rosenbusch, H., 1907, Mikroskopische Physiographie: v. 2, p. 92.

SANDER, B., 1948–1950, Einführung in die Geügekunde der geologischen Körper: Springer Verlag, Vienna, v. 1, 215 p., v. 2, 409 p.

STONE, S. W., and DENNIS, J. G., The geology of the Milton quadrangle, Vermont: Vermont, Geol. Surv. Bull., in press.

TURNER, F. J., and WEISS, L. E., 1963, Structural analysis of metamorphic tectonites: McGraw-Hill, 545 p.

VERMONT, GEOL. SURV., 1961, Centennial Geological Map of Vermont: Compiled and edited by Charles G. Doll, and others; scale 1:250,000.

WASHBURNE, C. W., 1940, Plastodynamics as indicated by geologic structure: Am. Geophys. Union Trans. 21st Ann. Mtg. p. 700–719.

WHITE, W. S., 1949, Cleavage in east-central Vermont: Trans. Am. Geophys. Union, v. 30, p. 587–594.

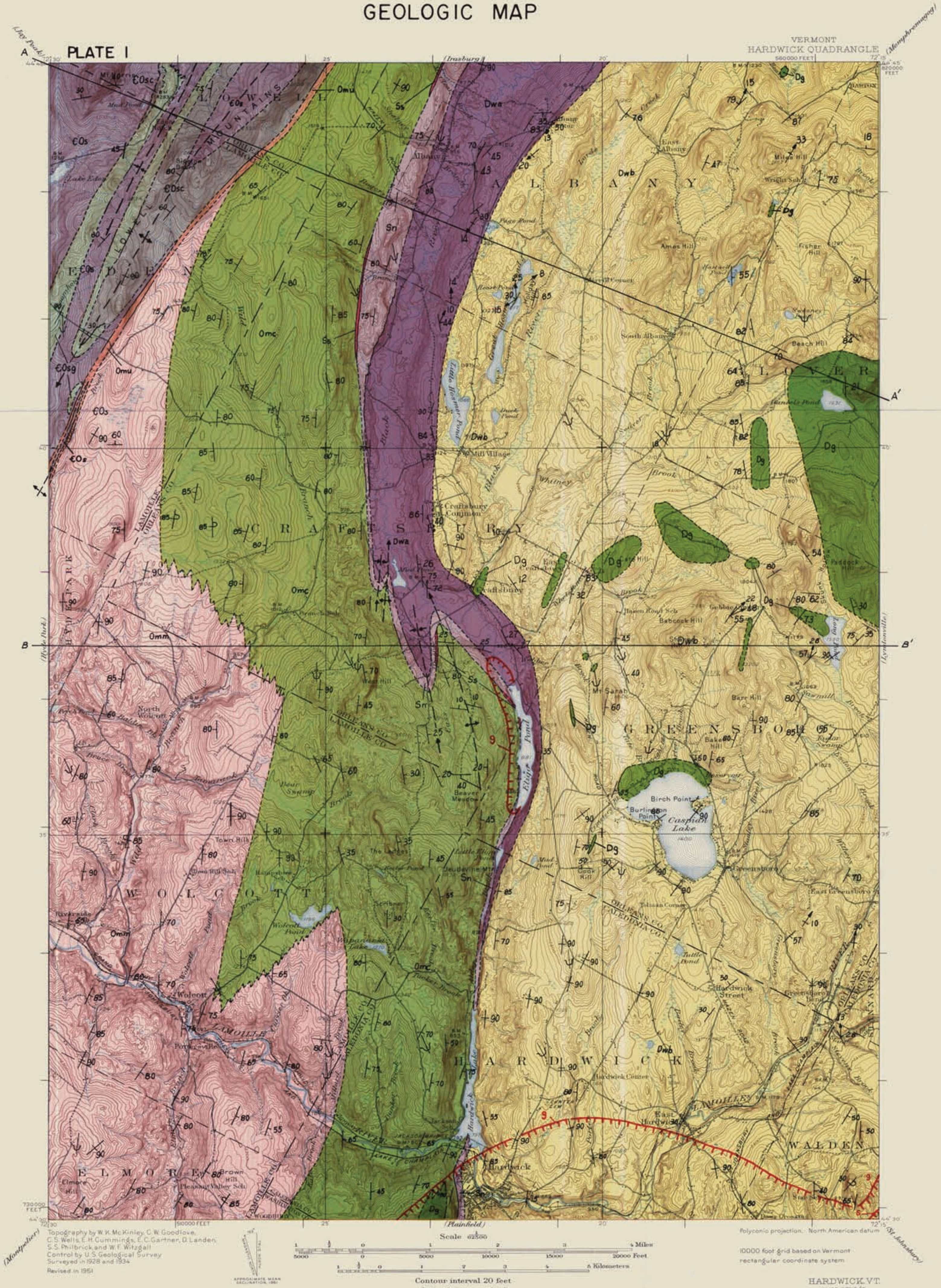
—— 1959, A revision of the lower Paleozoic stratigraphy in eastern Vermont: a discussion: Jour. Geology, v. 67, p. 577–581.

WHITE, W. S., and JAHNS, R. H., 1950, Structure of central and east-central Vermont: Jour. Geol., v. 58, p. 179–220.

WOODLAND, B. G., 1962, Lamprophyric dikes of the Burke area, Vermont: Am. Mineralogist, v. 47, p. 1094–1110.

GEOLOGIC MAP

PLATE I



LEGEND

Dg

POST-KINEMATIC PLUTONS
(New Hampshire plutonic series) Granodiorite, quartz monzonite, orbicular granite at Craftsbury.

Dwb / Dwa

WAITS RIVER FORMATION
Dwb, interbedded siliceous marbles, phyllites and quartzites (Barton River facies). Dwa, Ayers Cliff member: dominantly calcareous, with local abundance of polygenous pebbles and boulders (Irasburg conglomerate facies).

Sn

NORTHFIELD FORMATION
Dark gray slate, wider and increasingly calcareous toward the north.

Ss

SHAW MOUNTAIN FORMATION
Limestone, greenstone, conglomerate.

UNCONFORMITY?

Omm / Omc / Omu

MISSISQUOI FORMATION
Omm, "Pinstripe" granulite and slate (Moretown facies); Omc, abundant greenstone sills and dikes (Cram Hill facies); Omu, Umbrella Hill conglomerate: quartz pebble conglomerate.

ЄOsg / ЄOs / ЄOsc

STOWE FORMATION
Greenish quartz-chlorite-sericite phyllite with quartz bands; ЄOsg, greenstone; ЄOsc, carbonaceous phyllite and slate.

MAP SYMBOLS

- Well-defined contact
- Inferred contact
- Dip and strike of beds
- Strike of vertical beds
- Plunge and trend of fold axes
- Trend of glacial striations
- Abandoned mine or prospect
- Almandine isograd
- Staurolite isograd

GEOLOGY BY R.H. KONIG and J.G. DENNIS

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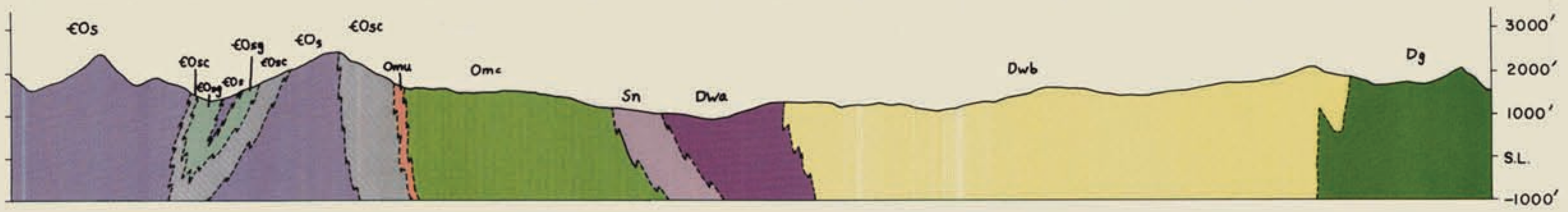
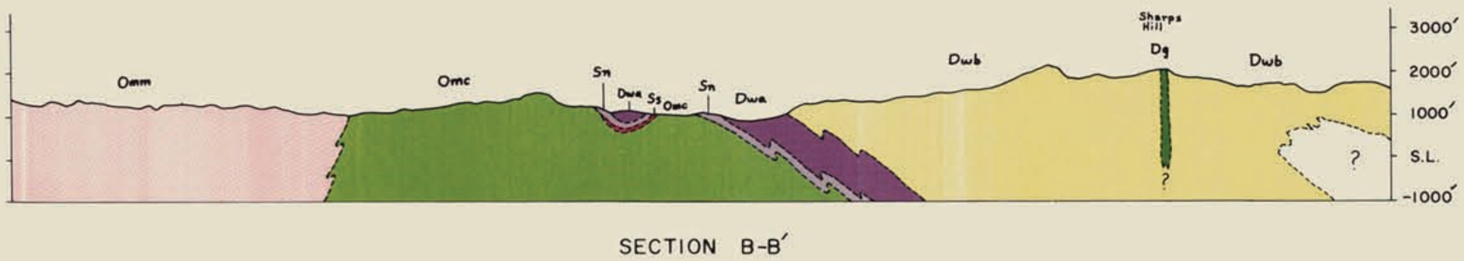
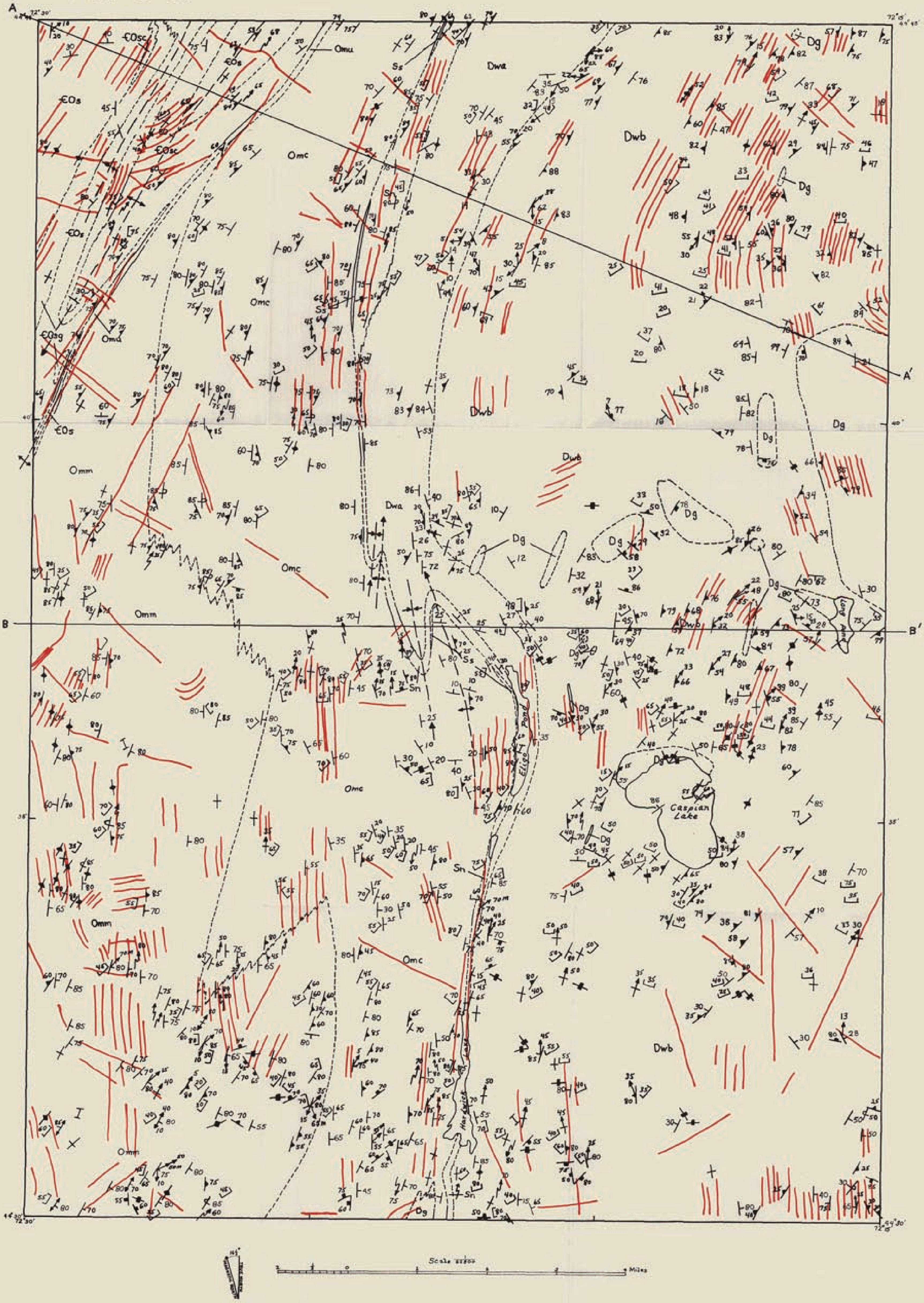


SECTION A-A′



SECTION B-B′

PLATE 2



TECTONIC MAP

EXPLANATION

LITHOLOGIC UNITS

Dg — GRANODIORITE

Dwb, Dwa — WAITS RIVER FM.

Sn — NORTHFIELD FM.

Ss — SHAW MOUNTAIN FM.

Omm, Omc, Omu — MISSISQUOI FM.

Єos, Єosg, Єosc — STOWE FM.

SYMBOLS

20 Inclined, Vertical — ATTITUDE OF BEDDING (ss)

20 Inclined, Vertical — ATTITUDE OF SCHISTOSITY (s_1)

20 Inclined, Vertical — ATTITUDE OF SLIP AND FRACTURE CLEAVAGE (s_2; s_3)

20 Inclined, Vertical — ATTITUDE OF JOINTS

20, 20m Inclined, Horizontal — BEARING AND PLUNGE OF LINEAR ELEMENTS [crinkle axis, bedding—cleavage intersection and mineral streaks (m)]

20 Dextral, 20 Sinistral — BEARING AND PLUNGE OF MINOR FOLD

Anticline, Syncline — AXIAL TRACE OF FOLD SHOWING DIRECTION OF PLUNGE

AIR PHOTO LINEARS

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