GEOLOGY OF THE PLAINFIELD QUADRANGLE, VERMONT

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ABSTRACT

Ordovician, Silurian and probable Devonian sedimentary rocks have been deformed, metamorphosed and intruded by Devonian adamellite and granodiorite. The igneous and metamorphic rocks form part of the folded eastern limb of the Green Mountain anticlinorium which lies 15 to 20 miles to the west. Five mappable units in the quadrangle are from oldest to youngest, Missisquoi, Shaw Mountain, Northfield, Waits River and Gile Mountain formations. The Waits River and Gile Mountain formations have been repeated by the Brownington syncline which extends from the Memphremagog quadrangle southeastward through the Plainfield quadrangle. Other folds in the quadrangle include the Woodbury syncline and the Nichols anticline. These folds were developed during the early stage of regional deformation and metamorphism in east-central Vermont and trend subparallel to the axis of the Green Mountain anticlinorium.

A later stage of deformation and metamorphism, which is evidenced primarily by folding and porphyroblastic staurolite, garnet, diopside, actinolite and biotite, is associated with the emplacement of Devonian granitic rock. The structural and metamorphic features formed during this disturbance are superimposed on and tend to conceal earlier structures, particularly in the eastern part of the quadrangle. Although the later structures have a more variable strike than the early structures they generally indicate that the rocks to the east of the quadrangle rose with respect to the rocks within the quadrangle.

INTRODUCTION

Location

The Plainfield quadrangle, covering an area of approximately 215 square miles, is defined by latitudes 44° 15′ and 44° 30′ north and longitudes 72° 15′ and 72° 30′ west in east-central Vermont (Fig. 1). The area lies mostly within Washington and Caledonia counties and contains the

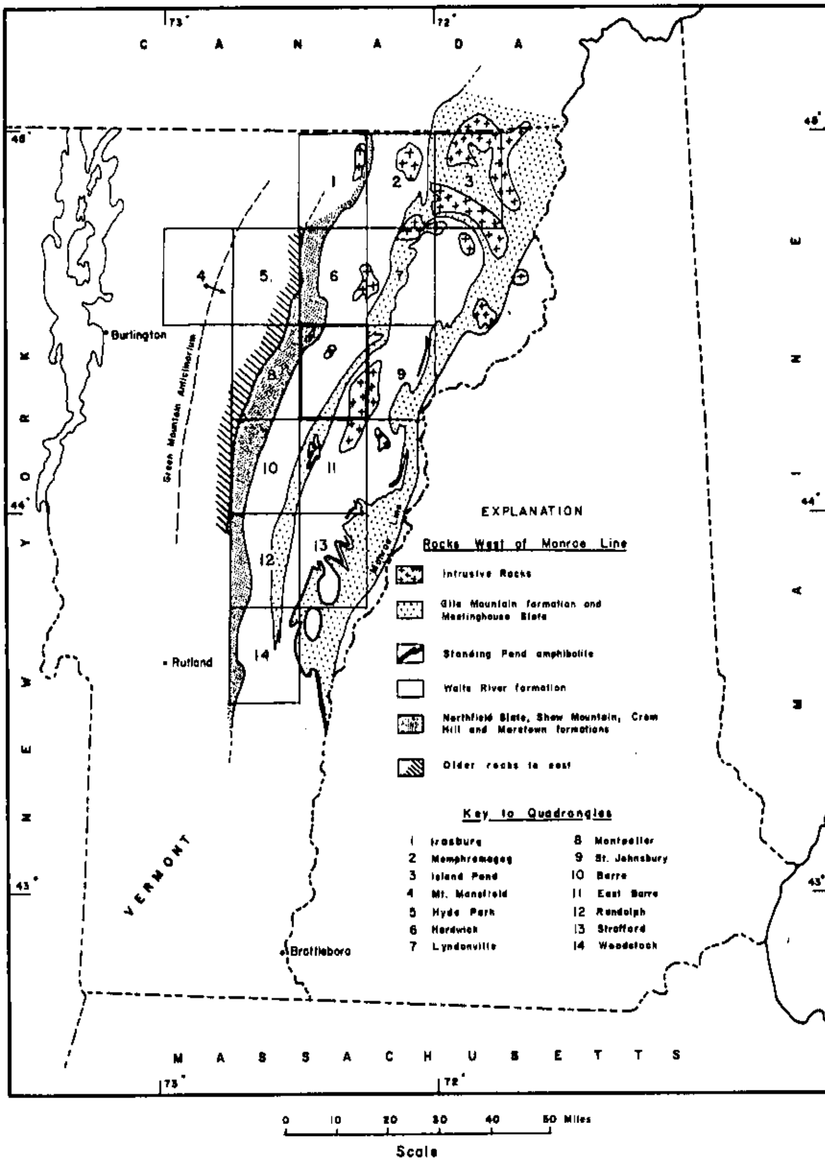


Figure 1. Regional geologic map showing location of quadrangles.

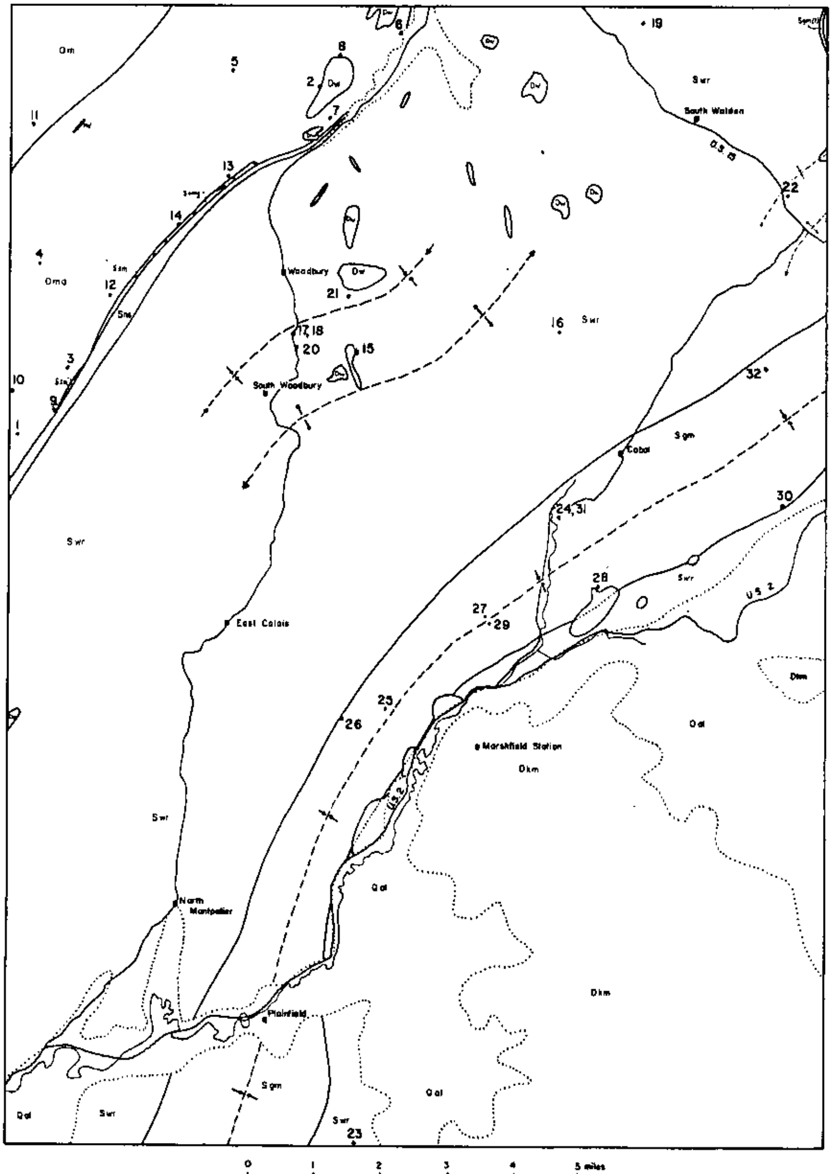


Figure 2. Locality map.

principal towns of East Montpelier, East Calais, Plainfield, Marshfield, Cabot, Lower Cabot, and Woodbury.

Geologic Setting

The Plainfield quadrangle is composed essentially of a thick sequence of folded and metamorphosed Lower Paleozoic sediments and undeformed Devonian granitic intrusions. These rocks are part of the Vermont Sequence which is separated from the New Hampshire Sequence by the Monroe line (Dennis, 1956). Between the Monroe line and the western edge of the Plainfield quadrangle the metasediments have been folded into the Browington syncline (Doll, 1951) and the Strafford-Willoughby arch (Eric and Dennis, 1958). Inasmuch as the Brownington syncline is the major structural element in the quadrangle it is considered in detail in the section on structural geology. The eastern limb of this syncline forms the western limb of the Strafford-Willoughby arch, the axis of which lies farther east in the St. Johnsbury quadrangle. West of the Brownington syncline a thick homoclinal sequence of steeply dipping rocks forms a part of the eastern limb of the Green Mountain anticlinorium. The axis of the anticlinorium lies approximately 15–20 miles west of the Plainfield quadrangle in the Mount Mansfield quadrangle and trends N. 5–15° E.

Previous Work

Adams (1845), Hitchcock (1861) and Richardson (1898) were among the earliest workers in Vermont to describe the geology in the vicinity of the Plainfield quadrangle. Even though these investigations were reconnaissance in nature they marked the first attempt to subdivide the rocks in this area. Included in these reports is not only a description of the stratigraphic sequence, but also brief accounts of the granitic rocks.

With the turn of the century a marked increase occurred in the amount of pertinent literature concerning the geology of the Plainfield quadrangle. Richardson (1902) began with a general discussion of the stratigraphic sequence on the eastern limb of the Green Mountain anticlinorium. In 1906 he discussed the physical and chemical relations between the Woodbury, Barre and Bethel granites and described the metasedimentary succession in the northeastern third of the quadrangle. Subsequently, Richardson (1914) described the geology and published the first large-scale geologic map at 1/62,500 for the townships of Hardwick and Woodbury, and in 1916 prepared a similar report for the townships of Calais and East Montpelier. Jones (1916), who had been a member of Richardson's field party, published a study of the physiography of the

Hardwick and Woodbury townships. Because of inadequate base maps it was difficult for these early workers to ascertain the position of lithologic boundaries, which combined with recent stratigraphic and structural advancements in Vermont, has necessitated a restudy of these areas.

Dale (1923) mentioned both the Hardwick and Woodbury granites in his comprehensive report on the granites of New England, and more recently Balk (1926) published a detailed structural study of the Woodbury, Barre and Bethel granites with a brief description of their relationship with the adjacent metasediments. Maynard (1934) and Chayes (1950 and 1952) report on petrographic studies of many Vermont "granites" which include specimens from the Woodbury granite in the Plainfield quadrangle.

Currier and Jahns (1941) and White and Jahns (1950) have contributed several stratigraphic and structural relationships which have facilitated the geologic mapping in much of east-central Vermont.

More recently, geologic studies of nearby quadrangles have been completed which consider the stratigraphic and structural relationships in eastern Vermont. These include the Memphremagog quadrangle and the southeastern portion of the Irasburg quadrangle by Doll (1951), the Lyndonville quadrangle by Dennis (1956) and the Hyde Park quadrangle by Albee (1957). Similar reports by Cady (1956), Murthy (1957 and 1958) and Hall (1959) concerning the geology of the Montpelier, East Barre and St. Johnsbury quadrangles, respectively, are of particular interest because of their positions immediately west, south and east of the Plainfield quadrangle. These reports deal in part with the same structural and stratigraphic problems that are found in the present area of study. The report by Eric and Dennis (1958), which in addition to considering the stratigraphy of the Concord-Waterford area, enumerates several structural relationships which are widespread in east-central Vermont.

Method of Study

Approximately 10 months were spent in the field from 1956 to 1958. During this time a detailed study was conducted on all but the Groton State Forest area in the southeastern corner of the quadrangle. This area was studied in reconnaissance because of prior work by Christman (1956).

Most of the mapping was done on a United States Geological Survey 15-minute sheet of the Plainfield quadrangle compiled in 1939–40 and revised in 1953. In areas of complex structure or closely spaced lithologic boundaries a three-times enlargement of this map was used. Aerial photographs were employed with considerable success in the less vegetated areas for location of outcrops and determining the trend of rock units and major joint sets. Most outcrops were located on the topographic map with the aid of an aneroid barometer. In heavily wooded regions of slight relief the pace and compass or resection method was employed.

Acknowledgments

The writer is indebted to Dr. Robert A. Christman under whose supervision this work was done and to Drs. Alfred L. Anderson and Charles M. Nevin for many helpful suggestions. Special acknowledgment is made to Wallace M. Cady and Alfred H. Chidester of the United States Geological Survey who gave freely of their time and knowledge of Vermont geology. Frequent discussions and field trips with V. Rama Murthy, Leo M. Hall, Ernest Ern Jr., Bruce Goodwin and Stephen Averill aided materially in the understanding of the geology of eastern Vermont.

The mapping project was supported by the Vermont Geological Survey under the direction of Dr. Charles G. Doll, State Geologist. Dr. Doll visited the writer frequently during the course of the field work and offered many helpful suggestions.

The writer was ably assisted in the field by Peter Stifel, Leonard Radinsky and Norman Specht during parts of the summer of 1957.

The kindness of many residents of Woodbury Lake is greatly appreciated, with particular thanks being extended to William Bartlett and family for their hospitality.

Physiography

Topography

The Plainfield area may be divided into three parts on the basis of topography. The southeast third of the quadrangle is dominantly composed of high, ovate hills with typically rounded tops and steep, irregular slopes. These hills are generally separated by broad U-shaped valleys. A second area of similar elevation has developed in the northwestern fourth of the quadrangle but, in general, broad valleys are lacking and small, poorly defined, narrow ridges are present instead of ovate hills. The third part is the intervening area, roughly 8 miles wide, extending northeast-southwest across the central part of the quadrangle. Here, the hills are commonly elongate, flat topped, and considerably lower in elevation than in the other two parts.

A good correlation exists between the bedrock and topography. The southeastern corner of the quadrangle is underlain predominantly by a uniformly resistant "granite". Consequently, the erosive action of ice and running water has been retarded in this area, thus accounting for its greater elevation. A similar situation occurs in the northwestern corner of the area where poorly fractured and very resistant quartzite controls most of the topography. In this area, however, small, poorly defined, narrow ridges have formed instead of the ovate hills which are characteristic of the southeastern corner of the quadrangle. These ridges are undoubtedly a reflection of the bedding and bedding schistosity in the quartzite. In contrast, the central topographic area is underlain principally by thin-bedded and well-fractured limestone, slate, schist and minor quartzite. These rocks offer less resistance to the destructive agencies and consequently are eroded to a lower more uniform elevation, with the trend of the narrow ridges controlled by steeply dipping primary and secondary foliation.

An exception to the uniform topography of the central topographic band is found between the town of Woodbury and Nichol's Ledge where several conspicuous hills with well-rounded summits have developed. These hills are composed of "granite" which is very similar in composition and texture to that found in the southeastern corner of the quadrangle.

Drainage

Portions of the drainage basins of the Winooski, Lamoille and Connecticut Rivers are situated in the Plainfield quadrangle. The divide which separates the southeasterly flowing streams of the Connecticut River basin, lies generally along a line between Little Spruce, Kettle and Owlshead Mountains and the southern end of Peacham Pond (Plate 1). In the northern fourth of the quadrangle the divide separating the Lamoille and Winooski drainage basins parallels the Woodbury Mountain Range from Hobart Mountain to Woodbury Mountain, thence, trends in an easterly direction towards Walden Heights. Inasmuch as the Winooski River drains most of the quadrangle its relationship to the underlying bedrock is considered in some detail below.

The Winooski River originates in the northeastern corner of the Plainfield quadrangle and flows west-northwest to Lake Champlain, whereas the underlying geologic structure trends approximately north-south; thus, the trend of the two features are about normal to each other. Inasmuch as the Winooski flows transverse to the underlying geologic structure it is an excellent example of a superposed river. In the Plainfield quadrangle this fact is demonstrated clearly where the Winooski cuts across the western margin of the Knox Mountain granite 1½ miles south of Marshfield. A slight westward shift of the river would have allowed the river to cut its valley into the presumably less resistant metasedimentary rocks of the Gile Mountain formation. As this did not occur it may be assumed that the Winooski River has been let down through an overlying cover onto the underlying geologic structure.

A deranged drainage pattern has been developed in many parts of the southeastern corner of the quadrangle. In this area the streams are generally not restricted to flow in any particular direction and are commonly associated with swampy conditions. Field work by the writer and Christman (1959, personal communication) indicates that these streams are flowing, for the most part, on unsorted glacial till, and are not presently being influenced by a fracture pattern in the underlying Knox Mountain granite.

Glaciation

The effects of continental glaciation are widespread in Vermont, and include erosional as well as depositional features. In the Plainfield area the erosive effect of glaciation is evidenced by glacial striae, glacially eroded valleys, and less commonly by roches moutonnées; abundant glacial till is indicative of widespread deposition.

An average of glacial striations in the quadrangle indicates a general S. 5° E. movement of the ice. At a given outcrop, however, striations trending in several directions often may be distinguished. Although they may range from S. 15° W. to S. 40° E., generally the range at a given locality is more restricted. The majority of these striae tend to fall into two groups, one with bearings of S. 10–40° E. averaging S. 25° E. and the other with bearings between due south and S. 15° W. averaging S. 7° W. Because of this grouping the question arises as to whether there was more than one direction of ice advance in the Plainfield quadrangle. Jones (1916, p. 92) and Richardson (1916, p. 117) have presented evidence for three separate groups of striations in the vicinity of the Plainfield quadrangle. These are, (1) S. 20° E. (oldest); (2) S. 30° W. (intermediate); and (3) due south (youngest). The S. 25° E. set of striations in this report is correlated with Jones' and Richardson's older set and the S. 7° W. set is correlated with both their intermediate and youngest set. This correlation necessitates an earlier ice advance out of the northwest followed by an influx of ice from the north or northeast.

A number of elliptical bedrock hills are located in the southeastern corner of the quadrangle and are interpreted as being roches moutonnées. Spice Mountain is the best example and several similar forms are represented by Deer and Little Deer Mountains and Silver Ledge. The profiles of these hills, when viewed from the northwest or southeast are asymmetrical, with steep southeast slopes and more gentle northwest slopes. The long axis of these features have a trend which varies from S. 40° E. at Spice Mountain to S. 15° E. at Deer Mountain. Thus, the general orientation of these hills indicates a major ice advance from the northwest in this part of the quadrangle.

Associated with the roches moutonnées are Osmore and Groton Ponds. They are both elongated in a S. 15° E. direction and lie in valleys which are typically U-shaped in cross section. Inasmuch as these U-shaped valleys have approximately the same strike direction as the nearby roches moutonnées they were probably formed by the same direction of ice movement.

In retrospect, glacial striations, roches moutonnées and glacially eroded valleys indicate at least one major direction of ice advance towards the southeast. The range of ice movement, as indicated by these features, is S. 15–40° E. Inasmuch as these features all indicate a definite southeasterly movement, it does not seem likely that glacial striations with bearings of due south to S. 15° W. would have developed at the same time. If this second set of striations is interpreted as not belonging to the ice advance that formed the roches moutonnées, U-shaped valleys and southeasterly trending set of striations, then Jones (1916) and Richardson (1916) are correct in assuming several periods of ice advance.

More than one direction of ice movement seems to be confirmed by the distribution of glacial erratics in the quadrangle. A very distinctive orbicular granodiorite crops out farther north at the town of Craftsbury in the center of the Hardwick quadrangle. Although the areal extent of this pluton is not definitely known because of the paucity of outcrops, it is probably confined to a few square miles. Erratic boulders of orbicular granodiorite have been observed at many localities in the Plainfield quadrangle. Most of these localities lie east of a north-south line drawn through a point about two miles west of Knob Hill Pond, which is located approximately one mile northwest of Marshfield. As the erratics occur south and slightly west of Craftsbury, the direction of transport must have been to the southwest in order to account for their present position in the Plainfield quadrangle. If this southwest displacement is

TABLE 1

Stratigraphic Sequence				Remarks
DEVONIAN	Lower . . . . ?	ST. FRANCIS GROUP	Gile Mountain fm. equals Westmore fm.	Fossil (Doll, 1943)
DEVONIAN	Lower	ST. FRANCIS GROUP	Waits River fm.	Fossils (Cady, 1950)
SILURIAN	Upper	ST. FRANCIS GROUP	Northfield fm.	
SILURIAN	Upper	?.	Shaw Mtn. fm.	Fossils (Konig and Dennis, in press)
SILURIAN	Middle			Unconformity
SILURIAN	Lower			
ORDOVICIAN	Upper			
ORDOVICIAN	Middle	MISSIS-QUOI fm.	Moretown mem.	Greenstone abundant in upper part.
ORDOVICIAN	Lower		Stowe fm.	Not present in mapped area.

attributed to a direction of ice advance, then a correlation between ice advance and the set of glacial striations having an average bearing of S. 7° W. is possible.

In summary it appears that the ice advanced in two directions in the

Plainfield quadrangle. The evidence indicating a southeast movement is one set of glacial striations, roches moutonnées and glacially eroded valleys. A second set of striations and the position of the erratic orbicular granodiorite boulders suggest a southwesterly advance. The southeasterly movement undoubtedly is associated with continental glaciation inasmuch as this general trend has been reported from many widely scattered areas in Vermont. The southwesterly movement appears to be local and very likely represents a later and minor ice advance, possibly controlled by the local topography. Such control may have been the low areas between Woodbury Mountain range and the hills in and around Groton State Forest. This depression would tend to funnel the ice in a slight southwest direction, roughly parallel to the Winooski River in the Plainfield quadrangle.

STRATIGRAPHY

General Statement

The stratigraphic sequence in the Plainfield quadrangle includes formations which range in age from Middle Ordovician to probable Lower Devonian: from oldest to youngest they include the Missisquoi, Shaw Mountain, Northfield, Waits River and Gile Mountain formations (Table 1). These formations have all been metamorphosed once and in most instances twice and have been intruded by acid igneous rocks of Devonian age. Two stages of deformation and metamorphism have folded the rocks so that they are now dipping nearly vertical or steeply to the west.

In this report the term limestone is used for carbonate rocks which are wholly recrystallized and technically should be called marble. In Vermont, the term marble generally is restricted to those rocks which are suitable for commercial quarrying.

Missisquoi Formation

Moretown Member

Distribution and Correlation

The Moretown formation (Osberg, 1952 and Cady, 1956) is equivalent to the Moretown member of the Missisquoi formation (Cady and others, in press). This stratigraphic nomenclature is used in accordance with the 1961 edition of the Vermont State Geological Map. The Moretown member extends from the Woodbury Mountains northwest beyond the edge of the Plainfield quadrangle. Cady (1956) has mapped this unit the length of the Montpelier quadrangle, and Albee (1957) extended it for approximately 8 miles farther to the western edge of the Hardwick quadrangle.

Farther north in the Irasburg and Memphremagog quadrangles Doll (1951) mapped a series of rocks which are stratigraphically equivalent to the upper portion of the Moretown member. He assigned these rocks to the Cram Hill member of the Missisiquoi formation (Cady and others, in press) because of their similarity to the rocks described at the type locality for the Cram Hill formation (Currier and Jahns, 1941) (Cram Hill member of this report). Thus, the upper part of the Moretown member must grade along strike into typical Cram Hill lithology somewhere in the Irasburg quadrangle.

Cady (1956) has reported a similar situation south of the Montpelier quadrangle. He states that the upper (eastern) part of Moretown member grades into typical Cram Hill lithology along strike, while the lower (western) part passes west of and stratigraphically below the Cram Hill into older rocks to the west.

Although the rocks of the Moretown are moderately well-exposed in the Plainfield quadrangle they are not easily accessible. For this reason an almost continuous section located several miles to the north in the Hardwick quadrangle, along Route 15, is suggested for study. Reconnaissance has shown that the section from Hardwick Lake to the town of Wolcott is very similar to the rocks of the Moretown member in the Plainfield quadrangle.

Type Locality (Osberg, 1952 and Cady, 1956)

The type locality for the Moretown is in eastern Moretown township on the east slope of the Northfield Mountains in the southwest quadrant of the Montpelier quadrangle. The member is mainly composed of a "granulite" which is commonly referred to as the "pinstripe" by recent workers in Vermont geology, and lenses of carbonaceous slate and phyllite which grade into the "granulite" chiefly along strike. Grit, conglomerate, metarhyolite tuff and crystalline limestone occur locally within the "granulite." The upper (eastern) portion of the member is characterized by abundant greenstone.

Lithologic Detail

In the Plainfield quadrangle, the Moretown consists of four predominant rock types. In order of decreasing abundance they are: (1) impure quartzite; (2) carbonaceous slate and phyllite; (3) greenstone; and

(4) subordinate amounts of limestone and metamorphosed dikes and sills.

Impure Quartzite—The impure quartzite, commonly called "pinstripe," is a thinly laminated, light-gray to greenish-gray, fine-grained rock. The laminated structure, resulting chiefly from alternate light-gray and greenish layers, is the most conspicuous feature of the rock. The light colored layers are generally 1–4 millimeters wide and are composed mainly of quartz with minor albite. The greenish layers are invariably thinner, seldom exceeding 1 millimeter in width, and are almost wholly made up of chlorite, muscovite and magnetite. In some of the coarser grained rocks occasional flakes of muscovite and/or biotite may show crosscutting relationships with the bedding and secondary foliation surfaces.

Although only two specimens of impure quartzite were studied in detail, it was found that in the light-colored layers both quartz, with poorly developed undulatory extinction, and albite are often recrystallized and slightly attenuated subparallel to the plane of foliation. The albite is untwinned and relatively fresh, containing only minor quantities of sericite and calcite as inclusions. Associated with the quartz and albite are a few larger grains of oligoclase (?) showing well-developed polysynthetic twinning. The oligoclase (?) represents detrital grains which have not been recrystallized. In contrast, the thin greenish layers consist mostly of sericite with lesser amounts of chlorite (both pennine and clinochlore) and magnetite. With an increasing amount of chlorite the layers become darker green making the "pinstripe" more conspicuous. In general it is estimated that muscovite (including sericite) comprises about 75 percent of the layer.

Other minerals occurring in accessory amounts in the impure quartzite (pinstripe) include tourmaline, apatite, zircon, iron ore and a carbonate. The estimated modes for a typical impure quartzite are listed in Table 2, specimen 148_S.

Field and laboratory work suggests that the trend of the laminations in the "pinstripe" are essentially parallel to bedding. In the field the laminae in the impure quartzite are oriented approximately parallel to the trend of juxtaposed lithologically dissimilar rocks. Thin section study supports this view in that the interlamination is not wholly the result of metamorphic segregation or intense shearing parallel to the laminae. The laminations are, therefore, interpreted as representing bedding in most areas.

A more massively bedded quartzite is found at many horizons in

TABLE 2

ESTIMATED MODES OF THE MORETOWN MEMBER

Sp. No.	152	311_s	252_s	295_s	148_s	212_s	499	506½
Quartz	51	30	17	40	81	56	82	27
Albite	7	..	..	..	1	4	tr	..
Oligoclase	..	..	..	..	3	15	..	tr
Muscovite*	12	28	33	6	6	tr	3	50
Biotite	8	28	..	..	tr	4	10	20
Calcite	..	..	..	13	2	..	3	..
Ankerite	..	..	..	..	1	..	..	..
Garnet	..	3	6	..	..	5	2	tr
Staurolite	..	5	..	..	..	..	..	..
Sillmanite	..	3	..	..	..	..	..	1
Chlorite	18	..	8	36	6	..	..	..
Epidote	2	..	.	tr	..	..	..	tr
Zoisite	..	..	35	..	..	..	..	..
Iron Ore**	1	2	1	5	tr	1	..	2
Apatite	tr	tr	..	..	tr	tr	tr	tr
Tourmaline	tr	1	..	..	tr	..	tr	..
Sphene	1	..	..	..	..	..	..	..
Rutile	..	..	tr	..	..	..	tr	..
Hornblende	..	..	..	..	..	15	..	..
Zircon	tr	tr	..	tr	tr	tr	tr	tr

*Includes sericite.

**Includes magnetite, ilmenite, leucoxene, pyrite and hematite.

152 Fine-grained, light gray weakly foliate impure quartzite. Locality 1, Fig. 2.

311_s Fine-grained, medium gray, thin-bedded, impure quartzite. Taken 50 feet from granite contact. Locality 2, Fig. 2.

252_s Coarse-grained, medium gray mica schist with large (5–10 mm.) crystals of zoisite. Locality 3, Fig. 2.

295_s Fine-grained, pale-green chloritic schist. Locality 4, Fig. 2.

148_s Fine-grained, light greenish-gray, impure quartzite (the pinstripe). Locality 5, Fig. 2.

212_s Medium-grained, medium gray, thin-bedded, garnet-hornblende quartzite. Locality 6, Fig. 2.

499 Fine-grained, light gray, thin-bedded quartzite. Locality 7, Fig. 2.

506½ Medium-grained, medium gray mica schist. Locality 8, Fig. 2.

the Moretown (Plate 3). This rock is similar in composition to the "pinstripe," but in general shows less grouping of the platy and equidimentional minerals into separate layers. Instead, the same minerals as are present in the "pinstripe" are more randomly dispersed throughout the rock, lending to it a very pale greenish-gray color.

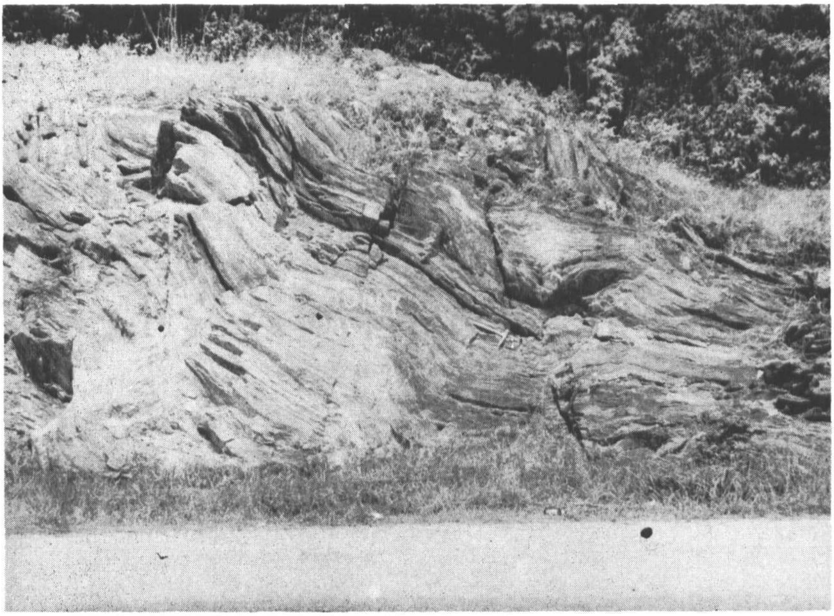


Plate 3. Gently folded quartzite in the upper part of the Moretown member at the intersection of routes 12 and 15 in the Hardwick quadrangle. Hammer handle is oriented approximately parallel to the bedding.

Carbonaceous Slate and Phyllite—Slate and Phyllite are most abundant in the upper part of the member. At many localities in the Plainfield quadrangle these rocks are in contact with either the base of the Shaw Mountain or Northfield formations. Where the Northfield slate and the carbonaceous slate and phyllite of the Moretown are in contact it is difficult to establish an exact contact line. In general, however, the slate and phyllite of the Moretown is coarser grained and a lighter shade of gray than similar rocks in the Northfield formation. Detailed mapping of some of the slate and phyllite in the upper part of the Moretown showed these rocks to be discontinuous along strike, that is, the slate and phyllite grades into more siliceous rocks along strike. This relationship has been demonstrated by Cady (1956) on a much larger scale in the Montpelier quadrangle.

The slate and phyllite appear medium to dark gray on fresh exposures, but weather rusty brown. This secondary coating is most pronounced in specimens that contain visible grains of pyrite and/or magnetite. With the exception of the pyrite and magnetite, the mineralogy is obscured by the fine-grained texture of both the slate and the phyllite. In thin section, quartz, sericite and opaque minerals make up the bulk of the rock. In general, the slate appears to contain a greater percentage of quartz than the phyllite. Inasmuch as the slate and phyllite are commonly found closely associated, undoubtedly having undergone nearly the same degree of deformation, the greater abundance of quartz in the slate may be responsible for the apparent lower grade of metamorphism reflected by the slate in comparison to the adjacent phyllite. The dark color of both the slate and phyllite is attributed to the presence of finely disseminated carbon, even though it probably makes up only a few percent of the rock by volume.

Greenstone—In this report the name greenstone is used solely as a field designation for light-gray to greenish-gray metamorphosed rocks which appear to contain a considerable amount of detrital igneous matter or which have an igneous appearance. As it is often difficult to establish the origin of such metamorphosed rocks in the field, it is felt that this more general usage of the term is desirable.

Typical greenstone consists of a fine- to medium-grained greenish-colored rock ranging in thickness from several inches to about 20 feet. Although bedding is not easily detected in these rocks, careful study often reveals its presence. At many localities the bedding is accentuated by thin layers of leached carbonate, either calcite or ankerite, or by color banding due to minor differences in composition in adjacent layers. Although it could not be definitely established, these bedded greenstones may represent waterlaid volcanic detritus which has been partly contaminated by carbonate locally precipitated from the sea water. The remaining unbedded greenstone appears to be metamorphosed sills and dikes, with the former being most abundant. Inasmuch as these sills and dikes are essentially parallel to the nearly vertical dipping bedrock it is difficult to distinguish a sill from a dike, except in areas where cross-cutting relationships exist.

Chlorite, carbonate, epidote, feldspar, muscovite and cross-cutting biotite sometimes may be identified megascopically in a typical greenstone. Usually these minerals are so small that their presence is barely detectable except in the coarser grained varieties. In the coarser grained varieties a light-colored feldspar occurs as 1–3 millimeter, equidimentional grains which may cause the rock to appear as a coarse-grained grit or fine-grained conglomerate. The more schistose variety of greenstone may show distinct blades or knots of chlorite or epidote which are slightly attenuated parallel to the schistosity. Regardless of the texture,

TABLE 3

ESTIMATED MODES OF GREENSTONE IN THE MORETOWN MEMBER

Sp. No.	248_s	346_s	323_s	218	528	215_s
Quartz	26	25	23	30	28	36
Albite	..	..	..	43	40	30
Oligoclase	..	..	26	10	8	6
Chlorite	4	29	28	12	16	12
Muscovite*	..	tr	1	tr	tr	4
Biotite	20	3	..	1	..	..
Epidote	45	25	..	3	..	8
Calcite	4	10	9	..	4	2
Ankerite	..	..	12	..	3	..
Iron Ore**	1	8	tr	1	1	2
Zircon	..	..	..	..	..	..
Tourmaline	tr	..	1	..	..	tr
Apatite	..	tr	..	tr	tr	..

*Including sericite.

**Includes hematite, magnetite, pyrite, ilmenite and leucoxene.

248_s Schistose, medium-grained, dark yellowish-green sill or dike. Locality 9, Fig. 2.

346_s Massive, fine-grained, greenish-gray sill or dike. Locality 10, Fig. 2.

323_s Massive, fine-grained, medium gray sill or dike. Locality 11, Fig. 2.

218 Schistose, medium-grained, greenish-gray greenstone. Locality 12, Fig. 2.

528 Schistose, fine-grained, greenish-gray metasedimentary greenstone. Locality 13, Fig. 2.

215_s Bedded, weakly schistose, medium-grained, greenish-gray metasedimentary greenstone. Locality 14, Fig. 2.

however, the most conspicuous feature of the greenstone is its massiveness due to the almost complete lack of visible bedding and the weakness of the secondarily developed fracture system.

Six holocyrstalline greenstone bodies were studied microscopically in order to obtain more concise mineralogical data. The mineral percentages given in Table 3, are rather unexpected in that quartz is commonly an essential constituent. Carbonate in the form of calcite and/or ankerite is primarily a late-formed mineral, probably originating either by the dissociation of originally more calcic minerals during metamorphism or by secondary calcification. This latter process is considered the principal source for most of the undeformed, euhedral ankerite. In contrast to the ankerite the fine-grained plagioclase is often elongated subparallel to the plane of secondary foliation. The larger quartz and plagioclase

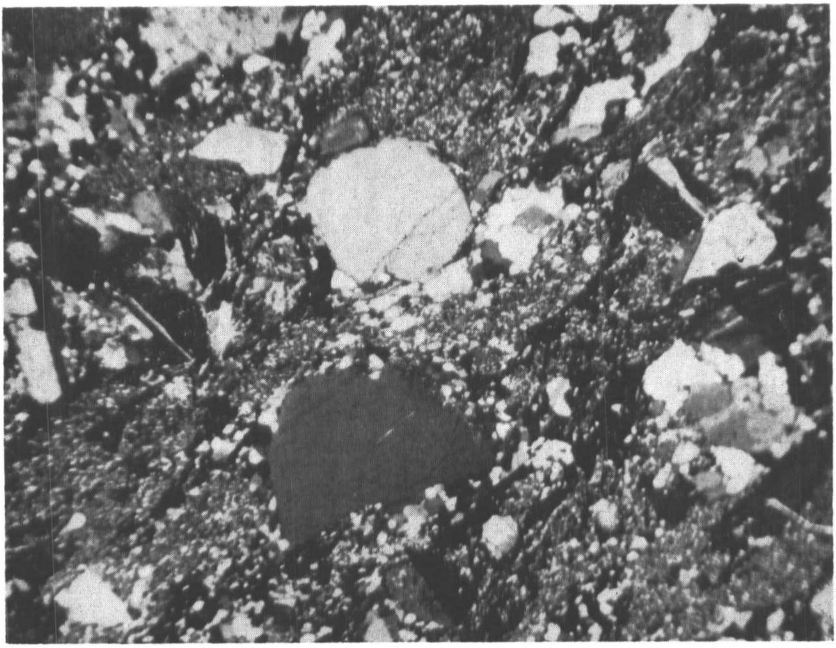


Plate 4. Photomicrograph of bedded greenstone of the Moretown showing the angular relationship of the larger grains of quartz and twinned plagioclase to the finer grained quartz-mica-chlorite groundmass. Nicols crossed $\times$ 90.

grains are angular and in the case of quartz show poorly developed undulatory extinction and occasional lamellae or fractures (Plate 5), whereas the plagioclase grains are often twinned, rarely zoned, and somewhat altered to epidote, calcite and sericite (Plate 4). Twinned feldspar, as well as most of the larger quartz grains, is undoubtedly detrital and is sodic oligoclase, whereas the plagioclase found filling voids or intergranular spaces in the finer grained groundmass is untwinned albite and developed during metamorphism or recrystallization. Some degree of silcification has undoubtedly taken place in the sills and dikes, but no conclusive textural relationships were observed in any of the specimens studied.

A two-fold origin of the greenstones is necessary. Therefore, those greenstones which are composed of essential amounts of quartz, feldspar and chlorite and possess some degree of bedding probably originated as volcanic debris which has been contaminated by processes of normal sedimentation. This material has been metamorphosed to form a meta-

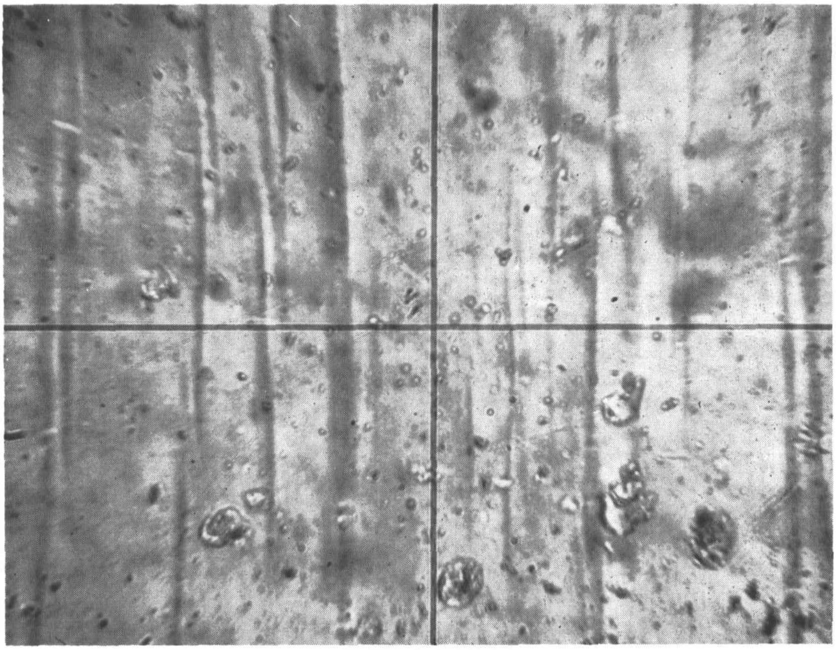


Plate 5. Photomicrograph of lamellae or fractures in a quartz grain of a bedded greenstone in the Moretown. Nicols crossed × 1100.

graywacke or a quartz-albite-chlorite schist in the more highly deformed areas. Unbedded greenstone, including both sills and dikes, is distinguished by the abundance of mica and epidote and the absence of feldspar. Although it is difficult to deduce the exact composition of the original rock these unbedded greenstones are believed to have been intermediate to basic in composition, possibly equivalent to a diabase prior to metamorphism.

Other Rock Types—A few metamorphosed sills and dikes of acid to intermediate composition are associated with the greenstone. Their characteristic colors range from tan in the acid varieties to light gray in the rocks of intermediate composition. Although most of these rocks have a poorly developed schistosity the intermediate varieties, when less than 2 feet wide, may have a well-developed schistosity. In thin section, these rocks are typically holocrystalline and subporphyritic with phenocrysts of twinned oligoclase and strained quartz surrounded by a fine-grained groundmass of quartz, albite and sericite. Most of the plagioclase is crowded with coarse laths of unoriented muscovite. Accessory chlorite, magnetite and epidote are scattered randomly through the rock.

Occasional beds of impure, medium-gray crystalline limestone occur in the formation. The rock weathers to a reddish-brown, sponge-like mass which may reach a depth of several inches or more. This sponge-like material contains residual quartz, mica and mafic material; the carbonate has been decomposed and removed from the rock.

Thickness

In metamorphosed areas it is often difficult to determine formation thicknesses because of structural complexities. Even if the major structures are correctly interpreted the effect of complex minor folding, fracturing, and flowage are often beyond interpretation and seriously impair the accuracy of the recorded thickness. The rocks in the Plainfield quadrangle are no exception to this general condition. Consequently, although an attempt has been made to evaluate the effect of the prevailing dips and the major and minor structural features, the results are strictly estimates of the relative thicknesses.

As only the upper (eastern) two-thirds of the Moretown member crops out within the Plainfield quadrangle, the unit must be traced into the Montpelier quadrangle (Cady, 1956) to arrive at a value for its thickness. A minimum exposure width of 3.75 miles is obtained approximately 1.5 miles northeast of the town of Worcester in the Montpelier quadrangle. This figure gives a thickness of slightly over 19,000 feet if only major structural features are considered. Minor structures, which consist mostly of drag folds that range in amplitude from microscopic dimensions to several feet or more, are widespread in the Moretown. Plate 3 shows a section of gently folded quartzite in the Moretown which may be used to represent the effect of minor parallel folding on thickening. Examination of the photograph and similar exposures in the field indicate that thickening as a result of folding is about 20 percent. Inasmuch as the majority of the drag folds in the Moretown are considerably more complex than those shown in the above illustration, many are isoclinal, it seems possible that the thickness of 9,000 to 10,000 feet might be in the correct order of magnitude.

Age

As previously stated the upper (eastern) part of the Moretown member, which crops out in the northwestern part of the Plainfield quadrangle, occupies an equivalent stratigraphic position with the Cram Hill member of the Missisquoi formation. Currier and Jahns (1941, p. 1496) have suggested a Middle Ordovician age for the Cram Hill, based on its correlation with a part of the graptolite-bearing Magog slates of Trenton age in southern Quebec. No additional information regarding the age of the formation was found as a result of the present study.

Shaw Mountain Formation

Distribution

The Shaw Mountain formation has been described as a discontinuous, thin sequence of conglomerate, tuff, and limestone in the Barre quadrangle by Currier and Jahns (1941). Even though the formation is exposed discontinuously along strike, Currier and Jahns were able to trace the Shaw Mountain formation by detailed mapping from the vicinity of Bethel (Randolph quadrangle) to Hobart Mountain (Plainfield quadrangle), and in reconnaissance north to the Canadian boundary, for a total distance of approximately 80 miles. Since then, mapping in the Montpelier, Plainfield, Hardwick and Irasburg quadrangles has firmly established the presence of the Shaw Mountain formation in these areas.

In the Plainfield quadrangle the Shaw Mountain is exposed in two lenticular masses along the eastern slopes of the Woodbury Mountains. The largest of these areas extends for a distance of about three miles, with the best exposures occurring in eastward-flowing consequent streams. An easily accessible section may be examined in an open pasture at a point 0.3 miles N. 20° W. of Smith Pond. Other convenient exposures are located farther north approximately 500 feet N. 65° W. of the road intersection at the southern end of Valley Lake.

Type Locality

(*Currier and Jahns, 1941, p. 1496–1501*)

The Shaw Mountain formation has its type locality near the base of the north slope of Shaw Mountain, 2 miles south-southeast of Northfield in the Barre quadrangle. Three distinct rock types comprise the bulk of the formation. From oldest to youngest these include: (1) a basal white to pinkish-brown, massively bedded quartz conglomerate containing abundant pebbles of vein quartz and minor quantities of greenstone, slate, phyllite, quartzite, rhyolite and jasperoid; (2) a thin-bedded soda rhyolite tuff composed of fine-grained quartz, alkali feldspar, sericite and albite; and, (3) a white to slightly bluish crinoidal limestone with numerous interbeds of tuff.

Lithologic Detail

The three rock types characteristic of the Shaw Mountain formation at its type locality are not always found in the Plainfield quadrangle. Instead, most of the section is composed of thin-bedded calcareous quartzite which locally grades into a fine-grained, metamorphosed quartz conglomerate. Interbedded with these rocks are smaller amounts of greenstone, calcareous phyllite, blue crystalline limestone and a fissile, light-colored tuffaceous rock.

Calcareous Quartzite

Calcareous Quartzite is the most abundant rock type in the formation. On a fresh exposure the rock is light gray, but upon weathering develops a light-tan to dark-brown cellular rind which may be as much as one to two inches thick. The porosity of the rind results primarily from the leaching of calcite and/or ankerite, whereas the rind's brown color is attributed to residual iron oxide developed during the decomposition of the ankerite.

Quartz is the most abundant mineral, making up approximately 40 percent by volume of the rock. The remaining portion of the rock is composed of about equal amounts of calcite and/or ankerite and feldspar, which includes perthitic orthoclase, microcline and oligoclase. Both potash feldspars and oligoclase contain abundant inclusions. In orthoclase, the included material is generally albite which produces a well-developed perthite which is suggestive of replacement. The microcline and oligoclase may be fresh but some of the oligoclase is altered and contains inclusions of sericite and lesser amounts of calcite. Other accessory minerals include magnetite, muscovite, zircon, epidote, chlorite, leucoxene and graphite.

Commonly associated with the calcareous quartzite is a calcareous phyllite which contains both sericite and calcite as essential constituents. This rock generally is poorly exposed and occurs as small lenticular masses within, or stratigraphically above the quartzite. In the latter case it forms the upper boundary of the formation. At one locality this rock type also occurs at the lower contact with the Moretown.

Quartz Conglomerate

Quartz conglomerate is usually found at or near the base of the Shaw Mountain formation but may occur locally through the lower third of the formation. The pebbles consist of quartz and alkali feldspar and have diameters ranging from 4 to 25 millimeters: they are dimensionally oriented subparallel to the trend of northerly plunging minor fold axes. With the exception of increased grain size, the rock appears to have a composition similar to that of the previously described calcareous quartzite. At several localities the quartz and feldspar pebbles are absent and the conglomerate grades into a relatively pure quartzite.

Greenstone

Greenstone crops out as three lenticular bodies within the most northerly exposures of the formation. When fresh the rock is light to medium greenish-gray and contains visible grains of dark green amphibole and feldspar in about equal proportions. Upon weathering a thin brown coating or rind is developed particularly on those rocks which appear to have been altered by the introduction of a carbonate, chiefly ankerite. The greenstone, both altered and unaltered, is not confined to any particular horizon in the formation except that it occurs above (east of) the quartz conglomerate in sections containing both quartz conglomerate and greenstone.

Other Rock Types

Blue crystalline limestone and fissile, light-colored tuffaceous rock make up less than 5 percent of the Shaw Mountain formation. The limestone occurs as small lenticular masses or pods averaging less than 10 feet in length and one foot in width. It is confined to the upper horizons of the calcareous quartzite. Associated with this crystalline limestone, near or at the very top of the formation, is a poorly exposed, light-tan rock which resembles a tuff. As no detailed study was made on this rock its origin was not established.

Thickness

In the Plainfield quadrangle the Shaw Mountain formation shows little evidence of folding, faulting or flowage phenomena. Therefore, it is only necessary to consider the effect of dip in determining the thickness of the formation. Assuming an average dip of 70 degrees the thickness of the Shaw Mountain formation ranges from 0 to 450 feet.

Age

A Middle Ordovician or younger age has been suggested for the Shaw Mountain formation by Currier and Jahns (1941, p. 1501). This determination is based on both paleontological evidence from the Shaw

Mountain formation and its position stratigraphically above the Moretown. Cady (1956) has placed the Ordovician-Silurian boundary at the base of the Shaw Mountain formation so that the formation is at least Lower Silurian. More recent paleontological discoveries in the Hardwick quadrangle by Konig and Dennis (in press) has elevated the Shaw Mountain to probable Upper Silurian.

Northfield Formation

Distribution

The Northfield Slate (equivalent to Northfield formation of this report), as redefined by Currier and Jahns (1941, p. 1501), has been mapped almost continuously from Braintree Hill in the Randolph quadrangle to a point approximately 1.5 miles east of Woodbury Mountain in the Plainfield quadrangle where the formation becomes covered with alluvium. The formation reappears in the vicinity of Hardwick and has been traced to the southern edge of the Irasburg quadrangle (Konig and Dennis, in press). Doll (1951) has mapped the formation from this point northward to the southern shore of Lake Memphremagog. Thus, the Northfield formation has been mapped for a distance of about 70 miles in Vermont.

In the Plainfield quadrangle the Northfield formation crops out in the valley east of the Woodbury Mountain Range as a series of steep westwardly dipping beds. Both the upper and lower part of the Northfield formation are well exposed on the valley slopes, but its central part is seldom observed. The paucity of outcrops in this central part has resulted in the lack of a complete stratigraphic section along any one traverse. The most complete section may be seen near the mouth of the eastward flowing stream located midway between Mud Pond, Woodbury Mountain, and Buck Lake. In this section the upper (eastern) contact of the Northfield formation with the Waits River formation is well exposed, but its lower contact with either the Shaw Mountain or the Moretown is concealed. This lower contact may be observed at many localities along the east slopes of the Woodbury Mountain Range at an elevation of 1300–1400 feet.

Type Locality

(Currier and Jahns, 1941, p. 1503)

The Northfield formation receives its name from rocks in the vicinity of Northfield in the Barre quadrangle which is the center of an old slate mining district. These abandoned slate quarries apparently serve as the type locality for the light- to dark-gray slate which comprises the bulk of the formation throughout its strike distance in Vermont.

Other rock types include a basal conglomerate, which is well exposed in Shaw Brook south of the town of Northfield, crystalline and dolomitic limestone, soda rhyolite, siliceous nodular zones and tuffaceous beds. These rock types are discontinuous and make up only minor portions of the formation.

Lithologic Detail

In the Plainfield quadrangle the Northfield formation consists of three distinct lithologies: (1) carbonaceous slate; (2) bluish-gray limestone; and, (3) greenstone. The nodular zone, soda rhyolite and tuffaceous beds described at the type locality were not observed in the Plainfield quadrangle, possibly because of the paucity of outcrops in the central portion of the formation.

Carbonaceous Slate

The slate is typically dark gray to black when fresh, but on weathering may develop a light tan to dark brown stain on the cleavage and bedding schistosity surfaces. This stain does not usually cover very large areas on the foliation surface but is restricted to the vicinity of euhedral crystals of pyrite. Streaks of mica and/or a sulphide often mar the cleavage and bedding schistosity surfaces. This lineation usually cuts across the trend of minor drag folds or crinkles developed on the same surface. When the slate becomes more highly distorted by folding or is located near plutonic rocks porphyroblastic mica and/or garnet are developed and the rock grades from a slate into a phyllite. Cady (1956) describes the Northfield formation as being ". . . composed of about equal amounts of quartz and sericite, both very fine grained, with 5 to 10 percent of opaque constituents, principally carbon and ilmenite, which are accountable for the dark shades. Carbon is not as abundant as it is in the slate of the Moretown."

Limestone

Limestone is most abundant in the upper fourth of the formation, and with the exception of its lesser abundance, is indistinguishable from the limestone in the overlying Waits River formation. The limestone in the Northfield formation occurs as 6- to 12-inch thick, bluish-gray, lenticular beds which weather to produce a spongy or cellular brown rind composed mainly of quartz, graphite and iron oxide. Because of the abundance of quartz in relation to calcite in the rock it is more properly referred to as a calcareous quartzite. In this report, however, the term limestone is used even though the quartz content may be as high as 70 percent. Near the contact with the Waits River formation the limestone becomes more massive and abundant and in parts of the Waits River formation it predominates over the slate and phyllite. The contact has been arbitrarily drawn where the limestone to slate-phyllite ratio is approximately 1 to 6.

Greenstone

Greenstone in the Northfield formation is much less abundant than in the underlying Shaw Mountain formation but its occurrence is quite similar. In contrast, however, the greenstone of the Northfield formation is finer grained and contains about 15 percent ankerite. The ankerite crystals are euhedral and have been introduced after most of the deformation had subsided. The greenstone in the Northfield formation is the most easterly important occurrence of this rock type in the Plainfield quadrangle.

Thickness

In the west-central part of the quadrangle, near Curtis Pond, the Northfield formation has a thickness of approximately 850 feet, but increases to a maximum of 1,350 feet farther north near Smith Pond. North of Smith Pond it becomes progressively thinner, with a minimum thickness of 100 feet being recorded approximately 3/4 of a mile north of Buck Lake.

Age

Because of the unfossiliferous nature of the Northfield formation chronological position is dependent upon stratigraphic relationships with adjacent formations. In the Plainfield quadrangle the Northfield formation conformably overlies the Shaw Mountain formation which is very probably Upper Silurian and conformably underlies the Waits River formation which is considered to be Devonian (Konig and Dennis, in press). Thus, the Northfield formation is considered to be Upper Silurian.

Several specimens of carbonaceous slate and limestone were decomposed and examined for microfossils, but the residual material revealed no conclusive organic remains. In one sample of coarsely crystalline limestone, several ellipsoidal pieces of recrystallized carbon about 1 millimeter long with longitudinal striations or grooves were observed, but they could not be related to any known organic form.

Waits River Formation

Historical Development

Adams (1845, p. 49, 62) described a wide band of grayish-blue siliceous limestone, mica slate and argillaceous slate in east-central Vermont as the calcereo-mica slate and placed it in his Primary System. Hitchcock (1861) referred to the same group of rocks as the calciferous mica-schist. Further study by Richardson (1898, p. 296) resulted in a subdivision of the calciferous mica-schist into two dominantly calcareous units, the Washington limestone, and two dominantly siliceous units, the Bradford schist. In 1906, however, Richardson discovered that both of these names were preoccupied and proposed the terms Waits River limestone and Vershire schist, respectively, for these rocks. Currier and Jahns (1941, p. 1491) changed the Waits River limestone to the Waits River formation because the unit included other rock types in addition to limestone. The Vershire schist was altered to the Ticklenaked formation (White, quoted by Eric, 1942), and then to the Gile Mountain schists (Doll, 1944, p. 18–19). The term Memphremagog slate was used by Doll (1944, p. 16) for the combined Waits River formation and the Standing Pond amphibolite.

Detailed mapping in the Memphremagog quadrangle by Doll (1951) resulted in the subdivision of the Waits River formation into the Ayers Cliff and Barton River formations, dropping the term Waits River as being all too inclusive. Doll, in the same report, recognized the Westmore formation and commented on its resemblance to the Gile Mountain formation in the Strafford quadrangle. Following Doll, Dennis (1956) retained the names Ayers Cliff and Barton River, but considered them as members of the more inclusive Waits River formation. Dennis (1956) equated the Westmore and Gile Mountain formation dropping the term Westmore from the section. As a result the Waits River and Gile Mountain formations are equivalent to Adam's (1845) calcereo-mica slate.

Recently Murthy (1957 and 1958) proposed a major stratigraphic revision for the rocks of east-central Vermont. He found evidence in the East Barre quadrangle which favored correlation of Doll's Westmore formation with the Gile Mountain formation as well as the Northfield formation with the Meetinghouse Slate. This correlation placed Barton River lithology stratigraphically below the Westmore-Gile Mountain formation so that the eastern band of calcareous rocks would be the youngest formation in east-central Vermont. Thus, the eastern band of calcareous rocks became the Waits River formation and the western band the Barton River formation. These two formations in addition to the Westmore formation are included in the Barre group (Murthy, 1958, p. 285).

Eric and Dennis (1958, p. 18) retained the name Waits River for the eastern band of dominantly calcareous rock, but considered the Westmore-Gile Mountain sequence to lie stratigraphically above Murthy's Waits River formation (eastern calcareous band), making the Barton River and Waits River equivalent. Dennis (1956, p. 32) included the Northfield, Waits River, Gile Mountain and the top of the Meetinghouse Slate in the St. Francis group. According to Dennis (1956) the St. Francis group correlates with rocks in Quebec which have been included in the St. Francis "series" (Cook, 1950).

In this report, the name Waits River formation is used for the two dominantly calcareous units and Gile Mountain formation for the two dominantly siliceous units in east-central Vermont.

Distribution

The Waits River formation has been mapped in detail throughout the greater part of eastern Vermont (Fig. 1). In the Woodstock and Randolph quadrangles, the dominantly calcareous rocks of the Waits River formation are separated by a band of phyllite, schist and quartzite which in this report is called the Gile Mountain formation. These two bands of Waits River are referred to as the eastern and western bands of the Waits River formation. The eastern band terminates in the Island Pond quadrangle, but the western band continues through the Memphremagog quadrangle into Canada.

In the Plainfield quadrangle the Waits River formation occurs as two northeasterly trending units which dip nearly vertically in the westernmost exposures to about 30 degrees west in the more easterly exposures. Only the western band is completely exposed in the area. The width of the formation ranges from 6 to 7 miles, with the best exposures occurring along U. S. Route 12 between the town of South Woodbury and Greenwood Lake. The eastern band crops out for a distance of less than one mile between the Gile Mountain formation and the Knox Mountain granite in the eastern part of the quadrangle. A typical exposure of these rocks occurs at Molly's Falls, located about one mile northeast of Marshfield.

Type Locality

Inasmuch as the Waits River formation occurs as two separate bands throughout much of east-central Vermont, two areas containing representative lithologies are given. The eastern band is typically exposed in the vicinity of the village of Waits River (Murthy, 1957, p. 36) and the western band in the city of Newport along the main highway to Derby and on the south flank of Shattuck Hill (Doll, 1951, p. 25).

Lithologic Detail

Both the eastern and western bands of the Waits River formation are composed of complexly folded, thin- to massively-bedded impure limestone and quartzite. Interbedded with these rocks is dark gray slate, phyllite and schist. Minor amounts of micaceous quartzite and amphibolitic limestone are present, especially in the gradational contact zone with the Gile Mountain formation. Metamorphosed dikes and sills are rare and appear to be the metamorphosed equivalents of rocks of dioritic composition.

The estimated modes for several rock types of the Waits River formation are listed in Table 4.

Limestone and Calcareous Quartzite

Limestone and calcareous quartzite comprise approximately 50 to 60 percent of the formation. These rocks are grayish-blue when fresh, but upon weathering develop a thick, cellular or sponge-like rusty-brown rind. This rind is particularly well developed in the more fissile rocks. Alternating light and medium grayish-blue layers ranging in thickness from a fraction of an inch to several feet reflect the bedding. In general, the thickness and color of the beds are related, with the darker layers being thinner and vice versa. Some of the darker colored limestone and particularly the calcareous quartzite possess a moderately well-developed schistosity which is essentially parallel to the bedding. This schistosity results from oriented mica, chlorite and to a lesser extent calcite and quartz grains. As the mica and chlorite content decreases, the bedding schistosity becomes less conspicuous, eventually only being detectable microscopically in the form of elongated calcite and quartz grains. The contact between the Waits River and Gile Mountain formations is defined by the relative abundance of the limestone and calcareous quartzite. In making a traverse from the Waits River towards the Gile Mountain formation, a contact line is drawn where the carbonate rock makes up less than 25 percent of the exposures.

At a few localities an amphibolitic layer is developed at the contact between phyllite and limestone. This layer does not usually exceed 6 inches in width and represents the gradational contact which occurs between the two rock types. The amphibole in this layer is green and somewhat acicular, probably possessing a composition similar to that of actinolite.

Slate, Phyllite and Schist

Slate, phyllite and schist are medium to dark gray and have a grain size which is almost wholly a reflection of metamorphic intensity, with the coarser grained varieties being more closely associated with acid igneous rocks. Inasmuch as the slate, phyllite and schist were very similar in composition prior to metamorphism, the mineral suite listed in Table 4 for several of the more schistose varieties may represent the general composition of all three rock types. The metamorphism is considered to have been essentially isochemical for all of the argillaceous rock types included in this section. The slate, phyllite and schist in the Waits River formation weather rusty-brown. This alteration aids in distinguishing the slate and phyllite of the Waits River formation from similar rocks in the underlying Northfield formation.

Secondary structural features are abundant in these argillaceous rocks. The most prominent feature is a foliation which is oriented essentially parallel to the bedding. Streaks of mica and/or iron sulphide are oriented subparallel to the dip of the rock in many of the slates and phyllites.

Other Rock Types

Fine-grained, light-gray micaceous quartzite, dark-gray, coarse-grained amphibolitic limestone and a light-gray, medium-grained metadiorite (?) make up a minor portion of the Waits River formation. The micaceous quartzite is most abundant near the Waits River-Gile Mountain contact. In addition to quartz, the quartzite contains minor quantities of muscovite, biotite and feldspar. This rock type is indistinguishable from the quartzite in the Gile Mountain formation. The amphibolitic limestone occurs chiefly in the upper (eastern) third of the formation usually as less than 2-foot thick layers which are discontinuous along the strike. This rock contains calcite, quartz, actinolite and/or diopside in essential amounts and is believed to be the metamorphic equivalent of rocks similar in composition to the previously described

Table 4

ESTIMATED MODES OF THE WAITS RIVER FORMATION

Sp. No.	184_s	399_s	3 l_s	3sh	373_s	2	22	30	257
Quartz	15	37	40	35	10	9	25	..	26
Albite	..	..	..	..	..	..	..	..	5
Microcline	20	..	..	..	..	..	..	..	..
Calcite	10	..	55	4	20	..	..	55	..
Muscovite*	..	15	5	57	5	78	57	..	32
Biotite	..	28	..	..	..	5	3	10	25
Phlogopite	..	..	..	..	65	..	..	..	..
Chlorite	..	..	..	..	tr	1	10	..	..
Epidote	tr	..	..	..	tr	..	4	..	4
Actinolite	5	..	..	..	..	..	..	30	..
Garnet	..	2	..	..	..	4	..	..	2
Staurolite	..	10	..	..	..	..	..	..	3
Diopside	49	..	..	..	..	..	..	..	..
Kyanite	..	8	..	..	..	..	..	..	tr
Iron Ore**	..	..	tr	4	tr	3	1	3	2
Zircon	..	tr	..	..	tr	tr	tr	tr	..
Tourmaline	..	..	tr	tr	tr	tr	..	..	tr
Apatite	..	..	tr	..	tr	..	..	..	tr
Sphene	1	..	..	..	..	..	..	..	..
Rutile	..	..	..	tr	..	..	..	..	tr
Graphite	..	..	tr	..	..	..	..	2	1

*Includes sericite.

**Includes magnetite, ilmenite, leucoxene, pyrite and hematite.

184_s Thin-bedded, medium-grained, light greenish-gray, diopsidic limestone. Locality 15, Fig. 2.

399_s Medium-grained, medium-gray, garnet-staurotite-kyanite schist. Locality 16, Fig. 2.

3 ls Massive, fine-grained, bluish-gray, siliceous limestone. Locality 17, Fig. 2.

3 sh Fine-grained, dark-gray phyllite. Locality 18, Fig. 2.

373_s Medium-grained, dark gray phlogopite schist. Locality 19, Fig. 2.

2 Medium-grained, medium gray garnet schist. Locality 20, Fig. 2.

22 Medium-grained, medium gray mica schist. Locality 21, Fig. 2.

30 Bluish-gray amphibolitic limestone. See plate 18. Locality 22, Fig. 2.

257 Medium-grained, medium gray garnet-staurolite schist. Locality 23, Fig. 2.

limestone located farther west. A few dikes or sills of metadiorite (?) are exposed approximately one mile N. 20° E. of Kents Corners in the west-central ninth of the quadrangle. This is the only known meta-igneous rock locality in the Waits River formation in the Plainfield quadrangle.

Thickness

A minimum width of approximately 30,000 feet is recorded for the Waits River formation in the west-central and central portions of the quadrangle. As the rocks in this section are complexly folded it is impossible to accurately determine the thickness of the formation. After subtracting the effect of average dip of about 50 degrees and applying a factor of 3 to account for tectonic thickening due to repetition by minor folding and shearing a relative thickness of 7,600 feet is obtained.

Age

In this report the Waits River formation is considered to lie stratigraphically above the Northfield formation and below the Gile Mountain formation. The Northfield formation is believed to be Upper Silurian because of its position above the fossiliferous Shaw Mountain formation. Somewhat controversial fossil remains have been reported from the Gile Mountain formation by Doll (1943a and 1943b) which are indicative of a Middle Silurian to Lower Devonian age. Thus, the Waits River formation should not be older than Upper Silurian or younger than Lower Devonian.

Cady (1950) described fossil cup corals from the western band of the Waits River formation near Montpelier, and identified them as being probable Middle Ordovician in age. However, in his 1956 report he relegated them to the Silurian. This age received further support by Morin (1954, as quoted in Dennis, 1956, p. 28) who assigned a Siluro-Devonian age to the St. Francis group as a result of its strike alignment with Devonian rocks in Gaspé. Inasmuch as the Waits River formation is part of the St. Francis group, it would not be older than Silurian. In this report the Waits River formation is considered to be Lower Devonian.

Gile Mountain Formation

General Statement

In this report the rocks which Doll (1951, p. 33) assigned to the Westmore formation in the Memphremagog quadrangle are included in the Gile Mountain formation. This change in terminology is necessary because the Westmore formation strikes into the original (eastern) band of Gile Mountain in the southern portion of the Island Pond quadrangle (Dennis, 1956, p 36). The rock nomenclature for the Gile Mountain formation has been considered under the Waits River formation.

Distribution

The Gile Mountain formation appears as two continuous, but separate, bands which extend from the northern half of the Woodstock quadrangle to the Island Pond and Memphremagog quadrangles (Fig. 1). In the Woodstock quadrangle the western band of Gile Mountain is either structurally terminated or dies out because of a facies change along strike. In the Island Pond and Memphremagog quadrangles the eastern and western bands of Gile Mountain merge to form a 25- to 30-mile wide unit which strikes into Canada (Fig. 1).

In the Plainfield quadrangle the Gile Mountain formation is well exposed along the west side of the highway between Marshfield and Lower Cabot. Other localities include a series of exposures at higher elevations west and northwest of Marshfield, as well as in the vicinity of Cabot Plains in the northeastern portion of the quadrangle.

Type Locality

(*Doll, 1944, p. 18*)

Inasmuch as the Gile Mountain formation occurs as two distinct units which commonly have been considered stratigraphically unequivalent, two type localities have been established. The eastern band of Gile Mountain (Doll, 1944, p. 18) has its type locality in the Strafford quadrangle on Gile Mountain. According to Doll (1944, p. 18) the formation consists ". . . principally of quartz-mica schists . . . rocks in subordinate amounts are thin beds of massive and sheared quartzite, occasional coarse feldspathic schist, calcareous beds and some graphitic layers". The western band of Gile Mountain (Doll's Westmore) is typically exposed in the southeastern corner of the Memphremagog quadrangle and includes interbedded schist and phyllite and lesser amounts of limestone and quartzite (Doll, 1951, p. 33). Inasmuch as the eastern and western bands of Gile Mountain are considered stratigraphically equivalent in this report, the true type locality is in the Strafford quadrangle because of its precedence.

Lithologic Detail

Slate, phyllite and schist interbedded with micaceous quartzite are the most abundant rocks in the formation. They are often associated with minor amounts of limestone, amphibolitic and diopsidic limestone and at one locality greenstone. With the exception of the greenstone, no other meta-igneous rock was observed in the formation.

The contact between the Gile Mountain formation and the underlying Waits River formation was determined on the basis of both limestone content and the type of quartzite present. In making a west to east traverse from the Waits River formation into the Gile Mountain formation, the position where the limestone content diminishes to about 25 percent marks the contact between the two formations. This contact can also be recognized by the color and composition of the quartzite in the Gile Mountain formation. The Gile Mountain quartzite is light gray and usually contains less than 30 percent impurities, whereas quartzites in the underlying Waits River formation are medium gray and usually contain 45 to 50 percent impurities. The transition from medium gray quartzite to light gray quartzite generally coincides with the contact line established by the limestone content.

Slate, Phyllite and Schist

Slate, phyllite and schist are generally dark gray and appear very similar so that their present structural and textural differences probably are chiefly the result of metamorphism. Slate and phyllite are most abundant in the western half of the formation, but give way gradually to more schistose rocks to the east. Inasmuch as the Gile Mountain formation roughly parallels the western margin of the Knox Mountain granite the distribution of the slate, phyllite and schist is the result of metamorphism related to the adjacent granite. The mineralogical expression of the metamorphism associated with the Knox Mountain granite is the presence of large porphyroblasts of unoriented biotite, garnet and staurolite which frequently show cross-cutting relationships with most foliation surfaces. The estimated modes for several of the more schistose rock types are listed in Table 5.

Inasmuch as slate, phyllite and schist are relatively incompetent to deformation in comparison to quartzite, such features as bedding schistosity, mineral streaming, cleavage, folding, etc., are found at many exposures. The significance of these features will be discussed in the section on structural geology.

Quartzite

The quartzite in the Gile Mountain formation is usually light gray and thinly bedded with the individual beds ranging from 1 to about 3 inches in width. In general, this rock is most abundant in the central portion of the formation and is best exposed along the highway between Marshfield and Lower Cabot. Although quartzite makes up 30 to 40 per-

TABLE 5

ESTIMATED MODES OF THE GILE MOUNTAIN FORMATION

Sp. No.	183_a	308	440	203_a	20_a	202_a	111	183_b	378
Quartz	73	55	40	23	16	58	40	48	22
Albite	..	15	..	..	..	..	..	..	..
Oligoclase	5	..	10(?)	..	..	2	4	8	..
Muscovite*	tr	8	..	..	..	..	12	10	50
Biotite	16	4	7	tr	..	tr	33	25	15
Calcite	..	5	..	tr	46	10	..	..	..
Chlorite	1	10	..	..	..	tr	..	1	tr
Epidote	..	..	..	..	2	tr	5	..	tr
Actinolite	..	..	..	65	..	..	..	..	..
Hornblende	..	..	40	..	..	19	..	..	..
Diopside	..	..	..	..	35	..	..	..	..
Garnet	3	..	3	7	..	9	2	5	1
Staurolite	1	..	..	..	..	..	1	2	10
Kyanite	..	..	..	..	..	..	1	..	..
Iron Ore**	1	3	tr	4	1	2	2	1	2
Zircon	tr	..	tr	tr	..	tr	tr	tr	tr
Tourmaline	tr	tr	..	..	..	tr	tr	tr	tr
Apatite	tr	tr	tr	..	..	tr	tr	tr	..
Sphene	..	..	..	1	tr	..	..	..	..
Graphite	..	..	..	..	..	..	tr	tr	..

*Including sericite.

**Includes magnetite, ilmenite, leucoxene, pyrite and hematite.

183_a Medium-grained, light gray impure quartzite. Locality 24, Fig. 2.

308 Thin-bedded, light gray albitic quartzite. Locality 25, Fig. 2.

440 Coarse-grained, dark gray amphibolitic limestone. Locality 26, Fig. 2.

203_a Coarse-grained, medium gray amphibolitic limestone. Locality 27, Fig. 2.

20_a Medium-grained, light gray diopsidic limestone. Locality 28, Fig. 2.

202_a Medium-grained, medium gray amphibolitic limestone. Locality 29, Fig. 2.

111 Medium-grained, medium gray mica-garnet schist. Locality 30, Fig. 2.

183_b Coarse-grained, medium gray mica-garnet-staurolite schist. Locality 31, Fig. 2.

378 Coarse-grained, medium gray mica-garnet-staurolite schist. Locality 32, Fig. 2.

cent of the section exposed in this area, traverses made several miles farther to the south and north across the formation did not show a similarly placed quartzite rich zone. Apparently the quartzite exposed between Marshfield and Lower Cabot must grade imperceptibly into more argillaceous rocks along strike. Although all gradations exist between pure and impure quartzite the typical quartzite of the Gile Mountain formation is composed of more than 50 percent quartz and lesser amounts of feldspar, mica, chlorite, calcite, garnet, staurolite, zircon, tourmaline, apatite and opaque. The estimated modes for several specimens of quartzite from the Gile Mountain formation are listed in Table 5.

Carbonate Rocks

Limestone, or more correctly marble, and amphibolitic and diopsidic limestone comprise about 10 percent of the formation. These rock types are exposed as 1- to 2-foot thick, randomly scattered beds which are often very similar in appearance to rock types in parts of the underlying Waits River formation. In a west to east traverse from the Waits River formation through the Gile Mountain formation limestone, which comprises 50 to 60 percent of the Waits River formation, not only decreases in abundance towards the Gile Mountain formation but acquires increasing amounts of dark green amphibole and more rarely pyroxene. At a horizon which is approximately defined by the staurolite isograd (Plate 1) amphibole and pyroxene occur in essential quantities and the rock becomes dark green to black and coarse grained. Associated with these coarse-grained rocks are approximately equal amounts of weakly amphibolized limestone and pure limestone. Farther east in the Gile Mountain formation these coarse-grained rocks containing actinolite and/or calcium hornblende or diposide, predominate over other carbonate rock types. The gradual transition from impure limestone to amphibolized limestone to coarse-grained amphibolite or diposide-rich rocks from west to east across the quadrangle reflects the increasing grade of metamorphism which is in part related to the emplacement of the Knox Mountain granite.

Greenstone

A 6- to 12-inch wide layer of fine-grained, garnetiferous greenstone was observed 0.8 miles N. 87° W. of Marshfield Station at an elevation of 840 feet at the contact between the Gile Mountain formation and the eastern band of Waits River. Although this layer could only be traced for about 10 feet along strike it is significant because it may be equivalent to greenstone (pillow lavas) reported in the St. Johnsbury quadrangle by Dennis (1956) and Hall (1959), which are located approximately on the contact between the eastern band of Gile Mountain and Waits River. Unfortunately, this was the only greenstone found in the Gile Mountain formation in the Plainfield quadrangle.

THICKNESS

The Gile Mountain formation has an outcrop width of approximately 7,400 feet in the area between Plainfield and Marshfield. Assuming an average dip of 65 degrees and repetition caused by major folding a thickness of about 3,400 feet is obtained. This value is in excess of the true value because no attempt has been made to account for repetition due to minor structural features.

Age

The age of the Gile Mountain formation has not been definitely established. In this report it is considered to be younger than the Waits River formation, which is Lower Devonian. As both the Gile Mountain and Waits River formations are cut by undeformed Devonian plutonic rocks, the Gile Mountain formation is probably Lower Devonian. This age is supported by fossil remains reported from the Gile Mountain by Doll (1943a and 1943b).

INTRUSIVE IGNEOUS ROCKS

Introduction

Igneous rocks are widespread in the Plainfield quadrangle. Individual bodies range in size from 6- to 8-inch thick sills and dikes to plutons measured in terms of many square miles. Most of the plutonic rocks are concentrated in the southeastern and north-central parts of the quadrangle (Plate 1). The southeastern mass of igneous rock is called the Knox Mountain granite (Richardson, 1906) and the north-central intrusions are known collectively as the Woodbury granite (Richardson, 1908). A third and more restricted area of granite is located in the west-central part of the quadrangle and is called the Adamant granite (Cady, 1956). The term "granite" in this report is used in its broader sense to refer to a group of granular, quartz and feldspar-rich rocks. Technically, these "granites" have an average composition of adamellite.

Other rocks considered in this section include aplites, pegmatites, basic dikes and quartz veins. These rocks occur as sill and dike-like bodies which are usually most abundant in the vicinity of the larger plutonic bodies.

Woodbury Granite

General Statement

The Woodbury granite crops out as a number of small intrusives, usually less than one square mile in area, in the north-central portion of the quadrangle (Plate 1), and includes all the granite bodies between South Woodbury and Hardwick, in addition to those in the vicinity of Nichol's Ledge and along the Woodbury Mountain range.

The larger of these plutons commonly form topographic highs which locally afford good exposures. The smaller bodies, however, are poorly exposed and their contact relationship with adjacent metasediments is mostly concealed. Woodbury granite is best exposed in several abandoned quarries located 1 to 2 miles northeast and east of Woodbury.

Petrography

Woodbury granite is light to medium gray, when fresh, and has a variable grain size from one pluton to the next. The granite exposed in abandoned quarries located east of Woodbury is generally medium grained, with an average grain size of approximately 1.5 millimeters. In contrast, many of the exposures at Nichol's Ledge are porphyritic with phenocrysts of microcline commonly attaining diameters of 15 to 20 millimeters. All gradations between these two extremes have been observed in the Plainfield quadrangle, but the common variety is medium grained.

Microscopic analysis of 13 specimens of Woodbury granite (Table 6) shows the average rock to contain 42 percent oligoclase, 18 percent potash feldspar, 27 percent quartz, 8 percent biotite, 3 percent muscovite, and 1 percent opaque and non-opaque accessory minerals. Oligoclase is subhedral and commonly zoned, twinned and partially altered to sericite and minor amounts of epidote and/or calcite. This secondary alteration is usually best developed parallel to cleavage traces and zonal structures in the oligoclase. In addition to the sericitic alteration numerous coarse laths of unoriented muscovite are present in the plagioclase. These are the principal occurrence of muscovite in the Woodbury granite. Some of the plagioclase grains are partially rimmed by myrmekite which is particularly well developed where the plagioclase is in contact with microcline.

Microcline is the most abundant potash feldspar, although minor amounts of orthoclase are sometimes present in the rock. Much of the potash feldspar is bleb and patch perthite and with the exception of orthoclase shows little or no secondary alteration; orthoclase is partially altered to kaolin. At Nichol's Ledge most of the microcline occurs as 15 to 20 millimeter phenocrysts which contain inclusions of plagioclase, biotite, muscovite and more rarely quartz.

Strained, anhedral quartz is scattered randomly through the rock. Its irregular distribution, its tendency to fill voids between most other minerals and the partial replacement of both plagioclase and potash feldspar by quartz clearly show that most of the quartz formed later than feldspar, biotite and some of the muscovite. The relationship be-

TABLE 6

MODAL ANALYSES OF WOODBURY GRANITE

Specimen Number	Plagioclase	Potash Feldspar	Quartz	Biotite	Muscovite	Opaque Accessories	Non-Opaque Accessories	Number of Counts
213	35.32	22.27	32.62	7.08	2.32	tr	tr	1594
516	39.36	18.18	30.21	6.04	4.88	0.25	0.19	1579
170_s	47.43	13.52	26.69	9.17	2.21	0.06	0.55	1450
43_s	44.15	16.20	21.72	13.25	4.06	0.05	0.55	1796
59_s	34.53	24.18	29.94	5.18	5.76	tr	0.41	1700
4_s	36.00	33.92	21.77	3.46	4.08	tr	0.39	1301
174_s	42.08	9.69	30.46	9.38	5.85	tr	2.51	1300
NL-1,2	42.09	12.75	35.63	6.08	2.90	tr	tr	2708
W-11	36.83	15.76	27.26	5.89	9.85	. .	4.23	1086
518	35.26	19.66	28.34	12.80	2.57	0.11	1.13	964
$64\text{-}2_{sh}$	50.10	11.38	21.48	12.86	3.46	tr	0.77	1415
263_s	48.37	12.28	25.67	9.32	3.38	0.17	0.17	1718
312_s	59.00	11.25	23.69	2.18	2.37	0.06	0.81	1600

tween muscovite and quartz is not clear, but in several places muscovite was observed to fill small fractures in earlier formed feldspar and biotite, but not in fractured quartz, indicating that some of the quartz is younger than muscovite.

Other minerals found in accessory amounts include apatite, zircon, ilmenite, magnetite, pyrite, rutile and sphene. The ilmenite, sphene and zircon are usually associated with biotite, the zircon occurring as minute inclusions and the ilmenite and sphene lying adjacent to or being partially surrounded by discrete grains of biotite. Both sphene and ilmenite are largely altered to leucoxene.

The modal analyses listed in Table 6 for the Woodbury granite show a considerable variation in the plagioclase-potash feldspar ratio for different specimens, with some specimens being equivalent to adamellite and others to granodiorite. An average of the 13 modes (Table 7) gives a composition which lies about mid-way between adamellite and granodiorite.

Adamant Granite

Adamant granite (Cady, 1956) is exposed as dike-like masses along the join between the Plainfield and Montpelier quadrangles near the town of

Adamant in the Montpelier quadrangle. The largest of these bodies is approximately one mile long and one-eighth of a mile wide, with the larger dimensions generally parallel to the strike of the adjacent metasediments. With the exception of this body, the Adamant granite in the Plainfield quadrangle occurs as small dikes which generally show concordant relationships with the adjacent metasediments and have a nearly vertical dip. These dikes are 5 to 20 feet wide and outcrop discontinuously for a mile or more along strike.

The Adamant granite is composed of about 37 percent oligoclase, 19 percent potash feldspar, 31 percent quartz, 6 percent each of biotite and muscovite and accessory sphene, epidote, sericite, rutile, calcite, apatite, leucoxene and magnetite and is classified as an adamellite. Comparison of the Adamant and Woodbury granites shows the Adamant granite to be poorer in plagioclase and richer in quartz, but due to insufficient study no conclusions regarding this difference are justified at this time.

Knox Mountain Granite

The Knox Mountain granite (Richardson, 1902) extends from the center of the East Barre quadrangle northeast through the Plainfield quadrangle and into the western part of the St. Johnsbury quadrangle (Fig. 1). Despite poor exposures it appears likely that the entire 7 by 20 mile elliptical area is underlain by similar plutonic rocks. In many areas, particularly in the contact zone, these massive rocks are crowded with unaltered xenoliths of adjacent metasedimentary rock. Where this contact zone cuts across formation boundaries it is sometimes possible to map the contact of the formation by the type and position of xenolith present. Thus, in the Plainfield quadrangle the contact between the Waits River and Gile Mountain formations may be traced in the so-called "mixed border zone" of the Knox Mountain granite (Plate 1).

The composition of the Knox Mountain granite differs from the Woodbury granite in that the Knox Mountain granite is poorer in plagioclase and mica and richer in potash feldspar and quartz than typical Woodbury granite. Murthy (1957, p. 80) published the results of 9 modal analyses of the Knox Mountain granite in the East Barre quadrangle. The average composition of these analyses is 49 percent quartz, 28 percent potash feldspar, 12 percent plagioclase, 7 percent biotite, 4 percent muscovite and 1 percent accessory minerals, making the Knox Mountain granite more acidic than either the Woodbury or Adamant granites.

Flow Structures in Granite

Some parts of the Woodbury, Adamant and Knox Mountain granites possess primary foliation. This planar structure is most strongly developed in the more micaceous granites, in which case, most of the biotite flakes are oriented with their cleavage faces subparallel to the margins of the pluton. In the Fletcher quarry, which is located about one mile due east of Woodbury, subparallel biotite flakes form a plane of foliation which in many places is nearly vertical.

At several localities in this quarry, as well as in the lower quarry on the west side of the same mountain, minor concentrations of oriented biotite have resulted in the unusual formation of conspicuous parallel layers (Plate 6). In the granite adjacent to these concentrations biotite is similarly oriented but more uniformly distributed. Although these layers were observed only in the Woodbury granite quarries they may be present in the Knox Mountain and Adamant granites, but due to the smaller granite exposures were not seen.

Nature of Contacts

Although the contact zone between plutonic and metasedimentary rocks usually is not well exposed in the Plainfield quadrangle, several of the abandoned Woodbury granite quarries clearly demonstrate the nature of this contact. In the Fletcher quarry typical Woodbury granite is exposed in contact with thin-bedded phyllite and limestone of the Waits River formation (Plate 7). The contact is sharp and locally disconformable, with the metasediments and the granite apparently unchanged in composition near the contact. Balk (1926, p. 73–90) has sketched and described several other localities which show similar contact relationships. He believes that the granite passively intruded the metasediments with only minor disturbances. Although this relationship has been substantiated for much of the Woodbury granite a more forceful type of intrusion is necessary to account for the regional warping of the metasediments around the Knox Mountain intrusions, as well as for the development of minor folding and cleavage which is related to the intrusion of the Knox Mountain granite.

Origin and Emplacement of the Granite

General Statement

It is not within the realm of this report to discuss the origin of plutonic rocks, but rather to present and briefly interpret the information ob-

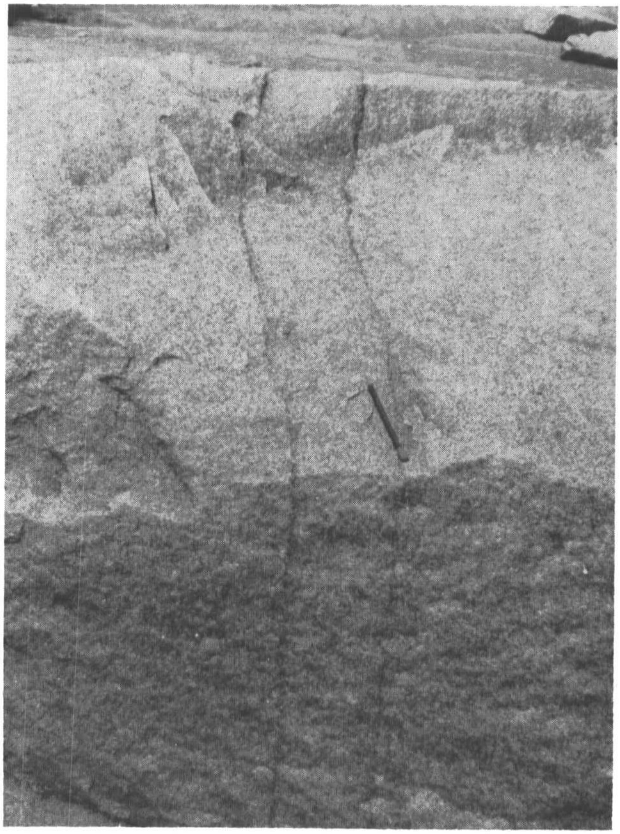


Plate 6. Unusual primary flow structure in Woodbury granite one mile due east of Woodbury in the Fletcher quarry. Pencil oriented approximately parallel to the trend of foliation as outlined by the two narrow concentrations of biotite.

tained from the study of the granites in the vicinity of the Plainfield quadrangle. This information has been obtained from both field work and subsequent petrographic studies.

Modal Analysis

The Woodbury, Knox Mountain and Barre granites have been variously studied by Mayner (1934), Chayes (1950 and 1952) and Murthy (1957). Chayes (1952, p. 248) published modal analyses of 8 specimens taken from the Woodbury granite. The average of these modes and those obtained by the writer are compared with average modal analyses of the

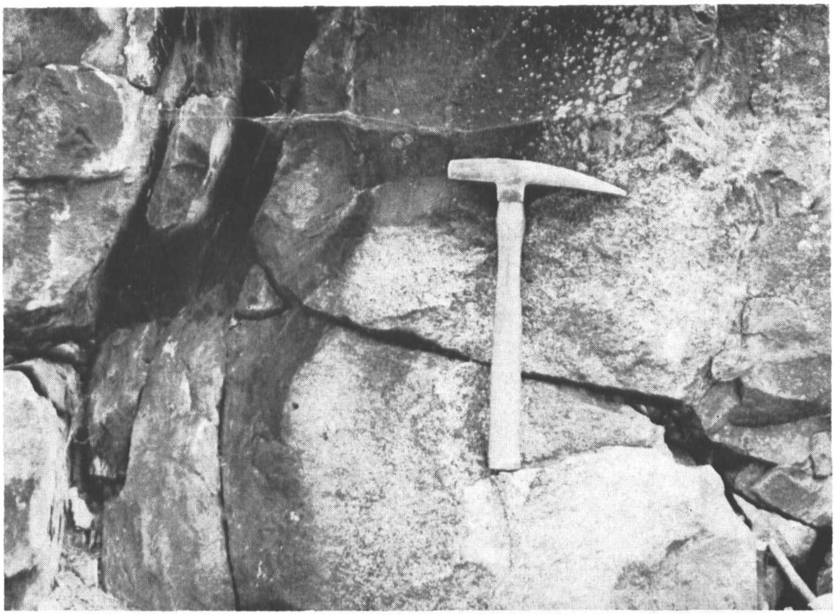


Plate 7. Contact relationships between light colored Woodbury granite (near hammer handle) and darker colored metasediments in the Fletcher granite quarry. Hammer handle nearly parallel to the dip of metasediments.

Barre granite from the East Barre quadrangle by Chayes (1952, p. 248) and Murthy (1957, p. 74) in Table 7. Although no detailed petrographic study was performed on the Knox Mountain granite by the writer, the average modes determined by Murthy (1957, p. 80) for this granite are listed for comparison with the Woodbury and Barre granites.

Comparison of the Woodbury and Barre granites shows the Woodbury granite to have a higher plagioclase content and a lower mica content. The lower mica content in the Woodbury granite results from the reduced amount of muscovite. Inasmuch as the muscovite is chiefly contained in plagioclase as coarse laths, it is likely that most of the muscovite represents a late stage replacement of plagioclase. The muscovite content, therefore may be added to the plagioclase for comparison of the Woodbury and Barre granites. This greatly reduces the difference between the amount of plagioclase in the two granites, making their average modal analyses nearly identical.

The plagioclase (including muscovite), potash feldspar and quartz content of 21 specimens of Woodbury granite are plotted on a ternary

Table 7

AVERAGE MODAL ANALYSES OF THE WOODBURY, BARRE AND KNOX MOUNTAIN GRANITES

Worker	Number of Specimens	Plagioclase	Potash Feldspar	Quartz	Biotite	Muscovite	Opaque Accessories	Non-Opaque Accessories	Name of Granite
Konig	13	42.4	17.0	27.3	7.9	4.1	0.1	1.1	Woodbury
Chayes	8	43.0	18.7	26.5	8.8	2.4	.. 0.6 ..		Woodbury
Average		42.7	17.8	26.9	8.4	3.3	.. 0.9 ..		
Murthy	9	34.7	20.1	24.3	9.8	9.8	.. 1.8 ..		Barre
Chayes	22	35.2	19.4	27.2	8.1	8.3	0.2	0.8	Barre
Average		35.0	19.8	25.7	9.0	9.1	.. 1.4 ..		
Murthy	9	12.3	27.9	49.4	6.9	4.5	.. 0.8 ..		Knox Mountain

diagram (Fig. 3). The portion of the diagram enclosed by the heavy solid line corresponds to Bowen's (1937, p. 17) thermal valley for the system $NaAlSiO_4$ — $KAlSiO_4$ — SiO_2. These points all fall within a relatively small area which is either in or on the left side of Bowen's thermal valley. According to Bowen (1937) fractional crystallization of a basaltic liquid gives a residue whose composition should lie in or near this thermal valley and further that the composition of glassy rocks commonly falls in or near the thermal valley. Inasmuch as the different samples of Woodbury granite have a relatively uniform composition and fall in or to one side of the thermal valley, a magmatic origin is indicated for the Woodbury granite. Similar studies have been conducted on the Barre granite by Chayes (1952) and Murthy (1957) which gave results very similar to those obtained from the Woodbury granite of this report. Because of this similarity the Woodbury and Barre granite are undoubtedly genetically related.

The Knox Mountain granite contains appreciably more quartz and potash feldspar and less plagioclase than either the Woodbury or Barre granites (Table 7). A plot of the average composition of the Knox Mountain granite on a quartz-plagioclase-potash feldspar ternary diagram (Fig. 3) gives a point which lies well above and slightly to the left of Bowen's thermal valley. Comparison of this point with those of the Woodbury and Barre granites (Fig. 3) shows that the Knox Mountain

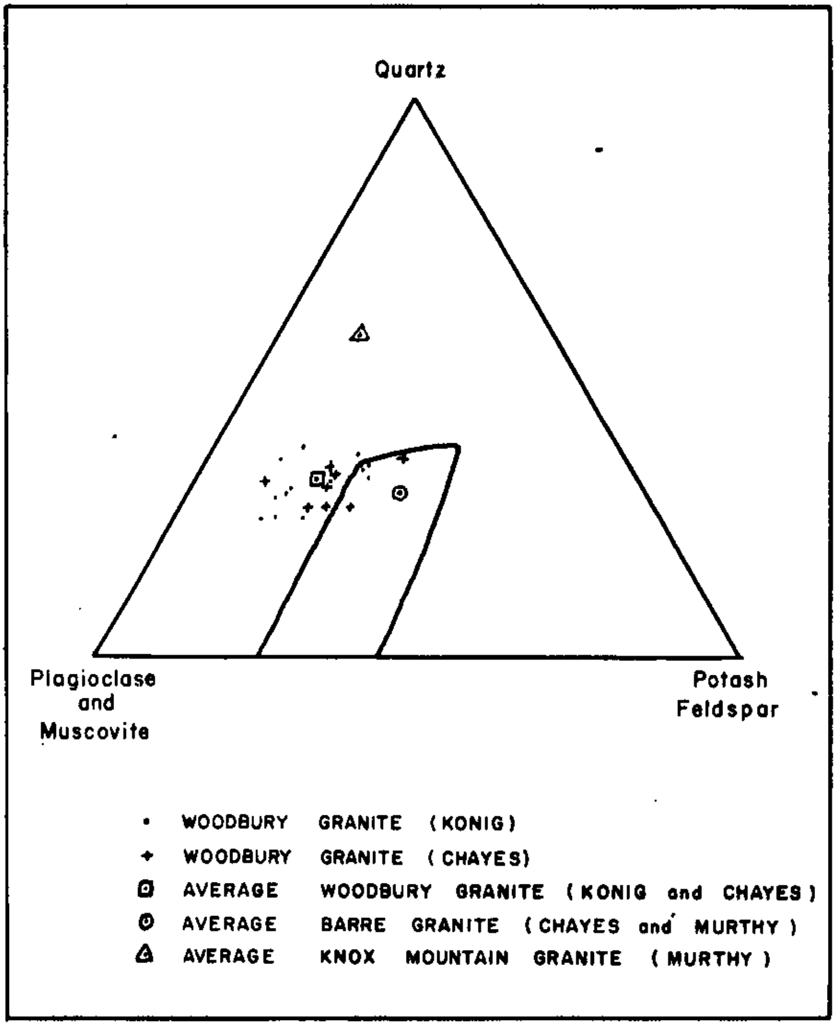


Figure 3. Quartz-plagioclase-potash feldspar diagram showing position of Bowens' thermal valley.

granite is more acidic, suggesting that it may represent a later stage crystallization product of the same magma which gave rise to the Woodbury and Barre granites.

The mode of emplacement of the Adamant, Knox Mountain and Woodbury granites is not wholly understood and is probably somewhat different in each case. In the case of the Knox Mountain granite the evidence favors a forceful intrusion with only minor amounts of assimilation. This is indicated in three ways: (1) inclusions of adjacent country rock in the granite are largely unaltered; (2) the country rock conforms to the shape of the intrusion; and (3) the country rock is drag folded and fractured into a pattern which is indicative of a rising mass of rock in the vicinity of the Knox Mountain granite.

The mechanism for the emplacement of the Adamant and Woodbury granites has resulted in conformable contacts with the country rock. Balk (1927) believes that the Woodbury granite has for the most part passively intruded an area of highly deformed metasediments with a previously developed fold pattern determining the position of the intruded granite. The Adamant granite shows a similar relationship with the country rock except that the granite has been intruded into a steeply dipping homoclinal sequence of rock. Because of the small size of the Woodbury and Adamant granites, a more passive emplacement compared to that of the Knox Mountain granite is likely.

Basic Dikes

One new locality of basic dike rock was discovered as a result of the present study. It is situated in the Moretown member of the Missisquoi formation and is best exposed in a stream bed, at an elevation of 1300 feet, approximately one mile N. 72° E. of Hardwood Pond. Other basic dike localities in the Plainfield quadrangle have been enumerated by Richardson, Brainerd and Jones (1914) and Balk (1927).

The dike at this new locality is a massive, dark gray, porphyritic rock which weathers yellowish-brown. Phenocrysts of black hornblende, biotite and more rarely a light-colored carbonate embedded in a fine-grained groundmass are identifiable in hand specimen. The phenocrysts range from 1 to 15 millimeters in length. Upon weathering, a yellowish-brown rind is developed which usually does not penetrate the rock more than one-fourth of an inch. This zone of secondary alteration is frequently studded with what appear to be oxidized grains of subhedral ankerite.

In thin section the rock is holocrystalline containing phenocrysts of hornblende, augite, biotite and olivine (?). These minerals are embedded in a groundmass of oligoclase (43 percent), apatite (4 percent), and magnetite (8 percent). The hornblende (20 percent) is weakly zoned, brown, and has a 2V of about 70 degrees. Augite (21 percent), however, is strongly zoned with the innermost zone usually being pale green or blue and weakly pleochroic. This pleochroic core has a 2V of 53 degrees.

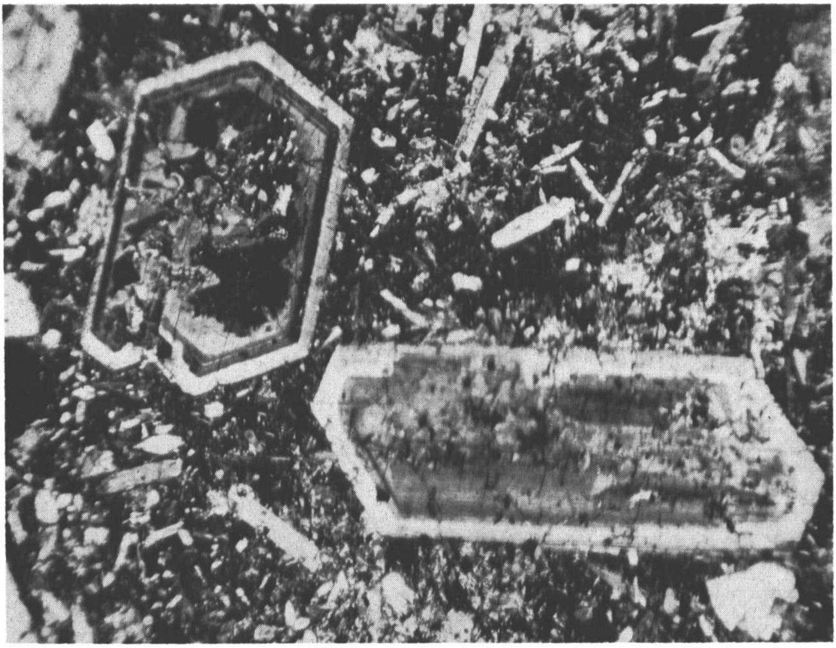


Plate 8. Photomicrograph of spessartite-kersantite lamprophyre showing large zoned crystals of augite in a matrix of brown hornblende (small laths) and plagioclase feldspar. Nicols crossed, × 40.

Each successive zone has a slightly larger optic angle, with that in the outermost zone being about 65 degrees. Phenocrysts of olivine(?), which are largely altered to antigorite, sericite, calcite and magnetite as well as brown biotite are present in accessory amounts. Other minerals present in the rock in trace amounts include sphene, zircon and quartz.

This rock has a mineral suite suggestive of a lamprophyre of spessartite-kersantite composition and is very similar to basic dikes reported in the East Barre quadrangle by Murthy (1957, p. 97–98).

Acidic Dikes and Sills

Acidic dikes and sills in the Plainfield quadrangle include pegmatites, aplites and quartz veins. The pegmatites occur as 5- to 10-foot thick sills and dikes which are composed of coarse-grained quartz, feldspar, mica and more rarely tourmaline and garnet. Aplites are light colored and form dike-like bodies composed of fine-grained quartz and feldspar as essential minerals and accessory mica and magnetite. Quartz veins which range in width from several inches up to 15 feet are usually very pure, only infrequently containing coarse knots of chlorite.

The aplites, pegmatites and more rarely quartz veins, are intruded into fractures, principally joints, in both metasedimentary and plutonic rocks. Many of the quartz veins are similar to earlier veins or segregations which have been folded and metamorphosed with the metasediments. In areas where early quartz veins are essentially parallel to bedding, subsequent tilting and metamorphism in the absence of minor folding may result in an identical attitude of the early quartz with much of the later emplaced quartz, so that the early quartz bodies become virtually indistinguishable from post tectonic quartz.

Joints

Longitudinal joints transect most of the granitic bodies in the area, but are best developed in the Knox Mountain granite. These joints are by definition parallel to the linear flow lines in the granite. On aerial photographs longitudinal joints appear as a series of well defined but discontinuous lines, which result from increased vegetation along narrow zones of well-developed joints. These joints trend N. 5° E. to N. 25° E., or roughly parallel to the long axis of the intrusion. The amount of dip, as determined in the field, is generally 60 to 90 degrees either to the southeast or northwest.

A similar joint set occurs in the Woodbury granite but is much less regular and more poorly defined on the air photos. Apparently the smaller size of these plutons has been a deterent to joint development. In areas of good exposure, field mapping has shown that in plan view the trace of longitudinal joints in the Woodbury granite is clearly curved, being controlled by the local flow structures in the granite. In the smaller elliptical granite bodies longitudinal joints and flow structures generally parallel the long axis of the intrusions. This relationship could not be demonstrated in the more northern exposures of the Woodbury granite because of the poor development of primary flow structures.

Cross joints by definition are those fractures which are developed normal to both longitudinal joints and primary flow structures in the granite. They are generally not as well developed as the longitudinal joints, but nevertheless are clearly visible on aerial photographs of the Knox Mountain granite. Measurements of air-photo linears indicate that the cross joints strike west-northwest. Field mapping shows these joints to dip steeply southwest or northeast. Cross joints were not observed in the Woodbury and Adamant granites on the air photos, proba-

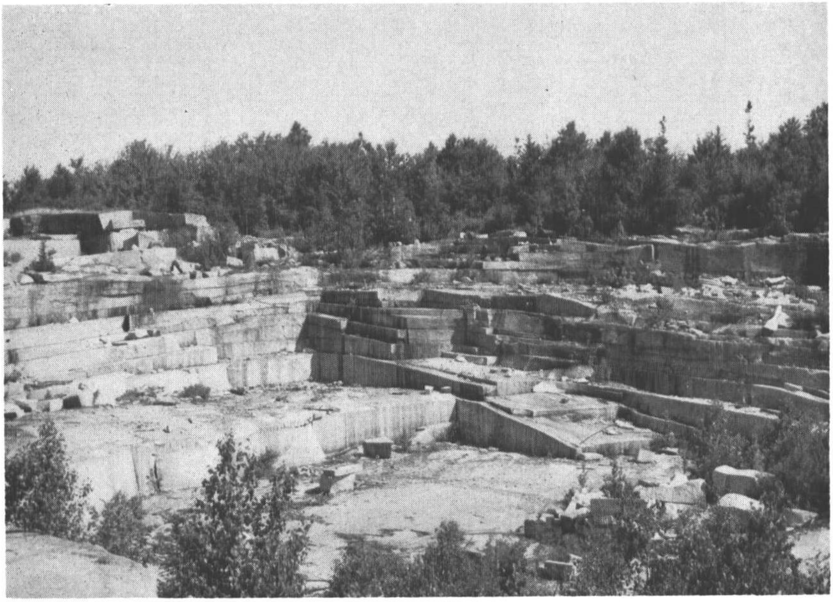


Plate 9. Sheeting, or horizontal jointing, developed subparallel to the overlying topography in the Fletcher granite quarry.

bly because of the limited exposure of these granites. Mapping by the writer confirms Balk's (1926) conclusions that cross joints in the Woodbury granite are not as well developed and have a more variable trend than the longitudinal joints. The cross joints often serve as planes of weakness along which mineralization, mainly in the form of quartz and pegmatite dikes, has taken place.

Sheeting

Sheeting, or horizontal jointing, occurs in most parts of the larger granite bodies in the Plainfield quadrangle and is best developed in the Fletcher quarry in the Woodbury granite (Plate 9). At the top of the quarry an average sheet of granite is approximately 12 inches thick, but progressively increases to a maximum of about 50 inches near the bottom. This feature together with the uniform texture and color of most of the rock makes the granite particularly well suited for building purposes. Because of glacial cover the relation between the thickness of the individual granite sheets and the glacially modified topography, as suggested by Jahns (1943) could not be definitely established. There is some suggestion, however, that the sheeting becomes somewhat thicker towards the southeastern margin of the Fletcher quarry. This gradual thickening is shown in the right hand portion of Plate 9.

Age

The Adamant, Knox Mountain and Woodbury granites all cut folded and metamorphosed sediments which are Lower Devonian in age. The granites, in turn, are cut by quartz veins, pegmatites and dikes of lamprophyric composition, the latter being considered as Permian or Triassic (Konig and Dennis, in press). The granitic material is considered to have been emplaced during the Devonian. This age is partially substantiated by the results of a Rb/Sr age determination of the Barre granite (Murthy, 1957, p. 95). This test gave an age of 350 ± 25 million years, which is indicative of Devonian (Kulp, 1961). Inasmuch as the Barre, Adamant and Woodbury granites are closely related with respect to location, composition, texture and structure, they are probably nearly the same age. The relationship between these granites and the Knox Mountain granite is not as evident, but because they all show similar evidence of being forcefully intruded into Devonian metasediments and are cut by dikes of similar composition, the Adamant, Barre, Knox Mountain and Woodbury granites are believed to be nearly coeval; thus, in this report they are assigned to the Devonian.

STRUCTURAL GEOLOGY

General Statement

Sedimentary rocks in the Plainfield quadrangle have been folded and metamorphosed twice. The strongest stage of deformation occurred following the deposition of the Gile Mountain formation and prior to the emplacement of the Woodbury, Knox Mountain and Adamant granites. This deformation resulted in regional metamorphism and folding with the axes of the major folds roughly paralleling the trend of the Green Mountain anticlinorium to the west. The Woodbury syncline, Nichols anticline and the Brownington syncline were formed in the Plainfield quadrangle during this disturbance.

During the waning stages, or closely following this earlier disturbance is the development of regional warping, doming and minor folding associated with the emplacement of granitic rocks in east-central Vermont. These structural features are variously developed in the Plainfield quadrangle and are interpreted as being formed to a large extent by the emplacement of the granitic rocks.

Structural Features

Bedding Schistosity

Bedding schistosity has formed in many parts of the Plainfield quadrangle. By definition bedding schistosity is developed parallel to original sedimentary bedding by slippage along bedding planes. This slippage often results in the formation of minor folds or crinkles, and mineral lineation on the schistosity surface. Bedding schistosity is most prevalent in folded argillaceous rocks, although it sometimes forms in micaceous limestone and quartzite. Where bedding is not easily distinguished, as in thick sections of slate or phyllite, it may be difficult to separate bedding schistosity from cleavage which has formed nearly parallel to the axial planes of larger folds. In the northwestern half of the Plainfield quadrangle these two structures may be distinguished by the fact that bedding schistosity surfaces are generally undulatory as a result of minor drag folding, whereas cleavage is considerably more uniform, with the cleavage surface only occasionally marred by minute folds or crinkles. In the southeastern half of the quadrangle the rocks are more highly deformed so that cleavage is considerably folded and may resemble bedding schistosity. Inasmuch as most of the larger folds in the quadrangle are nearly isoclinal, bedding schistosity and cleavage tend to merge on the limbs of folds and become indistinguishable. Conversely, in the axial region of the folds bedding schistosity and cleavage become more divergent and are easily distinguished. As a general rule, however, where bedding schistosity is well developed, cleavage is poorly developed and vice versa. The bedding schistosity forms in rocks which are composed of interbedded argillaceous and arenaceous layers whereas cleavage tends to be best developed in more homogeneous rocks, particularly argillaceous ones, in which original bedding planes are poorly developed.

Cleavage

Four types of cleavage, flow, slaty, fracture and slip, are recognized in the Plainfield quadrangle. Flow and slaty cleavage are characterized by the alignment of platy minerals parallel to the cleavage surface and by being more or less parallel to the axial planes of both major and minor early folds. Because of this relationship flow and slaty cleavage are referred to as early axial-plane cleavage, and because of their similarity in appearance and mode of origin are represented on Plate 2 (in pocket) as early flow cleavage. These cleavages are almost always confined to the more argillaceous rocks of the western band of the Waits

River formation. Superimposed on early cleavage is mineral lineation or streaming and small later drag folds or crinkles. Both of these features are easily mistaken for similar-appearing features developed on bedding schistosity. Because most of the early folds in the quadrangle are nearly isoclinal, the associated early cleavage is usually not distinguishable from bedding schistosity except in the axial regions of the early folds.

Slip cleavage (Dale, 1899, p. 209) is widespread in east-central Vermont and has been discussed in detail by White (1949) and more recently by Eric and Dennis (1958) and Hall (1959). The term "slip cleavage", as used in this report, refers to a cleavage which developed penecontemporaneously with a later stage folding in the Plainfield quadrangle. Thus, slip cleavage post-dates early flow, slaty and fracture (see below) cleavage and bedding schistosity. In the western half of the quadrangle slip cleavage clearly shows cross-cutting relationships with early cleavage. In the eastern half of the quadrangle, where folding and metamorphism are more intense, the relation between slip cleavage and early cleavage is less clear. Apparently in this area the slip cleavage becomes so well developed that it grades into a type of flow cleavage which, in this report, will be termed "later axial-plane flow cleavage". Both slip cleavage and later flow cleavage show axial plane relationships with later major and minor folds.

Critéria which may be used to distinguish slip cleavage from early cleavage are as follows:

1. Slip cleavage is expressed as minor drag folds or crinkles on both early cleavage and bedding schistosity surfaces (Plate 10), or may produce displacements, usually less than 1/8 inch, of bedding, bedding schistosity and/or early cleavage surfaces.
2. Slip cleavage planes are more widely spaced than early cleavage planes (compare Plate 11 and Plate 12).
3. Slip cleavage commonly forms an angle of 5 to 10 degrees with the axial planes of later drag folds (Plate 12). With increasing deformation and rock flowage, this angle tends to decrease and slip cleavage grades towards what is called later flow cleavage in this report.
4. Slip cleavage is generally less persistent along strike than early cleavage.

Although slip cleavage and early cleavage are usually distinguished by one or more of the above criteria, difficulty may arise where slip cleavage is exceptionally well developed. The individual shear planes become closely spaced and may form a type of flow cleavage which

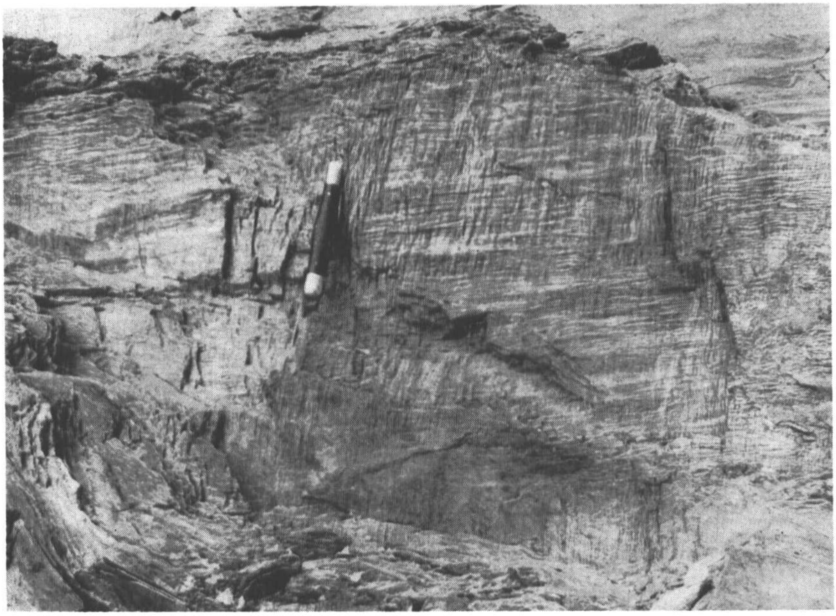


Plate 10. Two sets of small drag folds or crinkles on bedding schistosity surface of Waits River phyllite located along road on west side of Valley Lake.

resembles early flow cleavage. This condition has undoubtedly developed in some localities in the Gile Mountain formation. On the limbs of isoclinal folds where early flow cleavage and bedding schistosity are nearly parallel, cross-cutting slip cleavage might easily be misidentified as early cleavage cutting bedding schistosity. A misidentification of this nature would make structural interpretations hazardous, as the two cleavages show axial-plane relationships with two genetically unrelated folds. Thus, in the more highly deformed and metamorphosed areas in the Plainfield quadrangle the only reliable criteria for distinguishing these cleavages is that slip cleavage must show a cross-cutting relationship with the early cleavage of the northeast trending folds, a distinction which is often difficult to make.

Fracture cleavage is almost wholly restricted to the impure quartzite (the pinstripe) of the Moretown member of the Missisquoi formation. The individual fracture or shear planes are usually confined to the more argillaceous layers of the quartzite and are more widely spaced than typical flow and fracture cleavage planes. Small-scale drag folding of the interbedded argillaceous and arenaceous layers of "the pinstripe" often

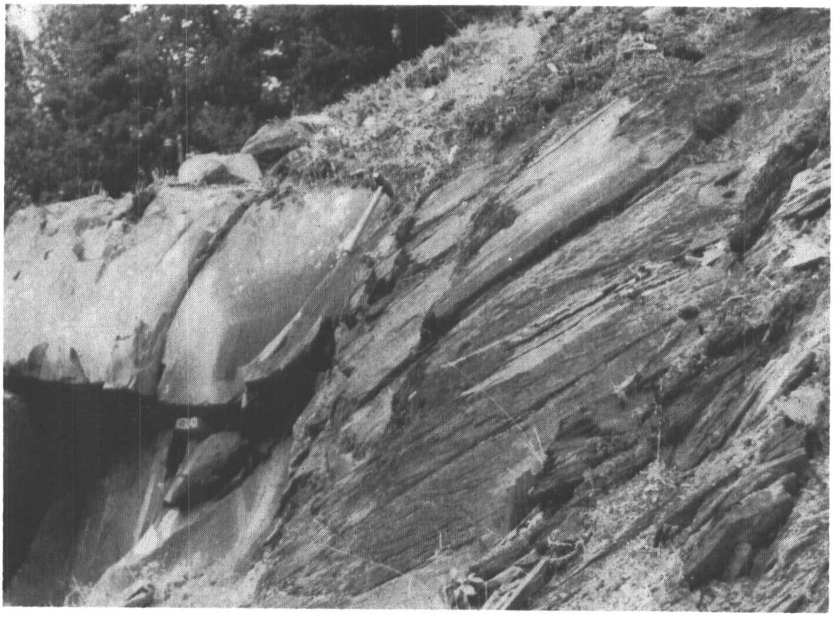


Plate 11. Early flow cleavage (right) dipping steeply towards massive limestone (left) in Waits River formation along east side of Route 14 (old Route 12) adjacent to Blake Falls.

results in local cross-cutting relations between fracture cleavage and bedding. Slippage parallel to these planes of fracture cause a small displacement of the beds on the short limb of the drag folds. Despite this slippage the term slip cleavage is not used here because slip cleavage, as restricted in this report, refers to cleavage of later drag folds. Thus, early fracture cleavage in the Moretown is undoubtedly related genetically to the early flow and slaty cleavage developed farther east in the more argillaceous rocks of the Waits River formation. Reconnaissance by the writer indicates that fracture cleavage in the Moretown grades into fracture cleavage associated with the axis of the Green Mountain anticlinorium in the vicinity of Mount Mansfield.

In conclusion, it appears that fracture cleavage is developed in most rock types during the initial stages of deformation. With increased folding and metamorphism it persists as "typical" fracture cleavage in the more competent, arenaceous rock types, but grades into what frequently has been called "slip cleavage" by many Vermont geologists in the less competent, thin-bedded, dominantly argillaceous rocks. How-

Plate 12. Late stage drag folding and related slip cleavage in interbedded limestone and phyllite of the Waits River formation along road on west side of Valley Lake. The slip cleavage is subparallel to hammer handle and shows cross-cutting relationships with poorly developed bedding schistosity.

ever, regardless of the amount of slippage associated with this cleavage it is considered to be early fracture cleavage. Where cleavage develops in an extremely uniform argillaceous rock in which there is little or no difference in grain size between adjacent beds the initial fracture cleavage may pass very rapidly into early slaty and flow cleavage. In competent, thick-bedded rocks, more intense deformation and metamorphism may completely destroy the early fracture cleavage. After the formation of early fracture, slaty and flow cleavage, continued or renewed deformation may develop new fractures or shear planes which cut the earlier formed structures. In this report, these later shears are called "slip cleavage." Thus, in the Plainfield quadrangle these features, from oldest to youngest, are (1) fracture cleavage; (2) slaty cleavage; (3)

flow cleavage; and (4) slip cleavage which locally grades into what is referred to as "later flow cleavage".

Minor Drag Folds

Minor drag folds in the Plainfield quadrangle range in amplitude from microscopic dimensions to 30 feet. These folds are best developed in the more argillaceous rocks, although they are found occasionally in relatively competent impure quartzite. Because the rocks in east-central Vermont have been affected variously by two stages of deformation, two genetically unrelated sets of minor drag folds have been formed. The first set of drag folds, referred to as early folds in this report, are usually isoclinal and trend north-northeast, essentially parallel to the strike of the Green Mountain anticlinorium. These early drag folds usually have axial-plane slaty and flow cleavage and give the correct shear sense for the folding associated with the formation of the anticlinorium (Plate 13). Inasmuch as early drag folds have been affected by a later stage of deformation, they are not very well preserved in the quadrangle.

A second set of drag folds, referred to as later folds in this report, are usually more open than the early folds, that is, they are seldom isoclinal. They show no consistent orientation with respect to the trend of the Green Mountain anticlinorium, with some of them striking nearly east-west. Later folds often possess essentially axial-plane slip cleavage and generally give a shear sense indicating that the rocks in the eastern part of the quadrangle rose with respect to those in the west. This movement undoubtedly is associated with the emplacement of granitic rocks in east-central Vermont and suggests that the plutonic rocks were, in part, forcefully intruded into the overlying metasediments. Local irregularities in this up-east shear sense occur in several areas in the Plainfield quadrangle and probably are related to the emplacement of the Woodbury granite.

Minor Flowage Folds

Minor flowage folds, with amplitudes from less than one inch to 6 feet, are almost wholly confined to the carbonate-rich rocks of the Waits River formation. These folds are usually isoclinal, show considerable thickening in the crest and trough regions and are oriented so that their axial planes are usually subparallel to the bedding in adjacent siliceous and argillaceous rocks (Plate 14). Differential erosion in the carbonate rock often produces alternate grooves and ridges. These erosional features are usually parallel to the axial planes of the flowage

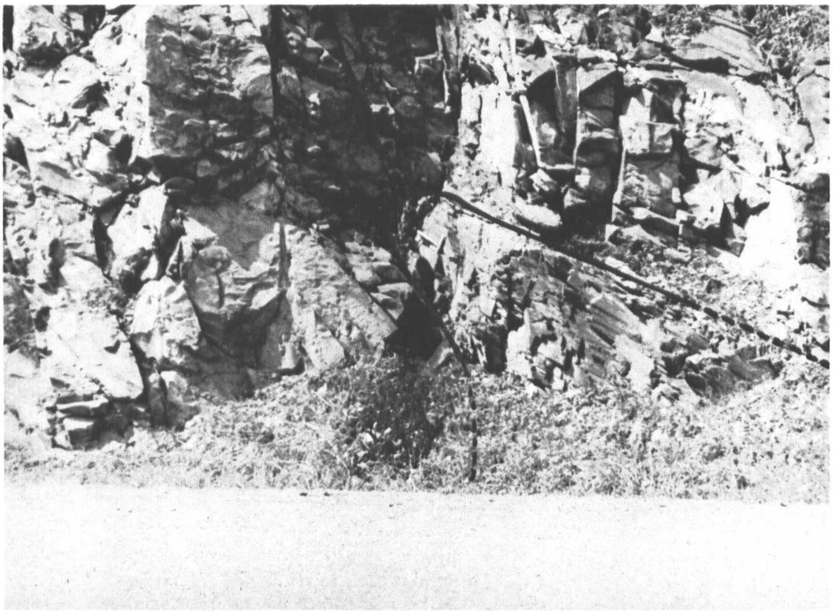


Plate 13. Early isoclinal drag fold (center) with well-developed, axial-plane slaty cleavage in Waits River formation located about one mile south of Woodbury on Route 14 near Blake Falls. The hammer is in phyllite near the nose of the fold with the handle oriented approximately parallel to the dip of axial-plane cleavage. More widely spaced vertical fractures are well-developed joints.

folds as well as to the bedding in adjacent more competent rocks (Plate 15). Flowage folds in the Plainfield quadrangle do not give a shear sense which is consistent with either the earlier or later stage of folding and consequently were not used for structural interpretations.

Mineral Streaming

Thin streaks of mica, usually biotite, and/or a sulphide commonly mar surfaces of bedding schistosity and early cleavage. This linear element is commonly nearly parallel to the dip of the surface upon which it is developed and very probably represents movement in the "a" tectonic direction during one or more stages of deformation which preceded the second stage of metamorphism in the Plainfield quadrangle. The angle between the trend of mineral streaming and the dip of the containing surface often approximates the plunge of the genetically related fold, much in the way illustrated by Nevin, (1949, p. 46) for slickensiding and folding.

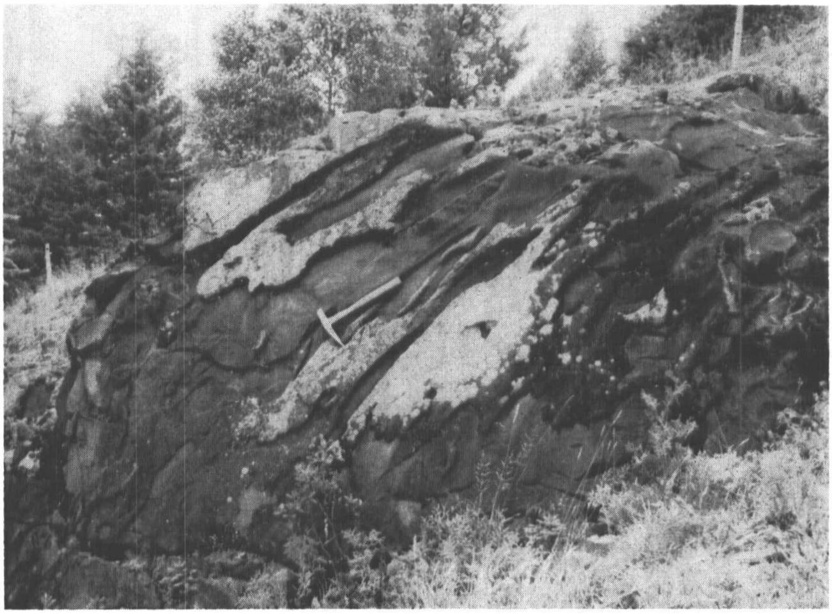


Plate 14. Flowage folds in impure Waits River limestone located approximately one mile northwest of South Walden on Route 15 in the Northeast $\frac{1}{4}$ of quadrangle. Hammer handle is oriented about parallel to axial planes of flowage folds.

Major Early Folding

General Statement

Major early folds are traceable for several miles or more along strike and trend approximately parallel to the Green Mountain anticlinorium. These folds are usually distorted by subsequent or continued deformation, so that their axial planes are gently folded or warped (Plate 1). In the Plainfield quadrangle three early folds are recognized and are named from east to west the Woodbury syncline, Nichols anticline, and Brownington syncline. These three structures are discussed in detail below along with other less definite major structures.

Woodbury Syncline

The axial region of the Woodbury syncline is exposed approximately one mile south of the town of Woodbury in a series of outcrops along Route 14. Although the axis of this fold is not exposed, its position is inferred from bedding-cleavage and drag-fold relationships seen along

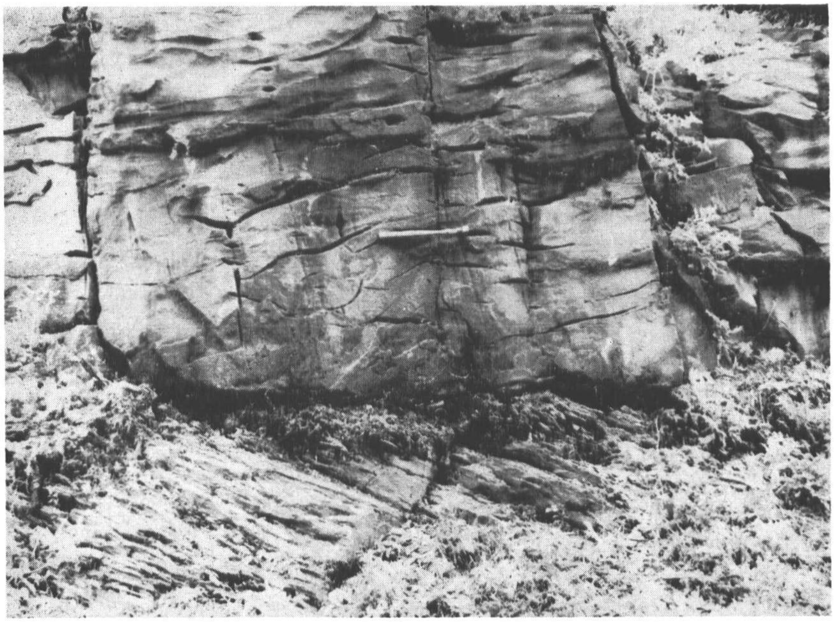


Plate 15. Folded and differentially weathered Waits River limestone located approximately one mile northeast of South Walden on Route 15. Hammer handle about parallel to both the axial planes of the flowage folds and subjacent contact between limestone and phyllite which has a well-developed early cleavage dipping about 20 degrees to the right.

the highway. In this general area the fold axis has a local trend of N. 60° E., parallel to the strike of early cleavage, and plunges 15 to 20 degrees to the northeast. Good exposures west of the fold axis consistently show bedding dipping more steeply than cleavage, indicating that the western limb is overturned with tops facing east (Plate 11). Early drag folds indicate a similar relationship. East of the fold axis the bedding-cleavage and early drag fold relationships are reversed indicating right-side-up conditions.

Inasmuch as minor drag folds should simulate the configuration of the major controlling fold, it is possible to describe the Woodbury syncline by analysis of the associated drag folds. On the east limb of this syncline, approximately 150 yards from the fold axis, early drag folds are isoclinal, contain good axial plane cleavage, involve minor flowage towards the axial regions and give a reliable shear sense for early major folding (Plate 13). Drag folds lying very close to the axis of the Wood-

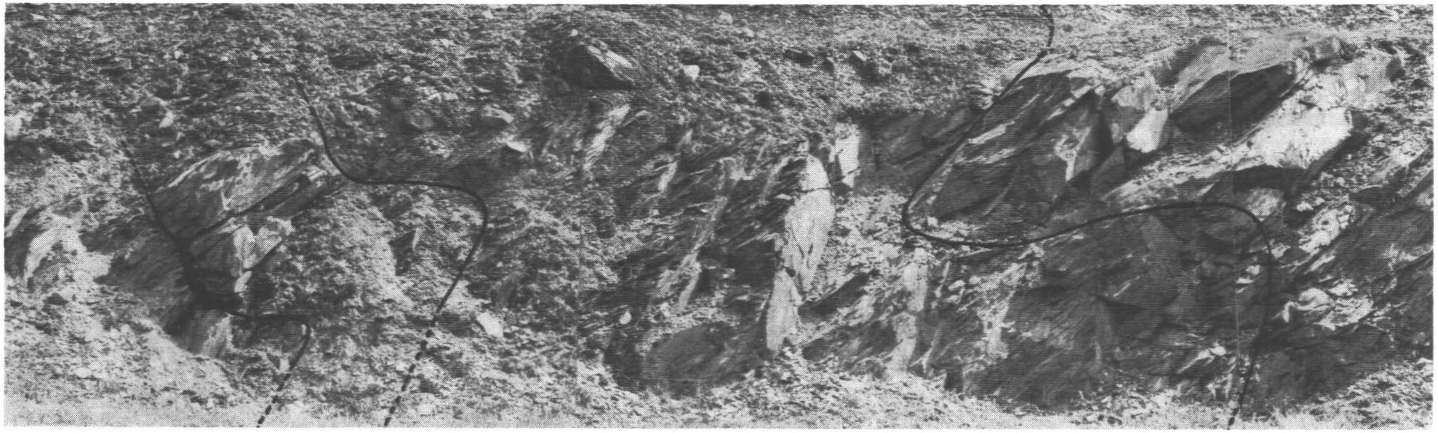


Plate 16. Early drag folds with northwesterly dipping axial-plane cleavage located close to the axis of the Woodbury syncline about one mile south of South Woodbury along Route 14 opposite Blake Falls. The folds are outlined by a heavy dark line which is drawn along the contact between limestone and phyllite. Widely spaced fractures near center of diagram which dip steeply southwest (to right) are well developed joints.

bury syncline are more open, but otherwise very similar to the drag folds located farther out on the limbs (compare Plates 13 and 16). Assuming that drag folds reflect the shape of the larger controlling fold, the Woodbury syncline must be a nearly isoclinal fold with only minor flowage of material into its axial region.

The northeast and southwest continuation of the Woodbury syncline is difficult to trace. To the northeast the Woodbury granite obscures many of the bedrock relationships and to the southwest lakes and glacial till seriously limit the number of exposures. Despite these limitations, the fold axis was mapped for about 5 miles and very probably extends even farther to the northeast. The trace of its axis is curved to conform roughly with the shape of the Knox Mountain granite (Plate 1).

Brownington Syncline

Previous Work

The Brownington syncline (Doll, 1951, p. 51–52) was first recognized by Richardson (1906, p. 90–94) near the town of Walden in the St. Johnsbury quadrangle. Richardson envisaged the syncline as a shallow, open fold containing dominantly non-calcareous rocks (his Bradford schist) which lay stratigraphically above the enclosing Waits River formation. In his report on the Memphremagog quadrangle Doll (1951) introduced the name "Brownington syncline" for this northeast-trending fold, placing the Westmore formation (Gile Mountain of this report) in the axial region of the fold and the Barton River formation (Waits River of this report) on either limb.

Dennis (1956) was able to trace the Brownington syncline southward through the Lyndonville quadrangle. Throughout most of the Lyndonville area the western limb of the syncline is reportedly overturned, with tops facing east and steep dips to the west. The beds on the eastern limb dip gently westward, thus forming a large east-facing fold. The axis of this fold lies somewhere within the Gile Mountain formation with Waits River lithology found to the east and west. These relationships are in general accord with those presented by Doll (1951). In the southern part of the Lyndonville quadrangle the Brownington syncline becomes more open, with the western limb dipping steeply to the east and the eastern limb dipping gently to the west. This change in the pattern of the Brownington syncline is very likely the result of a culmination along the axis of the Brownington syncline (Dennis, 1956).

Murthy (1957, p. 66–67) presents field evidence refuting the existence of Doll's Brownington syncline in the East Barre quadrangle. Instead he believes that the Westmore formation (Gile Mountain of this report) and the Barton River formation (Waits River in this report) form part of a westwardly dipping homoclinal sequence which make up the western limb of a tightly folded syncline, the axis of which strikes north-northeast and lies in the central portion of the East Barre quadrangle.

Thus, the Brownington syncline has been traced from the Memphremagog quadrangle through the Lyndonville quadrangle to the northern edge of the St. Johnsbury quadrangle, which is approximately four miles northeast of the present area of study. Hall (1959) has traced this syncline through the northwest corner of the St. Johnsbury quadrangle. South of the Plainfield quadrangle the Brownington syncline has not been recognized and the western band of Gile Mountain has been mapped as a part of a homoclinal sequence. The question therefore arises as to the type of structure contained in the Gile Mountain formation in the Plainfield quadrangle.

Analysis of the Problem

Any attempt to establish the structure of the Gile Mountain formation must take into account regional stratigraphic relationships as well as minor structural features within the Plainfield quadrangle. Although much of this stratigraphic and structural information has been previously discussed, it is briefly summarized below.

1. In the Plainfield quadrangle the western band of Gile Mountain generally parallels the western edge of the Knox Mountain granite.
2. To the north the eastern and western bands of Gile Mountain strike into each other (merge) in the southern portion of the Island Pond quadrangle.
3. The beds on the eastern margin of the Gile Mountain formation dip more steeply than beds farther west. This is in direct contrast to that reported in the Lyndonville quadrangle where no plutonic rocks are exposed along the eastern margin of the Gile Mountain formation.
4. The Waits River formation lies stratigraphically above the Northfield formation.
5. The trend of the Gile Mountain formation and the axes of early major folds in the Plainfield quadrangle have been deformed similarly.
6. Early axial-plane cleavage in the Woodbury syncline is cut by slip cleavage. This cleavage developed after the Woodbury syncline and is associated with the refolding of the synclinal axis.
7. Two genetically unrelated minor drag folds have developed in the Plainfield quadrangle. The first, or early drag folds, which formed

contemporaneously with the early major folds give a compatible shear sense for these folds. The second, or later drag folds, generally show a fold pattern which indicates that the rocks in the eastern part of the quadrangle rose with respect to those farther west.

8. Slip cleavage approximates axial-plane cleavage in the later minor drag folds.
9. The plunge of minor folds or crinkles on early flow cleavage and bedding schistosity surfaces is anomalous with respect to the formation of major early folds. There are two sets of these crinkles and the crest of each is often defined by the trace of slip cleavage.

Inasmuch as the two bands of Gile Mountain merge in the southern part of the Island Pond quadrangle as a result of a structural closure, the possibility of the central band of Waits River being a calcareous facies of the Gile Mountain formation is no longer tenable (Fig. 1). In the Memphremagog quadrangle the strike of bedding in the Gile Mountain formation trends generally north-northeast (Doll, 1951), whereas in the southern part of the Island Pond quadrangle a general east-west strike is reported where the eastern band of Gile Mountain merges with the western band. Thus, where these widely divergent strikes meet defines the position of a fold axis. If no additional evidence were available this fold could be either a southerly plunging anticline or a northerly plunging syncline. West of this structure the western band of Waits River is known to lie stratigraphically above the Northfield formation. If an anticlinal axis is placed in the western band of Gile Mountain a synclinal axis must lie somewhere in the western band of the Waits River formation to make the Waits River younger than the Northfield formation. Detailed study in the Memphremagog quadrangle by Doll (1951) shows no such structure in the western band of the Waits River formation. Similar work in the Plainfield quadrangle shows that even though a major early fold, the Woodbury syncline, is present in the western band of Waits River it is restricted to the quadrangle. In view of these relationships, the only alternative is to place a synclinal axis in the western band of Gile Mountain. Inasmuch as no termination or wrap around of the bedding is associated with this fold between the Memphremagog and Plainfield quadrangles, the Brownington syncline must extend into the Plainfield quadrangle according to Doll's and Dennis' interpretation.

Murthy (1957 and 1958) considered the Gile Mountain formation in the East Barre quadrangle to be composed of a thick sequence of homoclinally dipping beds. He believed this sequence to be part of the western limb of a large syncline whose north-northeast trending axis lies roughly in the central portion of the East Barre quadrangle. The axial zone of this syncline has been punched up and is called the Strafford anticline (Doll, 1944) and the Willoughby arch (Dennis, 1956). Murthy found no evidence in the East Barre quadrangle to support the presence of a syncline in the western band of Gile Mountain.

In the southern half of the Plainfield quadrangle the Gile Mountain formation consists of a series of metasediments which dip 40 to 60 degrees to the west, with the steeper dips generally occurring in the eastern half of the formation. Farther north in the quadrangle the dip becomes much more gentle with average dips of about 25 degrees to the west being common. In the southern part of the Lyndonville quadrangle the dip is east in the western part of the formation and west in the eastern part (Dennis, 1956). This convergent dip marks the most southerly extent of the Brownington syncline in the Lyndonville quadrangle. A similar relationship occurs in parts of the Gile Mountain formation in the Northwest corner of the St. Johnsbury quadrangle (Hall, 1959). According to Dennis (1956) this area of gentle dip in the Gile Mountain formation is the result of a minor culmination in the Brownington syncline. In the vicinity of this culmination the Gile Mountain formation, as well as the axis of the Brownington syncline, is warped or folded so that its trend changes from about north-south, north of the culmination to east-northeast, south of the culmination.

Inasmuch as the Brownington syncline enters the Plainfield quadrangle in the north with its axis lying in the Gile Mountain formation and this formation extends uninterrupted the entire length of the quadrangle, the Brownington syncline must also traverse the length of the quadrangle. Structural evidence in the Plainfield quadrangle which supports the presence of the Brownington syncline is rare. Early minor drag folds which developed during the formation of the syncline, although occasionally observed, are badly distorted and tightly compressed. This distortion appears to be most intense in the eastern part of the Gile Mountain formation, particularly adjacent to the forcefully intruded Knox Mountain granite (Plate 17). Superimposed on these early drag folds are later drag folds with axial-plane slip cleavage. In many areas, this slip cleavage is so well developed that it acquires the appearance of flow cleavage, a later flow cleavage, which is unrelated to the formation of the Brownington syncline. Inasmuch as this later fold pattern and slip cleavage indicates a rising mass of rock to the east of the Gile Mountain formation, the use of these later structures to interpret the early structure in the Gile Mountain formation would lead to an over-

Plate 17. Tightly folded and partially digested early drag fold in the Gile Mountain formation about one mile southeast of Marshfield on west side of U. S. Route 2. Light colored rock is Knox Mountain granite and dark colored rock is Gile Mountain biotite-garnet-staurolite schist. Hammer handle is about parallel to axial plane of steeply plunging fold.

simplification; the western band of Gile Mountain would appear to represent a homoclinal sequence of rock with a westerly dip. As a result of the emplacement of the granite the rocks in the Gile Mountain formation were not only compressed, as illustrated by the early drag folds, but were rotated in a counterclockwise direction causing a steepening of dip. This rotation was greatest close to the intrusion and became progressively less farther away to the west. Consequently, the rocks in the eastern part of the Gile Mountain formation dip more steeply than those in the western part, a situation which is just the reverse in the Lyndonville quadrangle where no igneous rocks occur on the eastern edge of the formation.

Small drag folds or crinkles developed on surfaces of bedding schistosity and/or early cleavage have been used in the past to determine the direction of plunge of the Brownington syncline. Inasmuch as these crinkles are produced primarily by slip cleavage and because slip cleavage is a later structure formed during the emplacement of granite, the orientation of most of these crinkles can not be used to interpret the early structures in the Gile Mountain formation.

In conclusion, it appears that the Brownington syncline continues through the Plainfield quadrangle, with the fold axis lying in the Gile Mountain formation. The fold is isoclinal and overturned to the east mostly because of the compressional effect caused by the deformation related to the Knox Mountain granite. Early drag folds and associated axial plane cleavage have been largely destroyed by the second deformation and minor drag folds and axial plane slip cleavage have formed which give a shear sense indicating that the rocks in the eastern part of the quadrangle rose with respect to those in the west. These structures have been superimposed on early structures developed with the Brownington syncline.

Nichols Anticline

The presence of the Nichols anticline is necessary between the Brownington and Woodbury synclines. Little structural and stratigraphic evidence was found to verify its existence except an area of nearly flat dips in the vicinity of East Long Pond and widely scattered bedding-cleavage relationships between Woodbury Lake and Coits Pond. The bedding-cleavage relationships indicate that the anticline is overturned to the southeast. The paucity of outcrops, resulting from heavy glacial overburden and the flat dips, makes it impossible to determine exactly the position of the fold axis. Nevertheless, it has been drawn so as to extend northeast from Woodbury Lake to the vicinity of Nichols Ledge (Plate 1).

Other Folded Areas

Other areas of probable major folding are located in both the northwestern and northeastern parts of the quadrangle. In the northwestern area the width of outcrop of the Moretown member increases nearly two-fold in comparison with the width to the southwest in the Montpelier quadrangle, without much variation in dip. Barring some unique sedimentary process or possibly faulting, this increased width of outcrop can be explained most easily as a result of repetition due to isoclinal folding. The only evidence for the existence of such folding is the sudden change in the minor drag-fold pattern (Plate 2). The fold pattern changes from dominantly sinistral to dominantly dextral in plan view in the central portion of the Moretown due west of Woodbury Mountain.

Whether this change in the fold pattern indicates the presence of a major fold could not be determined.

In the northeastern corner of the quadrangle, the Waits River formation and portions of the Gile Mountain formation are complexly folded. The folds are isoclinal and overturned to the east with beds dipping 30 to 35 degrees to the west. Two of these northeast-trending fold axes are shown on Plate 1. Most of these complexly folded rocks lie in an area of poor exposure and consequently individual fold axes could not be traced along strike. Reconnaissance in the adjoining portions of the Hardwick quadrangle failed to disclose conclusive data regarding these folds. Consequently, the area probably contains many more folds than could be mapped. The gentle westward dips and the culmination in the Browningtou syncline several miles to the east suggest that some degree of doming or arching of the bedrock is likely.

Later Folding

Later folding is so poorly defined in the Plainfield quadrangle that individual fold axes could not be definitely located. These folds are inferred mainly from the abundance of later minor drag folds. The direction of movement or shear sense shown by these drag folds is somewhat erratic, but in general indicates that the rocks to the east rose with respect to those to the west. This uplift is associated with the Strafford-Willoughby arch (Eric and Dennis, 1958). The axis of this arch is located several miles to the east in the St. Johnsbury quadrangle and has been mapped in the central part of the East Barre quadrangle (Murthy, 1957). The Knox Mountain granite occurs along the trend of the axis so it is likely that the intrusion may have been responsible, in part, for the development of the arch and may have caused the large-scale warping and folding of the formations and early structures in the Plainfield quadrangle. Thus, the later drag folds, as well as their axial-plane slip cleavage have been produced to a large extent by the emplacement of granitic rocks. A further effect of this uplift has been to tightly compress or collapse the Brownington syncline, destroying most of the early structures and imposing new ones upon it.

Faults

Several small reverse faults are exposed in the Woodbury granite quarries. They strike east-northeast, dip about 50 degrees to the southeast and contain abundant slickensides which have a rake, or pitch, of 50 to 70 degrees to the southeast. The attitude of the slickensides and irregularities on the fault plane indicate that the rocks on the southeast have moved relatively over those to the northwest. Balk (1927, p. 48 and 92) has reported structures with similar attitudes in the Bethel granite in the Randolph quadrangle and in the Barre granite in the East Barre quadrangle. The exact origin of these reverse faults is not known, but they suggest a regional tectonic shortening from the southeast following the emplacement of the granite. Inasmuch as post-tectonic basic dikes cut these slickensided surfaces (Balk, 1927, p. 92), the faulting must have occurred after the solidification of the granite and prior to the emplacement of the basic dikes. The total displacement along these faults probably is not great, as attested by the limited trace of the faults along strike and the absence of appreciable marginal displacement of the granite bodies.

Faults with similar orientations have been observed in the adjacent metasediments. These faults could not be traced for more than 20 to 30 feet along strike and never showed evidence of more than a few inches of vertical displacement. It is not known whether these faults are genetically related to those in the granite.

Joints

Joints are well developed in the Plainfield quadrangle and are easily measured in the field as well as on aerial photographs. Although no attempt was made to plot air photo linears, presumably joints, 600 joints were measured in the field and have been plotted on an equal-area stereographic projection (Fig. 4). This study indicates that four recognizable joint sets occur in the quadrangle. The dominant set trends approximately N. 55° W. and is nearly vertical. Symmetrically distributed about this set are two less well developed joint sets at N. 22° W. and N. 80° W. which may represent conjugate shears but more likely represent local irregularities in the strike direction of the dominant N. 55° W. set. The fourth set strikes N. 63° E., dips nearly vertical and is subparallel to the average trend of the bedding in the quadrangle.

In order to determine whether local warping or folding, as shown by the arcuate pattern of the formations in the Plainfield area, rotated or possibly resulted in the formation of joints, two additional stereographic projections were prepared for more restricted areas in the quadrangle. Areas in the southwestern and east-central parts of the quadrangle were chosen because of the large differences between the average strike of the bedding. In the southwestern corner the average strike is approximately N. 30 E., whereas in the east-central area the strike is about

N. 60° E. A plot of 100 joints from each area showed a similar joint pattern had been developed. These joint diagrams are very similar to the joint diagram for the entire quadrangle. The only difference is a weak development of two nearly vertical conjugate joints in the diagram for the east-central part of the quadrangle. These two joint sets strike about due north and N. 20° E. and may be related to the warping or folding of the formations in the quadrangle.

It is concluded that the major joint pattern in the Plainfield area is not related to the development of either the early or later folding inasmuch as the most prominent joints show little evidence of having been rotated with the bedding during late stage deformation. Because the late stage deformation is associated with the emplacement of the Knox Mountain granite, the joints are considered to be younger than the granite. Inasmuch as aplite and pegmatite dikes, which are thought to be only slightly younger than the granite, frequently intrude these joints, the joints are considered to be only slightly younger than the granite.

METAMORPHISM

General Statement

All of the rocks in the sedimentary sequence of the Plainfield quadrangle have been metamorphosed once and in most instances twice. The first stage of metamorphism was regional in extent, reaching its culmination of the garnet zone near the crest of the Green Mountain anticlinorium to the west as well as in the vicinity of the Worcester anticline in the Montpelier quadrangle. Later metamorphism is associated with the emplacement of the Adamant, Knox Mountain and Woodbury granites and usually obliterates the earlier stage of regional metamorphism in the eastern part of the quadrangle. The intensity of this later metamorphism is represented by the biotite, garnet and staurolite zones of metamorphism (Plate 1).

Early Regional Metamorphism

Prior to the emplacement of Devonian plutonic rocks in east-central Vermont, the area had undergone regional metamorphism. The culmination of this metamorphism, in the general latitude of the Plainfield quadrangle, is associated with older rocks in central Vermont. Christman (1959) reports that garnet occurs in Cambrian rocks near the crest of the Green Mountain anticlinorium. Rocks on the western flank of the anti-

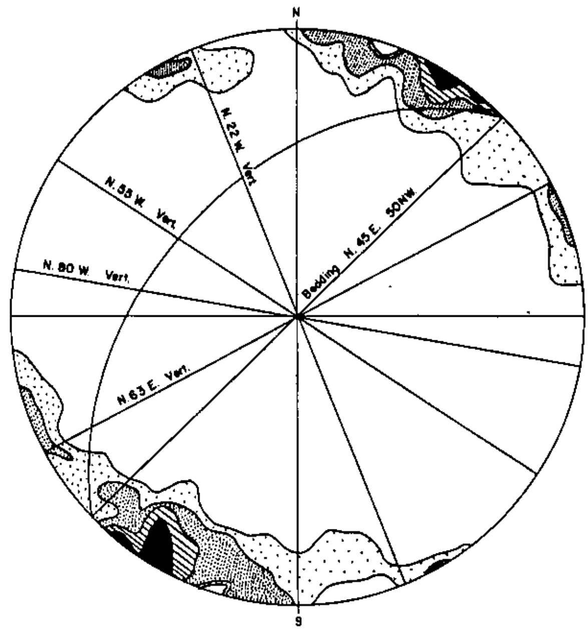


Figure 4. Contour diagram of 600 poles to joints in the Plainfield quadrangle. Contours 5–4–3–2–1.

clinorium generally contain a mineral suite which is indicative of a lower grade of metamorphism. On the eastern flank of the anticlinorium, however, regional metamorphism decreases to the east to the biotite zone and then increases to the garnet zone in the vicinity of the Worcester Mountain anticline in the Montpelier quadrangle (Cady, 1956). From this area eastward to the Plainfield quadrangle the rocks become progressively younger and contain a "lower grade" mineral suite. Although early regional metamorphic effects have been largely concealed by later metamorphism in much of the Plainfield quadrangle, rocks in the Moretown member in the northwest corner of the quadrangle contain chlorite and biotite which is indicative of the greenschist facies. This, combined with the absence of minerals showing retrograde metamorphism suggests that early regional metamorphism may have been low grade throughout the quadrangle.

Later Metamorphism

General Statement

Staurolite and garnet isograds have been drawn to represent points of equal pressure and temperature conditions in the Plainfield quadrangle. The mineral assemblage contained in these zones has developed largely in response to the intrusion of Devonian granite. These minerals crosscut all secondary foliation surfaces, with the exception of jointing, so that they may have formed after the principal stage of deformation associated with the emplacement of the granite. The staurolite isograd, marked by the first appearance of staurolite, is well defined and clearly parallels the contact of the Knox Mountain granite. An exception occurs in the northeastern corner of the quadrangle where the isograd swings away from the contact of the granite. As this general area is highly contorted and contains undeformed granitic dikes, it is likely that the dikes and the staurolite reflect the presence of a buried granitic body at a shallow depth.

The garnet isograd, marked by the first appearance of garnet, is poorly defined in the quadrangle because of the sporadic distribution of the garnet. However, it is clearly associated with the emplacement of the Knox Mountain and Woodbury granites. The irregular distribution of the garnet probably is due in part to the composition of the original sediments and in part to the presence of exposed and unexposed igneous rocks. Where argillaceous rocks are in close association with granite, garnet is abundantly developed, but where the rocks are farther from the granite, the garnet may be confined to the most favorable rock types for its development. In some cases, the garnet may reflect the presence of granitic bodies at depth. Because of its sporadic distribution the garnet isograd (Plate 1) is only approximate, and has been drawn around areas where garnetiferous rocks are rather widely scattered. If rock exposures were sufficient for detailed mapping, the garnet isograd probably would be farther east and subparallel to the staurolite isograd with many small, elliptical garnetiferous areas located farther to the west in the Waits River formation. Some of these elliptical areas would enclose small granitic exposures whereas others would reflect unexposed granite located close below.

Biotite Zone

The mineral assemblage in the rocks of the biotite zone was developed in response to both stages of metamorphism. Inasmuch as the later metamorphism equaled and, in places, exceeded the earlier regional metamorphism it was not always possible to distinguish the effect of one metamorphism on the other. At some localities muscovite and biotite are related to the later metamorphism. Because these minerals are truncated by joint planes, they must have formed before jointing and after the most recent stage of folding and cleavage development in the quadrangle.

Several index determinations on cross-cutting biotite from the more schistose rocks in this zone gave an average $N_y + N_z$ value of about 1.634. The 2V of the same biotite ranged from 5 to 15 degrees. According to Troger (1956, p. 83) biotite with these properties is classified as lepidomelane.

Carbonate-rich rocks occur only locally in the uppermost part of the biotite zone. In these rocks the most common assemblage is calcite, quartz, muscovite, biotite and chlorite with or without accessory magnetite, apatite, tourmaline and graphite. In contrast to this a calcareous quartzite of restricted distribution in the upper part of the Shaw Mountain formation is characterized by the mineral suite quartz, calcite, albite and microcline with or without accessory muscovite, chlorite, epidote, zircon, magnetite, leucoxene and graphite. This is the only known occurrence of a potash feldspar in the biotite zone of metamorphism in the quadrangle. In the upper part of the biotite zone, actinolite may develop in impure limestone along contacts with carbonaceous slate or phyllite. The typical mineral assemblage of this rock is calcite, quartz, mica and actinolite.

Greenstone is abundant in the biotite zone of metamorphism. The original mineral suite of these igneous or volcanic detrital rocks is not preserved in the biotite zone. Almost without exception the greenstone contains appreciable quantities of quartz and either plagioclase, epidote or carbonate. The absence of plagioclase in some of these rocks is usually compensated for by the unusually high percentage of epidote with or without carbonate. The composition of the original plagioclase in these epidote-carbonate rich rocks is unknown. In other igneous greenstones, however, the presence of oligoclase and/or albite and carbonate in the biotite zone of metamorphism indicates that the plagioclase was at least equivalent to oligoclase prior to metamorphism.

Garnet Zone

The mineral assemblages of the garnet zone are more complex than those of the biotite zone. Two different rock types are distinguished depending on whether the parent material was pelitic with a high alumina and silica content, or calcareous with abundant calcite and quartz.

Pelitic Schist—All high-alumina rocks which contain visible crystals of garnet and/or biotite have been classified as pelitic schists. Thus, shales elevated to slates during the early regional metamorphic stage, and containing later metamorphic minerals such as cross-cutting biotite and euhedral garnet, are considered schists even though the rock is

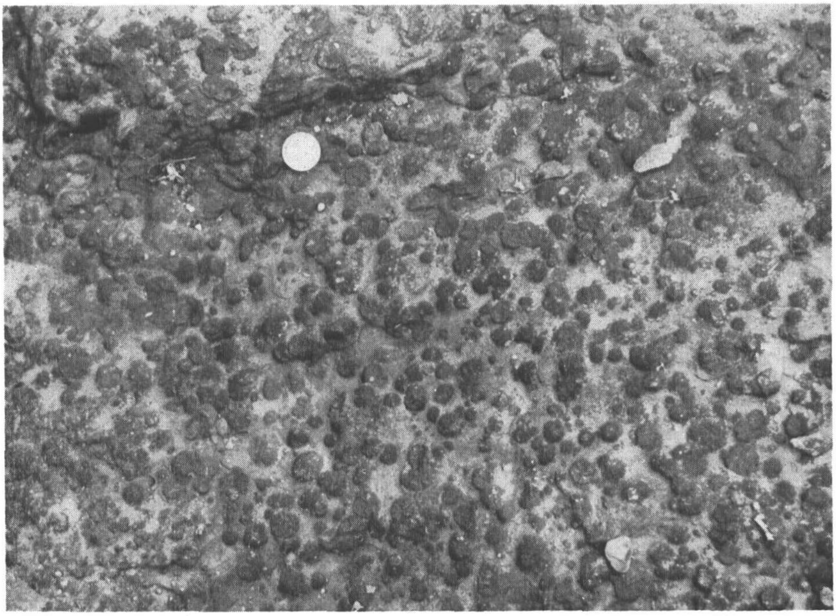


Plate 18. Amphibolized Waits River limestone located in railroad cut about ½ mile northwest of Walden Heights in the northeastern corner of the quadrangle. Specimen number 30 of Table 4.

basically a slate or phyllite. The most characteristic mineral assemblage in this group is muscovite, biotite, garnet and quartz with or without lesser amounts of albite, oligoclase, epidote and chlorite. Biotite occurs as porphyroblasts which indiscriminately cut all primary and secondary structures in the rock except joints. Determinations made on several grains of biotite showed it to have an $N_y + N_z$ index of about 1.635 and an optic angle of approximately 10 degrees. These data show that this biotite is the same as that in the biotite zone and likewise is classified as lepidomelane.

Near the axis of the Green Mountain anticlinorium in the Mount Mansfield quadrangle both garnet and albite porphyroblasts contain S-shaped inclusions (*si*) indicating simultaneous growth and rotation. The same minerals in the Plainfield quadrangle show no evidence of rotation either during or after their development. This relationship suggests that these minerals are not coeval in both areas. In the Mount Mansfield quadrangle they developed penecontemporaneously with the formation of the Green Mountain anticlinorium, whereas in the Plainfield quadrangle they formed after the most recent stage of folding and are associated with the emplacement of Devonian granite.

Calcareous Schist—Calcareous schist, consisting of essential calcite and quartz, comprises more than half of the rock within the garnet zone. Some of these rocks show little or no visible adjustment to metamorphism, whereas others have been largely altered to rocks containing essential amphibole (Plate 18). All gradations between amphibolitic and non-amphibolitic calcareous schist occur in the garnet zone of metamorphism. The quantity of amphibole developed in these rocks probably is a function of the original impurities in the limestone or calcareous quartzite. Highly amphibolitic limestone and quartzite are most abundant in the upper parts of the garnet zone.

The typical mineral assemblage of the calcareous schist includes calcite, quartz and tremolite with or without lesser amounts of epidote, lepidomelane and phlogopite. Diopside and microcline are abundant in some calcareous schists. Tremolite, diopside and biotite show cross-cutting relations with all primary and secondary S-surfaces, except joints; thus they post-date the youngest deformation.

Staurolite Zone

Mica-garnet-staurolite schist, biotite quartzite and amphibolitic or diopsidic limestone are characteristic of the staurolite zone. The schist and quartzite are the most abundant rock types and comprise about 85 percent of the zone. Amphibolitic limestone is next most abundant and the diopsidic limestone is only locally developed close to the margins of the Devonian granitic rocks.

Pelitic Schist—The typical mineral assemblage of pelitic schists is quartz, biotite, garnet and staurolite with or without lesser amounts of oligoclase, muscovite, chlorite and kyanite. Garnet and staurolite occur primarily as large, well-formed porphyroblasts which indiscriminately cut across all primary and secondary S-surfaces, except joints. This cross-cutting relationship with foliation surfaces also may be shown by biotite and more rarely muscovite. Staurolite porphyroblasts are usually twinned but small prismatic crystals are characteristic of some areas. In thin section, staurolite is invariably riddled with quartz inclusions as well as other minerals generally occurring in the groundmass of the schist. The traces of bedding, bedding schistosity, slaty cleavage, flow cleavage and slip cleavage occasionally are preserved in the larger staurolite crystals and prove a late-stage of development for the staurolite. The majority of the biotite, garnet and staurolite crystals show little or no preferred orientation. Kyanite is developed only locally and likewise is a late mineral. Index and optic angle determinations on biotite showed it to be lepidomelane with a $N_y + N_z$ value of about 1.635 and an optic angle of 5 to 10 degrees. Comparison of the indicies of biotite from the biotite, garnet and staurolite zones of metamorphism showed a maximum variation of .001. This demonstrates that the index of refraction of biotite is not a good indicator of the grade of metamorphism in the Plainfield quadrangle.

Amphibolitic and Diopsidic Limestone—Amphibolitic and diopsidic limestone occur most abundantly in the staurolite zone of metamorphism. Amphibolitic limestone occurs as thin, dark gray layers which are discontinuous along strike. The typical mineral assemblage is quartz, hornblende, biotite, garnet and oligoclase with variable amounts of calcite and staurolite. More rarely quartz and actinolite with lesser amounts of calcite and biotite develop. In spite of the low calcite content, these rocks are considered to have been impure limestone or calcareous quartzite prior to metamorphism.

Diopsidic limestone is almost wholly confined to a 200-foot wide zone surrounding the Adamant, Knox Mountain and Woodbury granites. Although these diposide-bearing rocks lie mostly in the staurolite zone, the staurolite isograd has not been drawn around the various intrusions of the Woodbury and Adamant granites due to the limited distribution of the staurolite in these areas. The typical mineral assemblage of this rock is calcite, diopside and quartz with or without lesser amounts of microcline, epidote and sphene.

Biotite Quartzite—Biotite quartzite is a major constituent of the staurolite zone. It contains a very uniform mineral assemblage, the most typical of which is quartz, biotite, oligoclase and muscovite with or without lesser quantities of garnet and staurolite. Garnet and staurolite only develop in the more impure quartzite and show cross-cutting relationships with all foliation surfaces.

ECONOMIC GEOLOGY

Granite, iron, gold and sand and gravel occur in the Plainfield quadrangle and have been actively sought in the past. Granite, sand and gravel, however, are the only materials which occur in sufficient abundance to have warranted exploitation. There are many abandoned granite quarries in the vicinity of Hardwick and Plainfield. The rock in these quarries is of good quality, easily accessible and because of the well-developed sheeting, or horizontal jointing, is well suited for use as a building stone and in some areas as monumental stone. Granite is being actively quarried about half a mile north of the village of Adamant in the Montpelier quadrangle. Even though these quarries lie outside the area, the same rock type strikes into the Plainfield quadrangle and is a potential source of granite.

Sand and gravel are widespread in the quadrangle but are most abundant along the Winooski River, Kingsbury Branch and Haynesville Brook. This material is easily accessible and is being actively quarried near Plainfield and South Walden.

Iron and gold have been obtained in small quantities. Nearly a century ago iron apparently was extracted from sand deposits located about one mile northwest of East Calais. The iron-bearing mineral is principally magnetite and minor amounts of ilmenite; together these minerals amount to less than 10 percent of the sand deposit.

Gold is reported to have been mined on the east side of Nelson Pond but the workings have been abandoned for many years. The gold probably occurs in quartz veins which have intruded the Waits River formation. Placer gold, derived from quartz veins, has been reported from several streams in and adjacent to the quadrangle.

REFERENCES CITED

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. Geol. Survey, Geol. Quadr. Map, GQ 102.

BALK, R., 1927, A contribution to the structural relations of the granitic intrusions of Bethel, Barre and Woodbury, Vermont: Vt. State Geologist, 15th Biennial Rept., p. 39–96.

BOWEN, N. L., 1937, Recent high temperature research on silicates and its significance in igneous geology: Amer. Jour. Sci., v. 33, p. 1–21.

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. Quadr. Map, G. Q. 79.

CADY, W. M. and OTHERS, in press, Bedrock geology and asbestos of the upper Missisquoi Valley and vicinity, Vermont: U. S. Geol. Survey Bull. 1122-B.

CHAYES, F., 1950, Composition of some New England Granites: New York Acad. Sci. Trans., 2nd series, v. 12, p. 144–151.

——, 1952, The finer-grained calcalkaline granites of New England: Jour. Geol., v. 60, p. 207–254.

CHRISTMAN, R. A., 1956, The geology of Groton State Forest, Vermont: Vt. Geol. Survey, p. 1–23.

——, 1959, Geology of the Mount Mansfield Quadrangle, Vermont: Vt. Geol. Surv. Bull. 12, 80 p.

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

DALE, T. N., 1899, The slate belt of eastern New York and western Vermont: U. S. Geol. Survey 19th Ann. Rept., pt. 3, p. 153–300.

——, 1923, The commercial granites of New England: U. S. Geol. Survey Bull. 738, 488 p.

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

DOLL, C. G., 1943a, A Paleozoic revision in Vermont: Amer. Jour. Sci., v. 241, p. 57–64.

——, 1943b, A Brachiopod from mica schist, South Strafford, Vermont: Am. Jour. Sci., v. 241, p. 676–679.

——, 1944, A preliminary report on the geology of the Strafford quadrangle, Vermont: Vt. State Geologist, 24th Biennial Rept., 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, J. H., 1942, Geology of the Vermont portion of the Littleton quadrangle: unpublished doctorate thesis, Harvard Univ., 101 p.

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

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

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

JAHNS, R. H., 1943, Sheet structure in granite: Its origin and use as a measure of glacial erosion in New England: Jour. Geol., v. 51, p. 71–98.

JONES, D. P., 1916, The physiography of Greensboro, Hardwick and Woodbury, Vermont: Vt. State Geologist, 20th Biennial Rept., p. 74–100.

KONIG, R. H. and DENNIS, J. G., in press, The geology of the Hardwick area, Vermont: Vt. Geol. Survey Bull.

KULP, J. L., 1961, The geologic time scale: Science, vol. 133, no. 3459, p. 1105–1114.

MAYNARD, J. E., 1934, Petrographic re-examination of the quartz-bearing plutonites of Vermont: Jour. Geol., v. 42, p. 146–162.

MURTHY, V. R., 1957, Bed Rock 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. Geol., v. 66, p. 276–286.

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., 1898, The calciferous mica schist and its associated terranes: unpublished thesis, Dartmouth College.

——, 1902, The terranes of Orange County, Vermont: Vt. State Geologist, 3rd Biennial Rept., p. 61–101.

——, 1906, The areal and economic geology of northeastern Vermont: Vt. State Geologist, 5th Biennial Rept., p. 66–115.

——, 1916, The geology of Calais, East Montpelier, Montpelier and Berlin, Vermont: Vt. State Geologist, 20th Biennial Rept., p. 111–149.

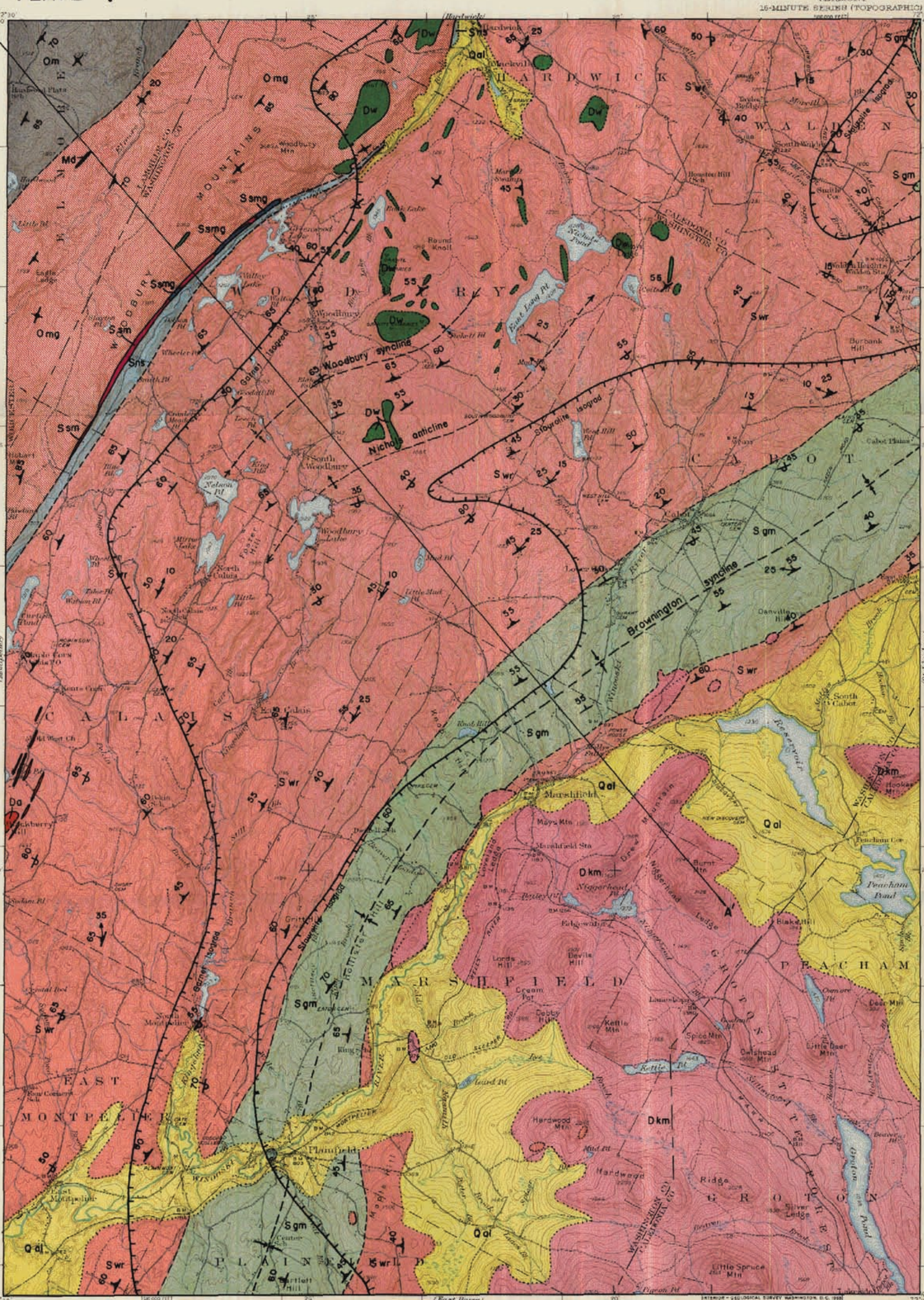
——, 1924, The terranes of Bethel, Vermont: Vt. State Geologist, 14th Biennial Rept., p. 77–103.

RICHARDSON, C. H., BRAINERD, A. E., and JONES, D. J., (1914), The geology and mineralogy of Hardwick and Woodbury, Vermont: Vt. State Geologist., 9th Biennial Rept., p. 294–336.

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

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

PLATE I



Topography by U.S.G.S. in 1939-'40

Geology by Ronald H. Konig
Mapped in 1956-'58

GEOLOGIC MAP OF THE PLAINFIELD QUADRANGLE, VERMONT

EXPLANATION

Qal
Alluvium and glacial drift

Md
Basic dikes

MISSISSIPPIAN (?)

Da
ADAMANT GRANITE

Dw
WOODBURY GRANITE

Dkm
KNOX MOUNTAIN GRANITE

DEVONIAN

Sgm
GILE MOUNTAIN FORMATION
Dark-gray phyllite and schist, impure quartzite and minor amounts of limestone and amphibolitic limestone.

Swr
WAITS RIVER FORMATION
Interbedded blue-gray siliceous limestone, calcareous quartzite and dark-gray slate, phyllite and schist. Minor amounts of amphibolitic limestone and light-gray quartzite occur in upper half of formation.

Sns
NORTHFIELD SLATE
Dark-gray slate and phyllite and minor amounts of blue-gray limestone and greenstone.

Ssm Ssmg
SHAW MOUNTAIN FORMATION
Light-tan calcareous quartzite and greenstone with lesser amounts of fine-grained conglomerate and blue crystalline limestone.

SILURIAN

Unconformity(?)

Om Omg
MORETOWN FORMATION
Thinly laminated quartzite, impure quartzite, dark-gray slate and phyllite with minor amounts of limestone (Om). Upper third of formation contains abundant greenstone (Omg).

ORDOVICIAN

STRUCTURE SYMBOLS

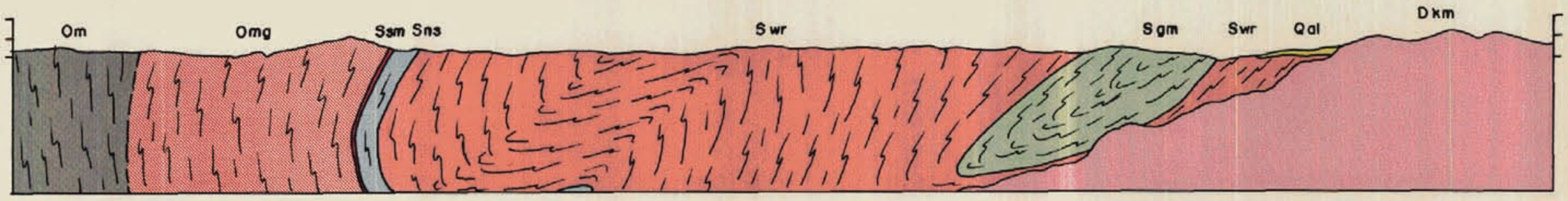
CONTACT
Solid where definite, dashed where approximate and dotted where inferred.

50 inclined, 40 overturned
STRIKE AND DIP OF BEDDING

60 inclined, 20 12 inclined with plunge of crinkle axis
STRIKE AND DIP OF BEDDING SCHISTOSITY

ANTICLINE
Showing trace of axial plane and plunge of fold axis.

SYNCLINE
Showing trace of axial plane and plunge of fold axis.



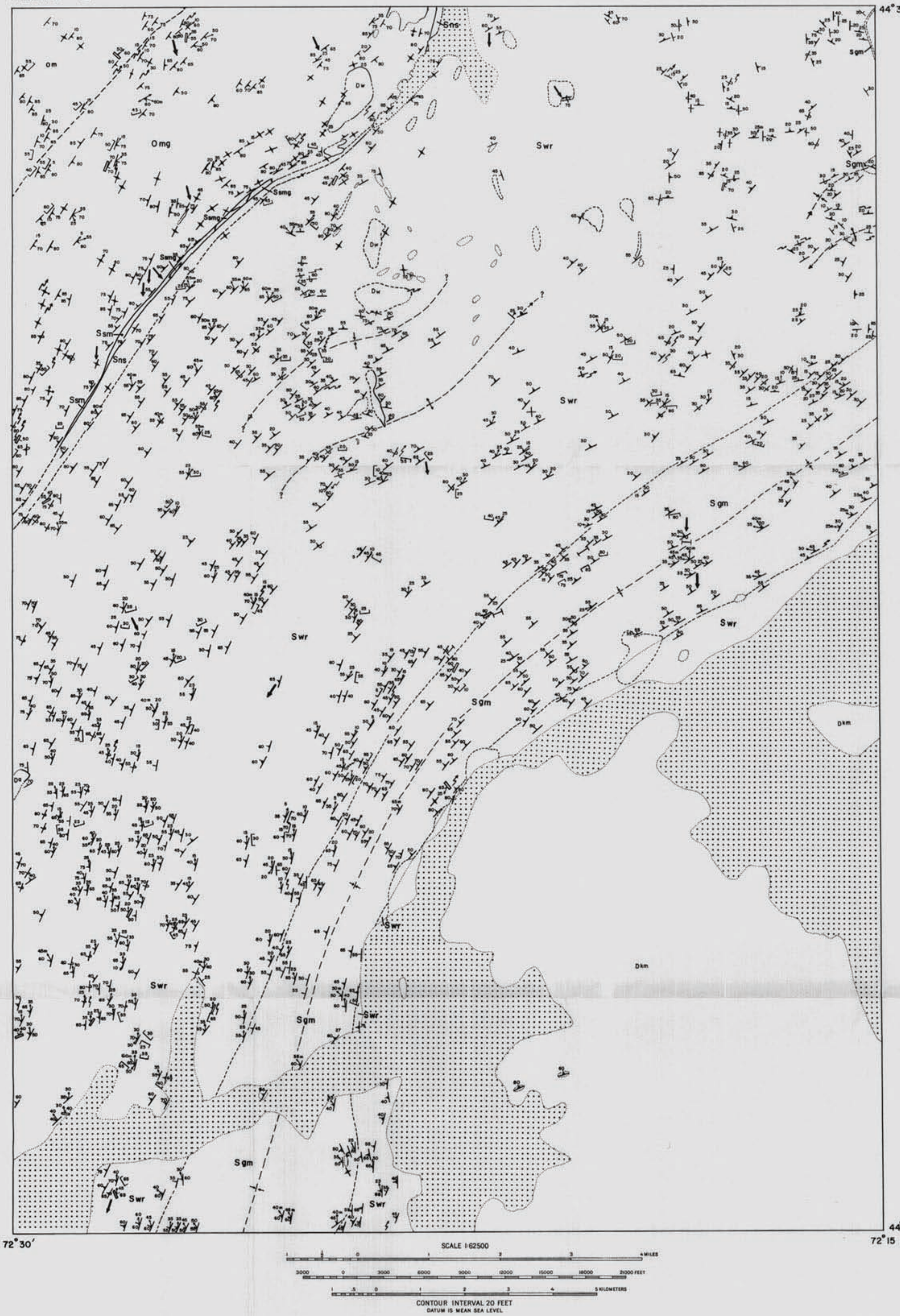
SECTION ALONG LINE A-A'

Author's Note

Change Northfield Slate to Northfield formation.
Change Moretown formation to Moretown member of the Missisquoi formation.

VERMONT GEOLOGICAL SURVEY
Charles G. Doll, State Geologist
(Bulletin No. 16)

PLATE 2



EXPLANATION

CONTACT
Solid where definite, dashed where approximate and dotted where inferred.

ANTICLINE
Showing trace of axial plane and plunge of fold axis

SYNCLINE
Showing trace of axial plane and plunge of fold axis

50 inclined — vertical — horizontal
55 overturned — 70 inclined with dip in direction of younger beds

STRIKE AND DIP OF BEDDING

45 inclined — vertical — 63 overturned
13 inclined with dip in direction of younger beds

STRIKE AND DIP OF BEDDING SCHISTOSITY

23 inclined — 34 vertical

STRIKE AND DIP OF EARLY FLOW CLEAVAGE

12 inclined — vertical

STRIKE AND DIP OF SLIP CLEAVAGE

10 22

STRIKE AND DIP OF AXIAL PLANE OF LATE MINOR FOLD AXIS SHOWING BEARING AND AMOUNT OF PLUNGE

dextral — sinistral
EARLY FOLD
dextral — sinistral
LATE FOLD

PLANE VIEW OF FOLDED BEDDING AND BEDDING SCHISTOSITY SHOWING TREND OF FOLD

25 — horizontal

BEARING AND PLUNGE OF MINOR FOLD OR CRINKLE AXIS. MAY BE COMBINED WITH PLANAR ELEMENTS.

33m

BEARING AND PLUNGE OF MINERAL LINEATION OR STREAMING. MAY BE COMBINED WITH PLANAR ELEMENTS.

BEARING OF GLACIAL STRIATIONS

FORMATION SYMBOLS AS SHOWN ON GEOLOGIC MAP.

STIPPLED AREA INDICATES ALLUVIAL AND GLACIAL DEPOSITS.

TECTONIC MAP OF THE PLAINFIELD QUADRANGLE, VERMONT

VERMONT GEOLOGICAL SURVEY
Charles G. Doll, State Geologist
(Bulletin No. 16)