GEOLOGY OF THE ISLAND POND AREA, VERMONT

By

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ABSTRACT

The Island Pond quadrangle lies in northeastern Vermont, between the Green Mountain anticlinorium and the Connecticut River.

Two recognizable metasedimentary formations are exposed within the quadrangle; the Gile Mountain formation and the Waits River formation. The Gile Mountain formation, composed predominantly of phyllites, schists, and quartzites, is shown to be synonymous with the Westmore formation as the two unite in a structural closure in the southwestern portion of the map area. The Waits River formation, characterized by a partly calcareous lithology, is believed, by the author, to be the youngest metasedimentary unit present. A thin amphibolitic band lying approximately at the boundary between the Waits River and Gile Mountain formations is tentatively designated as the Standing Pond volcanics. Although not distinguishable here, the Northfield and Meetinghouse slates, herein considered to be correlative, are believed to occur as phyllites and schists which occupy a stratigraphic position between the Waits River and the Gile formations.

The metasedimentary rocks of the Island Pond quadrangle are predominantly overturned and have been subjected to at least two periods of deformation. The deformational stages are demonstrated by two generations of folds and by two generations of cleavage. Characteristic of the early deformational stage is a schistosity parallel or sub-parallel to the bedding which acts as an axial plane cleavage to a series of small, tight folds. Slip cleavage cutting the earlier schistosity is a product of a later stage of deformation and is parallel to the axial planes of later folds formed contemporaneously with the slip cleavage.

An analysis of minor structural features and their implications when considered in respect to regional structures strongly suggests that the metasediments of the Island Pond area occupy the central portion of the inverted limb of a large recumbent anticline, the inverted crest of which is represented by the Brownington syncline, while the root zone lies

to the east. The structure plunges northeast. The Willoughby arch is a product of domal deformation on this inverted limb and its development gave rise to slip cleavage and folds of the second stage of deformation. These folds face away from the crest of the arch. The northern terminus of the Willoughby arch occurs in the southwestern portion of the map area where the bedding and early schistosity clearly swing around to delineate a structural closure. This closure is also indicated by the formational contacts.

Granitic rocks occupy about two-thirds of the map area. Three major granitic bodies are present: the Averill granite, the Nulhegan quartz monzonite, and the Echo Pond granitic complex. The last two are here newly named. Rocks of the Averill granite range in composition from granite to granodiorite while those of the Echo Pond granitic complex range from granite to gabbro. Metamorphic zones appear to be directly related to granitic intrusion.

INTRODUCTION

Location

The Island Pond quadrangle lies near the northeastern corner of the State of Vermont and is situated between longitudes 71°45′ and 72°00′ west and latitude 44°45′ north and the Canadian border (Figure 1). The eastern edge is less than twelve miles from the New Hampshire state line. The total area of the quadrangle is approximately 224 square miles which includes parts of Essex, Orleans, and Caledonia counties.

Geologic Setting

The Island Pond area lies in a belt of Lower Paleozoic eugeosynclinal metasedimentary rocks on the eastern limb of the Green Mountain anticlinorium. The lithologic units found in this belt, extending the length of Vermont from Massachusetts to Quebec, have been designated as the "Vermont sequence" to differentiate them from those of the "New Hampshire sequence." Speculation still exists regarding the exact relations between these two sequences. Structurally, the area is complex. Two or more stages of deformation have effected the rocks. A secondary series of domes and arches characterizes the belt, further deforming the strata which had previously been subjected to large-scale folding.

Granitic rocks which are found along this belt attain maximum development in the Island Pond area, comprising approximately two-thirds of the lithology exposed. These range in composition from granite to gabbro, with quartz monzonite most abundant.

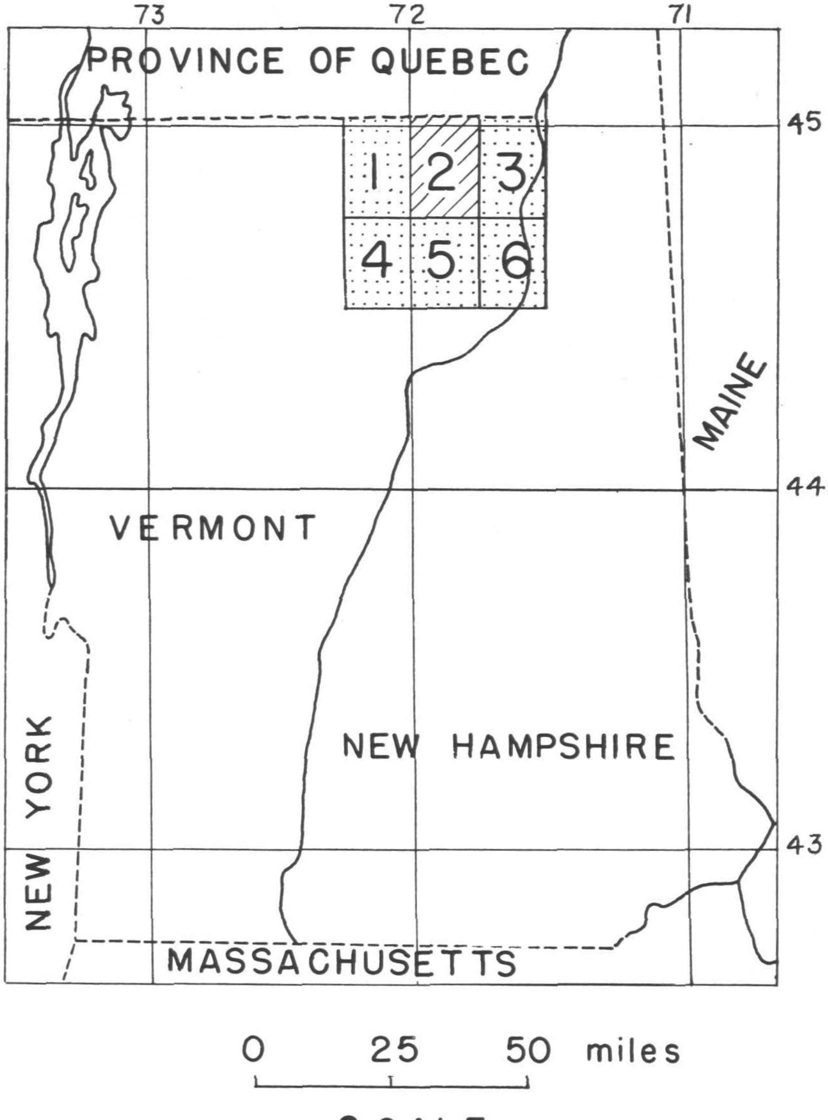

Figure 1. Index map showing location of area. Island Pond quadrangle is lined. Quadrangles are numbered as follows:

1. Memphremagog	4. Lyndonville
2. Island Pond	5. Burke
3. Averill	6. Guildhall

Previous Work

The work of Adams (1845, 1846) was the earliest to deal with the geology of the region. Reconnaissance studies were conducted by Hitchcock (1861) and Richardson (1906). Jacobs (1922) investigated a small segment of the southwest portion.

Neighboring areas in Vermont which have been mapped in detail are the Lyndonville quadrangle (Dennis, 1956) and the Memphremagog quadrangle (Doll, 1951). Mapping has been completed and awaits publication in the Averill and Burke quadrangles. The manuscript of the Guildhall quadrangle is in press. North of the International Boundary, recent detailed mapping has been done adjacent to the Memphremagog quadrangle (Cooke, 1950), and to the Island Pond and Averill quadrangles (Cooke, 1957).

Present Study

The primary purpose of the present study is to investigate the structural relations of the metasedimentary units exposed within the Island Pond quadrangle and to determine their implications upon regional structures and the stratigraphic sequence in eastern Vermont. As the large expanses of granitic rocks within the quadrangle have previously been neglected, their delineation, composition, and effects on the enclosing metasediments comprise an important part of the present study. Metamorphic effects and their areal distribution were investigated in order to discover their relations to regional tectonic events.

Method of Investigation

Field work on the Island Pond quadrangle was conducted during the summers of 1956, 1957, and 1958, with a total of approximately nine months. The fall and winter of 1958–59 were devoted to laboratory and library work, and to the preparation of the manuscript.

The standard United States Geologic Survey fifteen-minute topographic map of the Island Pond quadrangle on the scale of about 1 inch to the mile was used as a base. For further accuracy enlargements to the scale of three inches to the mile were prepared. Aerial photographs supplemented the topographic map. In a heavily forested terrain such as characterizes this region, location of points was difficult, and it was necessary to resort to various methods. These methods included: pace and compass, triangulation, use of an aneroid barometer, and the use of topographic features.

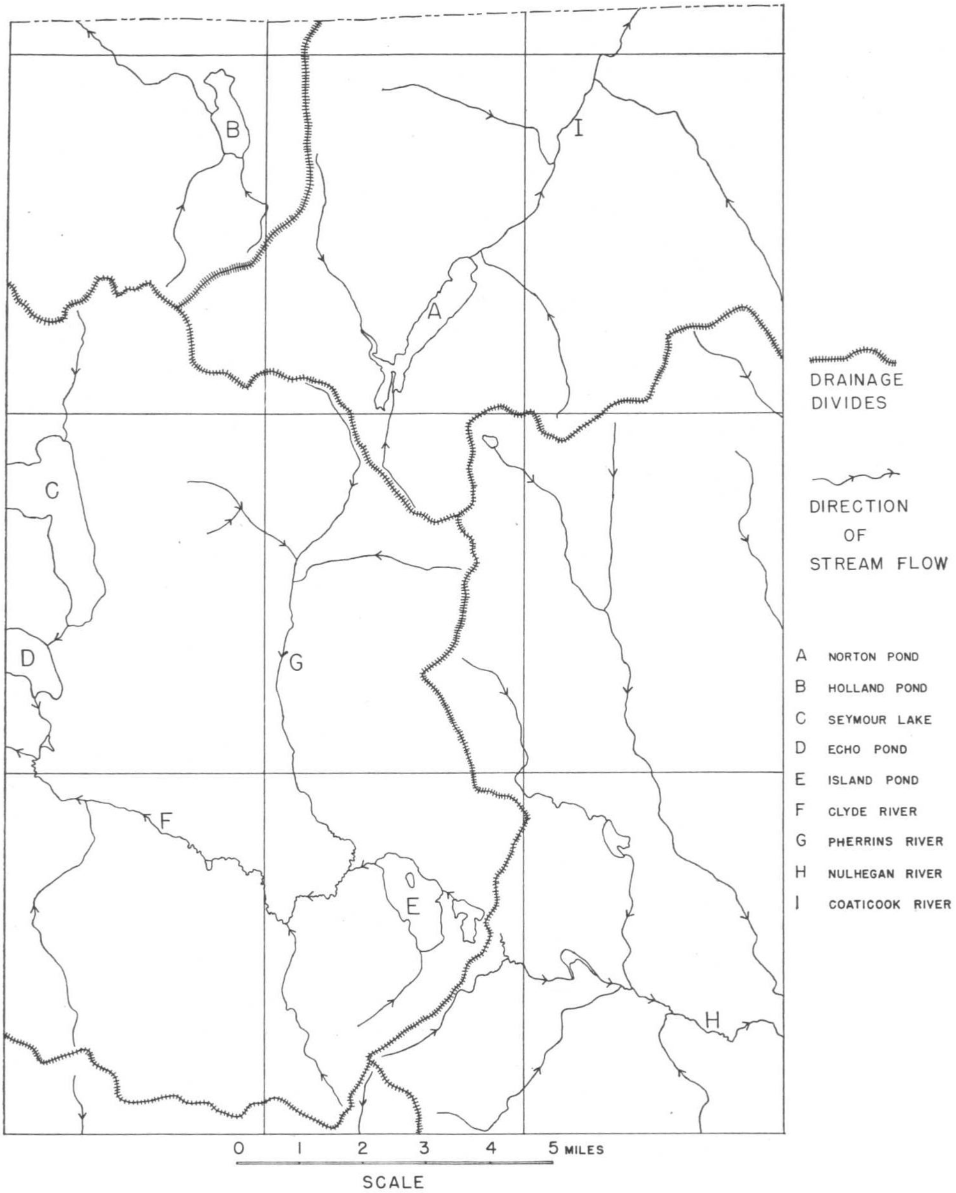

Figure 3. Major drainage divides of the Island Pond area.

highest and the lowest areas are underlain by granitic rocks. Gore Mountain and Bald Mountain are both composed of granite, while the prominent basin in the southeast corner of the area is also underlain by granite. Surrounding this basin is a ring of mountains exemplified in this area by Bluff Mountain and the mountains south of Island Pond. This chain is composed of metasediments and almost completely encircles the granitic basin as can be observed on the adjacent Averill, Guildhall, and Burke quadrangle maps. A similar situation is found to the east of Seymour Lake where Beechnut Ridge and its southeast extension to Bluff Mountain are composed of metasediments, while the lower land between the ridges and Seymour Lake is underlain by granite. For the most part, bedding in the elongate ridges of metasediments roughly follows the trend of the ridges. The crudely circular pattern and radial drainage of Gore Mountain and Bald Mountain suggest their granitic nature.

Five main rivers drain the area in four different directions. Eventually, however, all flow into the Connecticut River or northward to the St. Lawrence embayment. The major divides in the Island Pond area are shown in Figure 3. The northern area is drained northward by the branches of the Coaticook River and the Tomifobia River (not shown on map). The small area along the western portion of the southern border drains into the Passumpsic River, which flows southward into the Connecticut River south of St. Johnsbury. The waters of the basin in the southeastern portion of the map area drain for the most part into the Nulhegan River and its branches which join the Connecticut River at Bloomfield. The Clyde River flows westward to Lake Memphre magog, from which the waters reach the St. Lawrence embayment. Many of the streams in this basin take extremely circuitous routes. Some of the brooks in the northern portion of the basin first flow northeast, then southeast as they approach the Pherrins River. This river flows southward into the westward trending Clyde River west of Island Pond.

The drainage of the area, which is mature, has been modified by geologic structure and by the action of continental glaciation. The division into drainage basins by elongate, metasedimentary divides is a primary reflection of the structure. Joints in both granite and metasediments have often localized stream channels. Glacial effects are displayed strikingly by the divergence between drainage direction and structure found in the vicinity of Island Pond and Spectacle Pond. Although these two ponds lie within the structural basin of the Nul-

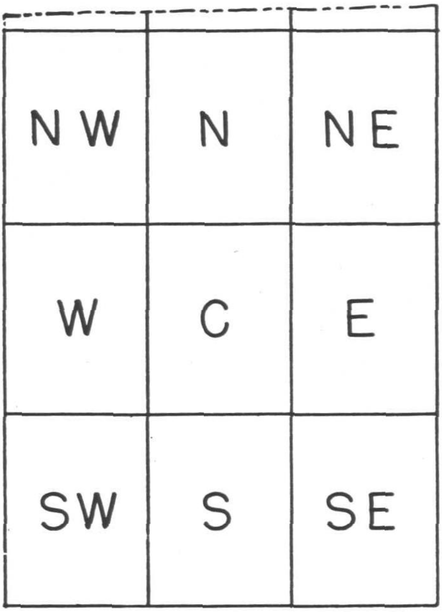

Figure 2. Reference letters of quadrangle divisions.

village of Island Pond whose hospitality and interest in this work made its accomplishment much easier and the author's stay in Island Pond an extremely pleasant one. Deserving especial thanks are the families of Frank LeFebvre and Omer Goulet. Their many kindnesses to the author and his wife will long be remembered with gratitude.

The interest shown in this project by Governor Joseph B. Johnson is recorded here with pleasure. Governor Johnson personally spent a day in the field with the author, and the people of Vermont are indeed fortunate to have had as their Chief Executive a man with such great foresight and enthusiasm for the investigation and development of the natural resources of the State.

Physiography

The topography of the area varies. The greatest elevation, 3330 feet, is the summit of Gore Mountain. Bald Mountain reaches 3315 feet. The lowest elevation is 1148 feet on the floodplain of the Clyde River southwest of the village of East Charleston. Total relief is 2182 feet.

Geologic structures affect the surface features. Anomalously, both the

A further modification of a method first proposed by Rich (1921) and modified by Dennis (1956) proved to be of value for indicating locations. As this method will be followed throughout the present report, it is discussed briefly. The quadrangle was sub-divided into nine equal parts along the lines of longitude and latitude. These parts were lettered according to their geographic location within the quadrangle. This arrangement is shown in Figure 2. The small segments between latitude 45° and the Canadian border were assigned to their neighboring ninths. Within each ninth a system of coordinates was used with the lower left hand corner the zero point. Four digits were used, the first two indicating inches and tenths of inches to the right and the second two digits indicating inches and tenths of inches north from the zero point.

Acknowledgments

The writer is primarily indebted to Dr. J. D. Ryan of Lehigh University under whose supervision the work was conducted, and whose advice in the field and laboratory investigations and in preparation of the manuscript was of great value. Other members of the Lehigh faculty deserving special mention are Dr. Bradford Willard, Dr. H. V. Tuominen, and Dr. H. R. Gault.

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It is with pleasure that the author acknowledges the help of Dr. Warren I. Johansson, Mr. Bertram Woodland, and the writer's colleagues from Lehigh, Ernest H. Ern, and Paul B. Myers. These fellow geologists working in related areas in Vermont greatly benefited the author's understanding of the regional geology by several discussions and field trips in their areas. The interest shown in the Island Pond area and time spent in the field with the author by Dr. W. M. Cady and Dr. A. Chidester of the U.S. Geological Survey and by Dr. John G. Dennis and Ronald H. Konig are greatly appreciated. Theodore T. Graham ably assisted the author during his third field season. The author also wishes to express gratitude to his wife for her constant enthusiasm and for her constructive criticism on the grammatical aspects of the manuscript.

The author is greatly indebted to the many folks in and around the

hegan River, they drain westward into the Clyde River. No appreciable divide exists between the two drainage areas at this point except for small morainal hills (Plate 1). Pherrins River and Oswegatchie Brook follow glacially modified valleys, and the meandering paths of the Clyde and Nulhegan Rivers wander upon terrains of glacial outwash and moraine.

Continental glaciation has also strongly modified the topography in many other ways. A prominent elongation and alignment of Holland Pond, Island Pond, and Seymour Lake is descernible with their long axes trending N16°W, N11°W, and N26°W, respectively. This glacially controlled trend is also exhibited by many smaller ponds such as Lewis Pond (N18°W), McConnel Pond (N22°W), Halfway Pond (N4°W), and Jobs Pond (N5°W). The larger ponds were studied by Mills (1951) who thought that Holland Pond and Seymour Lake occupy glacially gouged rock basins while Island Pond, Spectacle Pond, and Norton Pond lie upon deposits of glacial moraine. The work of the present author corroborates these ideas. The glacial trough of Seymour Lake reaches a depth of 167 feet while Island Pond is the second deepest body of water in the area with a depth of only 63 feet (Mills, 1951). Glacial striae on bedrock vary from N20°E to N35°W. Evidence therefore indicates that advance of the continental glaciers proceeded in a southwesterly to southeasterly direction.

Deposits of glacial till and stratified drift are common as can be attested by the numerous gravel pits. The Nulhegan basin is an area of extensive ground moraine. Numerous kames and thick glacial deposits occur adjacent to the Pherrins River and Oswegatchie Brook. A number of small eskers are also present. These trend in a general north-south direction. Thick outwash deposits occupy the valley of the Clyde River, extending from the village of Island Pond to beyond East Charleston. Erratics, often numerous, are a familiar feature on the landscape. These are mostly of granite and not infrequently are over ten feet in diameter.

SEDIMENTARY ROCKS

General Statement

Two mappable metasedimentary rock units are exposed within the Island Pond quadrangle. The formational names used in the present report are adopted from the stratigraphic nomenclature of eastern and northeastern Vermont: the Waits River formation and the Gile Mountain formation. Some differences exist concerning the stratigraphic relations of these two formations. This is due to differences in interpretation of the structural relations controlling the area of exposure of these formations in east-central and northeastern Vermont. Three main hypotheses of regional structure as outlined below are shown diagrammatically in Plate 3.

Doll (1951) and Dennis (1957) believed that a band of argillaceous and arenaceous metasedimentary rocks (the Westmore formation of Doll, the Gile Mountain formation of this report) occupied the trough of the large Brownington syncline, named by Doll (1951, p. 51). On the flanks of the syncline calcareous lithology (the Waits River formation of this report) was reported. Therefore, the Gile Mountain formation was considered to be the younger unit. On the eastern flank of the syncline, the Willoughby arch (Dennis, 1957, p. 36) caused further repetition of the formations. The stratigraphic sequences proposed by Doll and Dennis are:

Doll	*Dennis*
Westmore formation	Gile Mountain formation
Barton River formation	Waits River formation
Ayers Cliff formation	
Northfield slate	

Murthy (1957, 1958) refuted the concept of the Brownington syncline in the East Barre area. He (1957, p. 68) thought the stratigraphic units were deposited in homoclinal sequence constituting the west limb of a major syncline. Murthy (1957, p. 20) proposed two possible stratigraphic sequences:

Gile Mountain formation	Waits River formation
Waits River formation	Gile Mtn. fm. (-Westmore fm.)
Westmore formation	Barton River formation
Barton River formation	Northfield slate
Northfield slate	

The western synclinal limb was later pushed upward into a broad arched structure in the southern half of the East Barre area.

In the Island Pond area, the Gile Mountain formation and the Westmore formation unite in a structural closure around the northern end of the Willoughby arch (Plate 1). They are therefore the same; the name Gile Mountain formation takes precedence. In the Randolph quadrangle, (E. H. Ern, personal communication, 1959) the Waits River and Barton River formations also unite in a structural closure; the name Waits River formation takes precedence. In the Island Pond and

Randolph areas, structural relations indicate that a large-scale recumbent anticline has produced the structural repetition of the two formations. The Waits River formation is considered, herein, to be younger than the Gile Mountain formation.

Although not recognizable in the Island Pond area, the structural relations proposed in the present report indicate that the Northfield slate and the Meetinghouse slate are correlative and lie between the Waits River and Gile Mountain formations. Therefore, the stratigraphic sequence as proposed here is:

Waits River formation
Northfield slate
Gile Mountain formation

A band of amphibolite in the Island Pond area occupies the approximate boundary between the Waits River and Gile Mountain formations. This is tentatively correlated with the Standing Pond volcanics and is thought to be an important horizon marker.

Gile Mountain Formation

General Statement

The Gile Mountain formation crops out sporadically over much of the area. Phyllites and schists are its most abundant rocks. Interbedded with these are lesser amounts of quartzites and limestones. The formation has its type locality in the Strafford quadrangle where it was named by Doll (1944, p. 18). There it is composed "... principally of quartz-mica schist ... rocks in subordinate amounts are thin beds of massive and sheared quartzite, occasional coarse feldspathic schists, calcareous beds and some graphitic layers." The Westmore formation, a unit of similar lithology, was named by Doll (1951, p. 33) who established its type locality in the Memphremagog quadrangle. It is here correlated with the Gile Mountain formation, the name Gile Mountain taking precedence. These rocks are considered in the present report to be the oldest metasedimentary unit exposed.

Distribution

The phyllites, schists, and quartzites of the Gile Mountain formation are found throughout much of the quadrangle (Plate 1). The map pattern of this formation is broken by granitic rocks. In general, the Gile Mountain formation occurs in three large patches, each of which is separated from its neighbors by wide areas of granite. These three segments may be delineated individually as follows: to the northwest in the town of Holland is a band of the Gile Mountain formation striking roughly north and averaging about two miles in width. This band extends west into the Memphremagog quadrangle where it was designated the Westmore formation by Doll (1951, Pl. 1). Along the strike to the north it crosses the International Boundary where it is considered to be part of the St. Francis Group (Cooke, 1957). The Gile Mountain formation in this band is bounded on the south and east by granite. A second large area of Gile Mountain outcrops on the upper slopes of Bluff Mountain north of the village of Island Pond. This area is an irregular band some nine miles long with a maximum width of two and one half miles. It trends northeast along the line of Bluff Mountain and then swings to the east to enter the Averill quadrangle east of Lewis Pond. Its northern limit is on Middle Mountain. This segment of the Gile Mountain formation is almost completely surrounded by granite, with two exceptions, (1) to the east where it continues into the Averill quadrangle as a band only one mile wide, and (2) a small neck of metasediments averaging less than half a mile wide which projects northwesterly through Warners Grant from the western edge of the main mass south of Summit and connects with the one in the northwestern corner of the map area. A third large body of this formation in the southwestern part of the quadrangle is exposed. It is a crescent-shaped band about nine miles long and three miles wide at its greatest breadth. This band is bordered on the north and east by granite and on the south and west by the overlying Waits River formation, except for a small segment bordering the Standing Pond volcanics. It continues into the Memphremagog quadrangle to the west and the Burke quadrangle to the south. For convenience, these large masses of Gile Mountain formation will be spoken of as the northwestern, central, and southwestern Gile Mountain areas, respectively. An additional small unit of Gile Mountain underlies an area of less than one square mile southwest of the bend in Seymour Lake.

The invasion of granite has left no complete section of the Gile Mountain formation from which an estimate of thickness could be obtained. However, in the adjacent Memphremagog quadrangle, Doll (1951, p. 34) estimated the thickness to be 4300 feet.

Correlation

The Gile Mountain formation of the Island Pond quadrangle may be traced to the type locality in the Strafford quadrangle (Plate 3). Between these two end points the formation has been mapped in detail in the Littleton quadrangle (Eric and Dennis, 1958), the Woodsville quadrangle (White and Billings, 1951), the East Barre quadrangle (Murthy, 1957), and the Mt. Cube quadrangle (Hadley, 1950).

In the Memphremagog quadrangle, Doll (1951, p. 33) applied the name "Westmore formation" to rocks of similar lithology. At that time he suggested (*Ibid*, p. 34) that this formation might be correlated with the Gile Mountain formation at its type locality. South of the Island Pond area the Westmore formation of Doll lies west of the known Gile Mountain formation, the two units of schists and quartzites being separated by a calcareous formation. The western band has been mapped as far south as the Randolph quadrangle (E. H. Ern, personal communication, 1959). A difference of opinion exists regarding its stratigraphic position. Currier and Jahns (1941, p. 1491) considered this band in central Vermont to be part of the Waits River formation, but White and Jahns (1950, p. 189) thought that these non-calcareous rocks could be equivalent to the Gile Mountain formation. Dennis (1957, p. 19) believed that the Gile Mountain and Westmore formations are the same. Murthy (1957, p. 20) provided two alternatives, one of which would designate the Gile Mountain and Westmore as two distinct formations separated by the Waits River limestones, while the other would consider the Gile Mountain and Westmore formations to be equal. The present study indicates that these two formations are indeed the same. In the southwestern corner of the Island Pond area the arenaceous and argillaceous lithologies of the Westmore and Gile Mountain formations unite in a structural closure around the calcareous rocks of the Waits River formation. The nature of this closure will be discussed fully in the section on structure.

Lithology

Doll (1951, p. 33) in describing the rocks of the Westmore formation reported that ". . . the rocks are largely phyllites and schists, with smaller amounts of limestone and quartzites, all interbedded." A similar lithology characterizes the Gile Mountain formation of the Island Pond area. Although a rusty-red weathered surface is found on many of the rocks of this formation, it is not as common as in the Waits River formation. Bedding thickness, ranging from a fraction of an inch to two feet or more (Plate 4), may or may not be distinct. In areas of uniform lithology, foliation has often greatly obscured the bedding. However, where a contrast exists between rock types, bedding may be revealed.

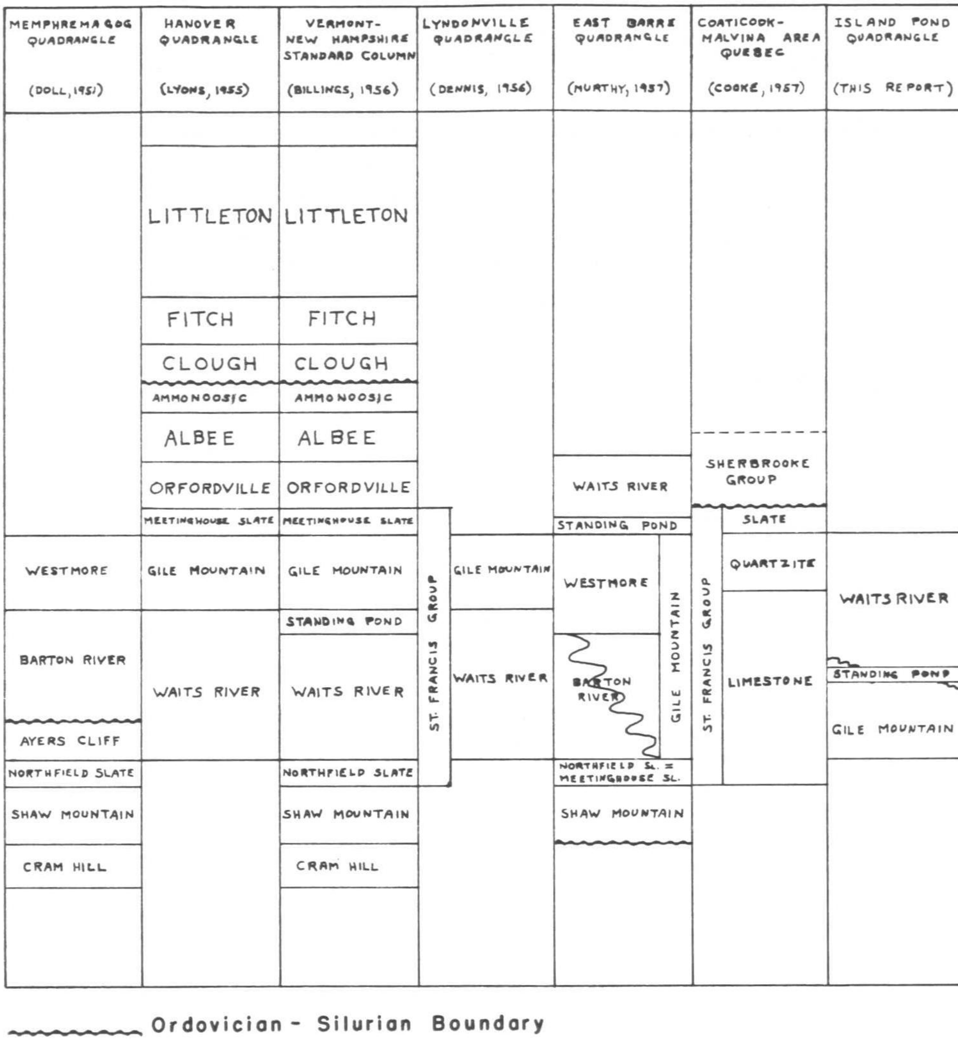


TABLE 1

CORRELATION CHART OF EASTERN VERMONT AND ADJOINING REGIONS

PLATE 4. Gile Mountain formation, alternating arenaceous and argillaceous beds, schistosity parallel to bedding. NW0625.

Even where schistose, alternating layers which were originally argillaceous and arenaceous have reacted differently to metamorphism, and bedding has frequently been preserved. The argillaceous beds are darker gray. Cleavage in these two lithologies also commonly shows a contrasting habit. Flow cleavage prevails in the arenaceous beds; slip cleavage is best developed in the argillaceous layers. Modal analyses showing the mineralogical compositions of some of the rock types characteristic of the formation are given in tables 2 and 3. As many of the minerals present are a result of metamorphic processes, the petrography of the metasediments will be discussed more fully in the section on metamorphism.

Fine- to medium-grained schists are common throughout the formation. When fresh they are light to dark gray and often weather brown. Quartz and biotite are almost always present and commonly constitute the bulk of the rock. Quartz-mica schists are the most prevalent rocks, but in regions adjacent to granitic bodies additional metamorphic minerals may contribute to the composition and commonly form andalusite-quartz-mica and sillimanite-quartz-mica schists. Hornblende, garnet-mica, staurolite, and feldspathic schists are also present. Anda-

TABLE 2

ESTIMATED MODES OF THE GILE MOUNTAIN FORMATION

Location	C1740	S2223	C3851	S1724	NW1344
Quartz	58.1	27.1	40.6	57.8	69.2
Biotite	25.9	34.4	39.0	30.4	22.6
Muscovite	3.4	.3	3.8	1.4	5.8
Chlorite	—	—	2.6	—	—
Sillimanite	8.3	9.8	11.6	8.2	—
Andalusite	—	22.8	—	—	—
Staurolite	—	—	—	—	1.0
Plagioclase	2.7	—	—	.5	—
Magnetite	.5	4.8	2.0	.9	.7
Other accessories	1.1	.8	.4	.8	.7
Number of Counts	1276	1557	1701	1587	1505

C1740. Quartz-mica phyllite
S2223. Andalusite-quartz-mica schist
C3851. Sillimanite-quartz-mica schist
S1724. Quartz-mica schist
NW1344. Quartz-mica phyllite

lusite is developed often as porphyroblasts, commonly one inch long. Among many of these porphyroblasts, carbonaceous inclusions indicative of the variety chiastolite can be readily observed. These porphyroblasts tend to have a crude alignment with the foliation, but many of them display a random orientation. Biotite, garnet, hornblende, and staurolite may also occur as porphyroblasts. Chlorite, sericite, plagioclase, and hornblende are common constituents of the schists. Hornblende schists may assume local importance.

The phyllites are fine grained, finely foliated, brown to gray, and often have a silvery sheen imparted to them by their high content of sericite. A similar luster is also found in many of the schists. Doll (1951, p. 35) noted that these rocks "... are on the whole comparatively of lighter color and more arenaceous than the same rocks in the Barton River formation." Quartz and mica are extremely plentiful constituents and either of them may be the major mineral present. Biotite frequently occurs as porphyroblasts giving the rock a spotted effect.

Dense, fine-grained, generally dark-blue-gray shades characterize the quartzites. They are usually highly jointed. A pronounced banding is exhibited by many of the quartzites, and, upon weathering, a peculiar undulatory surface is often developed along the surfaces of this banding.

TABLE 3

ESTIMATED MODES OF THE GILE MOUNTAIN FORMATION

Location	NW1123	S0423	S0613	NW1505	S1902
Quartz	72.1	47.7	36.7	32.8	10.0
Biotite	5.6	33.0	19.6	15.9	25.3
Muscovite	12.6	11.5	—	—	—
Chlorite	6.1	1.3	21.9	9.8	29.8
Plagioclase	—	.2	.1	4.1	16.4
Hornblende	—	—	12.7	31.4	—
Calcite	1.1	—	—	—	—
Garnet	—	—	—	—	16.8
Magnetite	.8	4.1	1.2	2.2	.6
Sphene	—	—	7.0	1.0	—
Other accessories	1.7	2.2	.8	2.8	1.1
Number of Counts	1597	1733	1474	1272	1457

NW1123. Micaceous quartzite
S0424. Quartz-mica phyllite
S0613. Hornblende-quartz-mica schist
NW1505. Quartz-hornblende schist
S1902. Feldspathic garnetiferous chlorite-mica schist

Quartz may constitute up to 85 percent of the rocks, but all are micaceous in varying amounts. Chlorite, calcite, magnetite, garnet, apatite, sphene, and plagioclase are minor accessories.

The calcareous rocks are highly siliceous and have been recrystallized to marbles. They are fine to medium grained and are generally light to dark gray, and may be mottled. Many of them are foliated. Quartz may make up 50 percent of the total mineral content, and biotite is often plentiful. Many other minerals may be present, some of the most common being plagioclase, hornblende, chlorite, sphene, diopside, and magnetite. The presence of calc-silicate beds interspersed in the Gile Mountain formation indicates the former existence of limestone members. Where limestones are numerous in the Gile Mountain it may become difficult to distinguish them from the calcareous lithology of the Waits River formation. Dennis (1956, p. 21) stated that "Greater amounts of impurities account for a higher proportion of amphibolite than in the Barton River formation." In general, the limestone lenses of the Gile Mountain appear to be more frequently schistose, less coarsely bedded, and more impure than those of the Waits River. However, exceptions may readily be found to this generalization.

Amphibolites constitute a minor portion of the Gile Mountain formation. They occur predominantly as very thin beds, rarely attaining great thicknesses. Hornblende makes up the bulk of the rock and imparts a foliation. Plagioclase, quartz, and biotite also are usually present.

A fifty-foot section of the Gile Mountain formation at locality SW1345, exhibiting in part the variety of lithologies embodied in the formation, is shown in Table 4. In this section, the phyllites are mostly of the quartz-mica variety, some being spotted with biotite. Graphite occurs as fine flecks disseminated throughout the rock. Sulfides are also present, some of the beds exhibiting small crystals of pyrite having a prominent rust-stained surface. The narrow amphibolites are fine grained and foliated. One of them is calcareous. Limestones are both massive and foliated, but the majority possess at least a slight foliation. They are blue gray, impure, and contain varying amounts of quartz and mica. One observed exposure contains carbonate beds in much greater amount than is common in the Gile Mountain. Bedding is well defined by the changes in lithology and no repetition of bedding due to folding could be detected.

Age

Paleontologic evidence in the Gile Mountain formation is sparse and controversial. Doll (1943a, p. 57–64) reported crinoid and cystoid calyces and two gastropods from the Waits River limestone in Westmore village. This limestone was later mapped as the Westmore formation by Doll (1951). These specimens were considered to indicate that the rocks were ". . . at least as young as Middle Silurian and very possibly of Lower Devonian age." However, doubt was expressed by some paleontologists as to the organic nature of the specimens (Doll, 1943a, p. 57). From the Gile Mountain formation in the Strafford quadrangle, Doll (1943b, p. 676–679) described a brachiopod which he identified as *Spirifer*, probably *murchisoni*. He, therefore, placed the Gile Mountain formation in the Lower Devonian. The validity of these specimens was questioned by White and Jahns (1950) and by White and Billings (1951).

No paleontologic evidence was found in the Island Pond area. In the present report, the Gile Mountain formation is believed to be the equivalent of the Westmore formation of previous reports. This is in accord with the evidence from fossils reported by Doll (1943a, 1943b). If that evidence is valid the age of the formation would range from early Silurian to early Devonian. As the question of age must take into consideration fossil evidence in the adjoining formations, it is considered in the discussion of the Waits River formation.

Table 4

SECTION OF GILE MOUNTAIN FORMATION
AT MAD BROOK DAM

Lithology	Thickness		Lithology	Thickness	
	Feet	Inches		Feet	Inches
Lithology *Thickness*	*Lithology*	*Thickness*	*Feet* *Inches*	*Feet*	*Inches*
North (top)					
phyllite	4	8	limestone		5
quartzite		8	amphibolite		3
phyllite		4	phyllite	2	1
amphibolite		5	limestone	2	3
quartzite		7	phyllite		9
phyllite		9	limestone	2	1
quartzite	4	6	phyllite	4	0
phyllite		7	limestone		9
quartzite	2	0	phyllite	1	10
phyllite		8	limestone	1	4
quartzite	1	5	phyllite		7
phyllite	7	5	limestone		7
amphibolite		2	phyllite	1	7
phyllite	2	5	limestone	1	6
amphibolite		4	phyllite	3	4
			South (bottom)		
				—	—
			Total:	50	3

Total Thicknesses and Percentages
of Lithologic Varieties in Section

Lithology	Thickness		Percentage
	Feet	Inches	
Phyllite	31	0	61.7
Quartzite	9	2	18.2
Limestone	8	11	17.8
Amphibolite	1	2	2.3

Standing Pond Volcanics

General Statement

A narrow band of coarse amphibolites in the southwestern portion of the Island Pond area has tentatively been designated as the Standing Pond volcanics. These amphibolites occupy a position roughly between the Gile Mountain and Waits River formations but are transgressive into the Gile Mountain for much of their outcrop (Plate 1). The name

"Standing Pond" was first used by Doll (1945, p. 17) in the Strafford quadrangle to refer to a band of amphibolites approximately following the Gile Mountain-Memphremagog (Waits River of this report) contact. Amphibolites in a similar stratigraphic position have been reported at many localities between the Island Pond and Strafford areas. They have also been traced well south of Strafford. The Standing Pond in the present area, though an amphibolite, is lithologically dissimilar in many respects to the rocks of the type locality.

Distribution

The Standing Pond volcanics are exposed as a thin band of amphibolite in the southwestern portion of the quadrangle (Plate 1). The main segment of this unit has its southeastern end on Meehan Hill from which it trends to the northwest, occupying the summit of Little Hedgehog and ending on the east slope of Pierce Hill. The band is about five miles long and commonly is less than a tenth of a mile wide. Approximately a mile of its length lies along the contact between the Gile Mountain and the Waits River formations. The remainder of the band is transgressive into the Gile Mountain formation. Another short segment of similar amphibolite is found at the southern border of the map area just east of Route 114. It continues on into the Burke quadrangle.

The thickness of the Standing Pond volcanics in the Island Pond area is estimated to vary between 200 and 400 feet.

Correlation

The amphibolitic rocks mapped as Standing Pond volcanics in the Island Pond area may be traced as a narrow, discontinuous band to its type locality in the Strafford quadrangle (Plate 3). Doll (1944, p. 17) proposed the name "Standing Pond amphibolite" to apply to a narrow band of amphibolite lying approximately between the Memphremagog formation (Waits River formation of this report) and the Gile Mountain formation. Since this unit in the Strafford quadrangle was ". . . found to occur either entirely in the limestones or along their contact with the mica schists," he considered it to be a member of the Memphremagog formation. It was thought to be either a metamorphosed volcanic or an altered sediment. White and Jahns (1950, p. 189) tentatively treated the Standing Pond as a volcanic unit in the Waits River formation because it was transgressive in relation to the boundary between the calcareous and noncalcareous rocks. Billings *et al.*, (1952, p. 39) subsequently called this unit the "Standing Pond volcanics" because in

New Hampshire the rocks changed along the strike into chlorite schists and soda rhyolite as the grade of metamorphism became less intense. Dennis (1956, p. 22) recognized the Standing Pond volcanics in the Lyndonville area along the Waits River-Gile Mountain contact. These amphibolites are lithologically different than those at the type locality and were adjudged by Dennis to be pillow lavas. In the East Barre area, Murthy (1957, p. 39) called a thin band of amphibolite roughly along the boundary of the Waits River and Gile Mountain formations the Standing Pond member of the Waits River formation. Amphibolites occupying a similar stratigraphic position are present in the Burke quadrange (B. G. Woodland, personal communication, 1958).

The northernmost limit to which these amphibolites have been traced lies in the Island Pond quadrangle. Here the band partially follows the Waits River-Gile Mountain contact but is transgressive well into the Gile Mountain formation for much of its length. For this reason, it may not properly be designated as a member of the Waits River formation in this area and the term "Standing Pond volcanics" is thought to be more applicable.

The correlation of such a narrow, discontinuous band as the Standing Pond over a long distance in a metamorphic terrain must of necessity be a tentative one. However, the amphibolites in the Island Pond area, although varying in lithologic detail from those at the type locality, do occupy a similar stratigraphic position and in all probability have an analogous origin. If this unit is correlative with the Standing Pond as proposed and if the Standing Pond is truly a volcanic horizon, then it would not be unreasonable to expect it to transgress lithologic boundaries.

Lithology

The amphibolite defined as the Standing Pond volcanics in this area occurs as a coarse-grained, massive amphibolite. In outcrop, the weathered surface is dark-brown to black and is characterized by numerous small protuberances caused by projecting porphyroblasts of hornblende. A fresh surface is greenish-black to mottled green-black and light-gray. Exposures are massive with a possible relict banding portrayed by parallel rows of widely spaced, narrow ridges on the surface of the amphibolite (Plate 5). The ridges are also composed of amphibolite. The majority of exposures are well jointed. The rock is dense and tough, commonly projecting as angular blocks above the land surface. Hornblende is megascopically the most prominent mineral, occurring as

PLATE 5. Standing Pond amphibolite, massive, possible relict banding portrayed by parallel rows of widely-spaced, narrow ridges parallel to hammer handle. Exposure on Meehan Hill.

porphyroblasts which frequently attain a diameter in excess of 1 cm. Quartz and plagioclase, where present, comprise the groundmass which is light gray and peppered with flecks of biotite. Foliation is not pronounced but is usually present as either a coarse parting controlled by the hornblende porphyroblasts or as an orientation and elongation of the light and dark constituents of the rock. Narrow, discontinuous, intercalated bands of phyllite and schist occur within the amphibolite.

Microscopically, the Standing Pond volcanics exhibit a variety of compositions, but in all specimens observed hornblende and chlorite constitute the major portion. Modal analyses showing the mineralogic characteristics of the Standing Pond in this area are given in Table 5. Chlorite occurs primarily as an alteration product of the hornblende, many large crystals of hornblende having been entirely altered to chlorite. Biotite also is altered to chlorite. Both quartz and plagioclase frequently exhibit a poikiloblastic texture with chlorite or hornblende. This is particularly characteristic of chlorite, with quartz and plagioclase existing as irregular patches within a large crystal of chlorite. A rim of quartz often borders the hornblende-derived chlorite. Quartz, plagioclase, and biotite are all common but are not universally present

(Table 5). In specimen SW3622, neither quartz nor plagioclase is present while biotite assumes a prominent proportion. In specimen SW2625, biotite is absent but quartz and plagioclase are approximately equal in amounts. The high quartz content may in part be due to the release of silica when the original pyroxenes were converted to hornblende, or by the further alteration of the hornblende to chlorite. However, at one locality a total absence of quartz was noted. Because the amphibolites are surrounded by the Gile Mountain formation for much of their length, silica may have been introduced from the contiguous siliceous sediments and from the intercalated beds of arenaceous rocks. Garnets, which are characteristic of the Standing Pond at its type locality, are here either totally absent or are found only in minor amounts as small crystals. In places the plagioclase is highly altered to sericite, giving the plagioclase surface a cloudy appearance. Hornblende, biotite, and chlorite occur frequently as porphyroblasts while the groundmass is commonly formed of small grains of quartz, biotite, hornblende, and plagioclase, all intimately intermixed. A microscopic foliation is imparted to the rock by the parallel dimensional orientation of the biotite, hornblende, and chlorite. Calcite, diopside, actinolite, garnet, and epidote occur at varied localities as minor accessories. Sphene and magnetite constitute the predominant opaques and are widely disseminated throughout the amphibolite.

Waits River Formation

General Statement

The Waits River formation comprises a small zone of predominantly calcareous rocks in the southwestern portion of the Island Pond area (Plate 1). Limestones constitute the prevailing lithology plus schists and phyllites which often assume local prominence. Calcareous rocks were found to make up at least 25 percent of any given section. The limestones are impure and recrystallized, commonly containing much quartz. In outcrop they are frequently characterized by a punky brownish weathered surface.

The name Waits River limestone was used as early as 1906 by Richardson, but in a much broader connotation than in the present report. The limestone here may be followed southward to its type locality in the East Barre quadrangle (Plate 3). The Barton River formation (Doll, 1951) is here believed to correlate with the Waits River formation. The name was restricted by Murthy (1957, p. 24) to a calcareous belt

TABLE 5

ESTIMATED MODES OF THE STANDING POND VOLCANICS

Location	SW1236	SW2625	SW3622
Quartz	18.0	15.8	—
Plagioclase	10.7	18.2	—
Biotite	16.9	—	26.1
Hornblende	23.5	37.7	34.3
Chlorite	28.2	19.8	30.1
Sericite	—	4.4	—
Calcite	—	—	2.8
Magnetite	.5	—	4.7
Other accessories	2.2	4.1	2.0
Number of Counts	1342	1322	1416

SW1236. Amphibolite
SW2625. Amphibolite
SW3622. Amphibolite

west of the Waits River formation and separated from it by a band of phyllites and schists. The western band of limestone lies beyond the borders of the Island Pond quadrangle. The two calcareous units are believed to be a structural repetition of the same formation.

DISTRIBUTION

The Waits River formation is exposed only in a narrow zone in the southwestern portion of the area (Plate 1). These predominantly calcareous rocks form a crudely arcuate belt which swings around the granitic bulk of Bald Mountain to the southwest and is encircled to the northeast by the Gile Mountain formation. Amphibolites, tentatively correlated with the Standing Pond volcanics, crop out along the contact between these two formations for a short distance northwest of Cold Brook. The belt of Waits River attains a maximum width of barely two miles, and it narrows to less than one-tenth of a mile where the granite encroaches northward toward the Gile Mountain contact. The length of the belt from northwest to southeast is approximately five and one-half miles. It continues to the south into the adjoining Burke quadrangle, and to the west in the Memphremagog quadrangle a narrow band of similar calcareous lithology has been traced continuing southwestward around the Goodwin Mountain granitic mass. This band was not differentiated from the Westmore formation by Doll (1951, Pl. 1).

As only the lower part of this formation crops out in the area of study no estimate of thickness could be obtained.

Correlation

The belt of predominantly calcareous rocks designated as the Waits River formation in the Island Pond quadrangle may be followed southward to its type locality in the East Barre quadrangle (Plate 3). The use of the name "Waits River" may lead to some ambiguity as it has been applied in various contexts throughout the development of geologic thought of eastern and northeastern Vermont. Therefore, in order to prevent confusion the history of the name will be traced and its usage in the present report defined.

The name "Waits River limestone" was first used by Richardson (1906, p. 115) to apply to the predominantly calcareous sequence of rocks in eastern Vermont. Richardson (1898) had previously named these same rocks the "Washington limestone" but that name was preoccupied. This sequence was a part of the belt designated earlier by Adams (1845, p. 49, 62) as the "Calcareo-mica slate" and by Hitchcock (1861, p. 475–488) as the "Calciferous mica schist." Currier and Jahns (1941, p. 1491) changed this name to the "Waits River formation" because along with abundant limestones the sequence also contained prominent thicknesses of phyllites and schists. Currier and Jahns therefore defined the Waits River formation as including all the rocks stratigraphically between the Northfield slate and the Gile Mountain formation. Doll (1944, p. 16) used the name "Memphremagog formation" to refer to the calcareous rocks in the Strafford quadrangle. This name was applied to the formation" . . . from its occurrence in the region covered by the quadrangle of that name." In the Memphremagog quadrangle, Doll (1951, p. 22) recognized three units within the Waits River, two predominantly calcareous and one composed primarily of phyllites and schists. For these units he proposed the names "Ayers Cliff formation," "Barton River formation," and "Westmore formation." The Ayers Cliff was considered to be the oldest and the Westmore the youngest. Dennis (1956, p. 16), working in the Lyndonville area, retained the names Ayers Cliff and Barton River but considered these units to be members of the Waits River formation. The Waits River formation crops out in two belts in the Lyndonville area which Dennis interpreted as repetition on the limbs of a syncline with the Westmore formation occupying the trough. Murthy (1958, p. 277) redefined the term "Waits

River formation" and used it in a restricted sense to apply only to the easternmost calcareous unit in the East Barre area. For the calcareous rocks west of the Westmore formation, he retained the name "Barton River formation." Murthy (1958, p. 283) considered these units to lie essentially in a homoclinal sequence on the west limb of a large syncline so that the age relations previously given to its members would be quite different. According to Murthy's interpretation, the Barton River formation is the oldest and the Waits River formation is the youngest. The Westmore formation is intermediate in age.

In the present report, the name Waits River formation is once again used to apply to both the Waits River and the Barton River formations of Murthy. The eastern and western calcareous units are believed to belong to the same formation which has been structurally repeated by a major fold. In the southeastern portion of the Randolph quadrangle the two bands of carbonate rocks merge to enclose the outcrop pattern of the central band of Gile Mountain formation (E. H. Ern, personal communication, 1959). However, rather than being a syncline as proposed by Dennis (1956, p. 17) the structural repetition of the Waits River formation is thought to take place in the nose of a recumbent anticline. The Waits River formation, therefore, is considered to be younger than the Gile Mountain formation by the present author.

Although this portion of the fold lies west of the Island Pond quadrangle, evidence will be presented in the section on structure which indicates the stratigraphic sequence proposed above. The same evidence also indicates that this postulated structure is one which is necessary in order to explain the sequence of calcareous and non-calcareous units as found in eastern and northeastern Vermont.

LITHOLOGY

Calcareous rocks are common in the lithology of the Waits River formation. These are interbedded with quartz-mica schists and phyllites, and quartzites, though not abundant, are also present in subordinate amounts. Thin amphibolite bands are infrequent components. As on the cliff to the west of Jobs Pond, limestones sometimes compose over 80 percent of the total lithology but more commonly the arenaceous and argillaceous members assume greater proportions with the limestone often comprising as little as 25 percent of the rocks. At such localities the rocks may be difficult to distinguish from those of the Gile Mountain formation. The exact boundary between the Waits River and Gile Mountain lithologies is frequently elusive and will therefore be covered in greater detail below. Modal analyses of some Waits River lithologies are given in Table 6.

Bedding is usually distinct, especially where the lithology varies. The contact between adjacent calcareous and argillaceous beds is usually sharp. Limestone may be massive bedded, over four feet thick, but more commonly strata range from an inch to two feet. Entirely calcareous bands may be only an inch thick or they may attain a thickness of more than 50 feet free of any intercalated argillaceous metasediments.

When fresh, the color ranges from light-gray to dark blue-gray, and is frequently mottled or banded with patches or bands of white. Bedding is often well defined. The weathered surface commonly exhibits a rough, red-brown, punky crust which may extend more than an inch into the rock. This weathered residue is a characteristic surface feature of the limestones. Small veins of calcite are found within some limestones. These are usually parallel or sub-parallel to the bedding but may cross it where they fill fractures. Siliceous veins, also present, display similar relations.

The limestones are predominantly impure, most containing quartz in excess of 20 percent of the total mineral content. In some instances the quartz content may exceed 50 percent. Recrystallized calcite is usually the major constituent, the rock in reality being a marble. However, in recognition of prevailing terminology the name "limestone" will be retained throughout the present report. The grain size averages between .02 and .05 mm in diameter. Biotite, muscovite, plagioclase, chlorite, hornblende, magnetite, and sphene are also frequently present in minor quantities. Finely divided carbon is widely disseminated throughout. At the contact with granitic rocks, lime silicate minerals are often developed with tremolite and diopside the most common. At such a contact on the cliff west of Jobs Pond, well-developed crystals of vesuvianite display a radiating habit. These clusters are up to an inch in diameter.

Quartzites are rare constituents of the Waits River and are normally thin-bedded. Two types are found, one of which is dark blue-gray, the other light-gray. All of the quartzites are impure. Calcite is often present, sometimes in appreciable amounts. Biotite, plagioclase, hornblende, and magnetite are also common constituents. A banding parallel to bedding is a conspicuous feature of many of the quartzite bodies.

In part, the schists and phyllites are similar to those previously described in the Gile Mountain formation. The predominant types are quartz-mica schists and phyllites, their fresh surfaces often being

TABLE 6

ESTIMATED MODES OF THE WAITS RIVER FORMATION

Location	SW4010	SW0436	SW0330	S0515	SW2125
Quartz	28.9	26.4	52.4	27.7	37.1
Plagioclase	.1	5.4	8.9	19.1	2.5
Calcite	50.2	44.3	21.4	12.0	18.4
Biotite	1.6	—	.5	38.8	—
Hornblende	12.2	14.7	9.8	—	37.1
Chlorite	1.0	.6	3.5	—	3.2
Diopside	—	5.4	—	—	—
Magnetite	4.7	.9	1.0	.6	—
Other accessories	1.3	2.3	2.5	1.8	1.7
Number of Counts	1667	1434	1280	1267	1368

SW4010. Siliceous limestone
SW0436. Siliceous limestone
SW0330. Calcareous quartzite
S0515. Calcareous quartz-biotite schist
SW2125. Calcareous quartz-hornblende schist

lustrous due to the high mica content. Hornblende schists and calcareous quartz-mica schists are also present. In general, both phyllites and schists are somewhat darker gray than their counterparts in the Gile Mountain formation. The color ranges from dark gray to black. This is a consequence of a higher content of carbonaceous matter within the schists and phyllites of the Waits River. The darker gray rocks reflect their higher carbon content. The carbon occurs as fine flecks. Sulfides are also prevalent. These commonly form small stringers parallel to the bedding. Upon weathering, they impart a rusty-brown surface stain to the rocks. This stain is a characteristic surface feature of the Waits River phyllites and schists. It may also be present in similar Gile Mountain lithologies but is not as widespread nor is it characteristic. Calcite may be a constituent of the schists and often contributes as much as 15 percent of the mineral assemblage. Biotite and sericite are the prevailing micas. Chlorite, hornblende, and plagioclase are frequent components. In regions contiguous to granitic masses metamorphic minerals abound.

Amphibolites are generally thin, foliated hornblende schists. They frequently possess quartz and calcite in appreciable amounts. Chlorite, plagioclase, epidote, sphene, and magnetite are accessories. In outcrop they may appear to be entirely amphibolitic but a microscopic examination reveals a quantity of additional ingredients.

The lithology discussed in this section is relative only to the lower part of the formation. Units higher in the stratigraphic column either lie beyond the area of study or have been destroyed by the invasion of the Bald Mountain granite mass.

Age

The structural interpretation of the present report considers the Waits River formation as overlying the Gile Mountain formation. The Barton River formation (Doll, 1951; Murthy, 1957) is here considered to be equivalent to the Waits River formation, the two units being a structural repetition of the same formation. If this is true, then data concerning the age of the Barton River formation is applicable to the present Waits River formation.

Evidence provided by fossils is meager and conflicting. Doll (1951, p. 26) in his report on the Memphremagog quadrangle mentioned elongate, lustrous markings on bedding surfaces, which "... might, from their shapes be suggestive of graptolites." These were thought closely to resemble similar markings in the Castle Brook locality at Magog, Quebec, which are associated with easily identifiable graptolites. If the identification is valid it makes the Waits River Ordovician. However, Doll (1951, p. 27) refers the Barton River formation to the Silurian. This age assignment is in part due to the belief that the Irasburg conglomerate (Doll, 1951, p. 32–33) is a basal conglomerate to the Barton River formation. The conglomerate overlies unconformably the Ayers Cliff formation, and Doll considered that it indicates a major break in the stratigraphic sequence, possibly between the Ordovician and Silurian. According to Doll, "This age assignment is also based upon the position of the formation stratigraphically below strata yielding fossils of Silurian age or younger."

Cooke (1957, p. 20) disputed the stratigraphic significance of this conglomerate and believed that it was "... merely an accident of nature" probably formed of boulders dropped by floating icebergs and that "... it implies no break whatever in the normal processes of sedimentation, and cannot therefore be held to indicate an unconformity." Earlier, Richardson (1906, p. 83) placed the same conglomerate at the base of the Ordovician, while Currier and Jahns (1941, p. 1509) classified it as an intraformational conglomerate in the Ordovician.

Fossil cup corals were reported by Cady (1950, p. 448) from phyllites of the Waits River formation north-northeast of Montpelier. These were believed to indicate probable middle Ordovician. Later, however, he (Cady, 1956) considered the Waits River formation to be Silurian.

Richardson (1919) reported numerous graptolite specimens in the Waits River but Foyles (1931, p. 252) later gave evidence that some of the so-called graptolites were in reality mica streaks of tectonic origin. Currier and Jahns (1941, p. 1505) reached a similar conclusion. In Canada, Ells (1887, p. 16–17) working in the Magog slates of the Castle Brook area described 'Llandeilan' graptolites. These were identified by Ruedemann as being both Deepkill and Normanskill. Clark (1934, p. 12) reported graptolites from the Tomifobia slates which resemble those of the Castle Brook locality. Graptolites were also mentioned by Cooke (1937, p. 42) in the St. Francis series near Lac Rocheaus and were identified by Rudemann as Normanskill.

The Tomifobia formation of southern Quebec was considered by Clark (1934, p. 1–20) and Ambrose (1943) to be equivalent to part of the Waits River formation. The Tomifobia was believed by them to be Ordovician. Cooke (1950) included the metasediments of the old Tomifobia formation as a part of the St. Francis group. The St. Francis group in Canada corresponds to the Northfield, Waits River, and Gile Mountain formations in Vermont. Cooke (1950, 1957) considered the St. Francis group to be Ordovician. His reasons were based partly on paleontological evidence previously mentioned and partly because the St. Francis group appeared to underlie the Sherbrooke group with great angular unconformity. Cooke (1950, p. 63) believed the Sherbrooke group to be early to middle Silurian.

Morin (1954, as quoted by Dennis, 1956, p. 28) advanced the possibility of a Siluro-Devonian age for the St. Francis group. This was suggested because of a strike alignment of the St. Francis group with known Devonian strata of similar lithologies in the Gaspe region.

Lyons (1955, Pl. 6) showed the Meetinghouse slate to be in conformable contact with the Orfordville formation of the New Hampshire sequence in a portion of the Hanover quadrangle. The Orfordville is overlain by the Albee, Ammonoosuc, and Partridge formations of the New Hampshire sequence, all of which are considered to be older than middle Silurian (Billings, 1956, p. 96) and presumably pre-Silurian. This would indicate an Ordovician age for rocks of the Vermont sequence.

In the present report, the units of the Vermont sequence are assigned to the Ordovician. However, it must be stated that they may well be Silurian or Devonian and that any age assigned to them must be tentative pending conclusive paleontologic evidence.

The Gile Mountain—Waits River Contact

The calcareous rocks of the Waits River and the argillaceous and arenaceous lithology of the Gile Mountain commonly grade into one another near the contact between these two formations. Therefore, this contact is an elusive one and it frequently becomes difficult to decide to which formation a particular outcrop should be designated, especially in a region where exposures are sparse and small. The major criterion utilized by most workers dealing with these formations has been the relative abundance of limestone beds. If limestones constitute 25 percent or more of the total lithology the rocks are commonly assigned to the Waits River. Dennis (1956, p. 22) stated that "Although the disappearance of the limestones, when going from the Waits River into the Gile Mountain is gradual, it occurs within a comparatively narrow zone usually within 1000 to 1500 feet." Additional criteria used to differentiate between the two formations have been: (1) the greater prominence of rusty-weathering in the Waits River; (2) the more frequent occurrence of sulfides in the Waits River; (3) the greater carbon content and hence darker gray of the phyllites in the Waits River; (4) the larger proportion of siliceous schists and relatively greater abundance of quartzites in the Gile Mountain. Also, limestones of the Gile Mountain often appear to be more foliated, less coarsely bedded, and more impure than those of the Waits River. Dennis (1956, p. 21) felt that a greater percentage of impurities in the limestones of the Gile Mountain account for a higher proportion of amphibolites in this formation. However, as the contact is approached, any of the criteria mentioned above may become gradational with the lithology of the adjacent formation. White and Billings (1951, p. 655–656) in the Woodsville quadrangle noted that large lenses of limestone in the Gile Mountain formation tended to contain more micaceous quartzite rather than mica schists interbedded with the limestone. Murthy (1957, p. 42) could not clearly discern this distinction in the East Barre area and relied upon the stratigraphic position within the Gile Mountain formation to distinguish them from rocks of the Waits River.

Where present, the Standing Pond volcanics may provide an indication of proximity to the Waits River-Gile Mountain contact. In many localities the contact is occupied by this unit but caution must be used as the Standing Pond has been found to transgress into both formations for short distances.

North of the International Boundary, Cooke (1957) did not subdivide the rocks of the St. Francis group into the formations recognized in Vermont. He did, however, differentiate between the most prominent lithologies present. This subdivision was made (p. 19) "... between parts in which limestone beds are moderately numerous and that in which they are rare or completely lacking." The contact between Cooke's "Impure dark limestone with quartzite interbeds" and his "Quartzite, minor slate and limestone" therefore lies well within the boundaries of the Gile Mountain formation as they are commonly delineated in Vermont. The first-mentioned zone would include all of the Waits River formation and a good portion of the Gile Mountain. This again indicates the elusive nature of the Waits River-Gile Mountain contact in the present area of study.

In the Island Pond area, all of the criteria mentioned above were utilized to differentiate between the two units involved. Of these criteria, the most useful was the relative percentage of limestone beds. It is often insufficient to apply this criterion to each individual exposure, as any given outcrop, particularly if small in extent, may not be representative of the total lithology. Therefore, it is frequently necessary to consider a series of exposures in order to derive a satisfactory representation of the lithology present.

PLUTONIC ROCKS

General Statement

Plutonic rocks underly approximately two-thirds of the Island Pond area (Plate 1). Three major bodies are present. These large granitic masses occupy the northeastern, southeastern, and west-central portions of the area. The west-central and northeastern masses are separated by and grade into a smaller complex of diorite, monzonite, and gabbro. For the sake of convenience, the basic complex is included with the west-central mass.

A smaller granitic zone supports Bald Mountain in the southwestern corner of the area. Numerous sills and dikes of granite are present in the metasediments surrounding the large masses. The petrography and structural features of the various masses differ, hence they will be discussed individually.

The Nulhegan Quartz Monzonite

General Statement

The Nulhegan quartz monzonite is exposed as a crudely circular mass occupying the southeastern portion of the area (Plate 1). Although it extends well into the Averill quadrangle to the east and for a short distance into the Burke and Guildhall quadrangles to the south and southeast, the major portion of this body is exposed in the Island Pond area. On a line due east from the village of Island Pond, it has a diameter of more than nine and a half miles.

The quartz monzonite is poorly exposed as it is restricted largely to a low, swampy basin with morainal debris. The basin is surrounded on all sides by an encircling chain of hills composed of Gile Mountain metasediments. The name "Nulhegan quartz monzonite" has been assigned to this unit because it underlies the topographic basin drained primarily by the Nulhegan River and its tributaries.

Petrography

The Nulhegan quartz monzonite is a medium- to coarse-grained granitoid rock, light- to dark-gray depending on the amount of biotite and other mafic minerals present. On a freshly broken surface it has a distinctive appearance with biotite clots flashing prominently upon a background of white quartz, potash feldspar, and plagioclase. A faint megascopic foliation is observed at a few localities, usually near the border of the pluton.

Plagioclase (oligoclase-andesine), potash feldspar, quartz, and biotite are the dominant minerals. Modal analyses of the Nulhegan quartz monzonite from widely separated localities are shown on Table 7. Biotite is always prominent, comprising from 13 percent to 27 percent of the rock (average, 16–18 percent). Quartz averages about 15 percent but may drop to as low as 9 percent. Plagioclase is commonly slightly more abundant than potash feldspar, but at some localities the two are approximately equal. Hornblende, chlorite, and sericite also generally are present. Sphene, the most abundant accessory, generally occurs in perfect, euhedral, wedge-shaped crystals. Other accessories in decreasing order of abundance are apatite, epidote, magnetite, and zircon.

The texture is hypidiomorphic granular. Potash feldspar and plagioclase occur as euhedral to subhedral crystals. Quartz is present as small, generally anhedral grains, many of which exhibit undulatory extinction.

Table 7

ESTIMATED MODES OF THE NULHEGAN QUARTZ MONZONITE

Location	S4130	S2546	SE0916	E3721	E1806
Quartz	13.9	18.6	9.5	16.0	12.1
Potash Feldspar	27.8	24.1	28.8	24.9	27.5
Plagioclase	33.1	30.3	29.1	24.6	34.9
Biotite	16.6	18.7	13.9	27.1	13.8
Hornblende	3.5	.2	1.4	1.4	2.6
Chlorite	1.5	6.1	11.6	3.3	5.6
Sericite	2.4	.7	4.8	1.0	1.5
Accessories	1.2	1.3	.9	1.7	2.0
Number of Counts	1352	1524	1329	1332	1440

S4130. Quartz monzonite
S2546. Quartz monzonite
SE0916. Quartz monzonite
E3721. Quartz monzonite
E1806. Quartz monzonite

This type of extinction is most prevalent in specimens taken near the border of the mass. Interstitial micropegmatite is sparingly present. Myrmekite exists infrequently in the plagioclase. A poikilitic texture is present in some of the large biotite grains, with quartz and plagioclase being enclosed. Sphene is most common either within the biotite or at its fringes. Sericite is a common alteration product of the plagioclase. Hornblende is frequently so highly altered to chlorite that little now remains of the original hornblende crystals. Biotite is also altered to chlorite.

Structural Relations to the Host Rocks

The contact between the quartz monzonite and the host metasediments of the Gile Mountain formation is not exposed within the area. At a number of locations a traverse could be conducted progressing from quartz monzonite to quartz-mica schist within a distance of less than one hundred feet, but the contact remained hidden.

Bedding in the encircling metasediments usually strikes parallel or sub-parallel to the interpolated contact and dips steeply toward the pluton (Plate 2). The dips are always greater than 45 degrees and most commonly are above 65 degrees. In places, especially at the northern edge of the mass where the metasediments are highly folded they dip away from the pluton. At many exposures in proximity to the quartz monzonite, the strike of the bedding diverges up to 30 degrees from the strike of the probable contact.

The contact between the Gile Mountain formation and the quartz monzonite appears to vary between gradational and sharp. In the stream bed at C2000 a transitional contact may be partially observed. Upstream at Elev. 1600 the Gile Mountain quartz-mica schist is well exposed. Downstream, the schists become more gneissic and contain numerous small veins of quartz which follow the foliation for a short distance and then cut across it. Next, the rock assumes the appearance of a fine-grained, melanocratic granite. This granitic rock is interspersed with metasediments upstream, and becomes less contaminated downstream until it grades into typical Nulhegan quartz monzonite. The zone of transition from normal schists to true quartz monzonite is 700–800 feet wide.

Internal Structural Features

Inclusions and Foliation

Inclusions of partially altered metasediments are common near the borders of the quartz monzonite. They are invariably small, rarely more than a foot long. At some localities they are numerous. A number of them occur in an exposure next to the road at S1240. In the larger ones, bedding and foliation can be identified (Plate 6), but in the smaller ones the original composition and structure have been obliterated (Plate 7). The trends of the long axes of these inclusions vary, but most appear to strike northwest, roughly parallel to the contact with the neighboring metasediments. The bedding in one of the larger inclusions has an attitude of N50°W, 63°NE while in another the foliation has an attitude of N79°E, 52°SE. These two have a similar dimensional orientation about N45°W and lie approximately in line. In the adjacent metasediments, bedding and foliation are commonly sub-parallel. This perhaps indicates some rotation of the inclusions, although it is possible that two segments of a single, highly folded bed are represented. The inclusions are interpreted as xenoliths. A faint banding of the quartz monzonite may be interpreted as flow banding. The banding trends about N45°W which is parallel with the long axes of the majority of the xenoliths. In some xenoliths where pronounced alteration zones are present, the original composition of the metasediments has been drastically changed at the contact. Also, surrounding many of the xenoliths, a zone is present in which the quartz monzonite is of slightly

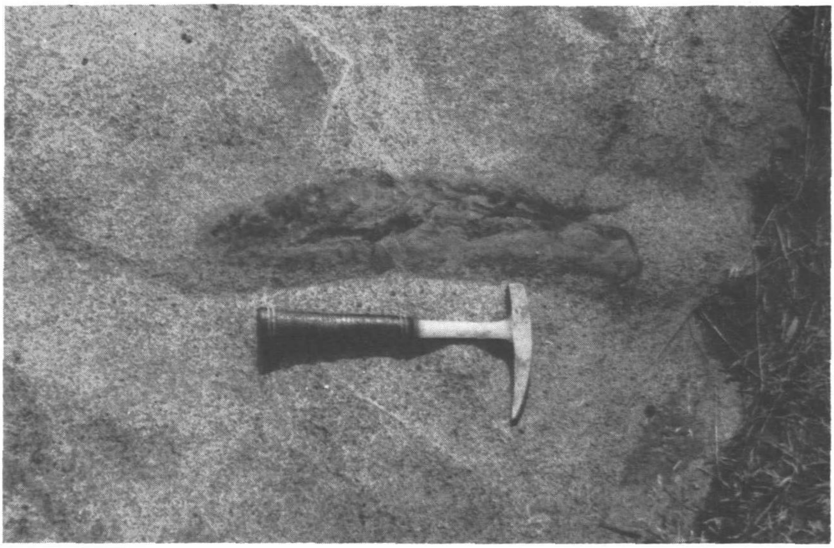


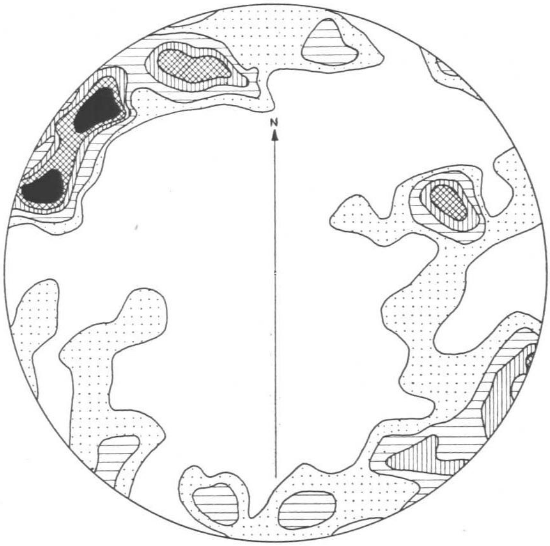
PLATE 6. Xenolith in Nulhegan quartz monzonite. Schistosity is parallel to hammer handle and dips toward it. S4012.

different composition and has a brown color. Such zones may attain a width of two inches, and are indicative of chemical interaction between the xenoliths and the enclosing rock.

Where observed, xenoliths in the Nulhegan quartz monzonite have a generally conformable alignment with the contact between the quartz monzonite and the metasediments. Flow lines in the quartz monzonite are neither common nor pronounced. They are restricted to the margins, and appear to have a parallel to subparallel relationship to the quartz monzonite-Gile Mountain contact.

Joints and Dikes

A plot of 114 poles of joints from the Nulhegan quartz monzonite is shown in Figure 4a. Although joints are found in diverse orientations, a major joint set appears to strike northeast and dip about 90 degrees. Many joints, especially those near the edge of the pluton are filled by a fine- to medium-grained leucogranite. This dike rock is much more resistant to erosion than quartz monzonite, and where outcrops exist in a stream bed, the dike rock stands up prominently above the surface of the quartz monzonite. Where numerous such veins are present, a striking latticework of small ridges may develop (Plate 8). Quartz veins



a. 114 joints in the Nulhegan quartz monzonite.
1–2–3–4–5%

Figure 4. Stereograms of joints in the granitic plutons.

also cut the quartz monzonite. At Elev. 1335 on the North Branch of the Nulhegan River, two prominent intersecting sets of leucogranite dikes are found, one trending N56°E and the other N27°W. At their intersection, the eastward trending dikes cut the other set and cause a displacement of four inches. This indicates two stages of dike formation and that adjustment of the host rock was still taking place at the time of emplacement of the dikes. At the same locality, horizontal joints are covered by leucogranite. This relationship can be observed in spots where the dike rock has broken off, leaving the underlying quartz monzonite exposed (Plate 9).

The Averill Granite

General Statement

An extensive granitic pluton which extends north into Quebec and into the Averill quadrangle to the east is located in the north and northeastern sections of the quadrangle. Exposures of this granite are sporadic in their distribution as the region is heavily forested and often covered by glacial debris. This body is roughly elliptical in plan with its longest

PLATE 7. Xenolith in Nulhegan quartz monzonite. Faint zoning of the xenolith can be distinguished near its edges, but metamorphic structures have been obliterated. S2819.

axis approximately east-west. In this direction, the outcrop area measures about fifteen miles. In a north-south direction, it has a maximum breadth of slightly more than nine miles. The rock is composed of pink to gray granite and quartz monzonite. Pegmatite veins commonly cut the granite.

This granite was traversed by Hitchcock's Section XIII (1861, p. 675–677) and its large extent noted at that time. The name Averill granite was applied to the eastern portion by Schroeder (1920, p. 40), and a brief description of the rock was given. North of the International Boundary, Cooke (1957, p. 29) described a continuation of the same granite and noted a likeness to the Stanstead granite of Quebec.

Petrography

The color of the rock ranges from light pink to light gray. The light pink variety is particularly prevalent in the northeastern segment of the mass but may occur throughout. In the region of the Averill lakes, Schroeder (1920, p. 40) described the Averill granite as ". . . a pink, two-mica granite of medium grain with a sub-porphyritic texture, the phenocrysts being microcline crystals, twinned according to the Carlsbad

PLATE 8. Intersecting dikes of fine- to medium-grained leucogranite cutting Nulhegan quartz monzonite. Dikes form a pronounced latticework in stream bed. Elev. 1335 on the North Branch of the Nulhegan River.

Law, and measuring 10 to 15 millimeters in length. The general color of the fresh normal granite is pink with small black specks. It bleaches upon exposure to the weather and becomes light gray to white." Cooke (1957, p. 28) describes the same mass exposed in Quebec as a ". . . very coarse-grained, rather light-grey, biotite granite." Although the color may vary, reflecting changes in composition, the granite is overall medium to coarse grained, and frequently porphyritic.

The composition of the Averill granite varies (Table 8) from granite to quartz monzonite. Quartz, potash feldspar, and plagioclase are the major constituents at all exposures. The plagioclase is predominantly oligoclase. Biotite and muscovite are both common constituents with biotite more abundant. Biotite comprises from 3 to 12 percent of the rock while muscovite rarely contributes more than 1 percent of the bulk composition. The most common accessory minerals are magnetite, sphene, chlorite, apatite, and zircon.

The texture is hypidiomorphic granular. Plagioclase commonly occurs as zoned euhedral crystals. Potash feldspar is plentiful as large, euhedral phenocrysts which assume a dominant role in the makeup of the rock. These are so large and numerous that in thin section, a single phenocryst

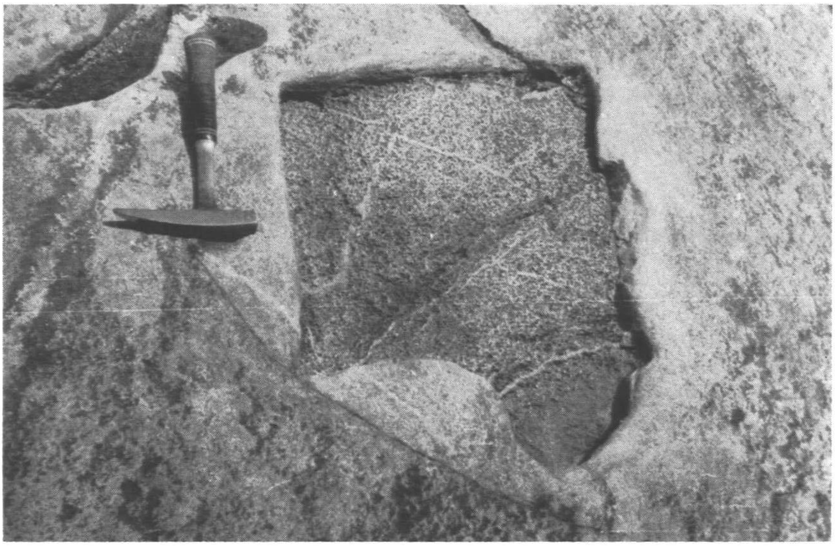


PLATE 9. Horizontal dike of medium-grained leucogranite in the Nulhegan quartz monzonite. Dike rock has partly broken off exposing the underlying quartz monzonite. Elev. 1335 on the North Branch of the Nulhegan River.

may comprise much of the slide and give a distorted picture of the mineral content. Quartz is present primarily as smaller, anhedral grains, occupying irregular spaces between the other components.Micropegmatite also is interstitial. Myrmekite is present in the oligoclase, especially in the quartz monzonites. Some of the potash feldspar has a poikilitic texture with enclosed rounded granules of oligoclase and quartz. A core of potash feldspar is in places rimmed by oligoclase. The potash feldspar core usually is altered to sericite, but the oligoclase border remains clear. Sericite is a common alteration product of potash feldspar. Biotite is partially altered to chlorite and granular sphene.

Structural Relations to the Host Rocks

Contacts between the Averill granite and the surrounding schists and phyllites are in part concordant and in part discordant. In the northwestern portion of the area, the contact is concordant when observed on a broad scale (Plate 2). However, in the vicinity of Mt. John, distinctly discordant relations were observed with the structure in the metasediments intersecting the contact at nearly right angles. A similar discordancy is prevalent along the contact to the east of Unknown Pond. The outcrop area of the pluton has a crudely elliptical shape as

Table 8

ESTIMATED MODES OF THE AVERILL GRANITE

Location	NW3249	N2850	N0616	C2554	NW1852
Quartz	23.1	38.1	37.3	21.9	27.4
Potash Feldspar	27.0	29.4	24.1	44.5	32.9
Plagioclase	38.6	27.0	26.4	26.0	23.9
Biotite	9.2	3.8	7.9	5.6	11.4
Muscovite	.6	.6	.2	.4	.9
Sericite	.3	.2	2.3	.7	2.1
Opaque accessories	.3	tr	.7	.1	.1
Other accessories	.9	.9	1.1	.8	1.3
Number of Counts	1472	1387	1260	1456	1331

NW3249. Quartz monzonite
N2850. Quartz monzonite
N0616. Quartz monzonite
C2554. Granite
NW1852. Quartz monzonite

previously mentioned. The long direction of the ellipse is almost at right angles to the regional strike of the metasediments.

Where observable, the contacts between granite and metasediments appear to be sharp. West of Holland Pond, coarse-grained, porphyritic granite is found in contact with schists which do not deviate from the normal attitude of sediments more remote from the intrusion. East of Page Hill, dikes of Averill granite cut directly across the undisturbed bedding of Gile Mountain schists. Some of these dikes attain a width of ten feet and are composed of coarse-grained granitic rock. Dikes and sills of Averill granite are a common feature in the surrounding metasediments. Most of these are small, but on the south side of Middle Mountain a sill several hundred feet thick crops out on the cliff face. Quartz veining also is a more common feature of the metasediments in the vicinity of the Averill granite. Near the contact west of Holland Pond, some exposures form elongated, rolling knobs with the long dimension trending slightly east of north. This trend is in close alignment with the prevalent strike of bedding in the adjacent metasediments.

Internal Structural Features

Inclusions and Foliation

Inclusions of country rock are rare in the Averill granite and foliation is almost lacking. The granite is nearly everywhere massive.

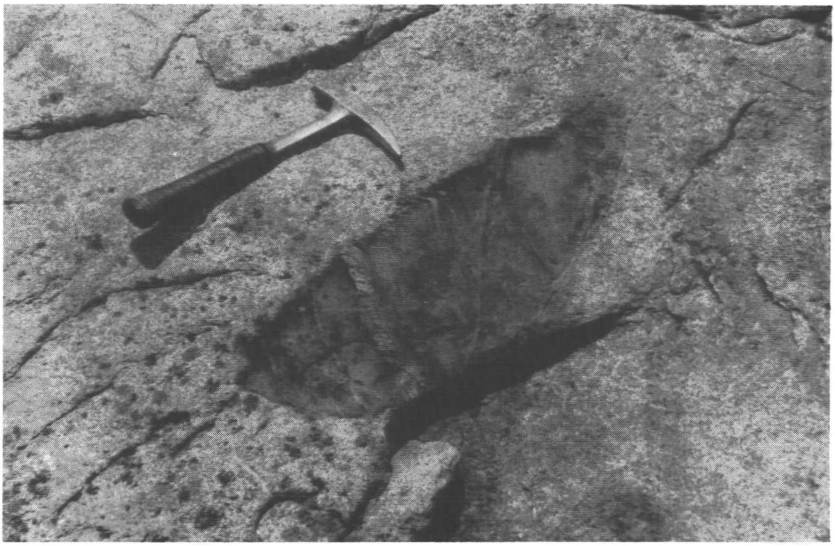


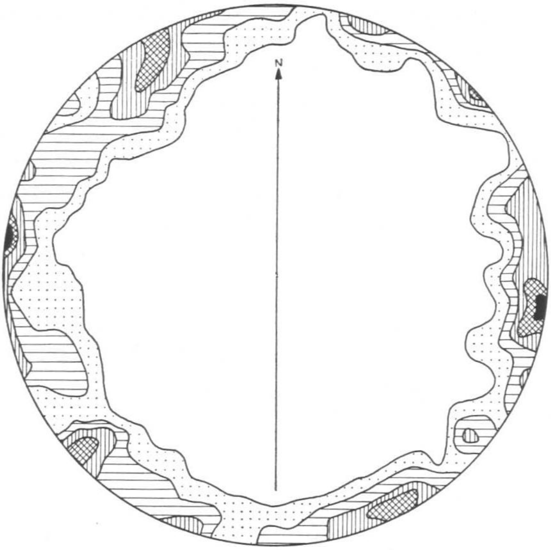
PLATE 10. Xenolith of Gile Mountain formation in a dike of Averill granite. Hammer handle is parallel to contact of dike with country rock. NW2339.

Those inclusions observed consist of small metasedimentary blocks with a marked dimensional orientation parallel to the wall rock (Plate 10). North of the contact along the eastern border of the area, numerous large xenoliths of this type were found. Four of these had bedding attitudes of N7°E, 24°SE; N41°E, 50°SE; N43°E, 74°SE; and N50°W, 35°NE, respectively. The nearby granite-metasediment contact is discordant. These relations suggest that the inclusions have been rotated and are xenoliths. The granite enclosing the xenoliths does not exhibit pronounced assimilation of foreign material. On Round Mountain nearer the interior of the massif, a block of metasediments is present (Plate 1). The metasediments here are greatly dissected by granite sills and dikes which separate the metasediments into many patches. Schistosity within the different blocks shows diverse attitudes. This isolated mass of metasediments possibly represents a roof pendant.

The potash feldspar phenocrysts which assume prominent megascopic proportions are oriented at random.

Joints and Dikes

Joints are abundant in the Averill granite. Schroeder (1920, p. 38)



b. 371 joints in the Averill granite.
1–2–3–4–5%

Figure 4. Stereograms of joints in the granitic plutons.

stated that the majority of joints in the vicinity of the Averill lakes strike N40°W. In the present study, poles of 371 joints were plotted on a stereographic net and contoured (Figure 4b). Only the more prominent joint sets were measured in the field. The stereographic plot clearly shows that joints within that part of the body located within the Island Pond quadrangle strike in all directions. The majority have dips greater than 75 degrees.

A concentration of joints strikes about N42°W in agreement with the conclusions of Schroeder. Other concentrations of importance are observed at about N6°E and N62°E. In all of these, the joints are steeply dipping to vertical. The joint sets trending N42°W and N62°E have divergent trends of 48 and 56 degrees respectively from the median set at N6°E. These may be related to the cross joints of Balk (1937, p. 27–42). Such an analogy must be tentative because the flow structure on which Balk based his classification is absent. However, the greatest concentrations of these joints would in general strike approximately perpendicular to the long axis of the massif. The diversity of joint trends within the massif may be due to the development of both cross and longitudinal joints.

In many localities, dikes of aplite, granite, or pegmatite fill the joint sets. Quartz veins are numerous and one mafic dike (described in a later section) was observed.

Flat-lying jointing or sheeting is present in many cliff exposures. The interval between these joints apparently increases with depth. Veining is not common in joints of this type.

Pegmatite dikes are frequently pinker than the host rock. The color is attributable to the greater abundance of potash feldspar crystals in the pegmatites. The pegmatites are of simple mineralogy, containing predominantly potash feldspar, quartz, muscovite, and biotite. Garnet is a frequent accessory. Many of the pegmatites are zoned. Some contain quartz in the center and potash feldspar at either edge. One pegmatite 25 inches wide was composed of alternating zones of pegmatite and fine-grained granite. On a line across the dike, these bands were as follows: 3 inches of pegmatite, 4 inches of fine-grained granite, 11 inches of pegmatite, 4 inches of fine-grained granite, and 3 inches of pegmatite. Some dikes have a pegmatitic center with fine-grained granite or aplitic border zones, while just as commonly the order is reversed. The contacts between various zones within the dikes are sharp as are the contacts between the dikes and the host rock. At least two generations of dikes are present in many areas with the later set cutting and displacing the earlier one.

The Echo Pond Granitic Complex

General Statement

A granitic complex containing a variety of igneous rocks occupies the west-central portion of the area. It is irregular in outline (Plate 1), measuring eight miles across on a line running south from the contact with metasediments on Beechnut Ridge, and a maximum of seven and a half miles on a line west-northwest. True granite dominates, but at least a quarter of the area is composed of more mafic igneous rocks of gabbroic and dioritic nature. The basic rocks appear to be restricted to the more southern and southwestern portions of the mass. The complex lies almost entirely within the Island Pond area, except for small extensions into the adjacent Memphremagog quadrangle north of Seymour Lake and encircling Echo Pond.

The complex derives its name from Echo Pond which lies within the western portion of the mass. Excellent exposures of light-gray, porphyritic granite are present in the pastures on the slopes rising from the southwest shore of Echo Pond.

Metasedimentary ridges enclose the complex to the north and east, and within the pluton are some large granitic hills such as Bear Hill and Dollif Mountain. In general, the rocks are poorly exposed, and wide areas are present where outcrops are lacking.

PETROGRAPHY

Granite, quartz monzonite, monzonite, diorite, and gabbro are present as components of the Echo Pond granitic complex. Of these, granite is by far the most common. Because of this diversity of rock types, it is necessary to discuss their petrographic details separately. Modal analyses of granite, monzonite, diorite, and gabbro from the complex are given in Table 9.

Granite

Megascopically, the granite is dark to light gray, medium to coarse grained, and is generally porphyritic. In the exposures south of Echo Pond, large phenocrysts of potash feldspar are excellently displayed (Plate 11). The rock is massive and joints are abundant. In general dikes are less common in the Echo Pond complex than in the Averill granite.

Quartz, potash feldspar, oligoclase, and biotite are the major constituents of the granite. Muscovite is usually present in small amounts. The most common accessories are apatite, zircon, sulfides, and sphene. Potash feldspar occurs as large euhedral phenocrysts, many of which have a poikilitic texture enclosing grains of quartz and oligoclase. The plagioclase is euhedral and usually zoned. Quartz commonly occurs as small grains dispersed throughout the section or as interstitial fillings between the feldspars. Micropegmatite and myrmekite are common. Zircon and apatite inclusions occur in some of the biotite grains. Biotite is altered slightly to chlorite, and some of the feldspars are partly sericitized.

Monzonite

The monzonite is restricted to areas in proximity to the metasediments along the southern border of the massif. It commonly shows a faint banding and contains numerous small inclusions of the country

TABLE 9

ESTIMATED MODES OF THE ECHO POND GRANITIC COMPLEX

Location	W0412	W2130	SW1656	SW3538	W0803	S0737
Quartz	31.4	19.8	34.1	4.2	2.1	—
Potash Feldspar	42.6	46.4	44.0	23.2	12.7	2.5
Plagioclase	17.4	24.1	14.3	35.6	58.7	46.8
Biotite	6.9	7.0	5.6	2.2	.4	2.2
Hornblende	—	—	—	23.9	15.0	28.1
Chlorite	—	.4	—	6.0	3.3	9.4
Muscovite	1.0	.4	1.0	.2	—	—
Sericite	—	.3	—	.4	5.3	—
Opaque accessories	.1	.2	.2	.3	.7	9.1
Other accessories	.6	1.4	.8	4.0	1.8	1.9
Number of Counts	1320	1551	1437	1443	1415	1542

W0412. Granite
W2130. Granite
SW1656. Granite
SW3538. Monzonite
W0803. Diorite
S0737. Gabbro

rock. Plagioclase (andesine) is usually the most abundant mineral, but potash feldspar is present in approximately equal amounts in some slides. Hornblende is a common constituent, but quartz is minor. Sphene, apatite, epidote, zircon, and magnetite are present as accessories. The plagioclase forms euhedral to subhedral phenocrysts. Quartz occurs only as anhedral, interstitial patches. Hornblende is highly altered to biotite and chlorite. It frequently contains many inclusions, euhedral, wedge-shaped crystals of sphene being the most common. Sphene also rims the hornblende as euhedral crystals or irregular grains.

Diorite

East of the village of East Charleston are found exposures of a fine-grained, banded diorite. The rock is tough, dense, and well jointed. Plagioclase (andesine) is the most abundant mineral while potash feldspar is present in much smaller amounts. Hornblende is common. Quartz is minor. Sphene, apatite, and magnetite are the most common accessories. Plagioclase forms euhedral to subhedral phenocrysts while potash feldspar and quartz are most commonly interstitial. Hornblende occurs as stout prisms and as acicular crystals. Zoning is a frequent characteristic of the plagioclase but myrmekite is not as prevalent as in

PLATE 11. Porphyritic granite south of Echo Pond. Potash feldspar phenocrysts are prominent.

the granites. Some hornblende crystals have a spongy texture and are partially altered to chlorite. Plagioclase is highly sericitized.

Gabbro

Mafic, coarse-grained, dark-gray to greenish-black gabbro is found in the vicinity of Dollif Mountain. Outcrops of it were found at only two major localities. The gabbro is massive, highly jointed, and is characterized by deep weathering, making a fresh specimen difficult to obtain.

Labradorite is the usual plagioclase feldspar present but some specimens contain andesine. Potash feldspar is present in small quantities and quartz is almost absent. The plagioclase is anhedral to subhedral and commonly not zoned. Hornblende is present as large ophitic and poikilitic plates enclosing plagioclase. Much of the hornblende is spongy and highly altered to chlorite. Black opaque iron minerals are common (up to 10 percent of the rock) as rounded grains throughout the thin sections. Some are surrounded by reaction rims of biotite. Apatite is also a common accessory.

Structural Relations to the Host Rocks

The Echo Pond granitic complex has sharp to gradational contacts. Bedding in the metasediments near the contact dips steeply, usually away from the contact but, in places, toward it. At the northern borders of the complex and along the southern end of Bluff Mountain the metasediments have been sharply deflected from their regional trend (Plate 2). At many localities, this deviation is up to 90 degrees. Along the southern border, the metasediments a short distance from the complex strike parallel to the contact and dip gently northeast. Closer to the contact, the strike is unchanged but the beds are vertical or overturned southwest.

Sharp contacts are most common along the northern and eastern margins. At these localities, coarse-grained, porphyritic granite is in contact with metasediments which are entirely normal in appearance. The contact along the southern edge is generally gradational. The adjacent metasediments are cut by numerous quartz veins and granite dikes, are highly contorted, and appear to have been more or less "granitized." The contaminated sediments grade into banded mafic granitic rocks which contain inclusions of country rock, and numerous ghosts of almost completely assimilated metasediments.

Internal Structural Features

Inclusions and Foliation

Inclusions of sedimentary rock are common, especially in the southwestern half of the pluton. On the slope south of Echo Pond, small ghosts are plentiful, the majority measuring only a few inches in length. These exhibit a considerable degree of uniformity in their orientation with the long axes trending from N6°W to N50°W (average about N25°W). A similar orientation was noted in many small inclusions near the contact on Cold Brook. This trend would be roughly parallel to that of the contact at its closest point. Some very large blocks of Gile Mountain formation completely enveloped in granite are present between Echo Pond and East Charleston. One of these exposed in a road cut measured more than twenty feet across. The bedding in this block strikes N85°W and dips 70°SW, an attitude which is nearly perpendicular to the regional trend of the metasediments. At its borders, smaller blocks enclosed in granite show considerable variation in the attitudes of bedding. These are interpreted as fragments of the larger block which have been broken off and rotated by a moving stream of magma. A large mass of metasediments (or group of blocks) is present on the northern slope of the hill between Echo Pond and East Charleston. Bedding in three separate blocks had attitudes of N68°E, 49°SE; N38°W, 56°SW;

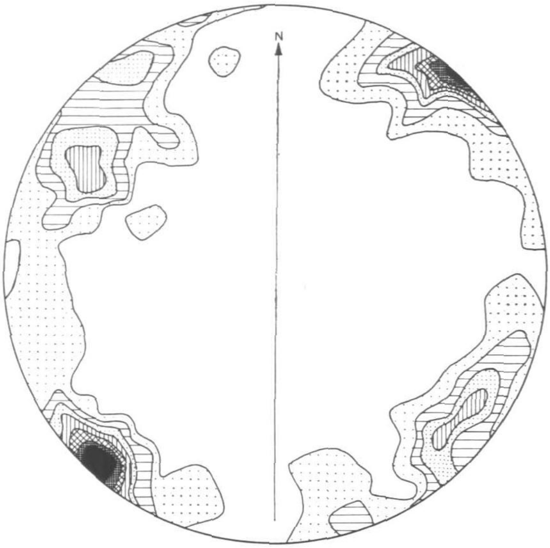
PLATE 12. Flow structure in diorite of the Echo Pond granitic complex. Hammer handle is parallel to banding. East of East Charleston on Route 105.

and N66°W, 51°SW. The variation at this locality also is indicative of rotation of the various blocks.

Structures attributable to flow are common in the more mafic rocks and are commonly associated with the xenoliths. In Cold Brook, the monzonite exhibits a banding which has a trend of N26°W. At the same locality a xenolith has its long axis aligned in a direction of N21°W. Near the summit of the hill north of East Charleston, diorite has a prominent banding which trends N11°W. East of the village of East Charleston, light and dark bands in the diorite trend about N15°W (Plate 12). Always a close conformity exists between the dimensional orientation of inclusions interpreted as xenoliths, the orientation of banding interpreted as flow lines, and the strike of the contact.

Joints and Dikes

Joints are common in this complex. A stereographic plot of the poles of 241 joints is shown in Figure 4c. A pronounced concentration of joints is noticeable striking at about N45°W and dipping steeply; a lesser concentration strikes at about N35°E and dips more gently. The northwest striking joints are longitudinal joints (Balk, 1937, p. 34–35); the northeast striking joints are cross joints.



c. 241 joints in the Echo Pond granitic complex.
1–2–3–4–6–8–10%

Figure 4. Stereograms of joints in the granitic plutons.

Dikes are not as prevalent within this pluton as in the two plutonic bodies previously discussed. The greatest development of dikes occurs in the southwestern half of the pluton. The dike rock is composed of aplite, fine-grained granite, or pegmatite. An eight foot thick pegmatite dike cuts the diorite east of the village of East Charleston (Plate 13).

Relation Between Granite and Mafic Members

The transition from granite to more mafic rocks appears to be a gradational one. Unfortunately, the sparsity of exposures makes the nature of this change difficult to define. Granite occupies exclusively the northern half of the area while mafic igneous rocks are restricted to the southern portions. No definite zonal arrangement could be assigned to the diorite, monzonite, and gabbro. Dikes of pegmatite clearly cut the diorite and granitic dikes are present filling joints within the monzonite. No dikes of mafic rocks were found cutting the granite.

Other Granites

A body of granite in the southwestern corner of the area underlies the summit and most of the slopes of Bald Mountain (Plate 1). This is

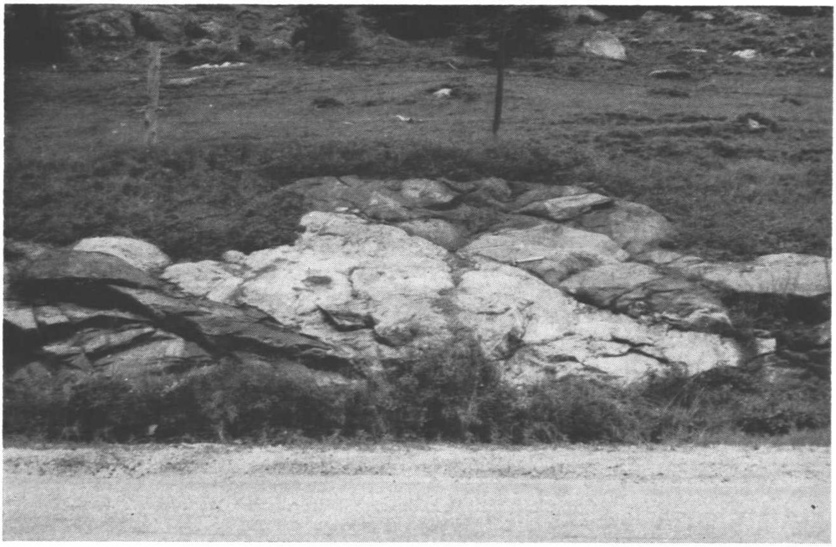


PLATE 13. Pegmatite dike cutting diorite of the Echo Pond granitic complex. Hammer lies on diorite. East of East Charleston on Route 105.

part of a larger pluton most of which lies within the Memphremagog and Lyndonville quadrangles.

Dennis (1956, p. 84–85) stated that the same body, where exposed in the Lyndonville area, had a composition which would be close to his estimated mode of "... plagioclase: 50%, microcline: 20%, biotite: 6%, others: 4%." The rocks were classified as granodiorites and quartz monzonites. A similar mode was obtained in the Island Pond area.

Dikes and sills of this granite in the surrounding metasediments are common. Sills are more frequent than dikes. On the eastern side of the mass sills are abundant and large, often making an accurate determination of the exact contact between the main pluton and country rock difficult. Dikes of pegmatite and leucogranite are common joint fillings in the granite. These often fill joint sets which intersect at right angles, one set being displaced by the other (Plate 14).

On a large scale, bedding in the metasediments exhibits a broad shift of strike around the northern end of this massif. Bedding roughly parallels the contact and usually dips gently away from the granitic mass. The strike of bedding gradually swings from about N45°W in the metasediments east of Bald Mountain to N30°E on the western side of

PLATE 14. Intersecting dikes of leucogranite in a darker granite. Compass points north. SW3701.

Goodwin Mountain (Doll, 1951, Pl. 1). Contacts between the two rock types are sharp.

Sills, Dikes, and Veins in the Metasediments

Granite and Pegmatites

Pegmatitic and granitic dikes within the granitic plutons have been discussed previously. Sills and to a lesser extent dikes are also common in both the Gile Mountain and Waits River formations. In metasediments close to the main masses of granite, sills are especially abundant. These are most commonly of granite or aplite. Pegmatites are also found but are not as plentiful in the sediments as they are within the granite plutons. At some localities, the occurrence of sills may be so frequent that alternating units of metasediment and granite occur.

Near the contact east of Page Hill are many fine examples of granite sills and dikes. Here, dikes are more abundant than elsewhere in the area. Many of them show sharp contacts with a porphyritic granite abutting against metasediments, while offshoots from the main dikes follow the bedding of the metasediments as sills (Plate 15). In some places two generations are clearly present, with an earlier set of sills

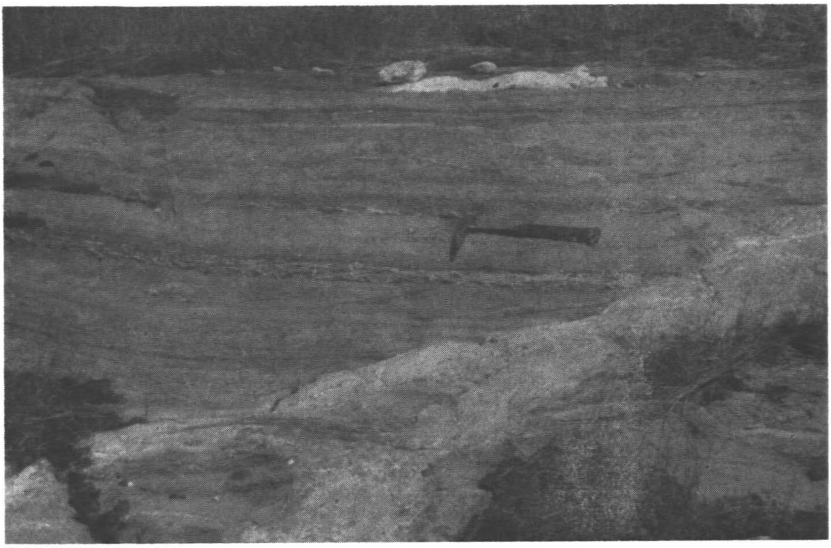


PLATE 15. Narrow granite dike cutting across bedding in the Gile Mountain formation. Hammer handle is parallel to bedding and schistosity. A two-inch wide granite sill follows bedding beneath hammer. NW2140.

often being offset along dikes which follow small fault planes (Plate 16). Some granitic dikes have been fractured and displaced parallel to the bedding (Plate 17), while others are ptygmatic. Several stages of sill and dike development are indicated.

Quartz Veins

Quartz veins are also common in the metasediments, especially in areas adjacent to major granitic masses. The veins are of several generations and assume diverse patterns. Ptygmatic veins, some large and exceedingly complex, are common, particularly in the metasediments south of the Echo Pond granitic complex. Associated with these are some quartz veins which have been fractured and faulted, with the quartz filling the fault lines so that the vein now has a pattern resembling a series of steps (Plate 18). Many quartz veins, either parallel to bedding or cutting across it, have been folded along with the metasediments, while others cut across the folding (Plate 19). In Mad Brook, a foot thick quartz sill has been fractured into blocks. The blocks have been separated along small faults and the surrounding metasediments have flowed between the blocks to heal the fractures. The successive stages in the

PLATE 16. Small granite dike following a fault plane in the Gile Mountain formation and offsetting a granite sill. Dike is to left of hammer head. Sill is above and parallel to hammer handle. NW2339.

formation of these quartz blocks completely surrounded by metasediments from their original mode of occurrence as a single quartz sill can be readily traced (Plates 20, 21).

In places, the sills and dikes of granite and pegmatite are jointed at right angles to the strike and some of the joints are filled with quartz (Plate 22). Some early quartz veins parallel to the bedding of the metasediments have developed boudinage. This may occur on a small scale with quartz bands less than an inch wide being fractured. Other nearby bands of quartz may be slightly bowed into the fractures along with the more plastic metasediments (Plate 23). Some small quartz veins which cut across the bedding have been crumpled into small corrugations by a later cleavage superposed on the vein (Plate 24).

Basic Dikes

Two post metamorphic, gray- to greenish-black basic dikes were found in the Island Pond area. One dike cuts the Gile Mountain metasediments at NW1344 on Page Hill and the other crosses the Averill granite at NE1838.

Both dikes are narrow, the one on Page Hill having a maximum ex-

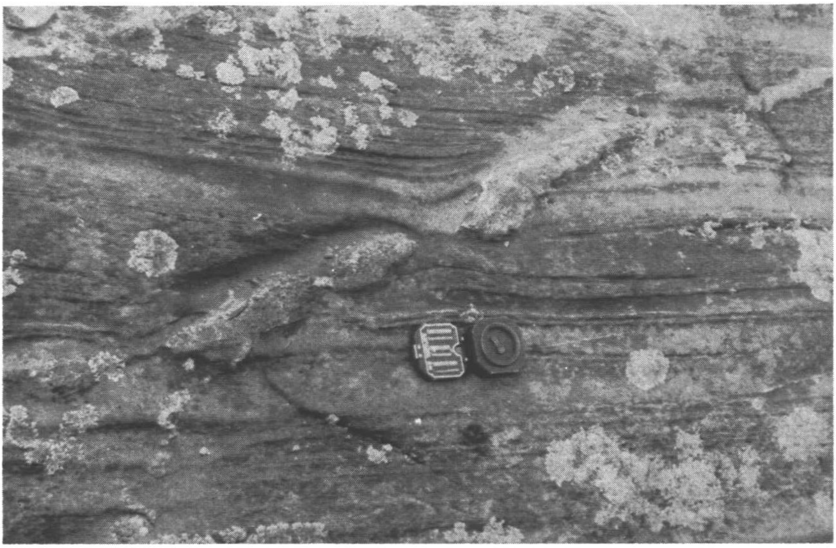


PLATE 17. A granite dike, fractured and offset along bedding in the Gile Mountain formation. Dike is to left of compass. Bedding and schistosity are parallel to edge of compass. NW2339.

posed width of 16 inches. This dike trends N78°W and has steep to vertical contacts with the metasediments. It cuts sharply across the bedding which strikes N6°E (Plate 25). The dike cutting the Averill granite has a trend of N54°E. The exact width of this dike could not be measured as its contacts with the granite are hidden.

A thick, rusty crust is characteristic of the surface of both dikes. On Page Hill this crust is 0.6 cm thick. Both dikes are highly fractured with the dike rock being broken into crudely rectangular blocks. The dike on Page Hill is fine grained while the one in the Averill granite is porphyritic. Both are dense and tough.

The major mafic constituent of the dike on Page Hill is biotite. Potash feldspar occurs predominantly as fine laths, while calcite is common as larger, anhedral crystals. Both calcite and potash feldspar have highly altered borders. Magnetite occurs as angular grains. This rock is classified as a minette (Williams, *et al.*, 1955).

The dike cutting the Averill granite has a well-developed porphyritic texture. The most common phenocrysts are euhedral plagioclase crystals, some of which exhibit excellent zoning. Euhedral phenocrysts of hornblende are also present in subordinate amounts. Numerous, spheri-

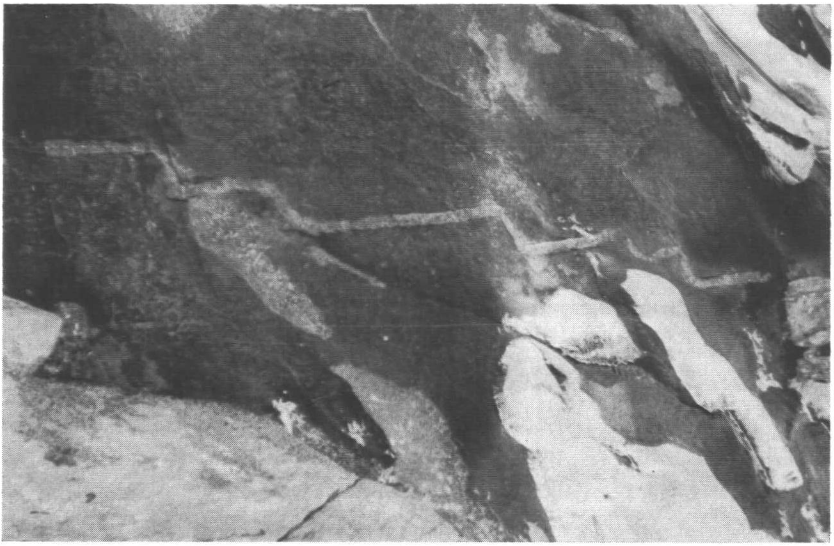


PLATE 18. Quartz vein forming a series of sharp steps in the Gile Mountain formation. Steps are approximately one foot long. Bed of Mad Brook at Elev. 1260.

cal pods of plagioclase which have been altered to sericite characterize this dike. The pods attain a maximum diameter of 7 mm in the sections studied. Olivine is present as anhedral crystals having pronounced alteration borders of brownish-red iddingsite. The groundmass has an intersertal texture and is composed primarily of andesine, the interstices being filled with biotite, chlorite, and sericite. Potash feldspar is a minor constituent and magnetite is the most common accessory mineral. The composition is that of a kersantite (Williams, *et al.*, 1955).

Interpretation

The present interpretation of the origin and mode of emplacement of the granite rocks of the Island Pond area is based largely on field relationships.

The large granite bodies of this area are almost certainly intrusive. This is indicated by the following features:

(1) The discordant contacts of the Averill granite and the occurrence of coarse-grained, porphyritic Averill granite in sharp contact with metasediments;

(2) The rotated xenoliths in the Averill granite, the Echo Pond granitic complex, and the Nulhegan quartz monzonite;

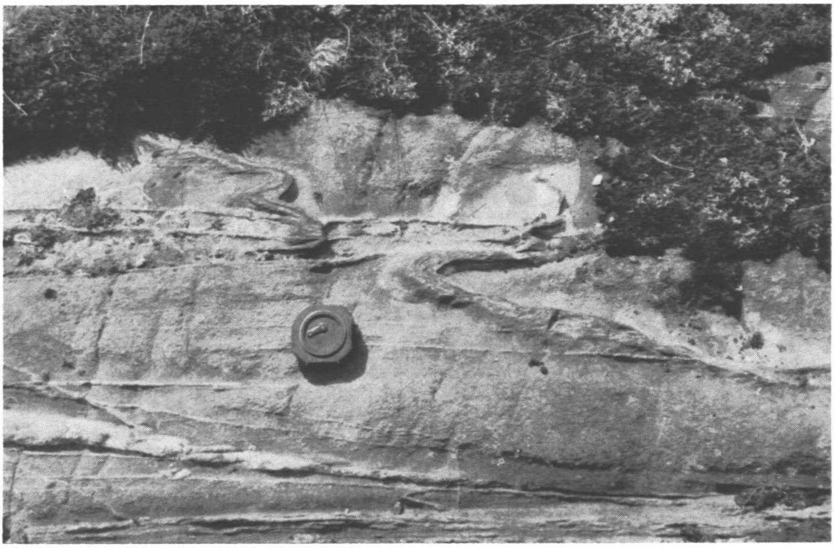


PLATE 19. Cross cutting quartz vein in the Gile Mountain formation. Vein has been folded and fractured along bedding above compass. Other, smaller quartz veins both follow bedding and cut across it. NW2339.

(3) The parallelism of xenoliths, foliation, and the contact with metasediments in the Nulhegan quartz monzonite and the Echo Pond granitic complex.

(4) The pronounced contortion and deflection of the metasediments surrounding the Echo Pond granitic complex.

(5) The apparent relation between grade of metamorphism and proximity to the granites (see following section on metamorphism).

Granitization occurs at the borders of many of the main masses. This is particularly true along the southern edge of the Echo Pond granitic complex and fringing the Nulhegan quartz monzonite.

Age of the Granites

The age of these granites is not known with certainty. Doll (1951, p. 45) favored a late Devonian age for the granites of the Memphremagog quadrangle. This conclusion was reached because they intruded the Westmore formation which was considered to be Middle Silurian or Lower Devonian. Cooke (1950, p. 102) stated that the Stanstead granite of Quebec was intruded during the Acadian orogeny, in Devonian time. Because the Averill granite, where exposed in Quebec, has an identical

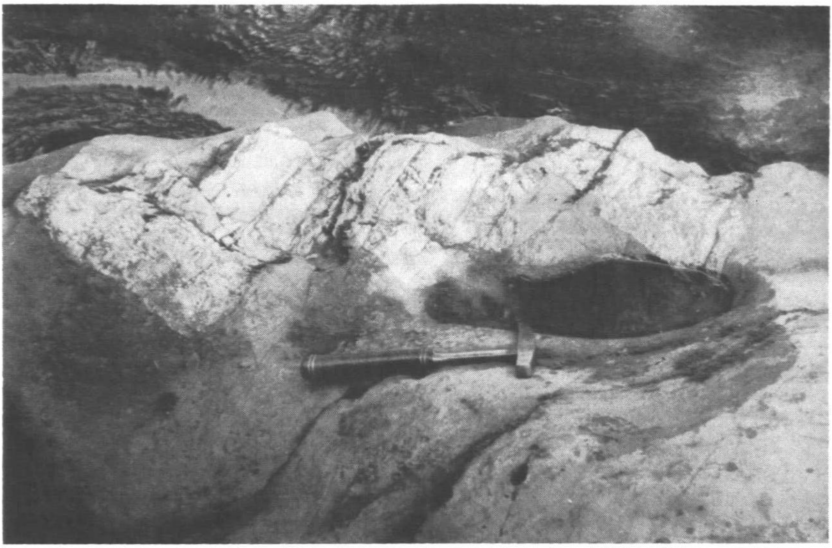


PLATE 20. Fractured and partially dismembered quartz sill. Note smaller fractures inside blocks parallel to the major edges. Bed of Mad Brook at Elev. 1260.

composition with the Stanstead granite, Cooke (1957, p. 28) believed it to be of the same age and origin. If as postulated in the present report, the metasediments of the Island Pond quadrangle are Ordovician, the age of the granites could be related to the Taconic or to the Acadian orogeny. As evidenced by their structural relationship to the enclosing metasediments and by lack of metamorphic effects in the granites, the granites are late- to post-tectonic. They are, therefore, considered to be Devonian (Acadian).

METAMORPHISM

General Statement

Four metamorphic zones have been recognized in the Island Pond area: the biotite zone, garnet zone, staurolite zone, and sillimanite zone. These zones are independent of formational contacts and are arranged concentrically around the major plutons (Figure 5). The sillimanite zone is the innermost zone; the biotite zone is the outermost zone. Thus the sillimanite zone is interpreted as representing the highest grade of metamorphism present; the biotite zone the lowest.

Each zone is marked by the first appearance of some particular index mineral from which the zone derives its name. The major limiting factor

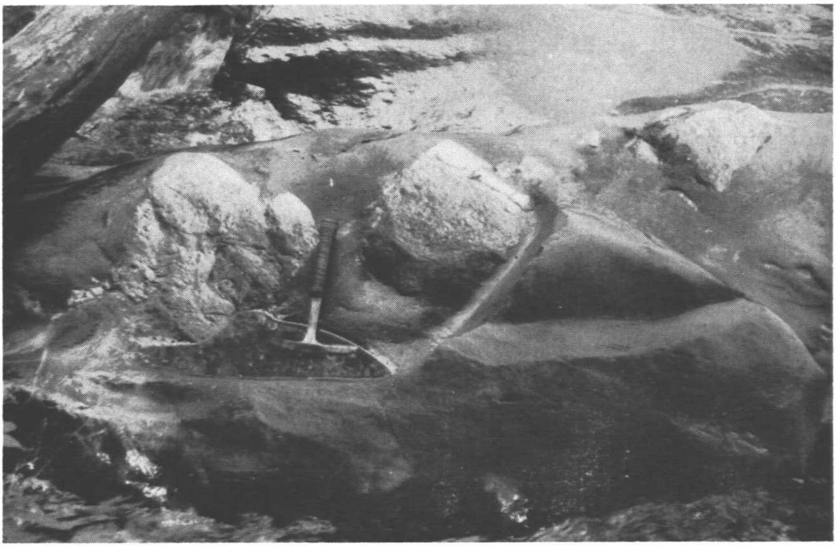


PLATE 21. Diamond-shaped quartz blocks in the Gile Mountain formation. Formed from quartz sill shown in Plate 20. Bed of Mad Brook at Elev. 1260.

of such a zonal classification is that only rocks of similar, original argillaceous composition can be utilized. Rocks of dissimilar chemical compositions would produce divergent mineral assemblages under the same conditions of elevated temperature and pressure. The facies classification, first clearly proposed by Eskola (1915, 1920), takes into account the variable chemical compositions of the rocks and recognizes several mineral assemblages as being formed under similar pressure-temperature conditions. Although the rocks of the Island Pond area do exhibit a variety of original compositions, argillaceous sediments are sufficiently common to allow the usage of a zonal classification.

It is believed that there were two stages of metamorphism. Minerals formed by the earlier stage (see section on structure) have been obliterated by higher grade metamorphic minerals which developed during emplacement of the granites.

Metamorphic Zones

Biotite Zone

The biotite zone follows and is adjacent to the contact of the Echo Pond granitic complex. Elsewhere, it is usually outside of other zones

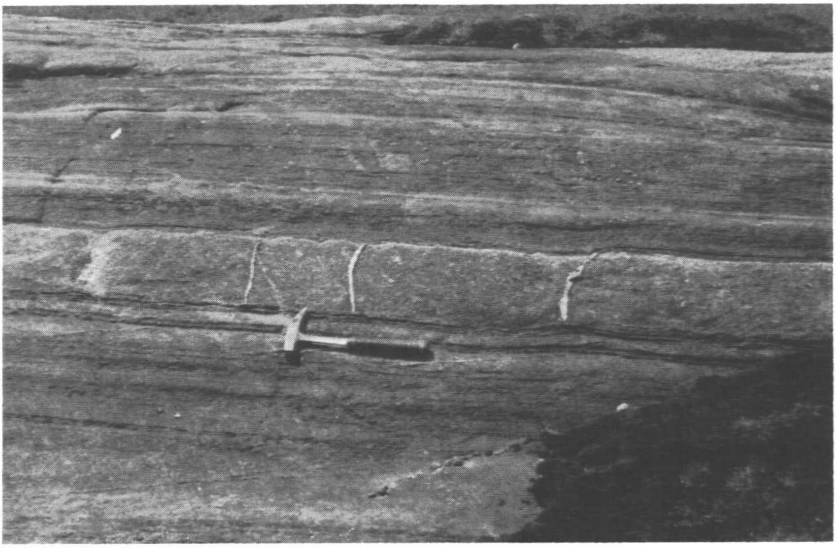


PLATE 22. Quartz veins filling fractures in a granite sill. Veins cut sill at right angles and are restricted to it. Sill is above and parallel to hammer handle. Gile Mountain formation at NW2339.

which encircle the granites. In general, rocks of this zone correspond to the biotite-chlorite subfacies of the green schist facies (Turner and Verhoogen, 1951, p. 476). Other common minerals in the biotite zone are quartz, muscovite, and chlorite. Plagioclase, calcite, and sericite may also be present.

Biotite also occurs within all the zones represented in the area.

Garnet Zone

The garnet zone is recognized with difficulty. The best outcrops in this zone are located in the south-central portion of the area east of Route 114. At this locality garnet (almandine) occurs as large single porphyroblasts or as clusters of porphyroblasts which cut across the planes of cleavage. Quartz, biotite, chlorite, sericite, and hornblende commonly are present. In places, concentrations of plagioclase feldspar form prominent zones.

Staurolite Zone

Staurolite is most prominent in the northwestern portion of the area north of Mt. John. This is perhaps the most ill-defined zone in the area

PLATE 23. Small-scale boudinage of quartz veins in the Gile Mountain formation. The central vein beneath the hammer is broken into boudins while the adjacent veins are bowed in toward the fractures. Hammer handle is parallel to bedding and schistosity. NW2339.

as the occurrence of staurolite is sporadic and usually only in small amounts. Adjacent to the Averill granite, it is associated with andalusite, biotite, quartz, and muscovite. Elsewhere andalusite is normally absent, but biotite, quartz, and muscovite remain common associates. Garnet may be present.

SILLIMANITE ZONE

The most distinct metamorphic zone is the sillimanite zone. This zone is confined to areas fringing the granites, and is prominent near the Nulhegan quartz monzonite. Large, euhedral porphyroblasts of andalusite are commonly associated. Quartz and biotite are the major constituents and muscovite usually occurs in smaller amounts. Chlorite, plagioclase, and garnet may or may not be present.

Mode of Occurrence of Important Minerals

CHLORITE

Chlorite is ubiquitous. It occurs in limestones, amphibolites, and schists along with all of the various minerals which are considered to be

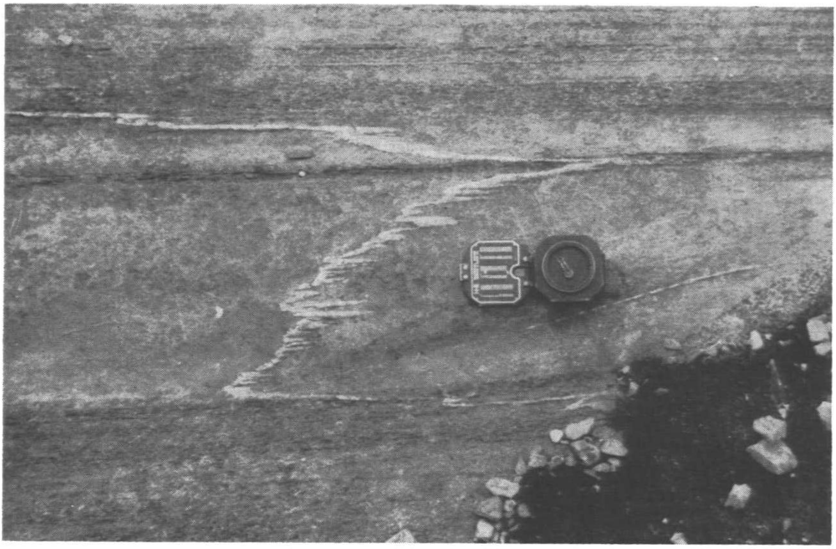


PLATE 24. Small quartz vein cutting bedding. Vein has become crumpled and corrugated parallel to schistosity. Schistosity and bedding are parallel to edge of compass. Gile Mountain formation at NW2339.

zonal indices. Therefore, chlorite does not possess zonal significance. Apparently, it is largely a product of retrogressive metamorphism. Garnet, biotite, and amphibole in many specimens are partially or completely replaced by chlorite. For example, at S1902, garnets have been totally replaced by chlorite, with the chlorite still retaining the perfect euhedral crystal outline of a garnet (Plate 26). Many garnets are mantled with chlorite.

Chlorite usually occurs as small flakes following the schistosity of the rock. Many of these flakes clearly are alteration products of biotite. However, large, undeformed, euhedral porphyroblasts of chlorite oriented independently of schistosity also are present. The occurrence of these crystals would suggest that they also are the product of retrogressive metamorphism.

Calcite

Calcite is widespread in the rocks of the Waits River formation. In the calcareous beds it is the dominant mineral present. It also occurs in calcareous members within the Gile Mountain formation. Quartz is a common associate of calcite in rocks of all zones, the two minerals having

PLATE 25. Basic dike cutting the Gile Mountain formation on Page Hill. Hammer lies on metasediments and handle is parallel to bedding. Contact with dike is to left of hammer head. Dike rock is highly fractured.

recrystallized side by side without mutual reaction. In zones adjacent to igneous bodies, calc-silicate minerals often are prominent. Even under this circumstance, calcite and quartz are still present in considerable amounts. Reaction between calcite and impurities such as chlorite might explain the presence of diopside, tremolite, or actinolite in the Waits River formation. Chlorite is usually present only in minor amounts and would be readily exhausted in the process of reaction long before the calcite would be used up.

Biotite

Biotite is the most common and widely distributed mineral in the metasediments. In the argillaceous rocks of the Gile Mountain and Waits River formations it constitutes one of the major minerals present. As previously indicated, it is found in all metamorphic zones, and is also a zonal index mineral.

Biotite is commonly found both as irregularly shaped and as well-defined porphyroblasts. The porphyroblasts are oriented parallel to the foliation of the rock or, in a few places, across the foliation. Opaque iron

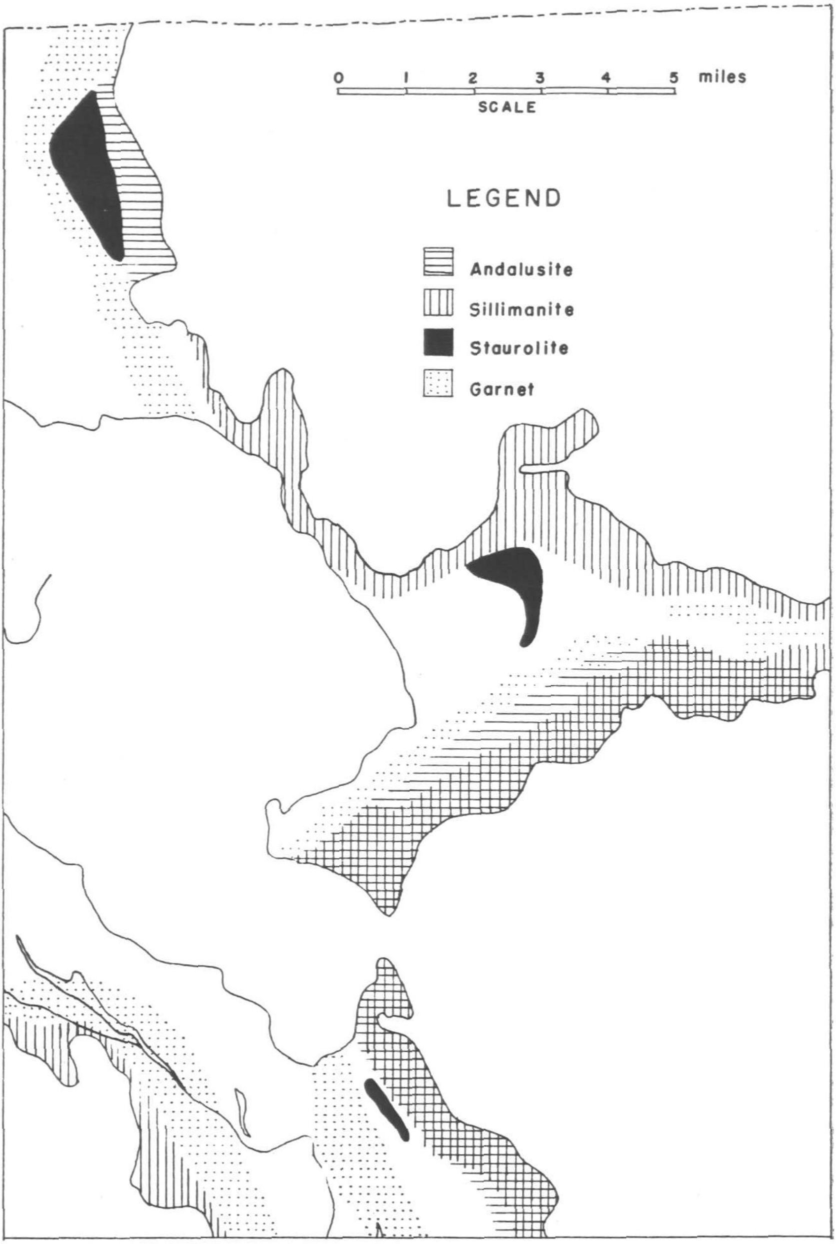


Figure 5. Distribution of metamorphic minerals in the Island Pond area. Cross-hatched areas andalusite-sillimanite.

PLATE 26. Photomicrograph of chlorite pseudomorph after garnet. Gile Mountain formation at S1902. Nichols not crossed. X12.

oxides appear to have provided nuclei around which some of the biotite porphyroblasts developed. Much of the biotite is altered to chlorite.

Garnet

Garnet is not a common mineral of the argillaceous metasediments although it is found at a number of widely separated localities. It is most commonly associated with quartz, biotite, and chlorite. Near igneous rocks, it is found with sillimanite, andalusite, biotite, and quartz. The garnets form porphyroblasts ranging in size from less than 0.5 mm in diameter to more than 1 cm in diameter. The porphyroblasts occur singly or in clusters. Zones in which garnets are numerous and well developed are generally narrow and of limited extent.

The garnets are commonly euhedral but some are irregular. The distribution of neither type seems to be controlled by structure, even where the rocks are strongly foliated. This lack of orientation suggests a late stage of development for the garnets. Inclusions of quartz and opaque minerals are numerous; sometimes to the extent that a pronounced sieve structure is developed. Many garnets are heavily altered to chlorite. Quartz and sericite are by-products of the alteration. Many small garnets have been entirely replaced, the crystal outline being all that remains to indicate the former existence of the garnet (Plate 26).

Garnet also occurs in pegmatites, granitic sills and dikes, and in some of the granite plutons.

ANDALUSITE

Andalusite is confined to argillaceous metasediments near granite bodies. This mode of occurrence is particularly well developed in a zone around the Nulhegan quartz monzonite, where andalusite in places constitutes more than 20 percent of the rock. Here it is associated with sillimanite and biotite. Andalusite, associated with staurolite and biotite, is also a common constituent of the metasediments near the western border of the Averill granite north of Mt. John.

Andalusite forms large porphyroblasts attaining lengths in excess of one inch (Plate 27). Some exceedingly large porphyroblasts were five inches long. Many of the andalusite porphyroblasts contain symmetrically arranged carbonaceous inclusions characteristic of the variety chiastolite (Plate 28). Various degrees of alteration to quartz and muscovite are observed. In general, the porphyroblasts have random orientations in the schists although at times they are oriented approximately parallel to the foliation. The random orientation and the fact that the porphyroblasts are mostly undeformed indicates that they are post-kinetic. This interpretation would support that of Harker (1932, p. 231) who stated that "These minerals," (i.e. andalusite and cordierite) "so commonly found in contact-aureoles and conspicuously absent from normal crystalline schists, are clearly marked as anti-stress minerals; and their occurrence here can be attributed only to a decided relaxation of shearing stress during the metamorphism which gave birth to them." Harker (*ibid*, p. 233) further believed that if shearing stress relaxed while the temperature remained high, suitable conditions would be present for andalusite to form at the expense of other aluminous silicates such as staurolite. These observations could easily be applied to much of the andalusite in the Island Pond area.

STAUROLITE

This mineral is most common in the northwestern portion of the map area, although it may be present elsewhere. Adjacent to the western border of the Averill granite north of Mt. John, porphyroblasts of staurolite are intermingled with large andalusite porphyroblasts. Such an association is apparently unusual (Harker, 1932, p. 232).

Staurolite occurs in granular aggregates but more commonly forms porphyroblasts of various sizes. Many of the porphyroblasts are shat-

PLATE 27. Large andalusite porphyroblasts in the Gile Mountain formation. Pencil is five inches long. S2616.

tered and broken, the fragments being widely separated. Doll (1951, p. 73) states that this "... is suggestive of either a recurring period of deformation or their development during the waning stages of the main orogeny." Some porphyroblasts have a perfect euhedral crystal form, showing excellent cruciform twins (Plate 29). Carbonaceous matter and quartz are the most common inclusions found within the staurolite. Although the inclusions are unoriented in most porphyroblasts, in some the carbonaceous matter is symmetrically arranged. This is particularly noticeable in the better developed crystals.

Sillimanite

Sillimanite is restricted to areas of intense thermally metamorphosed aluminous metasediments along the borders of the plutons. It is best developed in areas fringing the Nulhegan quartz monzonite and the eastern portion of the Averill granite. Its most frequent associates are biotite and quartz. Andalusite also commonly is present.

The mineral occurs in sheaf-like aggregates or as randomly oriented, isolated, needle-like crystals. It is considered to have formed late in the metamorphic history of the area. Some needle swarms are embedded in quartz. It seems probable that sillimanite did not form from the break-

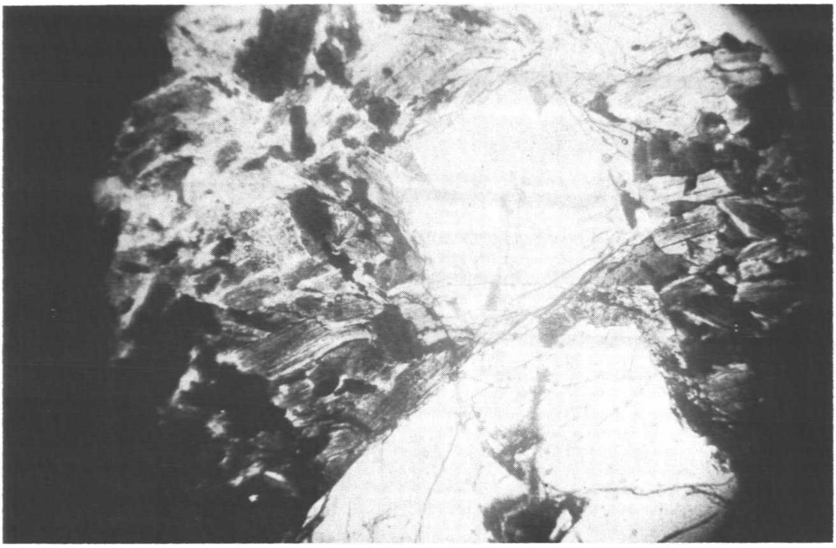


PLATE 28. Photomicrograph of andalusite cross-sections, variety chiastolite. Symmetrically arranged carbonaceous inclusions are shown. Gile Mountain formation on Page Hill. Nicols not crossed. X12.

down of muscovite since potash feldspar is not present in sufficient amounts. Andalusite has been found in lower grade rocks in the staurolite zone and perhaps sillimanite developed in part from the inversion of andalusite. This is also suggested by the occurrence of some large porphyroblasts of andalusite which have slender crystals of sillimanite formed at their borders.

Lime-silicate Minerals

Diopside, tremolite, actinolite, and vesuvianite are the major lime-silicate minerals present. These are concentrated in calcareous beds near igneous masses or in limestone xenoliths. Their greatest development is in the Waits River formation flanking the Bald Mountain granites but they are also present in some calcareous units of the Gile mountain formation. The local abundance of these minerals suggests introduction of material during metamorphism. In part they may be due to the chemical reaction between clay minerals and other impurities with calcite but the amount of clay available seems far too little to account for the quantities of calc-silicate minerals observed. Billings (1937, p. 546) believes that actinolite and diopside could be formed as products of the reaction between dolomite and quartz. This explanation

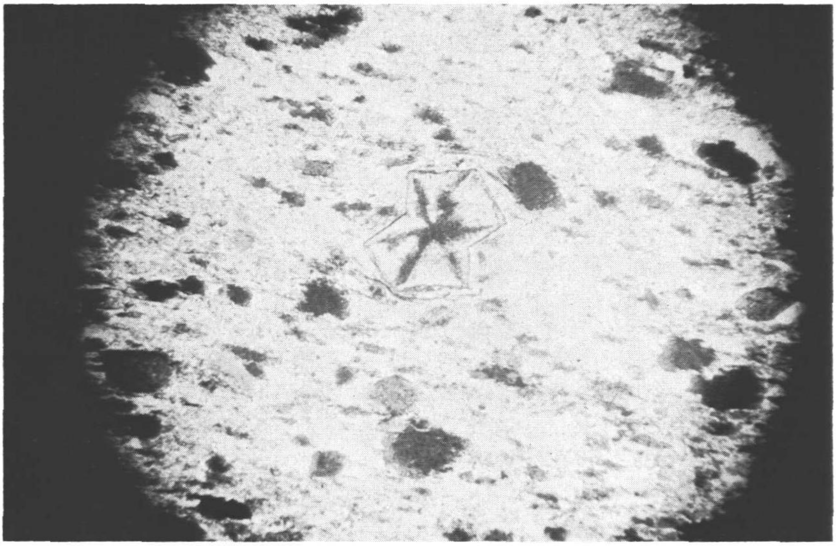


PLATE 29. Photomicrograph of twinned staurolite in quartz-mica schist. Gile Mountain formation on Page Hill. Nicols not crossed. X12.

is not satisfactory for lime-silicates in the Island Pond area because (1) the calcareous rocks are almost devoid of dolomite, and (2) the quartz content of the rocks is not affected by proximity to an intrusive body.

Hornblende

Hornblende is the most abundant mineral of the Standing Pond volcanics and in other bands of amphibolite which occur throughout the area. It is also found widely disseminated throughout the metasediments, especially in the limestones. Hornblende in the metasediments occurs in small euhedral crystals or forms large irregular porphyroblasts. Many of the porphyroblasts which are adjacent to quartz are highly corroded, and in the argillaceous sediments many exhibit a high degree of alteration to chlorite. In general, hornblende found in calcareous beds is only slightly altered to chlorite. The hornblende of the Standing pond volcanics has been altered heavily. Much of it is completely replaced by chlorite.

Interpretation

It will be shown in the section on structure that two stages of folding and cleavage can be recognized. Associated with the early folds is an early schistosity. Slip cleavage is contemporaneous with the later folds.

Igneous intrusion was in part contemporaneous with and in part later than the second stage of folding and cleavage.

Recrystallization is involved in the formation of schistosity. Therefore, it might be assumed that the minerals oriented parallel to the early schistosity were formed by recrystallization during the first stage of deformation. However, it is probable that the mineral assemblages created during the first stage of folding and metamorphism were again subjected to recrystallization during the second stage of deformation. For example, the early schistosity is most commonly defined by the orientation of biotite. It is likely that the early schistosity was originally defined by chlorite which was later recrystallized to biotite.

Porphyroblasts, as indicated earlier, are often undeformed and most commonly are oriented without regard to either slip cleavage or schistosity. This strongly suggests that porphyroblast growth was in large part due to some factor imposed after the major deformation of the region had ceased or was in its waning stages. Many staurolite porphyroblasts are shattered, indicating that this mineral was at least in part formed before deformation had diminished altogether. Randomly oriented porphyroblasts are characteristic of all mineral zones in the area. Particularly in the higher grade zones of metamorphism, porphyroblast growth appears to be geographically related to the granitic plutons; the metamorphic zones cutting across formational contacts.

In summary, two stages of metamorphism are represented. Minerals representing the first and less intense stage of deformation commonly display a dimensional parallelism with the planes of foliation. Porphyroblasts, formed during the second stage of metamorphism, evolved after the formation of slip cleavage. The later, more intense period of metamorphism, was produced by the intrusion of granites, after the main period of folding. This relationship further suggests the intrusive nature of the granites.

STRUCTURAL GEOLOGY

General Statement

The rocks of the Island Pond area are believed to occupy the eastern and central segments of the lower, inverted limb of a large recumbent anticline. The anticline trends roughly north-northeast. It plunges in that direction and is overturned strongly to the northwest; its recumbent crest is represented by the Browningston syncline of Doll (1951, p. 51–52) and Dennis (1956, p. 35–36). The central portions of much of the structure have been bowed upward by a later domal deformation which, according to Dennis (1956, p. 36–37), produced the Willoughby arch. The northern termination of this arch is in the southwestern portion of the Island Pond area where the Gile Mountain formation closes around the Waits River formation (Plates 1 and 2). The structural nature of this closure is indicated both by bedding and by cleavage.

Bedding is overturned through the Island Pond quadrangle and in a broad zone of metasediments of the St. Francis group north of the International Boundary (Cooke, 1957, p. 11–12). The recumbent anticline therefore continues northward through the Island Pond quadrangle, finally reaching its northern terminus well beyond the Canadian border.

Two or more stages of deformation exist throughout the area; the features produced by the second stage are superimposed upon and deform the products of the first stage deformation. Second stage deformation is largely due to the emplacement of the granites. These two periods or stages of deformation may be the result of either two distinct and chronologically widely separated periods of deformation or they may be different stages of the same orogeny. Pertinent data supporting either point of view is not available. Evidence for two stages of deformation has been noted previously by many workers. According to Dennis (1956, p. 44–46), early structures in the Lyndonville quadrangle include isoclinal drag folds and a schistosity developed parallel or sub-parallel to bedding which acted as an axial plane cleavage to the dragfolds; features indicative of second stage deformation include later drag folds and an associated axial plane slip cleavage. Dennis thought that first stage deformation took place during the formation of the Brownington syncline and early flexuring of the Willoughby arch. The second stage deformational effects are a consequence of doming in the center of the arch, causing flowage away from its crest. Eric and Dennis (1958, p. 31) noted similar deformational characteristics in the Concord-Waterford area. Cooke (1957, p. 14) also recognized two periods of deformation north of the International Boundary. He believed that: "The earlier, and principal, folding took place during the Taconic orogeny toward the end of the Ordovician period; the later folding is ascribed to the Acadian movement of the Devonian."

Terminology

Foliation

Foliation is a broad term used to refer to any planar elements within the rock. Hence, the term "foliation" could be used to indicate parallelism of minerals as found in schistosity and slaty cleavage, or to indicate closely spaced planes of parting such as are found in slip cleavage. It may also be utilized in reference to planar structures imparted to the rocks by original sedimentary deposition.

Cleavage

Cleavage is the property of a rock which enables it to cleave or split along definite, parallel, closely spaced planar surfaces. Each plane so formed is a surface of fracture caused by directed stress upon the rocks.

Two types of cleavage occur within the area: (1) slaty cleavage, (2) slip cleavage. Slaty cleavage is caused by the parallel arrangement of platy minerals. It is characteristically found in slates and other fine-grained metasedimentary rocks. Slip cleavage is cleavage along which some displacement has occurred. It forms parallel to the axes of minute folds or crinkles.

Schistosity

Schistosity, the most dominant foliation present, is a metamorphic foliation formed by the parallel orientation of more or less platy minerals. Muscovite and biotite are the minerals most commonly controlling the schistosity in the metasediments of the Island Pond quadrangle. Schistosity is essentially equivalent to slaty cleavage but is found in rocks of higher metamorphic grade.

Sinistral and Dextral Folds

The terms "sinistral" and "dextral" are used in the present report to refer to the patterns of asymmetrical minor folds. This terminology was first suggested by White and Jahns (1950, p. 197). The distinction between these two fold patterns is based on the direction of offset of the long limbs of the folds. If an observer stands on the long limb of a plunging fold and traces the bedding away from himself, a dragfold will show offsetting of the long limb either to the right or to the left (Figure 6). Offsetting to the right is characteristic of dextral folds while sinistral folds are offset to the left. White and Jahns believed that "These patterns ordinarily are a function of one component of the differential movement that formed the folds."

Recumbent Anticline

A recumbent anticline is an anticline which has been overturned to the extent that its axial plane is essentially horizontal or overturned.

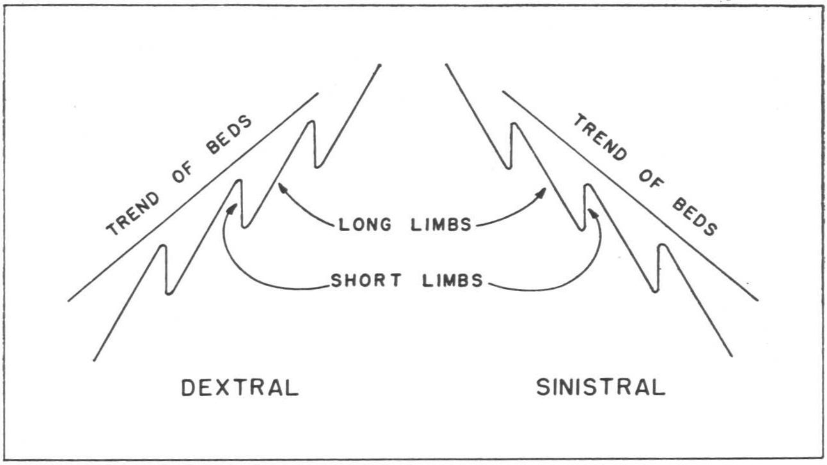


Figure 6. Sinistral and dextral plunging folds. Plan view.

Special terms are commonly utilized to refer to different features and portions of a recumbent anticline. Such terms used in the present report are root zone, inverted limb, normal limb, arch bend, and digitations. The parts of a recumbent anticline referred to by these terms are shown schematically in Figure 7.

Structural Features

Early Schistosity

Schistosity attributed to the early deformational stage is persistent throughout the area. It is commonly parallel or sub-parallel to bedding and generally can be referred to as bedding schistosity. Where platy, micaceous minerals control the schistosity as in the phyllites and schists; schistosity is the dominant feature of the rocks. Quartzites display a moderate to slight schistosity depending on the amount of micaceous minerals present. Narrow quartz stringers and a preferred orientation of constituent quartz grains within the quartzites aid in accentuating the foliation.

Many limestones also exhibit a parallelism of their micaceous components. However, most commonly foliation in the limestones is portrayed by a minute, intimate banding of quartz and calcite layers on a microscopic scale. These minerals, though far from tabular, also have a strong preferred orientation parallel to the foliation. Stringers of

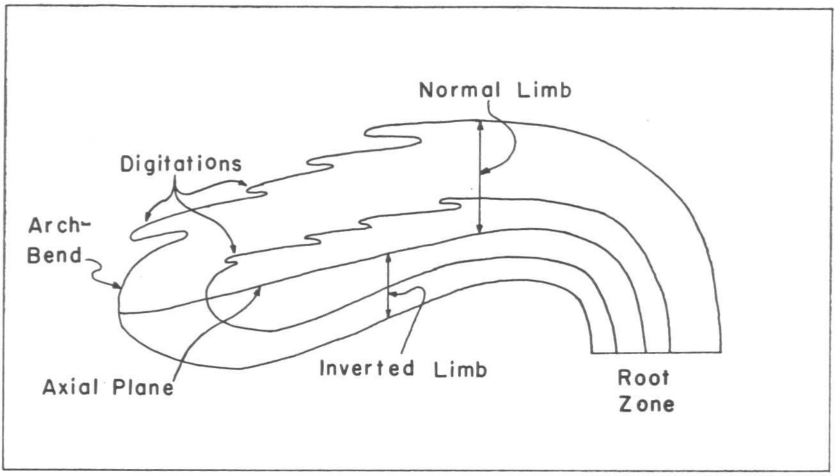


Figure 7. Terminology of parts of a recumbent anticline. Modified from Billings, 1954.

calcite and quartz in places follow this foliation. This foliation is often at an angle to the bedding and commonly is strongly contorted. However, the contacts between the limestones and adjacent rocks consistently show little or no distortion. The deformed foliation is interpreted as indicating continued plastic deformation of the limestones after the development of schistosity.

The early foliation acts as an axial plane cleavage to certain minor folds, cutting across the bedding in the noses of these folds. The folds are commonly tight and nearly isoclinal so that schistosity and bedding are approximately parallel on the limbs. Because of the axial plane relationship, these minor folds are considered to be of an early generation. The development of the schistosity must have been related to the development of these folds.

The regional trend of the metasedimentary rocks in northeastern Vermont and southern Quebec commonly is northeast or north (Doll, 1951; Dennis, 1956; Cooke, 1957). Several deviations from this trend are apparent in the Island Pond quadrangle (Plates 1 and 2). These deviations appear to be related either to position on a major structure or to the emplacement of granite plutons.

In the southwestern portion of the Island Pond quadrangle, the metasedimentary formations swing around the granites occupying Bald Mountain (Plate 1). The eastern and western belts of the Gile Mountain formation are connected in this area. Lenticular occurrences of the Standing Pond amphibolite can be traced into the quadrangle from the south, and extend northwestward around Bald Mountain. A narrow zone containing abundant calcareous units borders the Goodwin Mountain granite in the Memphremagog area. The calcareous units were mapped with the Westmore formation by Doll (1951, Pl. 1) but the present author was able to trace these units into the Waits River formation of the Island Pond quadrangle. Thus the outcrop pattern in this area suggests the closure of a large fold.

The attitude of the schistosity (generally parallel to the bedding) in the area of closure suggests the nature of this fold. Adjoining the Burke quadrangle, schistosity strikes at an average of N25°W; adjacent to the Memphremagog quadrangle it strikes about N65°W. The swing in strike between these two extremes is gradual. In the Memphremagog quadrangle, the swing in strike continues around Goodwin Mountain, and gradually resumes the normal regional trend (Figure 8). The predominant direction of dip is northeast. Dips become progressively steeper north and east from Bald Mountain. Near Bald Mountain dips as low as 25°NE are present. In proximity to the Echo Pond granitic complex, bedding and schistosity are vertical or dip steeply to the southwest. Where divergencies in dip occur between bedding and schistosity, the schistosity generally has a more gentle dip than bedding.

In the northwestern corner of the Island Pond area, both bedding and early schistosity strike fairly uniformly slightly east of north and dip between 30–60 degrees northwest. Local deflections of strike are found, particularly near the contact with the Echo Pond granitic complex where the strike is strongly to the northwest and the dip is steep to the northeast. Where a divergence exists in the angle of inclination between bedding and early schistosity, the schistosity has a more gentle dip. The prevailing attitude of these features in this locality follows the regional trend as exhibited in the Memphremagog quadrangle (Doll, 1951, Pl. 1) and in the region north of the International Boundary (Cook, 1957).

The central metasediments along Bluff Mountain generally strike northeast in regions which are most remote from granitic masses. Dips are commonly greater than 50 degrees and may be either to the southeast or to the northwest because the metasediments have been contorted into several folds of varying dimensions. Bedding and early schistosity are parallel. The strike of these features has many slight deviations in the area bordering the Nulhegan quartz monzonite, but even here a

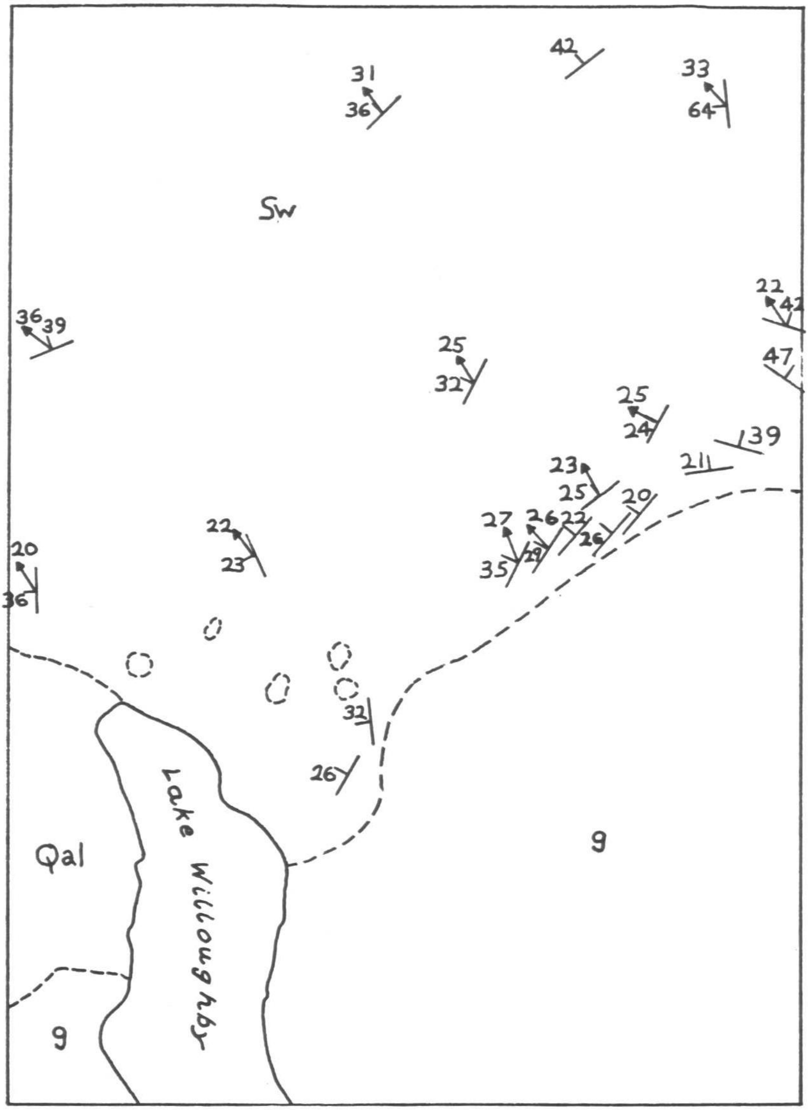


Figure 8. Foliation and lineation in the southeast portion of the Memphremagog quadrangle. (After Doll, 1951, Pl. 1).

trend to the northeast is visible. Strong deflections having a northwest strike occur in the extreme southern end of the band and occupy the small neck of metasediments trending northwest through Warners Grant. These strikes parallel the contact with the Echo Pond granitic complex and are restricted to a narrow zone in proximity to that contact.

Early Folds

The schistosity previously described acts as an axial plane cleavage to many small folds (Plate 30), indicating that the two features are a result of a single deformational stage. These folds are generally small, tightly compressed, and nearly isoclinal (Plate 31). The early schistosity, therefore, is parallel to bedding along the limbs.

Caution must be exercised in assigning deformed quartz veins to the category of either first or second generation folds and in utilizing them as drag folds in order to determine the movement sense associated with the deformational stages. Parallel quartz veins, only a few inches apart may exhibit deformational characteristics indicating opposing components of force on adjacent veins, one vein possessing a clear sinistral fold pattern while its neighbor is dextral (Plate 32).

Early folds appear to be sinistral wherever they are exposed in the Island Pond area. Their fold axes have plunges which commonly are gently inclined. In the southwestern metasediments, early folds are rarely exposed. Those observed generally plunge toward the northwest at angles approximating 20 degrees or less. A few along the northern borders of the metasediments where the beds have been most highly affected by the invasion of granites, plunge gently southeast. Early folds are more common in the central and northwestern patches of metasediments. In the central group, plunges of early folds are either toward the northeast or southwest, with southwest plunges being predominant. The northwestern Gile Mountain segment exhibits the most constant orientation of early folds. Most fold axes in this area trend between north and N10°E and plunge gently northeast. A few are horizontal; a few plunge gently southwest.

Late Slip Cleavage

A slip cleavage occurs as an axial plane cleavage to a second generation of minor folds or crinkles on the earlier schistosity surfaces. The crinkles form a pronounced "b" lineation on the earlier schistosity. At the intersection of slip cleavage and early schistosity, displacement of the schistosity occurs along the slip cleavage planes and in proximity

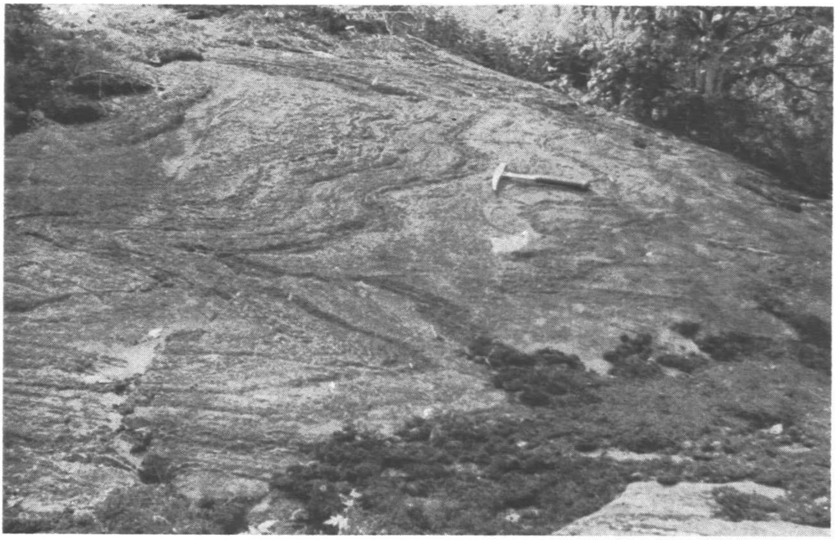


PLATE 30. Intersection of early folds on a horizontal plane. Schistosity is parallel to hammer handle. Gile Mountain formation at S1836.

to these planes the platy minerals defining schistosity tend to exhibit a crude parallelism with the planes of slip cleavage (Plate 33). Where developed to an advanced stage, slip cleavage becomes a later schistosity which cuts the earlier one. In many localities of alternating argillaceous and arenaceous lithologies, slip cleavage is highly developed in the argillaceous beds whereas the arenaceous units are characterized only by prominent early schistosity. The difference cannot be explained as due to refraction of the same cleavage by bands of altering competency. In places, both cleavage types exist within a single bed, the slip cleavage clearly cutting and deforming the earlier schistosity. Even where slip cleavage is strongly developed, microscopic examination usually reveals the persistence of the early schistosity.

Late Folds

Folds involving contortion of the early schistosity are characteristic of a second deformational stage (Plates 34, 35, and 36). The relationships of the later folding to the two generations of cleavage is clearly shown where beds of different lithology occur in the same fold (Figure 9). Arenaceous beds exhibit well-developed schistosity which is folded along with the primary bedding. Argillaceous layers are generally dominated by slip cleavage which is parallel to the axial plane of the fold.

PLATE 31. Early fold in the Gile Mountain formation. Hammer handle is parallel to axial plane of fold. S1836.

Late folds are consistently dextral in the southwestern and central metasedimentary belts. In the northwestern metasedimentary belt, the late folds are rare, but where present, they are sinistral.

In the southwestern metasediments, fold axes of the late folds plunge northwest, the angle of plunge being commonly steeper than the plunges associated with the early folds. Plunges greater than 50 degrees are common, the steeper plunges being most numerous in the eastern portion of the area. The direction of the plunges varies between N40°W and N85°W. A few in the western portion of the band trend about N20°W and plunge 20°NW.

Linear Elements

Lineations of several types are present in the metasedimentary rocks of the Island Pond area. These include fold axes, intersections of s-planes, parallel mineral streaks, and boudinage. Intersections of s-planes are most common. Such lineations are produced by the intersection of bedding and early schistosity, the intersection of bedding and slip cleavage, and the intersection of early schistosity and slip cleavage. The latter is most common and is expressed by parallel rows of crenulations on the early schistosity surface. These are nearly always parallel to the axes of late minor folds and therefore indicate the "b" direction

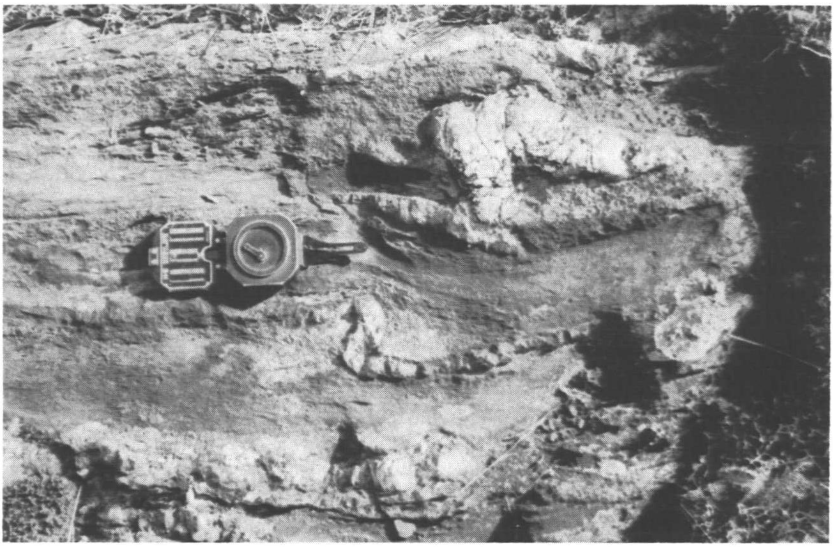


PLATE 32. Deformed quartz veins exhibiting conflicting fold patterns. The vein above the compass is sinistral while the one below it is dextral. Gile Mountain formation on Meehan Hill.

of late folding. Parallel mineral streaks also in "b" are common on the planes of schistosity and bedding. Minerals most commonly displaying this linear feature are biotite, amphiboles, and sulfides. Boudinage is most commonly observed among quartz veins. Phyllites and schists have flowed into the fractures separating quartz boudins (Plate 37). Boudinage is also observed in quartzites and in phyllites associated with limestone. Units exhibiting this structure range in thickness from less than an inch to over three feet.

In the southwestern band of metasediments, the prevailing plunge of linear elements is to the northwest. This is fairly constant (Plate 2), although near the northern and eastern borders where the other minor structural features exhibit abnormal attitudes, some lineations also deviate greatly from the regional trend. Linear elements in the northwestern metasedimentary belt plunge rather consistently north or north-northwest. Lineations in the central metasedimentary belt vary considerably in direction of plunge. However, the most common direction of plunge in this locality is toward the southwest.

In the Memphremagog quadrangle to the west, the northwest linear trend, dominant in most of the Island Pond quadrangle, continues

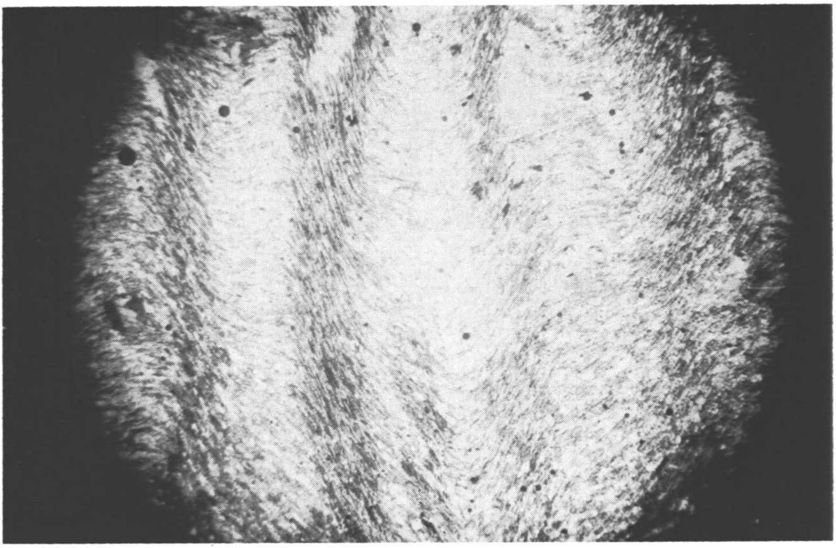


PLATE 33. Photomicrograph showing early stage in development of slip cleavage. Early schistosity is folded and slip cleavage is just beginning to develop. Gile Mountain formation. X12.

except in the northwestern portion of that area where plunges are to the northeast. Doll (1951, p. 70–71) suggests that the northwest plunges could be a result of the overturning of beds containing linear elements having an original northeast plunge. Doll (p. 70) states that: "Where the beds are overturned to the southeast, which is the dominant attitude of the beds northwest of the axial region of the Brownington syncline, the trend of the lineation is markedly northwest."

If these northwest plunges are a product of overturning, then similar plunges should not occur on the eastern flank of the Brownington syncline where Doll believed the beds to be in normal sequence. However, on the northwest flank of Goodwin Mountain in the Memphremagog quadrangle and in the southwestern portion of the Island Pond area, metasediments of the Gile Mountain and Waits River formations have the same strong lineation to the northwest. Therefore, no great deviation is found between trend and plunge of lineations on the west flank of the Brownington syncline and those on the east. If, as Doll suggests, this northwest plunge is due to rotation of linear elements by overturning, then the same conclusions must apply to beds both east and west of the Brownington synclinal axis. This would indicate that overturning

PLATE 34. Late fold in the Gile Mountain formation. Hammer handle is parallel to late cleavage. Early schistosity is folded as seen in small fold on left edge of exposure. S2715.

has influenced the entire sequence from at least the central portion of the Island Pond area westward through much of the Memphremagog quadrangle. This is precisely the situation which the present author believes to prevail in the area.

Joints

The rocks of the Gile Mountain (especially the more quartzitic beds) and the Waits River formations are well jointed. Poles of a number of joints were plotted on stereographic projections and the resulting plots contoured. Separate diagrams were made for each of the major metasedimentary masses exposed within the area of study. These are shown in Figure 10. A strong preferred orientation of joint planes is apparent in two of the diagrams. This is in sharp contrast to the more random distribution of joints in the granites (Figure 4). A map of the joints in rocks of the Island Pond quadrangle is shown in Figure 11.

The stereographic plots for the southwestern and northwestern metasedimentary masses are quite similar. Both exhibit a great concentration of steeply dipping to vertical joints which strike east-northeast. In each of the two plots, a minor concentration of joint sets is also

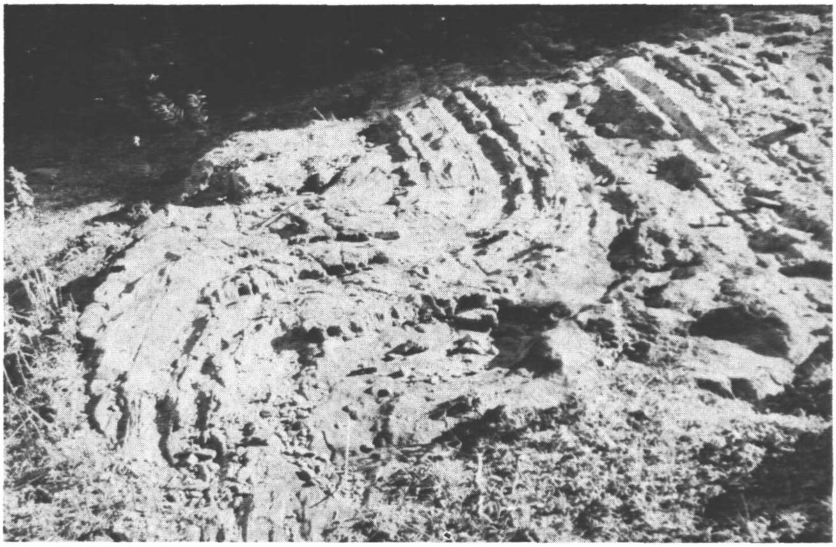


PLATE 35. Late, open, dextral fold. Gile Mountain formation at SW0748.

present. In the southwestern metasediments, this smaller concentration strikes northeast; in the northwestern metasediments, it strikes northwest.

In the northwestern metasediments lineations in "b" plunge toward the north or northwest. The acute angle between the two intersecting joint sets is toward the east. The joints, therefore, may be interpreted as shear joints associated with the folding.

If the two prominent joint sets in the southwestern metasediments are also shear joints, their orientation indicates a different direction of stress than that shown in the northwestern metasediments. Here the acute angle between the intersecting joint sets is to the northeast. This is not at right angles to the regional "b" direction. However, these metasediments lie between the Echo Pond granitic complex and the granites occupying Bald Mountain. During the emplacement of these plutons, the southwestern belt of metasediments would have been compressed along an axis which roughly bisects the acute angle between the joint sets. Thus, these joints could be shear joints related to the intrusions.

The central metasedimentary mass has the greatest diversity in its joint pattern. Two sets are most prominent. The major set strikes about

PLATE 36. Late, small, dextral drag fold. Schistosity is folded along with the bedding. Gile Mountain formation at S3314.

N45°W and dips steeply; the second set strikes about N30°E and dips more steeply than 60 degrees either to the northwest or to the southeast A third, steeply dipping set lies between these two. The broader distribution of joints in these metasediments is not surprising as all minor structural features in this area exhibit a wide diversity of orientations. The metasediments are bounded by granite. Intrusion of the granite would give rise to complex stresses in the metasediments.

Previous Hypotheses of Regional Structure

In the Memphremagog quadrangle, Doll (1951, p. 51–52) postulated a large synclinal structure (the "Brownington syncline") which was strongly overturned to the southeast (Plate 3). According to Doll (p. 51) "Its axial plane strikes northeast and is strongly overturned to the southeast, thus dipping gently to the northwest. The fold is characterized by a steep, inverted northwest limb in contrast to a southeast limb with gentle inclination." The trough of the proposed syncline is occupied by the Westmore formation (Gile Mountain formation of this report). Limestones of the Waits River formation crop out in a belt west of the trough.

Dennis (1956, p. 35–39) discussed a continuation of the Brownington

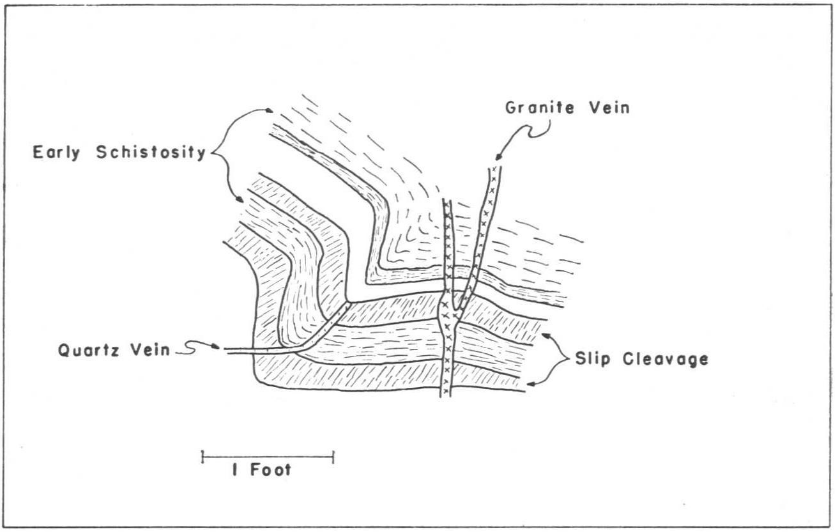


Figure 9. Dextral drag fold of the later deformational stage exhibiting two types of cleavage. Early schistosity and bedding are folded. The later slip cleavage acts as an axial plane cleavage to the fold.

syncline to the south in the Lyndonville quadrangle. One of the major lines of evidence by which Dennis substantiated the synclinal structure was that "The band of Gile Mountain formation in the area has nearly vertical dips in the west and very shallow westerly ones in the east, suggesting a synclinal trough between." Dennis recognized a large domal structure east of the Brownington syncline which he named the Willoughby arch. This arch in the Lyndonville quadrangle is characterized by a broad, flat top, shallow dips adjoining the Brownington syncline, and a steep eastern flank. The Waits River formation occupies the crest of this northward trending structure while rocks of the Gile Mountain formation are found on its east and west flanks. Minor structural elements of the first stage were believed to have been associated with the formation of the Brownington syncline while those of the second stage were attributed to the domal action which formed the Willoughby arch. Evidence considered by Dennis (1956, p. 67) to indicate domal deformation as the cause of this structure included the presence of flowage folding facing away from the crest of the arch and schistosity wrapping around the arch. Fold axes and boudinage in "a" were considered to be supporting evidence indicating doming.

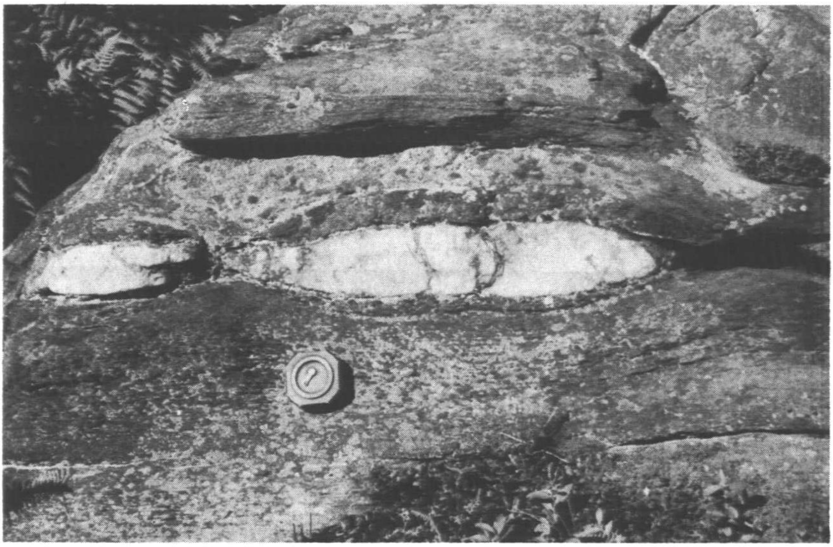
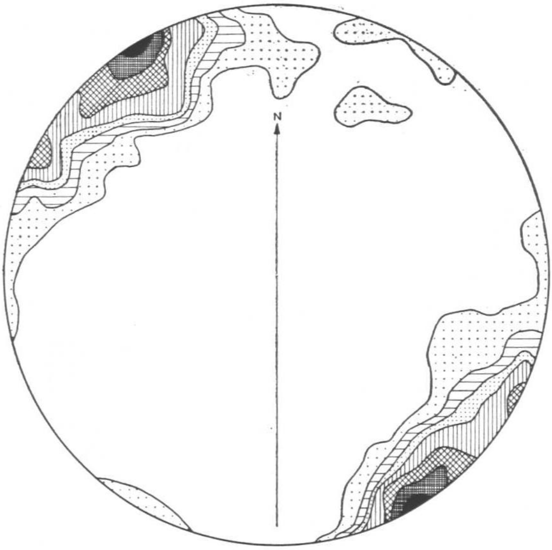


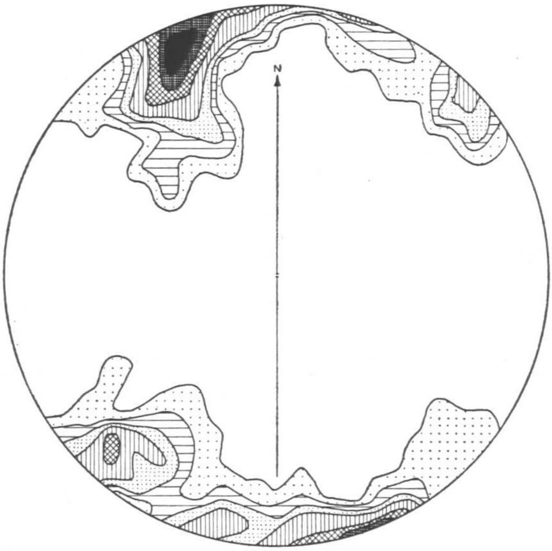
PLATE 37. Well-developed boudinage of quartz vein in the Gile Mountain formation. Curving of metasediments into the fracture is clearly seen. NW2428.

North of the International Boundary, Cooke (1957) described a constant overturning of bedding in the St. Francis group. The area exhibiting this overturning of bedding is immediately north of the Island Pond quadrangle and the eastern portion of the Memphremagog quadrangle. Cooke's evidence for overturning was based on bedding-cleavage relations, dragfolds, and, in a few places, primary sedimentary structures such as cross-bedding, graded bedding, and rill marks. Near the St. Francis thrust, the beds are nearly vertical but the dips become progressively more gentle toward the southeast until near the east side of the Coaticook map-area the dips average 50°NW. The overturned beds cover an areal width of twenty miles. This area is in strike alignment with the trough of the Brownington syncline but the beds in normal sequence reported on the eastern flank of that structure by Doll and Dennis were not observed by Cooke.

Southward along the strike in the East Barre area, Murthy (1957, 1958) objected to the proposed Brownington syncline and the stratigraphic sequence which it implied. The first stage deformational features were interpreted by Murthy (1957, p. 68–69) to indicate the presence of a major north-trending synclinal structure in the eastern part of the East Barre quadrangle. Calcareous rocks of the Waits River formation

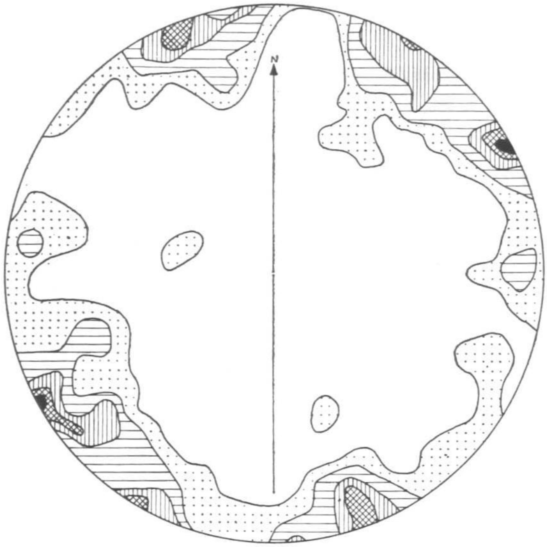


a. 225 Joints in the southwestern metasediments.
1–2–3–4–6–8–10%



b. 306 Joints in the northwestern metasediments.
1–2–3–4–6–8–10%

Figure 10. Stereograms of joints in the metasediments.



c. 205 Joints in the central metasediments.

Figure 10. Stereograms of joints in the metasediments.

occupy the center of the proposed syncline. Murthy, therefore, considered the Waits River formation to be the youngest unit present. Evidence cited by Murthy included the presence of early sinistral drag folds on the western limb of the fold and early dextral drag folds on the eastern limb. The early schistosity was also thought to be associated with this stage of deformation. The major tectonic element of the second stage of deformation was said to be a large domal structure extending from the southern part of the East Barre quadrangle southward into the Strafford quadrangle. The presence of the dome was shown by schistosity following around its northern end and by the rotation of early stage minor folds. From the direction of rotation of these folds, Murthy (1957, p. 69) inferred "... that the main tectonic stress of the second stage was upwards, but had a pronounced horizontal component." These rotated early folds had previously been postulated by White and Jahns (1950, p. 210) to be later folds formed at the time of the domal deformation.

The present author does not agree that the Brownington structure is a simple syncline. Its presence appears to have been substantiated largely by its steeply inclined to vertical western limb and an eastern limb of

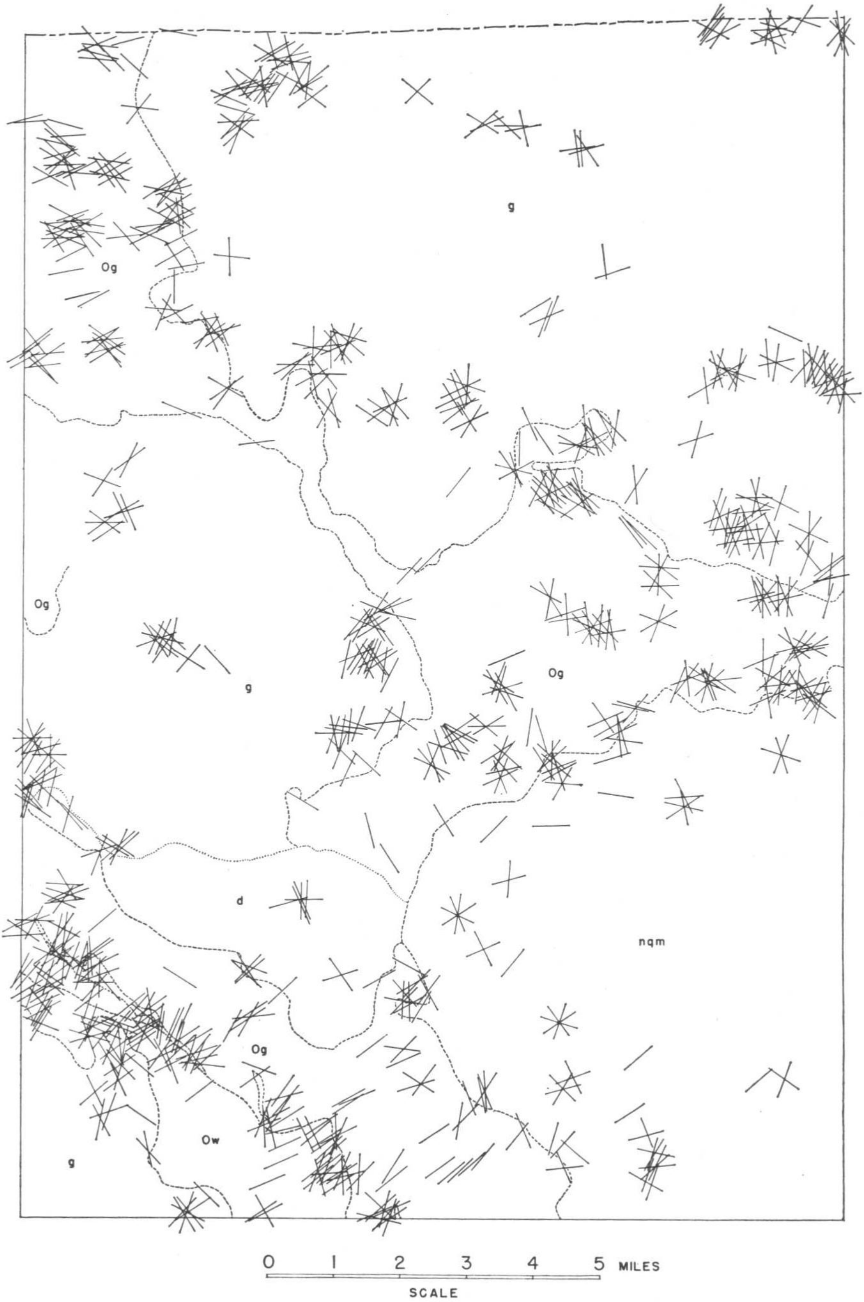


Figure 11. Distribution and strike of joints in the Island Pond quadrangle, Vermont. Formation symbols same as those on geologic map.

gently inclined westward dipping beds, suggesting a synclinal trough between (Doll, 1951, p. 51; Dennis, 1956, p. 35). North of the International Boundary (Cooke, 1957) a constant overturning of the St. Francis group is described. This casts some doubt on the presence of beds in normal sequence which were believed to occupy the gently inclined eastern limb of the Brownington syncline. Murthy (1957, p. 67) found sinistral drag folds on both margins of the Westmore formation in the East Barre area. In a normal synclinal structure, sinistral folds should occur on one limb and dextral on the other. In the southwestern portion of the Island Pond area in many localities early schistosity dips more gently than bedding. In the bed of Mad Brook, possible cross bedding and graded bedding were observed. The attitudes of these primary structures also suggest overturning. Thus, the Waits River formation must be younger than the Gile Mountain formation. Similar relations are found farther south in the Randolph quadrangle (E. H. Ern, personal communication, 1959). There, rocks in a series of cliff exposures exhibit excellent graded bedding in association with good bedding-cleavage relations, both of which indicate that the beds are overturned and that the Waits River formation is younger than the Gile Mountain. Finally, as mentioned previously in the present report, lineations on the eastern flank of the Brownington syncline in the Island Pond area plunge northwest as do the lineations on the steep inverted limb. If as Doll (1951, p. 70) suggests, this northwest trend of linear elements is a result of overturning, the same criteria should apply to both limbs of the structure and the gentle eastern limb should therefore be overturned as well.

Present Hypothesis

It is herein proposed that a large recumbent anticline involving the units of the Vermont sequence is the dominant structural feature in eastern and northeastern Vermont (Plate 3). This idea has been conceived jointly by E. H. Ern (from work in the Randolph quadrangle) and the present author. Previously, Eric and Dennis (1958, p. 61) briefly mentioned a large recumbent anticline as being a possible interpretation of the structural relations in eastern Vermont.

Smaller scale anticlinal structures recumbent to the west have been noted in the Strafford area by White and Jahns (1950, p. 212) who stated that "... the cleavage arch that dominates the central tectonic belt is not a simple anticline with older beds in the core and an uninterrupted sequence of successively younger beds on the flanks. The units that have been bowed up to form the arch are not stratigraphic units, but, rather, are large isoclinal folds, similar in appearance, though probably not in origin, to the recumbent folds of the Alps." Lyons (1955, p. 124–126) mentioned nappe-like overfolding in the Hanover area to the south.

The recumbent anticline as proposed here is a large-scale structural feature. Its inverted crest is represented by the Brownington "syncline" and its root zone is east of the Island Pond area. The axial plane lies across the Willoughby arch and has been bowed upward by later domal deformation as indicated by the pronounced arching in the southern portion of the Island Pond area, the Lyndonville quadrangle, and farther south in the East Barre and Strafford areas. The anticline is recumbent to the west and therefore the notation by Dennis (1956, p. 36) that "The Brownington syncline is one of the very rare east-facing major folds in a region of dominantly west-facing structures" is not valid. A major implication of this structure is the reversal of the stratigraphic sequence as proposed by Doll (1951, p. 15) and Dennis (1956, p. 12) and a change in the sequence proposed by Murthy (1957, p. 20). The allochthonous portion of the Waits River formation has moved westward and now lies in contact with autochthonous Waits River lithology in the Memphremagog quadrangle. Perhaps the present junction between allochthonous and autochthonous portions of the Waits River formation led to Doll's (1951, p. 22–32) recognition of the Ayers Cliff and Barton River as two separate formations. A feature such as the Indian Point syncline (Doll, 1951, p. 50) could be produced by a large digitation from the allochthonous unit of Waits River embedded on the autochthonous member.

Structural features characteristic of early deformation were implanted on the rocks prior to the formation of the recumbent anticline. This is shown by the characteristic sinistral nature of the early folds regardless of their position on the large structure. In the Island Pond area, early sinistral folds were noted on all three metasedimentary bodies, and yet these three masses occupy different positions on the recumbent anticline. In Quebec, Cooke (1957, p. 15) diagrammatically portrayed his early folds as being sinistral. In the Concord-Waterford area, (Eric and Dennis, 1958, p. 35) a vast majority of early folds present also have a sinistral pattern. Farther south, White and Jahns (1950, p. 200) stated that early folds have a dominantly sinistral pattern, while Murthy (1957, p. 67) utilized the sinistral fold pattern on both margins of the Westmore formation as evidence to refute the existence of the Brownington syncline. This prevailing sinistral pattern of the folds further suggests that at the time of their formation the beds possessing them occupied the western limb of a large syncline, the synclinal axis being to the east.

A few early dextral folds have also been reported. Dennis (1956, p. 63) noted folds of the early stage pointing toward the crest of the Willoughby arch in the Lyndonville area. Although he stated that such folds were rare, those on the east flank of the arch would be sinistral, those on the west flank would be dextral. In the southeastern corner of the East Barre area, Murthy (1957, p. 52–56) reported dextral folds which he considered to be rotated early folds. White and Billings (1951, p. 674, Fig. 10) show several such dextral folds in adjacent parts of the Woodsville quadrangle, but regard them as later folds. Early dextral folds are found west of Royalton in the Randolph quadrangle (E. H. Ern, personal communication, 1959).

A recumbent anticlinal structure must develop from a normal anticline. Therefore, early stages of its formation should give rise to structural features commonly associated with an anticline. In the case of drag folds, dextral folds should be developed on its western limb and sinistral folds on the east. Therefore, the early dextral drag folds present indicate that they were formed on the western flank of an anticline or on the eastern flank of a syncline.

In the present report, the early dextral drag folds are believed to indicate their formation on the western limb of the anticline prior to its having attained recumbency. Continued deformation placed these folds on the inverted limb in the position they now occupy in the Lyndonville and Randolph areas. The normal limb retained its overall sinistral pattern. The formation of early dextral folds could have been contemporaneous with the formation of the early sinistral folds or it could have been later. Their formation at a somewhat later stage appears to be indicated by the prevailing sinistral pattern of early folds. Perhaps the early dextral folds are indicative of a third stage of deformation between the two major ones. This stage, associated with the early formation of an anticlinal structure, led to the partial obliteration of sinistral folds and their replacement by a dextral pattern. The characteristics of both dextral and sinistral early folds are similar.

As the trend of a northward plunging, recumbent anticlinal structure is followed north, the normal limb should close around the inverted limb. In southern Quebec, Cooke (1950, Fig. 2) shows the extent of the overturned portions of the St. Francis group in the Memphremagog

(Quebec), Sherbrooke, and Scotstown map areas. Figure 12 of the present report is a composite sketch showing approximate areas of overturned strata of the St. Francis group in southern Quebec from data given by Cooke (1950, 1957). This area of overturned strata forms a striking map pattern which strongly implies a northward plunging structure.

The western limit of much of the St. Francis group in southern Quebec is marked by pronounced thrust faulting (for example the St. Francis thrust) (Cooke, 1950, p. 114–115). The presence of this thrust appears to be well substantiated, with thrusting toward the northwest. It is not illogical to expect such thrusting to be associated with the formation of a recumbent anticlinal structure.

Relations of the Northfield Slate

The Northfield slate has been shown to lie conformably beneath the Waits River formation in many areas (Currier and Jahns, 1941, p. 1501–1506; White and Jahns, 1950, p. 187; Doll, 1951, p. 15). Many attempts have been made to correlate this unit with the Meetinghouse slate found adjacent to the east of the easternmost Gile Mountain formation in Vermont. In the present report, the Northfield and Meetinghouse slates are believed to be correlative, their stratigraphic position lying between the Gile Mountain and Waits River formations. If this unit underlies the Waits River formation, the question is raised as to why beds of slate are not present between the Waits River and Gile Mountain formations in the central portion of the structure.

In the East Barre area, Murthy (1957, p. 29) described three distinct units within the Westmore formation (Gile Mountain formation of this report). Along the eastern and western margins of this formation he described members which were predominantly argillaceous, represented by mica schists. The central member, rich in arenaceous material, is composed of micaceous quartzites and quartz-biotite schists. The western member is estimated to be between 2000 to 2500 feet thick while the eastern member has a thickness of approximately 200 to 1000 feet. These argillaceous bands are also prominently displayed on the edges of the Gile Mountain formation of this band in the Randolph quadrangle (E. H. Ern, personal communication, 1959). It is suggested in the present report that the argillaceous units of the Gile Mountain formation in that area may be correlative to the Northfield-Meetinghouse lithology. Murthy (1957, p. 98) states that in the East Barre area metamorphism is most intense in the central portion of the area and

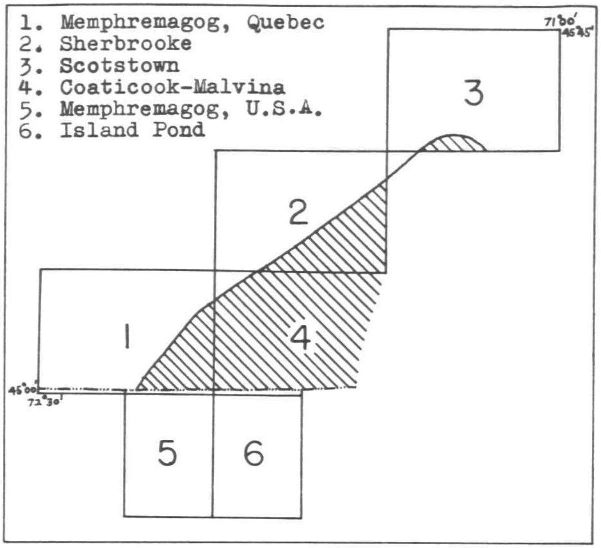


Figure 12. Distribution of overturned strata of the St. Francis group in Quebec. Ruled area indicates area of overturning. (After Cooke, 1950, 1957).

decreases in grade to the east and west. Similar relations are observed all along the structure northward to the Island Pond area. An originally argillaceous lithology upon being subjected to a low grade of metamorphism may be transformed to slate, while the same lithology if subjected to more intense metamorphism might well become a phyllite or mica schist. Therefore, it is postulated that the Northfield-Meetinghouse argillaceous lithology is represented in the central portions of the structure by phyllites and mica schists. Away from the locus of metamorphism, the unit is composed of slates. The difference in thickness between the argillaceous units bordering the Gile Mountain formation in the East Barre area is due to their occurrence on different positions on the recumbent anticlinal structure. The eastern band occupies the inverted limb while the western band is found at the arch bend.

In the Island Pond area, paucity of exposure did not allow delineation of components of the Gile Mountain formation. However, it was noted that in proximity to the Waits River formation argillaceous units are in greater abundance than elsewhere within the Gile Mountain.

The possibility also exists that in the original basin of deposition, the argillaceous sediments terminated at depth by facies change. They would therefore be absent in the central portions of the present structure.

If as proposed, the stratigraphic sequence from oldest to youngest is Gile Mountain, Northfield slate, Waits River, the problem arises as to why the Gile Mountain formation is not exposed west of the autochthonous unit of Waits River formation and the Northfield slate. These units were deposited on the east flank of the Green Mountain anticlinorium, and if subjected to normal erosive processes should show the complete sequence from Waits River on the east through Gile Mountain on the west. However, to the west, the Northfield slate is in contact with the older Shaw Mountain formation of Currier and Jahns (1941, p. 1496–1501), the Gile Mountain formation being absent.

In central Vermont, White and Jahns (1950, p. 187) state that the Northfield slate lies unconformably above the Shaw Mountain formation and conformably beneath the Waits River formation. In the Memphremagog quadrangle, Doll (1951, p. 15) also shows unconformable relations between the Shaw Mountain formation and the Northfield slate. In the present report, this unconformity is interpreted as due to the removal of the Gile Mountain formation by erosion on the upper portions of the western limb of the syncline in which the Vermont sequence was deposited. This erosion of the Gile Mountain formation and subsequent deposition of the Northfield slate upon the Shaw Mountain formation produced the unconformity between these latter two units.

Doming

The effects of a later deformational stage are shown in the Island Pond area by second generation folds and the development of slip cleavage. These features are best exhibited and interpreted in the southwestern portion of the map area. Here the termination of the Willoughby arch (Dennis, 1956, p. 36) is clearly shown by closure of the Gile Mountain formation around the Waits River formation, by a swinging of the Standing Pond volcanics to a northwest trend, and by bedding and schistosity, both of which wrap around the northern end of the arch (Plate 2). The above features strongly suggest that this closure is primarily of a structural nature. The closure is illustrated by the three cross-sections in Figure 13.

Late drag folds on this end of the arch are all of a dextral pattern and point away from the arch's crest. Slip cleavage parallel to the axial planes of the late folds also dips away from the crest. Dennis (1956, p. 67) interpreted similar characteristics in the Lyndonville quadrangle as good evidence for doming. The same conclusions are applicable to these later stage structural features in the southwestern portion of the

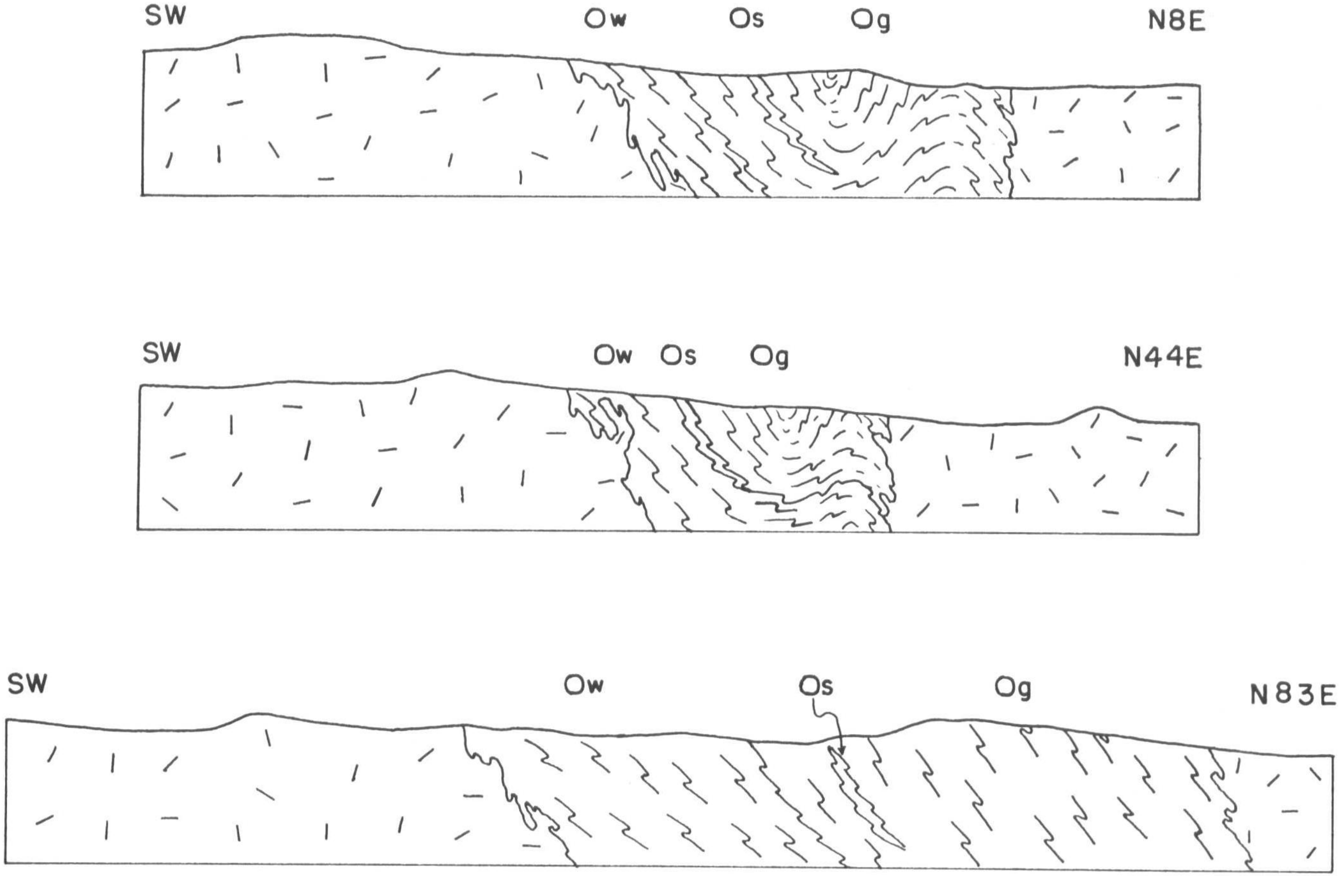


Figure 13. Cross sections radiating northeast in directions indicated from the southwestern corner of the Island Pond quadrangle. Drag folds shown are related to the later deformation. Formation symbols same as on Plate 1.

Island Pond area. Therefore, second stage folds and slip cleavage are believed to be products of upward domal movement imposed on the inverted limb of the previously formed recumbent anticline.

Similar domal structures have been recognized in many areas in eastern Vermont, the most prominent deforming the rocks of the Vermont sequence being the Strafford dome (Doll, 1944; White and Jahns, 1950; Murthy, 1957, 1958) and the Pomfret dome (Lyons, 1955). The exact mechanism for the intense upward movement is not known. White and Jahns (1950, p. 214–219) suggested that an upward welling or bulging of the calcareous rocks of the Waits River formation due to deep-seated deformation resulted in the formation of these arches. However, Bean (1953) reported that a study of gravity anomalies indicated definite negative anomalies under the Strafford and Pomfret domes. This indicates the presence of low density rocks in the central part of the domes beneath the higher density units of the Gile Mountain and Waits River formations. Lyons (1955, p. 125) suggested that upward flowage of granitic rocks would be consistent with the known structural relations. The decrease in grade of metamorphism away from the center of the Strafford dome (Murthy, 1957, p. 65) and the large areas near the center of that dome which are intruded by numerous granitic dikes are supporting evidence that igneous intrusion was the doming mechanism.

In the Island Pond area, an upward moving granitic mass could readily produce the later deformational features. The prodigious quantities of granitic rocks exposed within the area attest to their prominent role. That their emplacement was not passive is indicated by the contortion of bedding and schistosity in the metasediments near the granite masses.

Summary

The Gile Mountain formation which crops out in a belt east of the Willoughby arch and the Westmore formation which crops out in a belt west of the Willoughby arch, join in the southwestern corner of the Island Pond quadrangle. Hence, the two formations correlate. In a similar fashion, the Waits River and Barton River formations also structurally unite in the Randolph quadrangle (E. H. Ern, personal communication, 1959). In central Vermont, the Gile Mountain formation overlies the Waits River formation. However, the attitude of primary sedimentary structures and bedding-cleavage relations in the Island Pond and Randolph quadrangles, and in the southern portions of Quebec (Cooke, 1957), indicate that the beds in these areas are largely overturned. The Waits River formation is, therefore, younger than the Gile Mountain formation. Neither simple synclinal folding (Doll, 1951; Dennis, 1956) nor the deformation of a series of four units deposited in homoclinal sequence (Murthy, 1957) could explain these relationships. A recumbent anticlinal structure is suggested.

The distribution of early sinistral folds is interpreted to indicate that the beds originally occupied the western limb of a large syncline having its axis to the east. Early dextral drag folds partially obliterating still earlier sinistral drag folds, are evidence for an anticlinal structure. The early dextral drag folds formed on the west limb of this anticline. Upon continued deformation, the structure was overturned and became recumbent to the west. Early stage deformational features were retained during the formation of this structure as indicated by the prevailing sinistral pattern of early minor folds on the normal limb and early dextral folds on the inverted limb.

The Willoughby arch was created by a doming of the central portions of the anticline's inverted limb. During doming, slip cleavage and drag folds facing away from the crest of the arch were formed. Early schistosity and bedding were deformed and wrapped around the northern end of the arch in the southwestern portion of the Island Pond area. The pronounced effects of the numerous granitic masses in the Island Pond area and Bean's (1953, p. 509–538) gravity survey indicating negative anomalies associated with the domal structures in east-central Vermont, suggest that an upward moving granitic mass was the mechanism forming the dome.

To the west (Currier and Jahns, 1941; White and Jahns, 1950; Doll, 1951) the Northfield slate conformably underlies the Waits River formation. The Northfield slate lies unconformably on the older Shaw Mountain formation. The Gile Mountain formation is absent. The Gile Mountain formation is believed, therefore, to have been deposited upon the Shaw Mountain formation. Later, the Gile Mountain formation on the western portion of the basin of deposition was removed by erosion. The argillaceous sediments of the Northfield slate were then deposited. The Northfield slate, therefore, lies stratigraphically between the Gile Mountain and Waits River formations in other portions of the basin of deposition, and correlates with the Meetinghouse slate to the east. The Northfield-Meetinghouse lithology has not been recognized in the central portions of the structure. This could be due to: (1) change in metamorphic grade so that phyllites and schists formed instead of slates, or (2) facies change and the resulting termination of the argillaceous lithology at depth in the basin of deposition.

ECONOMIC GEOLOGY

Granites, though underlying a great proportion of the area, have had but little commercial utilization. One small quarry now long defunct and fallen into disrepair is present at SW1656 on the hill to the northeast of the intersection of Route 105 with the Clyde River east of the village of East Charleston. The granite here is similar in appearance to the renowned Barre granite. The stone from this quarry was used primarily as a local building stone in and around the village of Island Pond. A quarry in the Nulhegan quartz monzonite is present in the Averill quadrangle near the eastern border of the massif just north of the Canadian National Railroad tracks (P. B. Myers, personal communication, 1959). This stone was also used locally. Schroeder (1920, p. 41–42) recognized the commercial possibilities of the Averill granite, but these potentials have never been capitalized upon in Vermont. A short distance north of the International Boundary, quarries in the same granitic body have produced good stone which Burton (1932, p. 69) believed to be of good quality and well suited for "monument bases, hammered dies, and small building-stone." Mailhiot (1913, p. 217) had earlier mentioned first-class building stone being quarried in this area. Stone from the Gingras & Freres quarry situated a mile and a quarter north-northwest of Stanhope has been extensively used as a building stone (Cooke, 1957, p. 32).

Small cuttings into quartz veins in the Gile Mountain formation attest to attempts in the past to recover gold, but no such prospects have met with notable success.

Gravels of glacio-fluvial origin abound within the area and have been the most economically exploited material of a geologic nature. Their value is shown by the numerous gravel pits which dot such deposits. Many gravel pits may be found which are no longer in use, but a number of large workings are in active production. The material is used extensively for road metal, ballast on railroad beds, and for other purposes.

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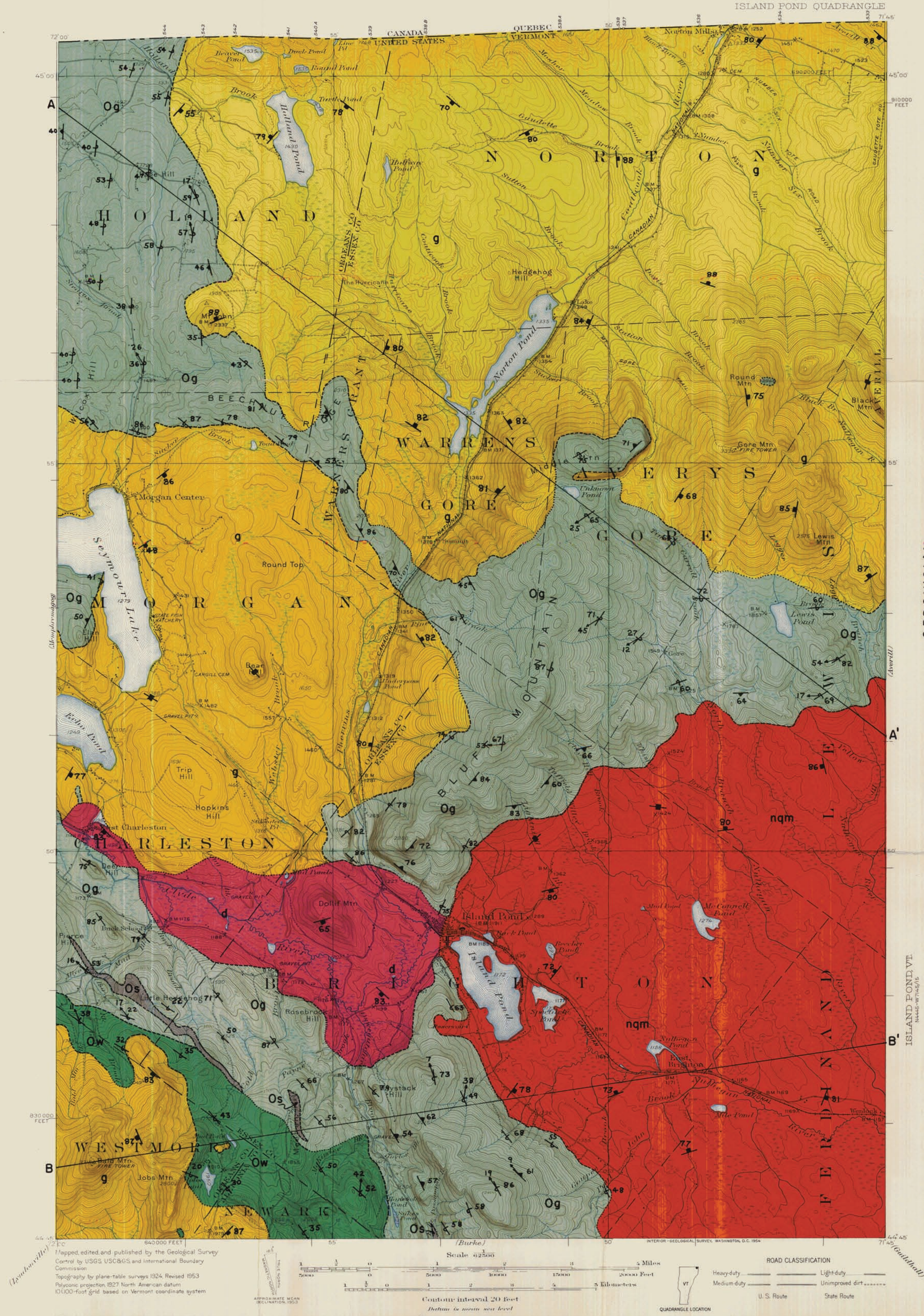
PLATE I

3223



LEGEND

DEVONIAN

d g

GRANITE

Medium- to coarse-grained gray to pink granite, granodiorite, quartz monzonite; —g; gabbro, diorite, monzonite; —d.

nqm

NULHEGAN QUARTZ MONZONITE

Medium- to coarse-grained quartz monzonite, biotite conspicuous.

ORDOVICIAN

Ow

WAITS RIVER FORMATION

Steel gray impure limestones weathering to brown punky crust, quartz-mica schists, phyllites, and quartzites.

Os

STANDING POND VOLCANICS

Coarse-grained massive amphibolites.

Og

GILE MOUNTAIN FORMATION

Quartz-mica schists, dark gray to brown phyllites, micaceous quartzites, and impure limestones.

Accurate and well-defined contact

Indefinite and gradational contact

Concealed or inferred contact

37 Strike and dip of beds

75 Strike and dip of overturned beds

53 Strike and dip of schistosity

22 Direction and plunge of lineation in b

85 Strike and dip of joints

Strike of vertical joints

VERMONT GEOLOGICAL SURVEY
Charles G. Doll, State Geologist
(Bulletin No. 20)
Published 1963

GEOLOGIC MAP AND STRUCTURE SECTIONS OF THE ISLAND POND QUADRANGLE, VERMONT

Geology by Bruce K. Goodwin
1955-1958

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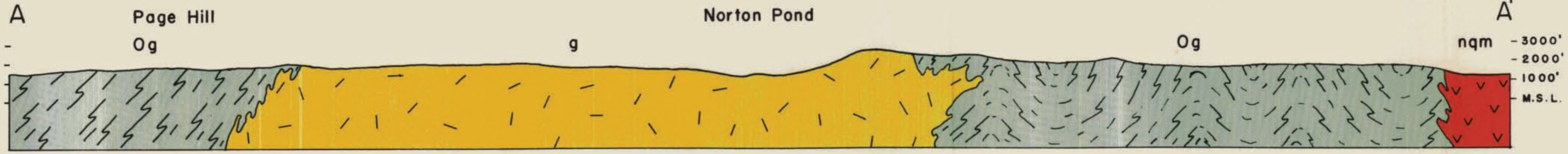

EASTERN VERMONT AND ADJOINING REGIONS

GENERALIZED GEOLOGIC MAP
AND
STRUCTURE SECTIONS

0 5 10 15 20 miles
SCALE

PLATE 3

VERMONT GEOLOGICAL SURVEY
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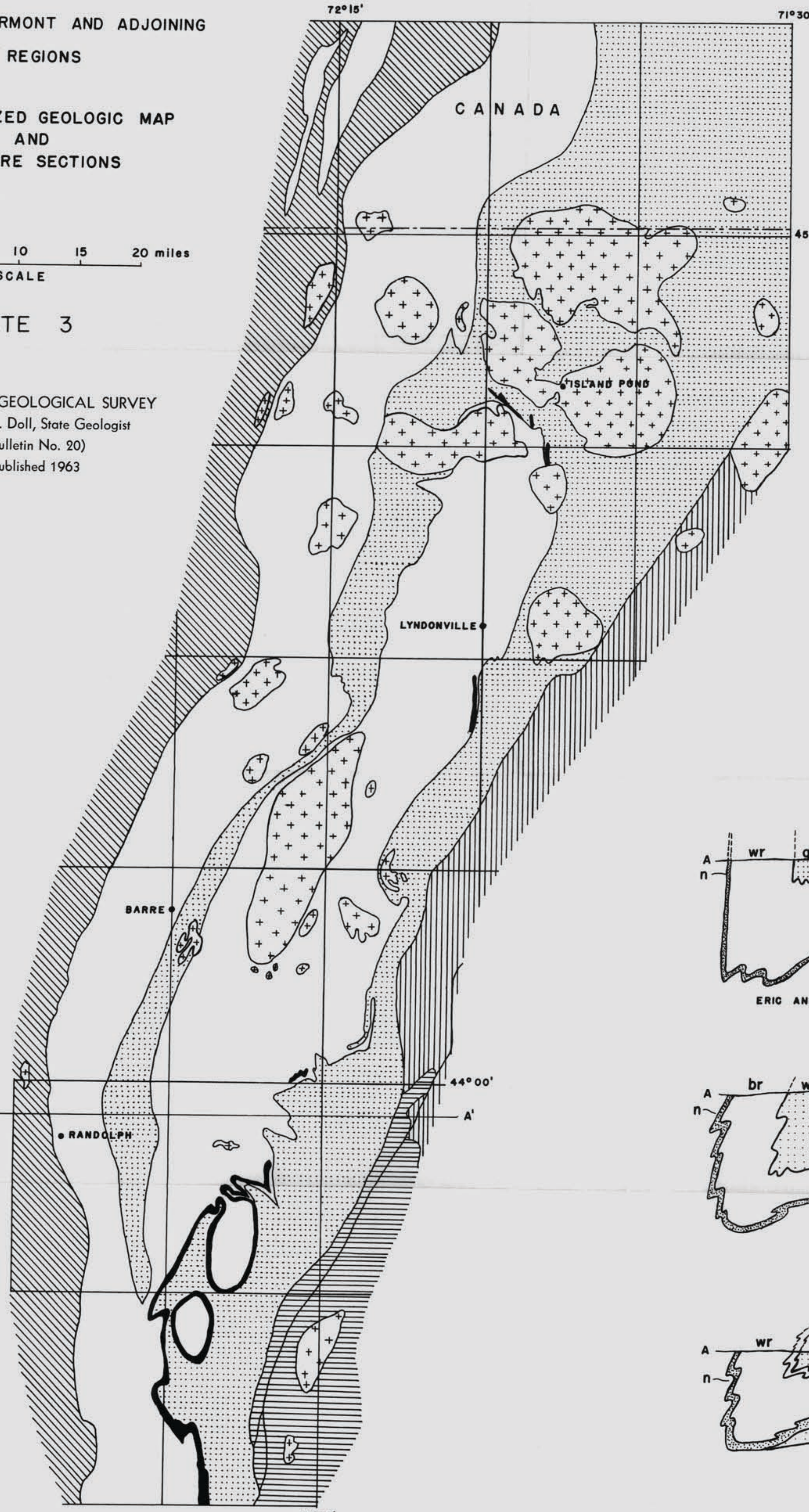


MODIFIED FROM DENNIS (1956, PL. 3)

LEGEND

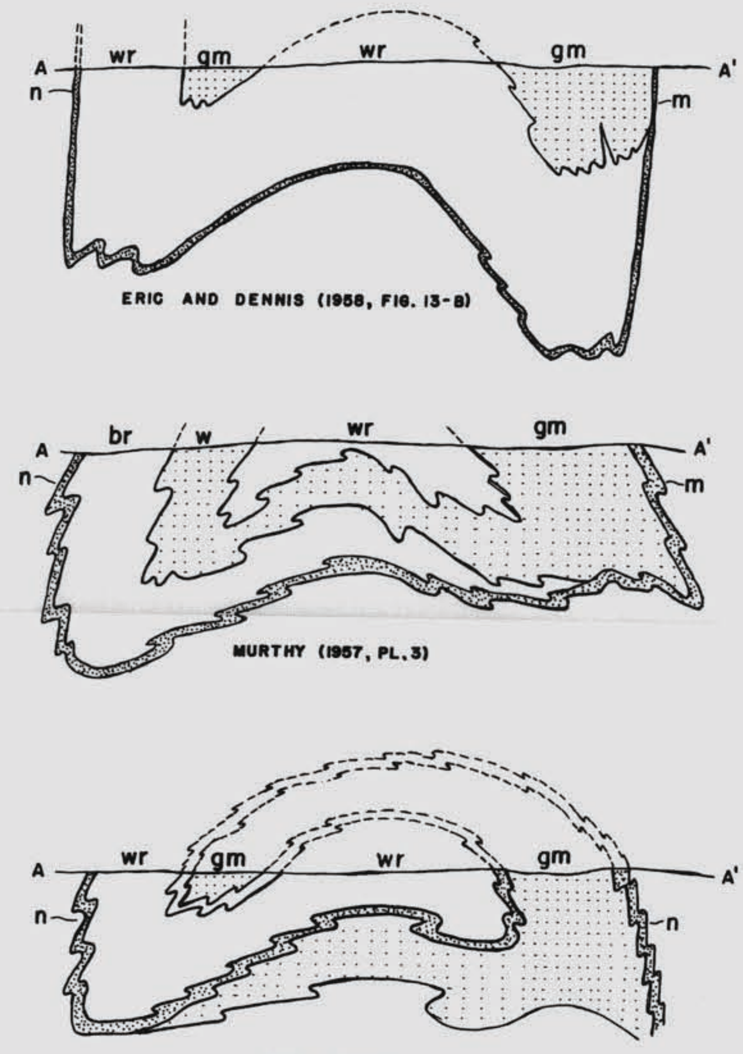
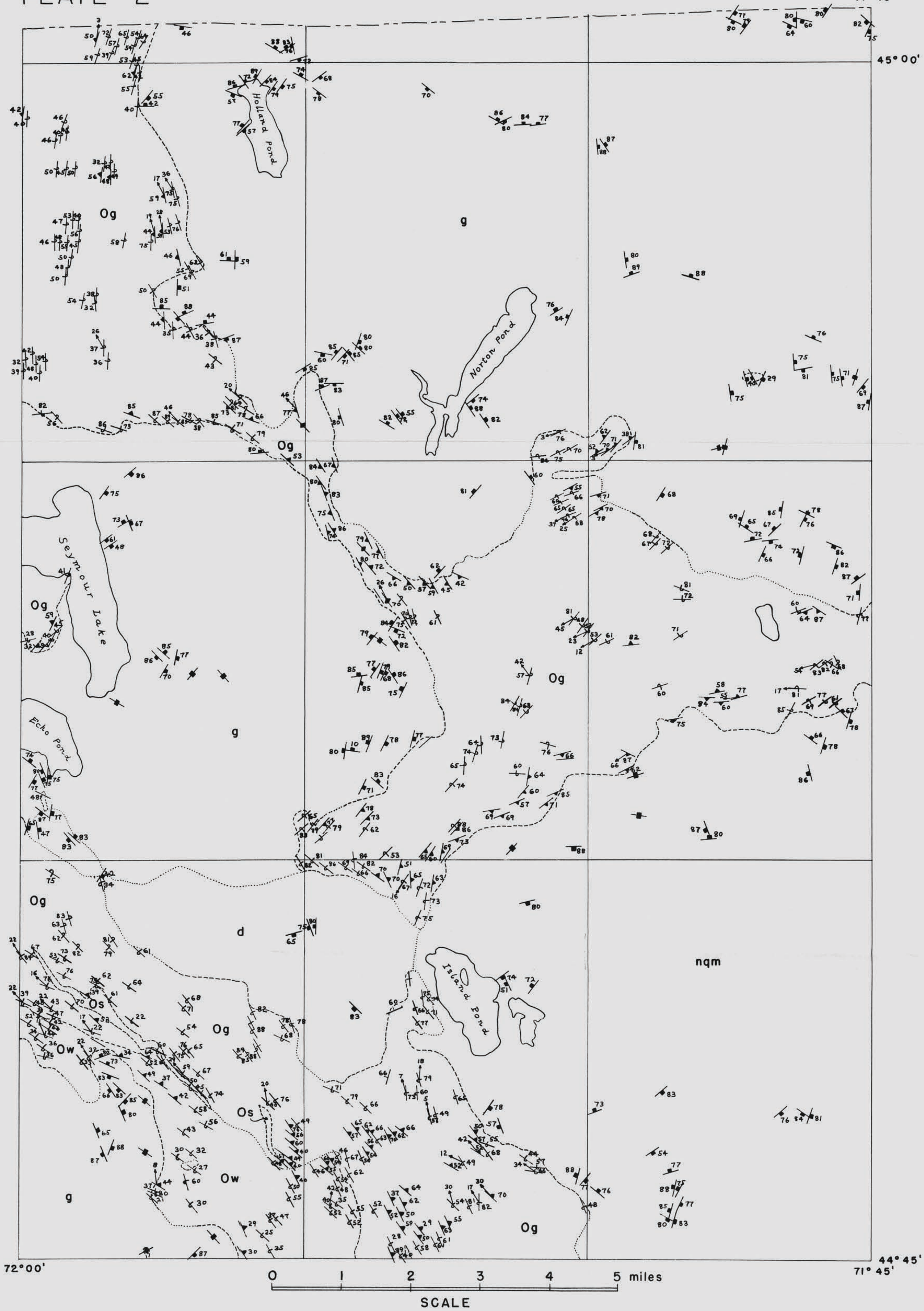


PLATE 2



LEGEND

Strike and dip of beds

Strike and dip of overturned Beds

Strike of vertical beds

Strike and dip of schistosity

Strike of vertical schistosity

Direction and plunge of lineation in b

Strike and dip of joints

Strike of vertical joints

Formation symbols as shown on geologic map.

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TECTONIC MAP OF THE ISLAND POND QUADRANGLE, VERMONT