BEDROCK GEOLOGY OF THE RANDOLPH QUADRANGLE, VERMONT

By
ERNEST HENRY ERN, JR.

VERMONT GEOLOGICAL SURVEY
CHARLES G. DOLL, *State Geologist*

Published by
VERMONT DEVELOPMENT DEPARTMENT
MONTPELIER, VERMONT

BULLETIN NO. 21 1963

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ABSTRACT

The Randolph quadrangle is situated in central Vermont and lies on the east limb of the Green Mountain anticlinorium. To the east and southeast of the quadrangle are the Strafford and Pomfret domes which mark the southern limit of the Willoughby arch.

Paleozoic metasediments and metavolcanics, representing nine formations, are exposed in the Randolph quadrangle as a series of north-trending parallel belts. From west to east these stratigraphic units have been identified as the Ottauquechee, Stowe, Moretown, Cram Hill, Barnard gneiss, Shaw Mountain, Northfield, Waits River, Gile Mountain and Waits River formations.

The stratigraphic units west of the Cram Hill formation are part of a homocline on the east limb of the Green Mountain anticlinorium and dip steeply to the east. The two belts of the Waits River formation, east of the homocline, are considered stratigraphically equivalent. There is a second or eastern belt of the Gile Mountain formation (type locality) east of the Randolph quadrangle.

Graded bedding in the Randolph quadrangle designates the western band of the Gile Mountain formation as older than the Waits River formation. However, the western Waits River belt is conformably underlain to the west by the Northfield formation.

Argillaceous members along the margins of the western band of the Gile Mountain formation have been assigned to the Northfield formation and are correlated with the Meetinghouse slate which is exposed east of the eastern belt of the Gile Mountain formation.

An unconformity at the base of the Shaw Mountain is considered an erosional horizon and explains the absence of Gile Mountain lithology west of the Northfield formation.

Two stages of deformation are indicated by the development of two generations of minor folds and of cleavage. These minor structures are important in delineating the major structural relations.

The early minor structures in the eastern two-thirds of the quadrangle strongly suggest that the western band of the Gile Mountain formation

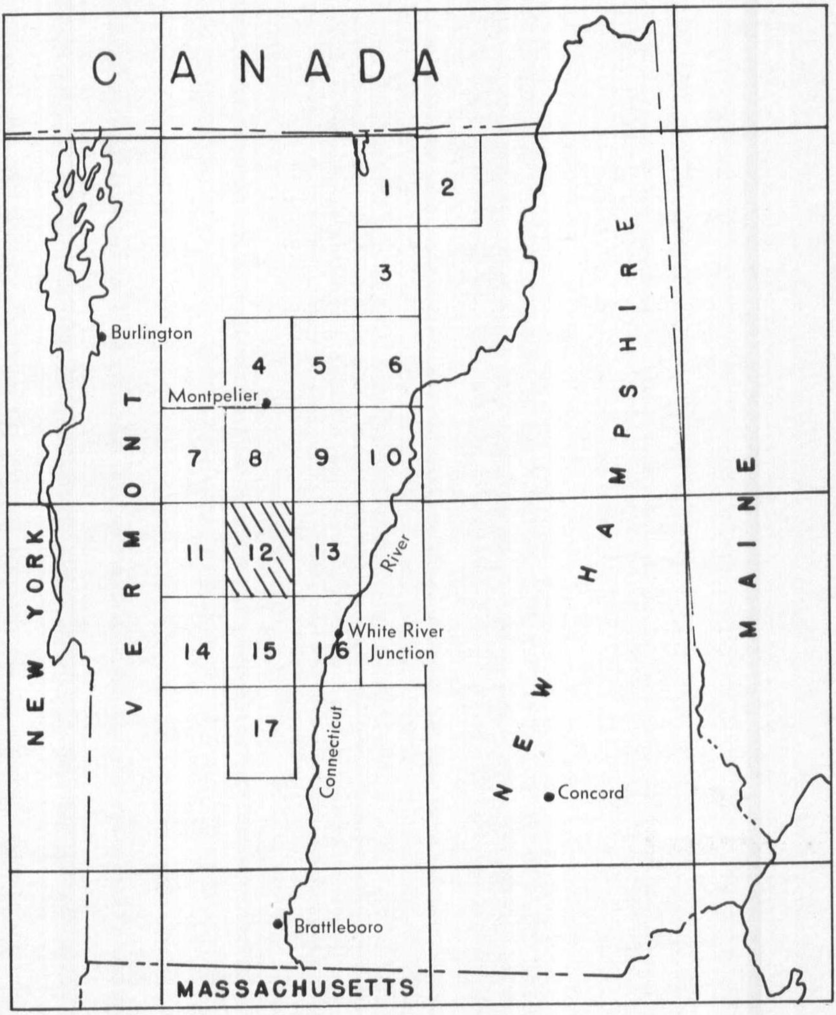


Figure 1. Index Map

Quadrangles are numbered as follows:

1. Memphremagog
2. Island Pond
3. Lyndonville
4. Montpelier
5. Plainfield
6. St. Johnsbury
7. Lincoln Mountain
8. Barre
9. East Barre
10. Woodsville
11. Rochester
12. Randolph
13. Strafford
14. Rutland
15. Woodstock
16. Hanover
17. Ludlow

is the nose and core of a major recumbent anticlinal fold or nappe-like structure which plunges to the north. The root zone of this major fold lies in the eastern band of the Gile Mountain formation.

The later minor structures are the result of the formation of the Strafford and the Pomfret domes. As the domes developed the axial plane of the recumbent fold was arched.

The present interpretation of the structure and stratigraphy calls for a revision of the stratigraphic units of east-central Vermont; namely, the sequence of formations above the Cram Hill is, from older to younger, Gile Mountain, Shaw Mountain, Northfield and Waits River.

A number of plutonic bodies are present in the Randolph quadrangle but they are small and have not appreciably affected the enclosing rocks.

INTRODUCTION

Location

The area under study includes the entire fifteen-minute Randolph quadrangle (Fig. 1)—the most centrally located quadrangle in the state of Vermont. Also included in this study is a small portion of the northeastern part of the Woodstock quadrangle to the south. The total area comprises approximately 229 square miles. The Randolph quadrangle is bounded by parallels 43°45′ and 44°00′ north latitude and 72°30′ and 72°45′ west longitude.

Four main highways traverse the area: Vermont Routes 12, 12–A, 14 and 107. The area is readily accessible by automobile.

Regional Geologic Setting

The Randolph quadrangle lies on the east limb of the Green Mountain anticlinorium (see Fig. 2) and is also situated just west of a series of domes and arch structures, the Willoughby arch, which extends in a north-south direction from the northern part of Vermont to Massachusetts.

The rocks east of the Green Mountains comprise a thick Paleozoic series of steeply dipping, north-trending eugeosynclinal metasediments interspersed with volcanics. The formations become progressively younger to the east and are intruded to a minor extent by several types of igneous rocks. The metasedimentary formations encountered in the Randolph quadrangle, from west to east, are the Ottauquechee, Stowe, Moretown, Cram Hill, Barnard, Shaw Mountain, Northfield, Waits River and Gile Mountain.

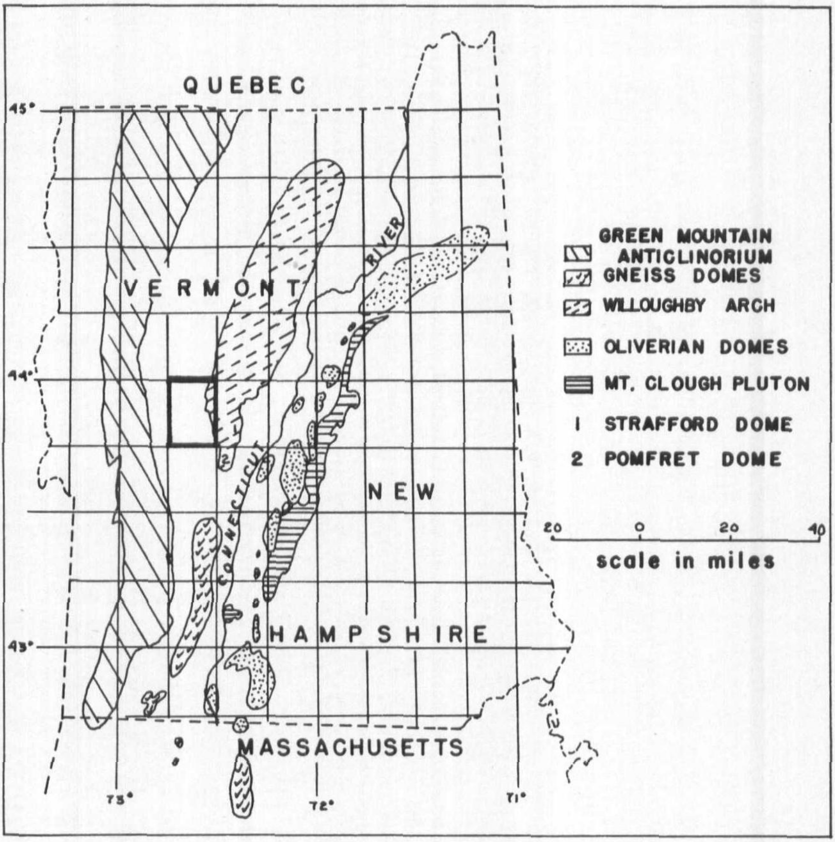


Figure 2. Map of the domal structures in northwestern New England. Modified from Lyons (1955), Figure 4. Randolph quadrangle in heavy outline.

A second band of the Gile Mountain formation (including the type locality) is exposed in the eastern part of the state and is overlain by the Meetinghouse slate. This is the termination of the rocks in the so-called Vermont sequence whose relationship to the rocks east of the Connecticut River in the New Hampshire sequence is still uncertain.

The structural setting of the rocks in central and eastern Vermont is the result of two major stages of deformation which produced two distinct types of minor folds and two types of cleavage. Part of the regional structural complexity is due to the superposition of the later deformational effects on the earlier one.

No fifteen-minute quadrangle in this region is sufficiently complete in stratigraphic units, structural features and exposures to reveal the stratigraphic and tectonic events which occurred in central and eastern Vermont. Reference will constantly be made to information available from surrounding quadrangles in order to clearly present the geologic position of the Randolph quadrangle with respect to the regional geology.

Previous Work

An excellent, but early, treatise on the complex geology of east-central Vermont is the monograph and the accompanying map published in 1861 by Edward Hitchcock. Although this was a reconnaissance survey, it has served as a basis for later and more detailed work.

In the early part of the century C. H. Richardson mapped a series of townships in eastern Vermont extending from the International Boundary southward to the state of Massachusetts. His reports on the townships of Northfield, Braintree, Randolph, Bethel, Barnard, Pomfret, and Woodstock were published in 1919, 1921, 1923, 1924 and 1927. He was primarily interested in tracing what he considered to be an erosional unconformity between the Cambrain and the Ordovician throughout the state. This horizon was later studied in detail by Currier and Jahns (1941) who pointed out its significance, not as the Cambrian-Ordovician boundary, but as an important fossiliferous horizon in the Ordovician. The horizon separates the dominantly argillaceous and arenaceous schists, gneisses and granulites on the west from the calcareous and argillaceous crystalline limestones, schists and phyllites to the east.

Richardson also included the area of the present study in reports he published on the Terranes of Orange County, Vermont (1902) and the Ordovician Terranes of Central Vermont (1919).

The granites within the area received attention by T. N. Dale (1909, 1923) and a comprehensive study of the Bethel granite was made by Balk (1927).

White's detailed studies in the Woodsville area, Jahns' mapping in the Barre quadrangle and reconnaissance field investigations by both writers in conjunction with work already available in nearby areas was presented as a comprehensive discussion of the regional geologic structures of east-central Vermont (White and Jahns, 1950). They clearly pointed out the existing problems and offered suggestions concerning the regional structure and stratigraphic sequence pending more detailed work in adjoining areas.

A study of gravity anomalies was conducted by Bean (1953) across the Randolph quadrangle in the latitude of Bethel as part of a large-scale investigation spanning from eastern New York, through central Vermont and central New Hampshire to the Maine border. A negative gravity anomaly was found associated with the Strafford dome and has had considerable bearing on delineating the origin of the domal structures east of the Randolph quadrangle.

Reports have been made on the following quadrangles adjoining the Randolph quadrangle: Barre (White and Jahns, 1950); East Barre (Murthy, 1957); Strafford (Doll, 1944); Hanover (Lyons, 1955); lower two-thirds of Woodstock (Chang, 1950); Rochester (Osberg, 1952) and (Hawkes, 1941); and Lincoln Mountain (Cady, in press).

Although considerable information has been compiled on the stratigraphy and structural features of the rocks in east-central Vermont, there is still a lack of agreement among the workers as to the regional structural setting. Problems which occur in the Randolph quadrangle that are significant to an understanding of the geology in east-central Vermont are the following:

(1) The stratigraphic and structural correlation of the formations variously mapped as Barton River and/or Waits River and the sequence, Westmore or Gile Mountain (?) and/or Gile Mountain.
(2) The significance of the strikingly similar lithologies of the Northfield and Meetinghouse formations.
(3) The significance of the Standing Pond volcanics with reference to the Waits River-Gile Mountain contact.
(4) The regional implication of the unconformity at the base of the Shaw Mountain and Northfield formations.
(5) Whether the closure of the western band of the Gile Mountain formation (Westmore formation of Murthy) in the Randolph quadrangle is a structural feature or due to a facies change.

Present Study

The area under consideration was mapped during a total of ten months time in the summers of 1956, 1957, and 1958. Thin section studies and the preparation of the manuscript involved the major part of the fall and winter of 1958–1959 as well as considerable parts of the two previous winters. Modal analyses of the formations were made following Chayes' method (1949).

The U. S. Geological Survey Randolph and Woodstock topographic quadrangles, scale of 1:62,500, were used as base maps. Enlarged versions, on a scale of approximately three inches to the mile, were used in critical areas and in the heavily wooded sections of the western portion of the quadrangle. Many of the outcrops were located by the method of resection. In the heavily forested areas locations were determined by pace and compass methods. Aerial photographs were also used in planning field work.

Acknowledgments

The author wishes to acknowledge his indebtedness to Dr. Bradford Willard of Lehigh University who first suggested this problem to him.

It has been through the direction and constructive criticism of Dr. H. R. Gault of Lehigh University who directed this work that the ready preparation of this report has been made possible. Dr. J. D. Ryan, also of Lehigh University, offered many helpful suggestions and gave valuable guidance both in the field and laboratory approach to the problem.

The field work was supported by the Vermont Geological Survey under the auspices of Dr. Charles G. Doll who visited me in the field several times. It was a pleasure to work for the Survey under his capable direction.

I am grateful to Dr. W. M. Cady and Dr. A. Chidester of the United States Geological Survey and Dr. James B. Thompson, Jr., of Harvard University for their constructive help and advice in familiarizing me with the regional picture and for visiting me in the field on a number of occasions.

To the other geologists working in Vermont I express thanks for the interest they have shown in this problem through discussions and field trips into areas of common interest. Among these are Bruce K. Goodwin, Ronald H. Konig, V. Rama Murthy, Leo Hall and Paul B. Myers.

Finally, I would like to note here my gratitude for the keen interest and sincere cooperation shown me by the residents of the Randolph area.

Topography

The Randolph quadrangle lies in the upland section of the Vermont Piedmont of the New England physiographic province (Jacobs, 1950). Two distinct types of topography and vegetal cover are evident within the quadrangle. The forested western third of the quadrangle is characterized by rugged, hilly to mountainous topography. The highest point is Rochester Mountain on the western border of the quadrangle with an elevation of 2,952 feet. Other prominent elevations are Deer Mountain (2,200 feet), Delectable Mountain (2,060 feet), Lee Hill (2,080 feet), Mt. Olympus (2,480 feet) and Pauls Peak (2,100 feet).

The rolling, open, flat-topped hills of the eastern two-thirds of the quadrangle (Plate III) are a contrast to the topography of the western third. Tunbridge Hill (elev. 1,940 feet) and Broad Brook Mountain (elev. 1,600 feet) form a prominent longitudinal range, trending north-south, which locates the outcrop area of the Gile Mountain formation and divides the two belts of the Waits River formation. The lowest elevations in the quadrangle are east of the village of South Royalton along the White River.

The geomorphic characteristics reflect the lithology, structure and relative resistances of the formations to weathering and erosion (see Plate I).

The Vermont Piedmont slopes gently to the south. Jacobs (1950) noted that somewhat south of the Canadian border, the elevation of the peneplain is 1,400 feet. In the latitude of Randolph the elevation is at 1,300 feet, while to the south, it is 1,200 feet.

Drainage

In the Randolph quadrangle the drainage system is one of maturity. The principal drainage system in the area is that of the White River and its tributaries which is the fourth largest river system in Vermont. The White River is the principal river flowing into the Connecticut River from eastern Vermont. An easterly flow of the main channel and a general southeasterly drainage holds within the Randolph quadrangle. Over-all the White River is approximately 57 miles long, drains an area of over 710 square miles and its decrease in elevation from its source at Ripton to White River Junction is about 3,360 feet.

The White River flows for eighteen miles in the quadrangle and is fed within the area by three of its five main tributaries. The First Branch of the White River joins the system in South Royalton. The Second Branch connects in Royalton and provides about twenty miles of drainage length with a drop in elevation of about 760 feet. Route 14 lies in its valley. The Third and largest Branch of the White River in the Randolph quadrangle joins the main system at Bethel and entails a decrease in elevation of 1,300 feet. It is approximately nineteen miles long. Gilead Brook, Camp Brook, Riford Brook, Thayer Brook, Battles Brook and Ayers Brook are all rapidly flowing tributaries to the Third Branch, each of which drains an area of almost five miles with a drop in elevation of approximately 1,100 feet. The latter two mentioned flow southward, whereas the others all flow to the east. Cleveland Brook, Locust Creek, Stony Brook, and Broad Brook all flow north into the main channel of the White River, while Lillieville Brook flows south.

PLATE III

Typical rolling terrane underlain by Waits River lithology. Braintree Mountains in background in view looking west from Hebard Hill.

The Second and Third Branches of the White River are classed as subsequent streams. The First Branch of the White River has been designated a superimposed stream (Meyerhoff, 1929) due to the control by sediment from the Connecticut River, which at one time covered the area.

Only two ponds or lakes are located in the quadrangle—Mud Pond and Pickles Pond.

Glaciation

The author was primarily interested in the bedrock geology. Little attention was given to the glacial cover and glacial deposits are not shown on the geologic map.

In the upland areas, striae on the more resistant rocks offer the best evidence for determining the direction of ice movement. In the northern part of the quadrangle the most prominent directions are due south, and south 25 degrees east. In the central and southern parts the most conspicuous directions are south 60 degrees west, south 25 to 30 degrees west and due south. Excellent evidence for ice transport occurs on

Braintree Hill in the northwestern section of the map in an area just south of Mud Pond where a glacial erratic of Stowe schist measuring approximately eight feet in height and twenty feet in diameter rests unsteadily on the Cram Hill outcrops (Plate IV). The local residents have named this erratic "Rolling Rock."

Numerous small but distinct drumlins and kames are evident throughout the area.

The upland areas are covered with a thin veneer of glacial material. In the valleys and tributaries of the White River sand, silt and gravel accumulated heavily along the river banks (Plate V, Fig. 1).

The valley drained by the Second Branch of the White River is a broad U-shaped, glacial valley (Plate V, Fig. 2), while its tributaries show both post and pre-glacial effects. The valley of the Third Branch of the White River is not as broad but it is characteristically U-shaped.

The valley of the White River running northeasterly from Riverside to Bethel shows excellent glacial grooving and scouring along the near-vertical cliffs bordering the north side of the valley. There is a maximum relief of more than 700 feet in many places.

STRATIGRAPHY

General Statement

The strata within the confines of the Randolph quadrangle form part of the east limb of the Green Mountain anticlinorium whose axis approximately parallels that of the Green Mountains. These strata represent a typical metamorphosed eugeosynclinal sequence composed essentially of argillaceous, arenaceous, and calcareous metasediments and metavolcanics. In western New Hampshire there are rocks of strikingly similar lithology and, to some workers, of comparable age. At present the rocks of the western "New Hampshire Sequence" and those of the "Vermont Sequence" have not been correlated with any certainty.

A break between the two sequences was discovered by Eric, White and Hadley (1941, p. 1900). They presented evidence that this break is a fault and designated it as the Monroe fault. The validity of this fault has been questioned in the areas studied by Kruger (1946), Lyons (1955), and Thompson (1958, personal communication) due to evidence suggesting a major unconformity at this break. Whether structural or stratigraphic, this break between the Vermont and New Hampshire sequences is significant in any proposed correlation of the rocks of the two sequences.

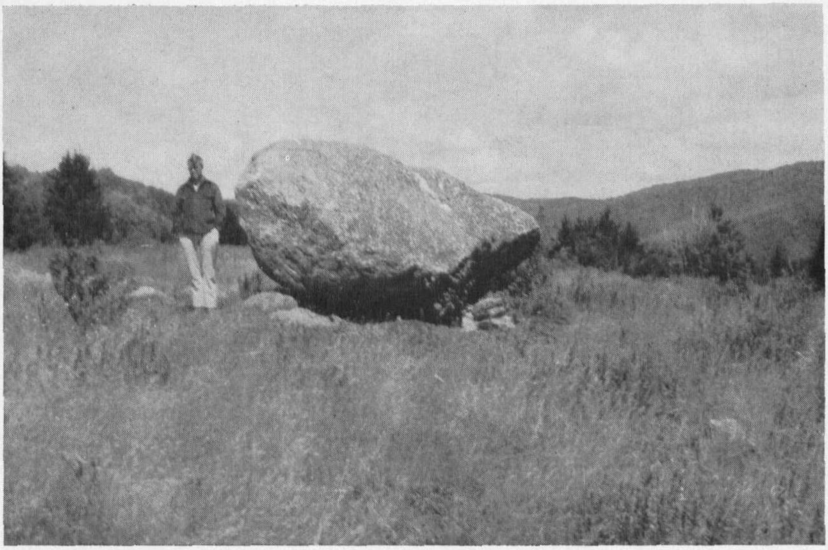


PLATE IV

"Rolling Rock." Glacial erratic of Stowe schist on Braintree Hill, just south of Mud Pond.

It has been generally accepted for east-central Vermont that the formations become progressively younger eastward from the core of the Green Mountains and form a steeply dipping homoclinal sequence. However, the repetition of the type Waits River and Gile Mountain lithologies in the eastern part of this sequence, and their stratigraphic and structural relationship have been the major problem in formulating an accepted correlation of the stratigraphic units in eastern Vermont. The present writer offers an interpretation that the structural and stratigraphic relations indicate a major recumbent anticline. This will be discussed in detail in the chapter on structural geology.

Stratigraphic Nomenclature

The stratigraphic nomenclature for the formations east of the Northfield slate in central and eastern Vermont is confused because of the diversity of names applied to the same or different rock units.

White and Jahns (1950, p. 187) encountered, in succession, in the Barre quadrangle and to the east: "(1) Four to six miles of predominantly calcareous rock, (2) Two to four miles of mica schist, phyllite and

PLATE V

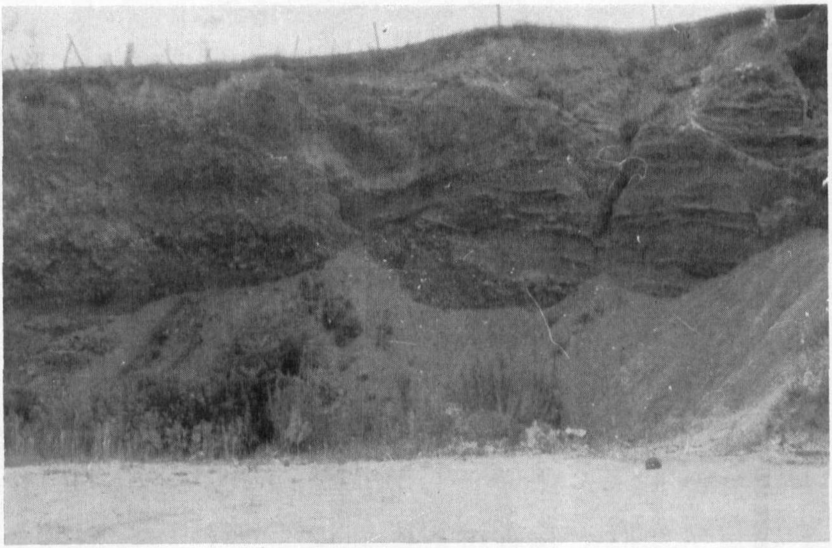


Figure 1. Stratified glacial till along Route 14, one mile north of East Randolph.

Figure 2. Glaciated valley of the Second Branch of the White River. View looking south from Southeast Hill School, Brookfield.

quartzite, (3) Twelve to fifteen miles of calcareous rock, and (4) Two to eight miles of mica schist and quartz-mica schist."

The third and fourth units in this sequence are on strike with formations whose type localities lie to the south. The third unit was correlated by White and Jahns (1950) with the Waits River formation, while the fourth unit and the type Gile Mountain formation were considered by them as synonymous.

White and Jahns (1950, p. 187) correlated the first calcareous unit with the Waits River formation. Tentatively, they assigned the second belt as belonging to the Gile Mountain formation and named it the Gile Mountain(?) pending more detailed work.

To the north in the Memphremagog quadrangle, Doll (1951) subdivided the first calcareous belt into the Ayers Cliff and the Barton River formations.

The non-calcareous unit (second unit of White and Jahns) east of the Ayers Cliff and Barton River formations was named the Westmore formation by Doll (1951, p. 33). At the time of his mapping no correlation had been established between these formations and the Waits River or Gile Mountain type formations to the east.

Dennis (1956, p. 16) retained the names Ayers Cliff and Barton River and designated them as members of the western band of the Waits River formation to distinguish between the eastern and western bands (units one and three of White Jahns) of dominant carbonate lithology. He also mapped the rocks on strike with Doll's Westmore formation as the Gile Mountain formation, believing that the two names were equivalent. Therefore, the name Westmore was dropped by him since the name Gile Mountain had precedence.

White and Jahns (1950), Doll (1951), and Dennis (1956) all considered the non-calcareous rocks (unit four of White and Jahns) of the type locality Gile Mountain formation to be the youngest in the Vermont sequence.

Murthy (1957, p. 22) also retained the name Barton River for the western-most band of calcareous rocks. However, he considered these rocks not as a member of the Waits River formation but as a separate formation and restricted the type Waits River formation to include only the carbonate rocks extending from the central and eastern parts of the East Barre quadrangle. Murthy retained the names Westmore and Gile Mountain for the two belts of noncalcareous lithology in the East Barre quadrangle (units two and four of White and Jahns). Murthy (1957, P. 31) concluded that "the stratigraphic position of the Westmore formation above the Barton River formation is not the same as the stratigraphic position of the Gile Mountain formation relative to the Waits River formation." He did, however, indicate that the Gile Mountain could be correlated with the Westmore formation. Stratigraphically, the Waits River formation is believed by Murthy (1957, p. 35) to be younger than the Barton River formation and to be the youngest unit in the Vermont sequence. The Waits River formation is restricted by him to be applicable only to those rocks occurring east of the Westmore formation.

The western band of the Gile Mountain formation has been determined, in the present study, to close structurally just south of the Randolph quadrangle. The present work also indicates that the two bands of the Waits River formation are the same stratigraphic unit.

In the Island Pond quadrangle, the two bands of the Gile Mountain formation again close together in the nose of a major fold (Bruce K. Goodwin, personal communication, 1959).

Therefore, the two units variously mapped as Barton River and/or Waits River are considered, in this report, as stratigraphically equivalent and are designated the Waits River formation (type locality-East Barre quadrangle). This formation is believed by the writer to be the youngest in the Vermont sequence. The two belts mapped as Westmore or Gile Mountain(?) and/or Gile Mountain are also believed equivalent stratigraphically and named the Gile Mountain formation (type locality-Strafford quadrangle).

The stratigraphic sequence as modified in the correlation of the stratigraphic units in east-central Vermont will be discussed in detail at the conclusion of the chapter on structural geology.

Ottauquechee Formation

Name and Distribution

The Ottauquechee formation was named by Perry in 1929 for a series of exposures in the township of Bridgewater along the Ottauquechee River.

The formation is poorly exposed in the Randolph quadrangle, cropping out along the west-central border of the quadrangle south of Rochester Mountain.

Description

The Ottauquechee formation within the Randolph quadrangle consists predominantly of graphitic black phyllites, graphitic phyllitic

TABLE I

CORRELATION CHART OF STRATIGRAPHIC UNITS

Townships of Richardson (1924)	Woodstock Quadrangle (Chang-1950)	Ludlow Quadrangle (Thompson 1950)	East Central Vermont (White and Jahns-1950)	Memphremagog Quadrangle (Doll-1951)	Hanover Quadrangle (Lyons-1955)	East Barre Quadrangle (Murthy-1958)	Randolph Quadrangle this report
					Littleton		
					Fitch		
					Clough		
					Ammonoosuc		
					Albee		
					Orfordville	Waits River	
					Meetinghouse	Standing Pond	
	Gile Mountain		Gile Mountain (=Gile Mtn?)	Westmore	Gile Mountain	Westmore	Waits River (Standing Pond)
Waits River limestone	Standing Pond / Waits River	Waits River	Waits River	Barton River / Ayers Cliff	Waits River	Barton River / Gile Mountain	Northfield = Meetinghouse / Shaw Mtn. / Gile Mountain
Memphrémagog Group slates and phyllites	Northfield	Northfield / Shaw Mtn.	Northfield / Shaw Mtn.	Northfield / Shaw Mtn.		Northfield? / Meetinghouse / Shaw Mtn.	
Missisquoi Group: Barnard Gneiss	Barnard	Barnard / Cram Hill	Cram Hill	Cram Hill'			Cram Hill / Barnard
Missisquoi Group: Sericite Schist / Quartzite / Hb'de Sch.	Missisquoi: upper / lower	Moretown	Arenites of the Braintree-Northfield Range				Moretown
Bethel Schist	Bethel	Stowe					Stowe
	Ottauquechee	Ottauquechee	Ottauquechee				Ottauquechee

▬▬ = Ordovician - Silurian boundary

TABLE II

ESTIMATED MODES OF THE OTTAUQUECHEE FORMATION

Rock	1	2
Quartz	40.4	31.7
Albite	6.6	0.3
Chlorite	35.8	41.3
Muscovite	4.8	18.1
Epidote	4.9	1.6
Graphite	5.2	6.1
Magnetite and Ilmenite	2.3	1.1
Tourmaline	tr	—
Number of counts	1315	1324

1. Banded quartz-chlorite-albite schist
2. Graphitic quartz-chlorite schist

schists, banded quartz-chlorite-albite schists, greenstones, and minor quartzites. The phyllites are thinly foliated, fine grained and the constituent minerals are not visible to the unaided eye except for an occasional biotite porphyroblast or cube of pyrite. The banded schists consist of alternating laminae of micaceous and granulose minerals. The average thickness of the laminae is about one-eighth inch. Quartz with small amounts of albite comprise the granulose laminae and chlorite and muscovite make up the micaceous laminae. Occasional porphyroblasts of albite are present in the schists.

Thick black vitreous quartzites which make up a considerable proportion of the lower part of the quadrangle are not exposed within the area.

Modes of the Ottauquechee formation are given in Table II.

The contact of the Ottauquechee schists and phyllites with the overlying Stowe formation is generally gradational. However, the contact with the Stowe is sharp where a greenstone member occurs at the top of the Ottauquechee formation in the vicinity of Mt. Olympus.

THICKNESS

The thickness of the Ottauquechee formation cannot be measured within the Randolph quadrangle since only the uppermost section is encountered. Osberg (1952), in the Rochester quadrangle to the west, estimates the thickness to range from 1,800 to 2,500 feet. To the south in the Woodstock area, Chang (1950) gives figures ranging from 2,600 to 3,600 feet.

Age and Correlation

Thus far, no fossils have been recognized in the Ottauquechee formation. Thompson (1950) correlated the formation with the Lower Cambrian black slates of the Schodack formation of the Taconic range. Osberg (1952) designated the Ottauquechee as lying between the eastern equivalents of the Lower Cambrian Cheshire and Monkton formations in the Green Mountain anticlinorium. The northward extension of the Ottauquechee formation into Quebec has been correlated with the Lower Cambrian Mansonville formation of Clark (1934, p. 11).

Tentatively, an age of Lower Cambrian has been assigned to the formation.

Stowe Formation

Name and Distribution

The name Stowe was first proposed by W. M. Cady but published by Osberg (1952) at Cady's suggestion.

Rocks of this lithology were first referred to as the Hydromica schist by Richardson (1921) and later renamed the Bethel schist (Richardson, 1924). These rocks were described in detail by Perry (1929).

The Bethel schist as mapped by Perry (1929) and Chang (1950) included the Stowe and portions of the overlying Moretown formation or what was earlier named the Missisquoi formation, a name since dropped from usage. The uppermost horizon of the Stowe has been determined to be stratigraphically lower than the base of the Missisquoi as used by Chang.

White and Jahns (1950) included the rocks of both the Stowe and the overlying Moretown formations under the general heading "Arenites of the Braintree-Northfield Range" pending more detailed investigation.

The greenstones in the Stowe formation were named the Brackett member by Osberg (1952) in the Rochester quadrangle and this designation has been followed in this report.

The Stowe formation crops out along the entire western margin of the Randolph quadrangle. Exposures are good.

Description

Two principal rock types characterize the Stowe formation in the Randolph quadrangle: pale-green, quartz-chlorite-albite-sericite schists with lenses of granular white quartz parallel to the schistosity and greenstones composed dominantly of quartz, albite, epidote, chlorite and carbonate.

The Stowe schists consist of bands, one to two millimeters thick, of quartz and albite separated by chlorite and muscovite. Poorly developed porphyroblasts of albite are common. In most localities the formation consists of distinctive lenticles of granular white quartz parallel to the schistosity. The lenticles are five to six inches long, a little more than an inch thick in their centers and taper at either end (Plate VI, Fig. 1 and 2).

The muscovite content of these schists is generally greater than the quartz content if the quartz lenticles are excluded, and muscovite and chlorite together generally exceed all quartz.

The rocks in the Stowe formation lying west of the garnet isograd show little lithologic variation. However, in the southwesterly exposures, where the garnet isograd (see Fig. 6) cuts across the formation, the quartz grains in the laminae of the schist are enlarged, all sericite is coarsened to muscovite and a much coarser grained rock becomes dominant.

Magnetite often appears on weathered surfaces as almost perfect octahedra up to two millimeters in diameter.

Greenstones are present throughout the formation interstratified with the schists. These beds, attaining a thickness of at least two hundred feet and an extent of no less than one mile, are shown on the geologic map (see Plate I). A number of cross-cutting greenstone dikes are also present.

The majority of the greenstones show a distinctive compositional banding with laminae between one-eighth and one-half inch in thickness (Plate VII). Individual bands are massive and they lack well-defined schistosity. Some bands are extremely rich in calcite or ankerite and resemble, in places, the weathered surface of the limestones in the Waits River formation. Nodules of nearly pure epidote are present up to four inches in thickness. A strict sedimentary origin seems unlikely since the composition of the greenstones closely approaches that of an andesite or basalt.

For more than half the length of the quadrangle the contact between the Stowe and overlying Moretown formation is readily determined by the presence of thick greenstone units (see Plate I). To the south, greenstone is absent and the contact is gradational and difficult to determine even in areas with good exposures. Cady (1956) indicates a transition zone between the Stowe and Moretown formations as much as five hundred feet thick in the Montpelier quadrangle.

PLATE VI

Figure 1. Large lenticle of granular white quartz paralleling the schistosity in the Stowe schists.

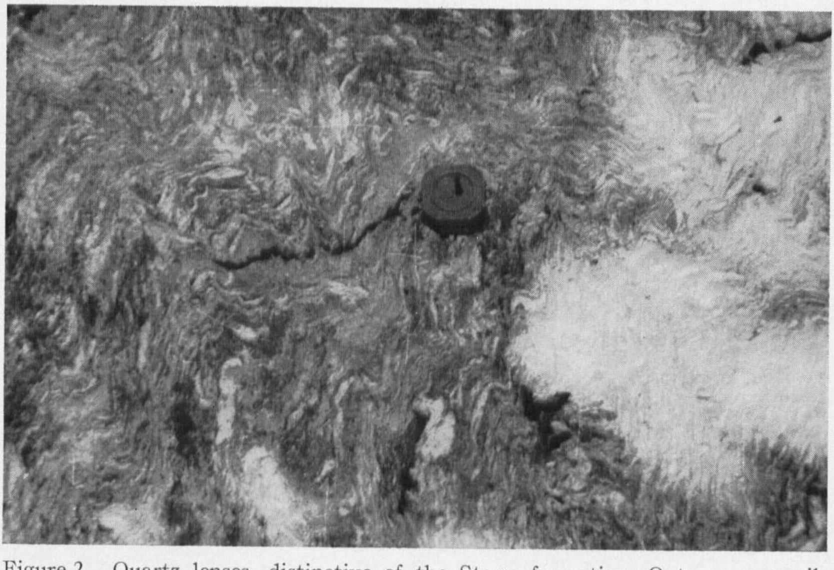


Figure 2. Quartz lenses, distinctive of the Stowe formation. Outcrop one mile northwest of Braintree.

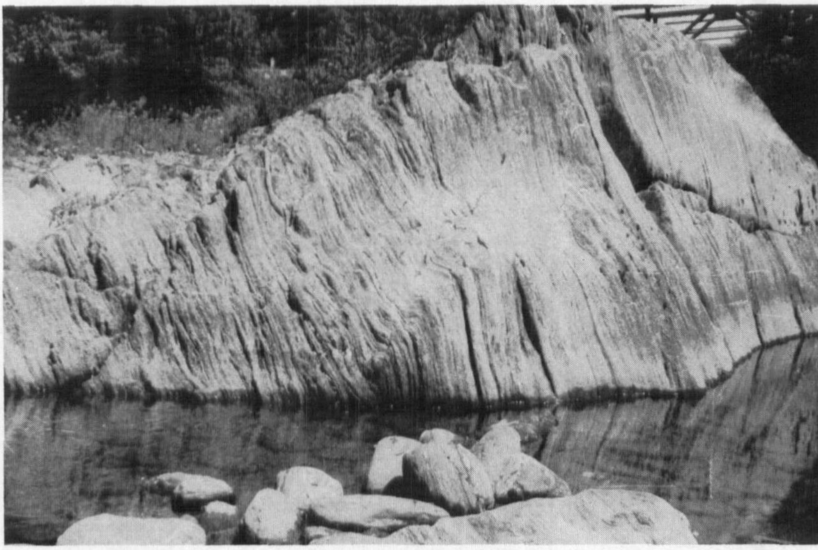


PLATE VII

Compositionally banded Brackett member of the Stowe formation. Exposure in the Third Branch of the White River, with the Riford Brook road bridge in the background.

A well-developed schistosity, which is a bedding schistosity, is prominent throughout the rocks in the Stowe formation. In certain areas, this schistosity is transected by a later schistosity.

Modes of the Stowe formation and Brackett member are given in Table III.

Thickness

The thickness of the Stowe formation of the Randolph quadrangle can be measured only in the vicinity of Rochester Mountain where its contact with the underlying Ottauquechee formation is exposed. At this point, the apparent thickness is of the order of 10,500 feet. The formation thins to the south where Chang (1950) has estimated a thickness of 2,000 feet. To the north in the Barre quadrangle, Jahns has noted a thickness of over 14,000 feet.

Age and Correlation

No fossils have been found in the Stowe formation. Fowler (1949) and Thompson (1950) correlated the Stowe with the Lower Cambrian

TABLE III

ESTIMATED MODES OF THE STOWE FORMATION

Rock	1	2	3	4	5
Quartz	26.3	40.6	36.0	14.3	11.2
Albite	10.5	5.8	17.7	13.2	22.3
Chlorite	13.7	43.7	23.1	16.1	27.1
Muscovite	38.1	2.8	18.7	3.5	2.2
Biotite	—	0.6	0.4	1.1	—
Clinozoisite	4.7	—	—	—	—
Epidote	—	3.8	0.7	19.3	22.5
Garnet	4.6	—	—	—	—
Calcite	—	0.1	1.3	29.3	12.8
Tourmaline	tr	—	—	—	—
Apatite	tr	—	—	—	—
Magnetite and Ilmenite	2.2	2.2	2.1	0.5	0.7
Graphite	—	0.2	0.1	—	—
Actinolite	—	—	—	2.7	1.2
Number of counts	1697	1406	1421	1465	1382

1. Muscovite-quartz-chlorite-albite schist
2. Chlorite-quartz-albite-epidote schist
3. Quartz-chlorite-muscovite-albite schist
4. Quartz-albite-calcite-epidote-chlorite schist (Brackett member)
5. Chlorite-albite-epidote-calcite schist (Brackett member)

Wallace Ledge slate of the Taconic area which conformably overlies the Schodack formation. The black slates of the Schodack formation have been correlated with the Ottauquechee formation (ref. cit.). Tentatively then, the Stowe formation is Lower Cambrian in age.

Moretown Formation

NAME AND DISTRIBUTION

The name Missisquoi Group (Richardson, 1924) was the first to be used for the sericite schists, quartzites, hornblende schists and chlorite schists stratigraphically above the Stowe formation (the Bethel schist of Richardson). In 1927, in the Woodstock area, Richardson subdivided the rocks of the Missisquoi group into two units: a lower sericite schist and an upper sericitic quartzite. Perry (1929) and Chang (1950) also recognized two units and separated the Missisquoi into the Lower Member and the Upper Member.

Since the boundaries of the Missisquoi Group were too obscure and arbitrary as defined, the name Moretown was proposed by Cady (1956). This formation was named for a series of rocks cropping out in eastern Moretown township on the eastern side of the Northfield Mountains in the Montpelier quadrangle.

Prior to the detailed description and stratigraphic analysis of the Stowe and Moretown formations the general term "Arenites of the Braintree-Northfield Range" was used by White and Jahns (1950) for the rocks lying stratigraphically between the Ottauquechee and Cram Hill formations. According to their description (White and Jahns, 1950, p. 184), the Moretown formation would be included in the upper part of the arenite sequence of the Braintree-Northfield range from approximately the top of the slate and phyllite horizon to the base of the overlying Cram Hill formation.

In the southwestern part of the Randolph quadrangle the central portion of the Moretown formation has been mapped separately as the Whetstone Hill member (Thompson, 1950). The base of the Whetstone Hill member coincides with the lower member of the Missisquoi formation of Chang (1950) and the base of the Missisquoi Group as mapped by Perry (1929).

The Moretown formation is exposed through the entire length of the western portion of the Randolph quadrangle. Extensive exposures of the Moretown pinstripe are accessible along Route 12-A, a mile and a half west of the village of Randolph (Plate VIII). The Whetstone Hill member extends from Blueberry Mountain (northwest of Bethel) southward into the Woodstock quadrangle, dividing the granulite along the strike into an eastern and a western unit. The Whetstone Hill member is well exposed where it crosses the White River and on Delectable Mountain.

Description

The most distinctive and abundant rock type in the Moretown formation is a quartz-chloritic-albite-sericite granulite referred to as the "pinstripe" by students of Vermont geology. Micaceous quartzites are common. Carbonaceous slate, phyllite and greenstones are present only locally.

The granulite is characterized by thick granular laminae separated by paper-thin, darker colored micaceous partings and it is this feature which produces the effect described as "pinstripe." The granular laminae range from a fraction of an inch to one-half inch in thickness. Quartz and albite make up nearly ninety per cent of the volume of the granular

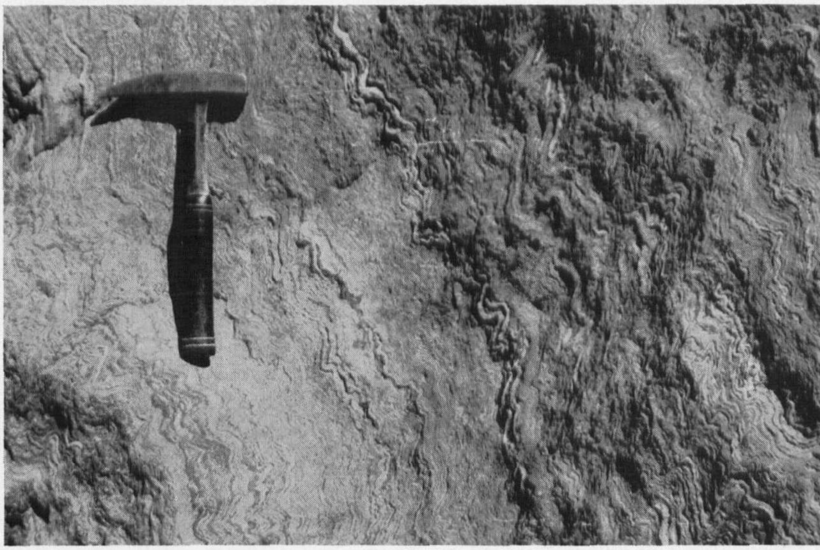


PLATE VIII

Strongly crenulated Moretown pinstripe, along Route 12-A, two miles west of Randolph.

laminae with chlorite, sericite and epidote constituting the major proportion of the thin laminae. The quartz and albite in the granular laminae are commonly anhedral and are elongated about parallel to the schistosity. The sericite and chlorite in the granular and micaceous laminae also parallel the schistosity. Garnet occurs within the micaceous laminae to the south.

The pinstripe appears to be of primary origin in the formation as the crude schistosity produced by the pinstripe is concordant with the bedding, and, in certain horizons, a slip cleavage distinctly cuts across these laminations.

The Whetstone Hill member of the Moretown formation consists of black phyllites and black to dark grey sericite-garnet-biotite-quartz schists. Tourmaline is an abundant accessory within these rocks and finely disseminated albite and quartz are present in minor quantities.

Typical modes of the Moretown formation appear in Table IV.

Thickness

In the northern part of the Randolph quadrangle, the Moretown formation is estimated to be more than 8,500 feet thick. Due to the tight

TABLE IV

ESTIMATED MODES OF THE MORETOWN FORMATION

Rock	1	2	3	4	5
Quartz	44.0	48.5	46.5	9.0	6.0
Albite	9.6	—	16.6	0.9	2.8
Chlorite	19.3	18.3	5.7	19.2	15.1
Sericite	19.2	21.9	24.7	57.6	50.9
Epidote	5.1	—	5.3	0.5	—
Biotite	1.1	9.3	—	5.6	16.7
Magnetite	1.8	1.9	1.2	1.5	0.4
Graphite	—	—	—	4.4	—
Apatite	tr	—	—	—	—
Tourmaline	—	tr	—	1.1	2.1
Garnet	—	—	—	—	6.0
Number of counts	1764	1670	1367	1567	1424

1. Quartz-chlorite-albite-sericite granulite
2. Impure quartzite
3. Quartz-sericite-albite pinstripe granulite
4. Black phyllite (Whetstone Hill member)
5. Black sericite-garnet-biotite phyllitic schist (Whetstone Hill member)

folding and crinkling a thickening factor of over two and one-half has been estimated. In the southern part of the quadrangle, where the Whetstone Hill member separates the granulite into two units, the western pinstripe belt (see Plate I) has been estimated to be approximately 11,200 feet thick, the Whetstone Hill member 2,100 feet thick and the eastern pinstripe belt 2,250 feet thick. The thickness of the Moretown formation in the southern part of the Randolph quadrangle would then be 15,550 feet.

AGE AND CORRELATION

Thompson (1950) noted the lithologic similarity of the Moretown formation with the Savoy schist of Massachusetts and considered the two continuous.

Others have noted the distinctive pinstripe appearance of the Albee formation of western New Hampshire and have been tempted to correlate the Moretown with it.

No formation in the Taconic sequence seems to correlate with the Moretown, and since no fossils have been found, the Moretown has tentatively been assigned an early Ordovician age, on stratigraphic position alone.

Cram Hill Formation

Name and Distribution

Currier and Jahns (1941) gave the name Cram Hill to rocks on and about Cram Hill southeast of Roxbury village in the Barre quadrangle. Southward, on strike from the type locality, similar rocks have been assigned to the Cram Hill formation in the Randolph quadrangle.

Currier and Jahns (1941) also named the distinctive basal quartzite of this formation as the Harlow Bridge member.

The Cram Hill formation extends from the northern border of the quadrangle to about one mile and one-half south of Randolph village. From this point it grades rapidly into the Barnard and the Moretown formations. Presumably, this gradation refers to a facies change.

The basal Harlow Bridge quartzite terminates as a unit of mappable width one mile and one-half below Mud Pond on Braintree Hill.

Description

There are three principal interbedded rock types within the formation: (1) splintery greenish-grey phyllite, (2) greenstone, and (3) feldspathic quartz-biotite-sericite schist. Locally black, siliceous schists and quartzites are present also.

Phyllite dominates in the northern part of the quadrangle. Along strike to the south, the greenstones predominate.

The splintery, greenish-grey phyllite is composed chiefly of quartz, sericite and chlorite. Locally it grades into gray to black slates. The greenstones are both massive and schistose and albite, epidote, chlorite and calcite comprise the bulk of these rocks. These greenstones probably are metamorphosed flows. The Cram Hill formation is also cut by dikes of greenstone of similar composition.

The thick Harlow Bridge basal quartzite has not been mapped south of the latitude of Peth. However, there is a marked appearance, in the lower part of the formation, of splintery phyllite interbedded with quartzite southward.

Modes of the Cram Hill formation are given in Table V.

Thickness

The thickness of the Cram Hill formation in the northern part of the Randolph area is of the order of 2,400 feet, thinning to the south to approximately 1,600 feet in the vicinity of Randolph village.

Age and Correlation

The Cram Hill formation in the Randolph quadrangle rapidly grades by facies into the Barnard gneiss and, in part, into the Moretown formation. The Barnard gneiss continues southward along strike through the Randolph and Woodstock quadrangles. In the upper part of the Ludlow quadrangle the Barnard gneiss grades back into Cram Hill lithology (Thompson, 1950). The Cram Hill formation and Barnard gneiss are therefore correlative.

The graptolitic middle Ordovician Magog slates of southern Quebec (Clark, 1934) have been correlated by Currier and Jahns (1941) with the Cram Hill formation. It has also been correlated with the Normanskill formation of the Taconic Sequence (Black River to lower Trenton) and the Hawley formation of Massachusetts (Thompson, 1950).

These correlations suggest a middle Ordovician age for the Cram Hill formation.

Barnard Gneiss

Name and Distribution

In 1927, Richardson named the Barnard gneiss for a belt of rocks in the township of Barnard in the Randolph and Woodstock quadrangles within the sericite quartzites of his Missisquoi Group.

These rocks are stratigraphically equivalent to the Cram Hill formation.

The Barnard gneiss is well exposed two miles south from the village of Randolph into the Woodstock quadrangle.

Description

The Barnard gneiss includes biotite gneiss, hornblende gneiss, calcareous hornblende gneiss, garnetiferous hornblende gneiss, greenstone, amphibolite and what appears to be a volcanic tuff. The contact of these rocks with the underlying Moretown formation is transitional. Amphibolitic beds are occasionally present in the lower part of the Barnard sequence helping to differentiate the contact. However, the transition from the rocks of the Moretown formation into the Barnard is usually determined by the fact that the beds become more feldspathic (at least twenty-five per cent by volume) in the lower part of the Barnard gneiss.

The Barnard gneiss is medium to coarse grained, well foliated and locally it is sheared. The essential constituents are quartz, albite-oligo-

Table V

ESTIMATED MODES OF THE CRAM HILL FORMATION

Rock	1	2	3	4
Quartz	23.4	7.7	19.7	74.1
Albite	4.2	42.9	34.1	7.4
Chlorite	29.8	11.6	4.6	3.8
Muscovite	—	—	—	11.1
Biotite	—	19.7	29.0	—
Epidote	0.8	6.2	0.2	2.5
Sericite	39.2	9.7	9.9	—
Magnetite	2.4	2.2	0.5	0.8
Graphite	0.3	—	—	—
Calcite	—	tr	2.0	—
Apatite	—	—	—	0.2
Garnet	—	—	—	0.3
Number of counts	1496	1459	1241	1659

1. Splintery, grey, sericitic phyllite
2. Feldspathic biotite-quartz-chlorite schist
3. Feldspathic-quartz-biotite schist
4. Quartzite (Harlow Bridge member)

clase, biotite, and hornblende with occasional almandine garnet. Minor constituents include epidote, chlorite, muscovite and calcite. In some occurrences calcite is sufficiently abundant to rank as a major constituent.

The plagioclase generally shows combined albite and pericline twinning and contains numerous inclusions of sericite and epidote. The inclusions are often arranged in a zonal pattern and are most abundant in the centers of the grains.

Augen of calcite are frequently visible within the greenstones in the Barnard gneiss (Plate IX, Fig. 2).

Relics of altered phenocrysts of albite are common in the gneisses, and small segregations of epidote in the amphibolite often suggest amygdales. Most of the lithologic types in the Barnard gneiss lie within the compositional range of common igneous rocks and many approximate the composition of a quartz keratophyre.

Modal analyses of the Barnard gneiss are given in Table VI.

Thickness

The average thickness of the Barnard gneiss in the Randolph quadrangle is estimated to be of the order of 6,000 feet. The thickness in-

Table VI

ESTIMATED MODES OF THE BARNARD GNEISS

Rock	1	2	3	4
Quartz	16.7	20.1	46.7	25.4
Albite-Oligoclase	30.9	13.9	33.3	32.1
Orthoclase	—	—	0.8	—
Hornblende	—	—	—	11.4
Biotite	29.4	1.0	0.3	—
Chlorite	1.4	11.0	13.1	10.2
Muscovite	4.6	6.4	5.6	—
Sericite	—	—	—	0.7
Epidote	9.3	14.6	0.3	0.8
Calcite	5.7	32.0	—	19.4
Magnetite	2.0	1.0	tr	0.1
Pyrite	—	—	tr	—
Number of counts	1492	1260	1563	1995

1. Biotite gneiss
2. Calcareous greenstone schist
3. Porphyroblastic tuff
4. Calcareous hornblende-chlorite gneiss

creases from the latitude of Bethel village (3,900 feet) southward to 8,400 feet.

Age and Correlation

Since the Barnard gneiss and the Cram Hill formation are considered stratigraphically equivalent, the discussion on the age and correlation of the Cram Hill formation is applicable.

The Barnard gneiss is assigned a middle Ordovician age.

Shaw Mountain Formation

Name and Distribution

The name Shaw Mountain was adopted by Currier and Jahns (1941) for beds lying unconformably above the Cram Hill formation at the approximate horizon of Richardson's "Cambrian-Ordovician" boundary in the Barre quadrangle. Although the formation is the thinnest one exposed in east-central Vermont, it is important stratigraphically as a lithologic and fossiliferous horizon.

The outcrop of the Shaw Mountain formation extends intermittently

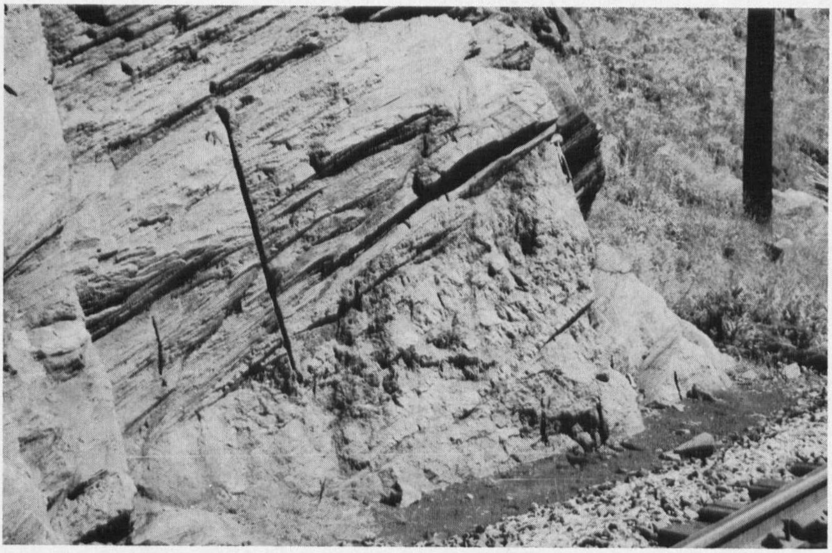


Figure 1. East dipping contact between the biotite gneiss and overlying greenstone in the Barnard gneiss. Railroad cut east of the Camp Brook Road.

Figure 2. Calcite augen in the greenstone in the Barnard gneiss. Same locality as Plate IX, Figure 1.

north from the village of Bethel in about the center of the Randolph quadrangle. It has not been reported in the Woodstock quadrangle to the south but reappears again in the northern part of the Ludlow quadrangle still farther south.

Description

At the type locality the Shaw Mountain formation consists of three lithologic units: (1) a basal conglomerate resting unconformably on the Cram Hill formation, (2) a sericite schist which in places is tuffaceous or calcareous, and (3) an upper crinoid-bearing limestone.

Only one small exposure of the quartz conglomerate was observed in the Randolph quadrangle—that being on Ferry Hill. The upper limestone was mapped at a few localities but it is thin and of limited extent. A crinoid stem was reported from the saddle on Ferry Hill by Currier and Jahns (1941) but no fossils have been observed within the formation by this writer. The bulk of the Shaw Mountain in the Randolph quadrangle consists of sericite schists which are locally calcareous and dominantly tuffaceous. The sericite schists and the white volcanic tuffs are good horizon markers lying between the Northfield formation and the Cram Hill formation or Barnard gneiss.

The tuffaceous rocks are fine grained and are composed dominantly of quartz, orthoclase, albite and sericite. When fresh, the rock is white to greenish-white but most often it has weathered to a tan or light brown and is characterized by small limonite segregations on the weathered surface. Biotite porphyroblasts are common.

In the Randolph quadrangle the Shaw Mountain formation appears to rest unconformably on the Cram Hill formation and Barnard gneiss to the south.

Modal analyses for the Shaw Mountain formation are given in Table VII.

Thickness

The Shaw Mountain formation is estimated to range from ten feet to three hundred feet thick. The thickness, however, changes markedly in short distances parallel to the strike and, in general, is less than fifty feet thick.

Correlation

Thompson (1950) traced the Shaw Mountain unconformity to the base of the Goshen schist in Massachusetts. The Goshen schist rests on top of the Hawley formation which has been correlated with the Cram Hill formation and the Barnard gneiss.

Northfield Formation

Name and Distribution

The rocks now known as the Northfield formation were first mapped in northeastern Vermont by Richardson (1906) as the "Memphremagog slates." This lithology was also referred to as the "clay slate" by Hitchcock (1861). In central Vermont, they were designated by both Richardson (1927) and Perry (1929) as the "Randolph phyllite." Currier and Jahns (1941) redefined them as the Northfield slate to include a sequence of gray slates with minor lenses of crystalline limestone which lie unconformably above the Shaw Mountain formation and conformably beneath the Waits River formation in the Barre quadrangle. These beds were later raised to formation status (Chang, 1950) due to the increasing abundance of phyllite in the formation to the south.

The Northfield formation is a readily recognized unit throughout the length of the Randolph quadrangle. The best exposures are located on Braintree Hill and just east of the village of Bethel.

Description

The Northfield formation in the Randolph quadrangle consists of gray slate and phyllite which characteristically weather yellow-brown on cleavage surfaces, and minor interbedded crystalline limestone which is particularly abundant near the top of the formation. Thin arenaceous bands are also prominent locally. The slates become less fissile to the south and grade into phyllites along the strike due to the regional increase in the grade of metamorphism to the southeast. No basal conglomerate, as described in the Barre quadrangle (Currier and Jahns, 1941), was noted, but the lower contact, where exposed, suggests a slight angular discordance both with the Shaw Mountain formation and the Barnard gneiss. The contact of the Northfield formation with the overlying Waits River formation is gradational.

The slates are fine-grained and contain approximately equal proportions of quartz and sericite which make up approximately eighty per cent of the rock. Minor amounts of chlorite, biotite and albite are present. Graphite and ilmenite are minor constituents which attribute to the color of the rock.

The phyllites of the Northfield formation contain considerably more sericite and less quartz and feldspar than the slates. Perfect cubes of pyrite occur locally in the phyllites of the Northfield. The phyllitic layers are intensely plicated with prominent garnet dodecahedra usually one-eighth of an inch in diameter.

Modal analyses of the slates and phyllites of this formation are given in Table VII.

Thickness

The Northfield formation is estimated to range between 500 and 1,250 feet thick in the Randolph quadrangle. Chang (1950) has estimated an average thickness of 1,000 feet for the formation in the Woodstock quadrangle, and in the Barre quadrangle, where the formation widens out, a thickness of approximately 4,000 feet has been proposed (White and Jahns, 1950, p. 191).

Correlation

In Massachusetts, Northfield lithology has been mapped as the Goshen schist while to the north, in Quebec, Clark (1934) has maintained a possible correlation with the lower part of the Tomifobia slates.

The Meetinghouse slate, which lies between the Monroe line and the eastern band of the Gile Mountain formation, has been suggested as a correlative of the Northfield formation (Murthy, 1957; Eric and Dennis, 1958).

Gile Mountain Formation

Name and Distribution

The type locality for this formation (Doll, 1944, p. 18) is in the southern part of the Strafford quadrangle, two and a half miles southwest of Copperas Hill. Stratigraphically, Doll defined the rocks of the Gile Mountain formation as lying between the Meetinghouse slate to the east and the Waits River formation to the west.

Rocks of the Waits River and Gile Mountain formations were originally included by Hitchcock (1861, pp. 475–488) under the title of "calciferous mica schist." Richardson (1898) clarified the early terminology somewhat by introducing the name Washington limestone for the calcareous units, and Bradford schist for the dominantly noncalcareous units. Later, since both names were pre-occupied, Richardson (1906, p. 115) distinguished these two units as the Waits River limestone and the Vershire schist, respectively.

TABLE VII

ESTIMATED MODES OF THE NORTHFIELD AND SHAW MOUNTAIN FORMATIONS

Rock	1	2	3	4
Quartz	40.4	39.1	19.2	41.0
Albite	3.5	18.1	—	4.8
Orthoclase	—	14.5	—	—
Sericite	24.0	21.3	66.7	38.9
Chlorite	8.4	4.0	3.0	6.2
Biotite	—	0.5	0.6	3.6
Epidote	1.1	2.3	—	1.4
Calcite	22.7	—	—	—
Apatite	tr	—	—	—
Garnet	—	—	6.4	—
Magnetite	tr	0.3	—	—
Ilmenite	—	—	2.1	2.0
Graphite	—	—	1.9	2.1
Number of counts	1287	1325	1646	1408

1. Calcareous quartz-sericite schist (Shaw Mountain)
2. Quartz feldspathic sericite tuffaceous schist (Shaw Mountain)
3. Garnetiferous phyllite (Northfield)
4. Slate (Northfield)

The ill defined Vershire schists of Richardson were later correlated with the Gile Mountain formation in the Strafford quadrangle by Doll (1944).

The western belt of the Gile Mountain formation follows along the entire eastern margin of the Randolph quadrangle and terminates structurally about a mile southwest of East Barnard in the northeast part of the Woodstock quadrangle. Topographically, the formation is a persistent ridge maker throughout the quadrangle.

DESCRIPTION

The lithologies of the Gile Mountain formation exposed in the Randolph quadrangle are very much the same as those described for the eastern belt of the Waits River formation except that the crystalline limestones are more abundant in the Waits River formation. The dominant rock types of the Gile Mountain formation include quartz-mica schists, black phyllites and micaceous quartzites. Minor proportions of sandy phyllites, siliceous crystalline limestones and feldspathic quartz-biotite schists are present locally. Beds of black quartz-calcite schists have been traced along the strike for a considerable distance.

Minor amphibolite beds are present along the eastern margin of the Gile Mountain formation in the Randolph quadrangle.

Modal analyses of the Gile Mountain formation are given in Table VIII.

The lithology of the western band of the Gile Mountain formation can be subdivided in the Randolph quadrangle into three units. Argillaceous phyllites and phyllitic schists are found along both the eastern and western contacts with the Waits River formation. The central unit is composed of dominantly micaceous quartzites and quartz-mica schists. A similar division has also been recognized in the East Barre quadrangle by Murthy (1957), but because of greater regional metamorphism, the argillaceous zones are dominantly micaceous schists in the East Barre quadrangle.

The micaceous quartzites of the Gile Mountain formation contain approximately sixty per cent anhedral grains of quartz in many exposures. Biotite and muscovite are common associates of the quartz along with minor shreds of chlorite. Euhedral porphyroblasts of garnet are common. Micaceous quartzite beds are as much as forty feet thick but generally are about eighteen inches thick. They are interbedded with schists and phyllites.

Impure recrystallized limestones, indistinguishable from those in the Waits River formation, are found in the Gile Mountain formation. These beds are particularly abundant near the contact with the Waits River formation making it difficult to delineate the contact.

The micaceous schists in the Gile Mountain formation are usually porphyroblastic (biotite and garnet) and rich in quartz. Anhedral muscovite, biotite and chlorite vary in abundance. The texture of the groundmass coarsens to the east.

Thickness

The thickness of only the western belt of the Gile Mountain formation can be determined in the Randolph quadrangle. The total outcrop width of this unit varies considerably along strike, but the average is approximately 14,000 feet, narrowing to the south where the formation closes structurally. Although large-scale repetition of beds by the minor folds have considerably thickened the formation, a thickness ranging between 5,200 and 5,750 feet has been estimated.

Table VIII

ESTIMATED MODES OF THE GILE MOUNTAIN FORMATION

Rock	1	2	3	4	5
Quartz	49.9	19.5	58.9	46.1	28.6
Albite-Oligoclase	—	24.8	0.8	25.5	2.8
Chlorite	—	35.4	3.1	0.5	26.5
Biotite	22.5	6.8	25.9	23.0	32.9
Muscovite	7.7	9.8	11.2	4.3	1.3
Calcite	19.8	—	—	—	—
Magnetite	tr	0.7	tr	0.3	0.9
Garnet	—	3.9	—	0.4	7.0
Actinolite	tr	—	—	—	tr
Number of counts	1326	1417	1305	1427	1564

1. Quartzitic biotite-calcite schist
2. Chloritic-mica-garnet phyllitic schist
3. Micaceous quartzite
4. Feldspathic quartz-biotite schist
5. Porphyroblastic garnetiferous-biotite-chlorite schist

Correlation

Cooke (1950) correlated the upper part of the St. Francis group in Quebec with the Gile Mountain formation. In Massachusetts, a correlation has been suggested between the Leyden argillite and the Gile Mountain formation (Thompson, 1950).

In southeastern Vermont, the Gile Mountain formation thins abruptly and Lyons (1955, p. 143) has suggested that the Gile Mountain beds interfinger with the lower part of the Orfordville formation of the New Hampshire sequence.

Standing Pond Volcanics

Name and Distribution

The name Standing Pond was introduced by Doll (1944, p. 17) for the amphibolite horizon in the Strafford quadrangle which separates the calcareous rocks of the Waits River formation from the non-calcareous rocks of the Gile Mountain formation. Doll considered these rocks to be a member of the Waits River formation and named them the Standing Pond amphibolites.

The unit was subsequently named the Standing Pond volcanics by

Billings, *et al.*, (1952, p. 39) since the amphibolites vary lithologically along strike away from the type locality due to changes in the grade of metamorphism. Another reason for favoring the name Standing Pond volcanics is that away from the type locality, the volcanics are not confined to the "Waits River-Gile Mountain" contact as defined by Doll (1945).

The outcrops of the Standing Pond volcanics in the southeasternmost part of the Randolph quadrangle are exposed for less than a mile. The volcanic rocks separate the eastern band of Waits River from the eastern belt of the Gile Mountain formation.

Description

The most abundant lithologies of the Standing Pond volcanics in the Randolph quadrangle are garnetiferous amphibolites and coarse-grained hornblende schists. Minor fine-grained needle amphibolites are also present (Plate X). There is a slight preferred parallel orientation of the hornblende crystals in the coarser hornblende schists.

Hornblende generally comprises about sixty per cent of the fine-grained needle amphibolites and approximately thirty per cent of the hornblende and hornblende-garnet schists.

Intensely shattered porphyroblasts of almandine garnet up to an inch and one-half in diameter are present in the garnetiferous amphibolites and schists.

Oligoclase-andesine is present as a major constituent in the lithologies of the Standing Pond volcanics. Quartz is abundant in the schists but very minor in the amphibolites and minor quantities of epidote, chlorite, muscovite, biotite, calcite and magnetite are normally present in all the rocks.

Modal analyses of Standing Pond volcanics are listed in Table IX.

Whether these rocks were originally flows or intrusives is not known. Dennis (1956, p. 22), however, described the occurrence of pillow lavas at this horizon in rocks mapped as Standing Pond in the Lyndonville quadrangle. The modal analyses of these rocks of probable volcanic origin are richer in quartz than would be expected for a flow, suggesting the possibility of a sediment rich in tuffaceous material.

Thickness

The thickness of the Standing Pond volcanics is estimated to be about 450 feet in the Randolph quadrangle. To the northeast in the Strafford quadrangle, Doll (1944) estimated the thickness to range from ten to

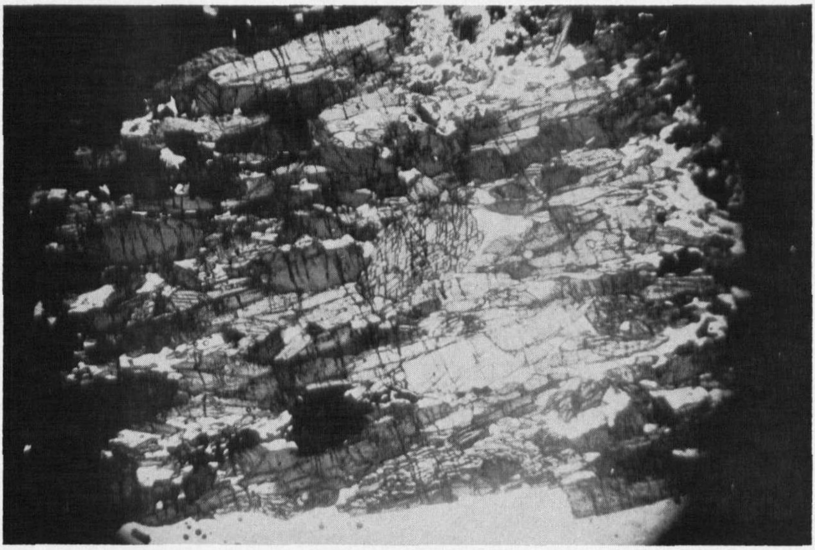


PLATE X

Photomicrograph of oriented hornblende crystals in the needle amphibolite of the Standing Pond volcanics. (X12)

three hundred feet, whereas to the southeast, in the Hanover quadrangle, a thickness ranging from 125 to 650 feet has been reported by Lyons (1955).

Waits River Formation

Name and Distribution

The rocks comprising the Waits River formation were first named the "calcareo-mica slate" (C. B. Adams, 1845, p. 49). Later Hitchcock (1861, pp. 475–488) mapped this formation as the "calciferous mica schist." The name Waits River was introduced by Richardson (1906, p. 86) for exposures at Waits River, Vermont, in the East Barre quadrangle. Richardson designated these rocks as the Waits River limestones. Currier and Jahns (1941, p. 1491) considered the name Waits River limestone inadequate. The unit so mapped contained not only crystalline limestones, but considerable quantities of phyllite and mica schists as well and the Waits River was elevated to formation status.

Two bands of the Waits River formation are exposed in the Randolph quadrangle and are separated by the Gile Mountain formation.

TABLE IX

ESTIMATED MODES OF THE STANDING POND VOLCANICS

Rock	1	2	3
Quartz	17.7	0.3	26.7
Oligoclase-Andesine	28.7	17.1	16.9
Biotite	4.7	6.9	10.0
Muscovite	10.5	1.7	—
Sericite	—	—	1.6
Chlorite	8.4	4.6	5.1
Epidote	—	2.0	2.2
Hornblende	27.8	60.0	31.2
Actinolite	—	tr	—
Calcite	tr	4.3	1.0
Garnet	tr	1.1	2.6
Magnetite	2.1	1.8	2.7
Tourmaline	tr	—	—
Number of counts	1593	1391	1214

1. Hornblende schist
2. Needle amphibolite
3. Hornblende-garnet schist

The western band of the Waits River formation extends in a north-south trending outcrop belt following, for the most part, the Third Branch of the White River and underlying the rolling topography of Hebard, Fish and Quarry Hills. This belt is bordered on the west by the Northfield formation and on the east by the Gile Mountain formation.

The eastern unit of the Waits River formation lies east of the western band of the Gile Mountain formation and extends eastward into the Strafford quadrangle. In the northeastern portion of the Woodstock quadrangle, the eastern and western units of the Waits River formation join southwest of East Barnard village.

DESCRIPTION

The rocks in the two bands of the Waits River formation are dominantly calcareous, but differ somewhat in lithology due to metamorphism. The western band is composed of the following interbedded rock types, in order of decreasing abundance: (1) thick and thin bands of blue-grey recrystallized impure limestone which is often quite siliceous. The limestones have all been well recrystallized and correctly should be termed marbles. Due to long established local usage, they will be referred to as impure crystalline limestones because of their poor commercial quality as compared to the marbles found in western Vermont. These rocks are interbedded with, (2) fine-grained black phyllites which, in most instances, show porphyroblasts of almandine garnet, (3) minor quartzites and micaceous quartzites.

In the eastern band, the siliceous impure crystalline limestones are the dominant rock type. Garnetiferous black phyllites are less abundant than in the western band, and quartz-biotite schists, quartz-calcite schists and quartzitic beds are more prevalent and are interbedded with the calcareous units. Numerous interbeds of feldspathic quartz-biotite schist are also present.

Although the calcareous horizons make up sixty to seventy per cent of the Waits River formation, they are more common in the lower part of the formation. The individual interbeds of limestone range in thickness from about four inches to over six feet. The normal thickness, however, is approximately one foot. As the crystalline limestones become richer in mica they grade into calcareous schists.

The siliceous limestones contain abundant recrystallized calcite which normally makes up at least sixty per cent of the volume of the rock. Quartz is always present in excess of ten per cent and most of the impurities have been recrystallized to chlorite and the micas. Disseminated graphite and magnetite are always present but their quantities are not constant.

Table X presents several modal analyses for the formation.

Thickness

Considerable plastic flowage along with intense minor folding are believed to have increased the thickness of the Waits River formation considerably.

The western band of the Waits River formation in the Randolph quadrangle is estimated to be between 5,500 and 9,200 feet thick. The upper contact of the eastern band is not exposed in the Randolph quadrangle and no estimate of its thickness could be made. To the south in the Woodstock quadrangle, Chang (1950) estimated a thickness of 2,500 feet. White and Jahns (1950, p. 191) estimated an apparent thickness for the eastern and western units of approximately 20,000 feet.

Correlation

The Waits River formation has been traced northward by Cady and Doll into the Tomifobia slates (Ambrose, 1943) of southern Quebec.

TABLE X

ESTIMATED MODES OF THE WAITS RIVER FORMATION

Rock	1	2	3	4
Quartz	30.5	15.2	1.0	63.3
Albite-Oligoclase	8.8	1.6	—	2.6
Chlorite	3.9	3.3	10.6	0.8
Muscovite	52.0	—	5.9	—
Sericite	—	6.9	—	3.5
Biotite	—	0.8	21.3	22.4
Calcite	0.1	69.1	57.7	—
Epidote	0.1	0.3	—	—
Garnet	4.1	—	—	6.7
Magnetite and Graphite	0.6	2.7	3.6	—
Magnetite	—	—	—	0.7
Sphene	—	—	—	tr
Number of counts	1360	1494	1221	1771

1. Garnetiferous phyllite
2. Siliceous impure crystalline limestone
3. Black biotite-chlorite schistose limestone
4. Garnetiferous quartz-biotite schist

Age of Formations Above the Cram Hill

The Cram Hill formation is, at present, the most reliably dated unit in east-central Vermont. It is the same stratigraphic unit as the Magog slate in southern Quebec (Cooke, 1950, pp. 46–48) which has yielded a graptolite fauna accepted as Middle Ordovician in age.

The rocks in the formations which lie east of and are stratigraphically younger than the Cram Hill formation have yielded a limited number of fossils and "fossil"-like materials. The ages that have been assigned to these stratigraphic units have ranged from Middle Ordovician to Lower Devonian. At present, there is no unanimity of agreement on age assignment.

Crinoid stems were reported by Currier and Jahns (1941, p. 150) from the crystalline limestones in the upper part of the Shaw Mountain formation in the Barre quadrangle. These were identified by Josiah Bridge and P. E. Raymond as indicating an age of at least Middle Ordovician. This agrees with the fossil-dated age of the Magog (=Cram Hill).

Graptolite-like materials from the Northfield and Waits River formations (Richardson, 1916, pp. 142–145; Richardson and Camp, 1919, pp. 114–115) were identified by Ruedemann (1947) as graptolites ranging between Beekmantown and Lower Trenton in age, but the organic nature of these materials has since been questioned by Foyles (1931) and Currier and Jahns (1941). The supposed fossils are now believed to be smears of micaceous minerals on cleavage planes.

A fossiliferous horizon in the lower part of the Waits River formation of the Montpelier quadrangle was described by Cady (1950). V. J. Okulitch identified some forms as cup corals, probably Streptelasma and possibly S. corniculum, suggesting that the lower part of the Waits River ranges from Black River through Trenton.

Clark (1934, p. 12) described some graptolites (Normanskill age) from the Tomifobia formation of southern Quebec as resembling those described from the Magog slates to the west. Since the Tomifobia formation is considered to be the northern correlative of the Waits River, a Middle Ordovician dating is suggested for the Waits River formation.

Large crinoid calyces were reported by Doll (1943a, p. 57) from a locality near the village of Westmore, Vermont, in the Memphremagog quadrangle. Winifred Goldring and others believed these fragments to be of Silurian or possible Devonian age. The organic nature of this find, too, has been questioned.

Doll (1943b) identified a brachiopod from the Gile Mountain formation in the Strafford quadrangle as probably Spirifer murchisoni (Lower Devonian), but the identification as a fossil has been questioned by White and Jahns (1950) and White and Billings (1951).

In southeastern Vermont, Lyons (1955) has described the last unit in the Vermont sequence, the Meetinghouse slate (=Northfield, this report), in contact with the Orfordville formation of the New Hampshire sequence. Farther east, the Orfordville is overlain, in sequence, by the Albee, Ammonoosuc and Partridge formations whose ages have been determined to range from mid- to pre-Silurian. This interpretation was based on the existence of a marked unconformity at the base of the Silurian in New Hampshire (Billings, 1937).

The paleontologic evidence is weak and the identifications are conflicting from the units lying above the Cram Hill formation. No fossils were uncovered in the present study. However, in view of the major structure proposed in this report and its stratigraphic implications, the present writer is of the opinion that the age of the stratigraphic units lying above the Cram Hill formation range from Middle to Upper Ordovician.

STRUCTURAL GEOLOGY

General Statement

The structural setting of the Randolph quadrangle is one of intense folding. Two distinct stages of deformation are inferred, but evidence for major faults and large-scale igneous injections is lacking.

The formations in the western portion of the Randolph quadrangle are in homoclinal sequence on the east limb of the Green Mountain anticlinorium. The steep dip of the rocks is to the east and frequently the beds are overturned. In the central and eastern portions of the quadrangle overturned west-dipping rocks are prominent. The dip of these overturned beds becomes more gentle eastward toward the Strafford quadrangle.

The Randolph quadrangle is situated west of the Strafford dome and northwest of the Pomfret dome, which together make up the southern termination of the Willoughby arch (Dennis, 1956) (see Figure 2). The arch continues north to the international border.

Two distinct types of minor folds and two types of cleavage suggest two major orogenic stages with superposition of the effects of the later one on the earlier one. Because of this situation the major structural relations are not easily determined, and it is only through the careful study of the minor structural features that the major structures can be defined.

Minor Structural Features

Foliation

Foliation, as used in this report, refers to any megascopically visible planar structure due to mineral orientation, and to banding resulting from changes in composition or grain size, whether of primary or secondary origin.

The planar features in this geologic setting of intense folding are often offset to the extent that a trend, rather than strike, of foliation is necessary. This surface (Fig. 3) may actually transect the minor fold limbs at a considerable angle.

(a) *Bedding*

Bedding is any primary compositional banding in the rocks. Banding due to metamorphic processes often simulates bedding but is not included. Compositional and textural differences are the most reliable

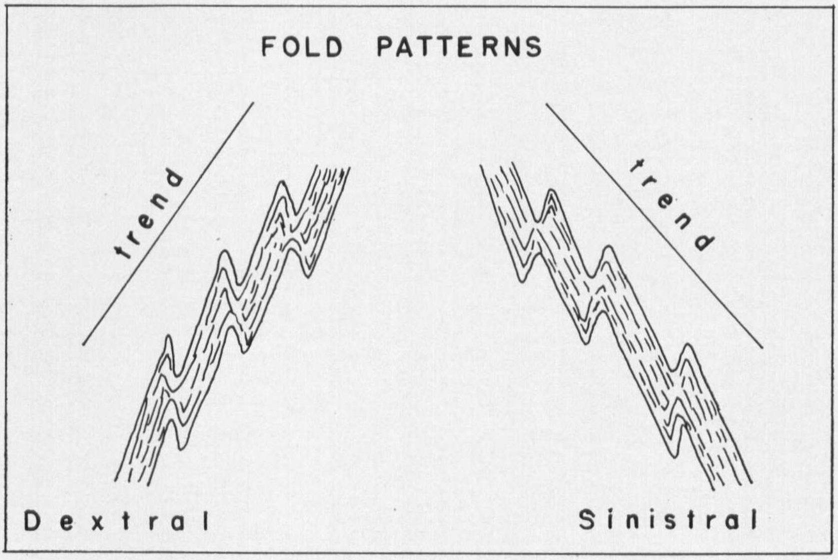


Figure 3. Dextral and sinistral patterns of drag folds.

criteria for distinguishing bedding in the rocks of the Randolph quadrangle.

Bedding is particularly well preserved in the rocks of the Gile Mountain and Waits River formations in the Randolph quadrangle, especially in crystalline limestones interbedded with phyllites (Plates XI and XII). In areas of thick series of phyllitic rocks, it is difficult to recognize bedding, especially in zones of greater metamorphism.

(b) *Schistosity*

Schistosity is a foliation caused by the parallel or near-parallel arrangement of platy minerals. It is the result of recrystallization by metamorphism and, in the rocks of the western portion of the Randolph quadrangle, is due to the parallel alignment of principally chlorite and sericite; to the east, of muscovite and biotite.

(c) *Cleavage*

Cleavage, as used here, refers to the planar property of a rock which enables it to break along closely spaced, parallel surfaces. In contrast with schistosity planes, cleavage surfaces do not necessarily involve the

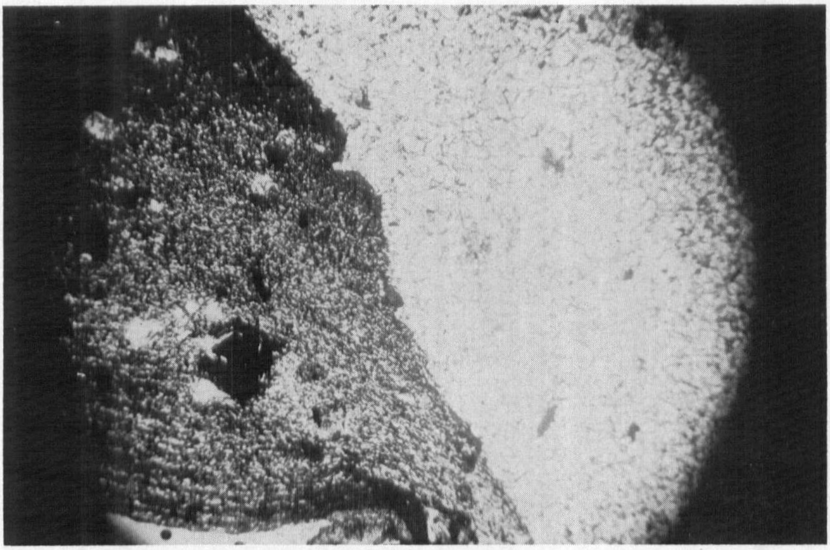


PLATE XI

Photomicrograph of a contact between a garnetiferous phyllite and quartz mica schist within the Gile Mountain formation. (X12)

parallel alignment of minerals. However, mimetic recrystallization may occur along cleavage planes, closely simulating schistosity.

Two prominent types of cleavage are evident within the Randolph quadrangle; flow cleavage (schistosity) and slip cleavage. To a minor extent, fracture cleavage is also developed.

The schistosity observed is flow cleavage and is due to the orientation or parallelism of minerals (Leith, 1923). The mineral parallelism consists of the crystallographic orientation of the micaceous or elongate minerals, and the non-directional minerals like quartz, feldspar and calcite as well.

The flow cleavage or schistosity is approximately parallel to bedding in much of the area, but locally it transects bedding at a small but measurable angle. Schistosity is particularly well developed within the Moretown formation. It cuts across the bedding in the nose of minor folds simulating an axial plane cleavage, but parallels the bedding on the limbs of these folds.

In any west to east traverse across the area, the schistosity gradually changes from a northwest strike to a northeast strike and is about parallel to the trend of the bedding. In the western third of the quad-

PLATE XII

Figure 1. East-dipping bedding in the Gile Mountain formation, one-half mile southeast of North Royalton.

Figure 2. Bedding within the Gile Mountain formation. Outcrop along Randolph Center-East Randolph road, one-half mile east of Blaisdell School.

rangle, the dip of the cleavage is greater than that of the bedding, but to the east, the dip of the cleavage is less than that of the bedding, indicating that the beds are overturned in approximately the eastern two-thirds of the quadrangle.

The second type of cleavage is referred to as slip cleavage in preference to the term fracture cleavage by geologists working in the east-central Vermont and New Hampshire region. The term, as first used by Dale (1896, p. 209), referred to cleavage planes that transected bedding confined to recurring narrow bands of slippage. This is the same type of cleavage described by Leith (1905, p. 120) as a type of fracture cleavage which he called "fault-slip-cleavage" or which Mead (1940, p. 1010) referred to as "shear-cleavage." Slip cleavage is a feature due more to flowage than fracture. Rupture or displacement along the cleavage planes need not take place and the ability of slip cleavage to form as a plane of weakness depends upon the sub-parallel arrangement of the platy minerals on the potential shear planes.

The slip cleavage post-dates the earlier schistosity and grades eastward across the Randolph quadrangle into a second generation schistosity that transects the earlier schistosity (flow cleavage). Since the intensity of metamorphism increases to the southeast in the Randolph quadrangle, what is cleavage in the lower grade metamorphism, becomes a schistosity in the higher grades (White, 1949). In exposures showing both the early schistosity and slip cleavage, the slip cleavage strikes at a slightly greater angle to the east. In many parts of the quadrangle, particularly to the south, the slip cleavage is so intensely developed that it completely obliterates the earlier schistosity. The best development of slip cleavage in the Randolph quadrangle is in the phyllitic rocks of the Northfield, Gile Mountain and Waits River formations (Plate XIII).

Fracture cleavage (Mead, 1940, p. 1010) is developed in the rocks to a minor extent. It is limited to the crests of the larger folds, particularly with competent quartzitic interbeds where fracture cleavage is developed at a slight angle to the axial plane of the folds.

Mineral parallelism, diagnostic in part of slip cleavage, is totally absent.

Lineation

The linear features observed in this study are the result of mineral streaming, crinkles, intersections of bedding and cleavage (either slip cleavage or schistosity) and, at times, the intersection of the earlier schistosity with the slip cleavage.

PLATE XIII

West-dipping bedding displayed by slip cleavage in the Waits River formation. Outcrop one mile north of the Bethel Gilead road in the railroad cut.

Mineral streaming caused by the shearing out of platy minerals is oriented down the dip in the foliation plane and, generally is almost normal to the axes of the minor folds. This linear feature primarily involves chlorite and the micas along the foliation plane and is best developed in the western part of the quadrangle. To the east, streaming is much less conspicuous. Crinkles are commonly found on foliation planes and plunge in a northerly direction parallel to the fold axes of the younger folds. Infrequently, amphibole needles are normal to the fold axes.

Intersections of bedding and flow cleavage are not well developed in the schists in the western portion of the Randolph quadrangle since, in this area, the schistosity is parallel or sub-parallel to the foliation planes. To the east, the intersections of bedding and schistosity and bedding and slip cleavage are most prominent. The plunge of these lineations, is dominantly parallel to the axial plane of the early folds. A plunging fold in the arenaceous "pinstripe" of the Moretown formation is figured in Plate XIV. The a, b, and c linear directions are clearly seen.

The intersections of bedding and slip cleavage are best developed in the western band of the Waits River formation. Where schistosity and slip cleavage occur together in an outcrop, the slip cleavage cuts across the schistosity at a measurable angle. The intersection of schistosity and slip cleavage is limited, for the most part, to the Gile Mountain and Waits River formations. It is prominent in tight isoclinally folded beds, particularly the phyllites.

Other minor lineations result from boudinage and the tear-drop quartz pods, particularly in the Stowe formation.

Joints

A detailed, systematic study of the joints was not carried on in this area. However, two distinctive joint sets are evident. Jointing is best developed in the more massive phyllitic (Plate XV) and quartzitic beds, although it is recognizable in the schistose rocks as well. For the most part, these are strike joints and cross joints. The strike joints are sub-parallel to the axis of the minor folds. They are steeply dipping to vertical and strike from N30°W to N30°E, west to east across the quadrangle. Some strike joints are filled with milky white quartz. The cross joints most commonly dip steeply north and range in strike from S75°W to N75°W.

Minor Folds

(a) *General Statement*

The minor folds will be discussed under two categories since two distinctly different types are evident within the Randolph quadrangle. That two generations of folding are present in nearby areas has been discussed in detail by White (1949), White and Jahns (1950), Lyons (1955), Murthy (1957), and others.

Folds ranging in amplitude from microscopic dimensions to those tens of feet across, depending upon the thickness of the rocks, are

PLATE XIV

North-plunging fold in the Moretown formation, one mile northeast of Whitcomb Hill School, Stockbridge.

included in this discussion. However, the amplitude of most of the folds is less than one foot.

That the early and later folds are the result of separate diastrophism is indicated by the fact that the plunges of the fold axes of the early and later folds are separated by a measurable angle. Associated with the tight early folds is a contemporaneously formed schistosity (flow cleavage) sub-parallel to the bedding on the limbs of the early folds but transecting the bedding at the crests. The later folds are characteristically more open than the earlier and a superimposed slip cleavage is present which has deformed the earlier minor structures as well as bedding. The schistosity wraps around the noses of these later folds unlike that of the earlier folds where the schistosity parallels the axial planes.

The terms "dextral" and "sinistral," (see Fig. 3), as used and described by White and Jahns (1950), are applied to the minor folds in this report. The differentiating factor between these two terms is "that as one stands on a long limb and looks along its strike (to the north), the next long limb beyond an intervening short limb appears to be off-

PLATE XV

Cross joints, looking east at north-plunging outcrop of Gile Mountain phyllite, one mile northeast of Randolph Center.

set. If it is offset to the right, the fold pattern is dextral; if to the left, sinistral." (White and Jahns, 1950, p. 197).

(b) *Early Folds*

The early folds are abundant throughout the entire quadrangle. Most of these folds are tight or isoclinal (Plate XVI, Fig. 1). The strike of the axial planes changes from northwest in the Stowe formation, in the west, to northeast in the Waits River formation on the east. The plunge of the early folds increases to the north from approximately 10° in the vicinity of East Barnard, to 40° north of North Randolph. In the southeasternmost corner of the quadrangle, the folds plunge south.

The schistosity, associated with the early folds, is recognized in the field by the sub-parallel arrangement of the micaceous minerals or bands of oriented nonmicaceous minerals which form parallel to the axial planes of the earlier folds, and are seen to transect the bedding in the noses of these folds (Plate XVI, Fig. 2). This early cleavage is clearly shown in the schists and granulites.

Folds in the argillaceous slates, phyllites and micaceous schists are tightly compressed with sharp crests and troughs. In the more compe-

PLATE XVI

Figure 1. Overturned isoclinal folding in the Shaw Mountain formation, one-half mile south of Old Church, Bethel.

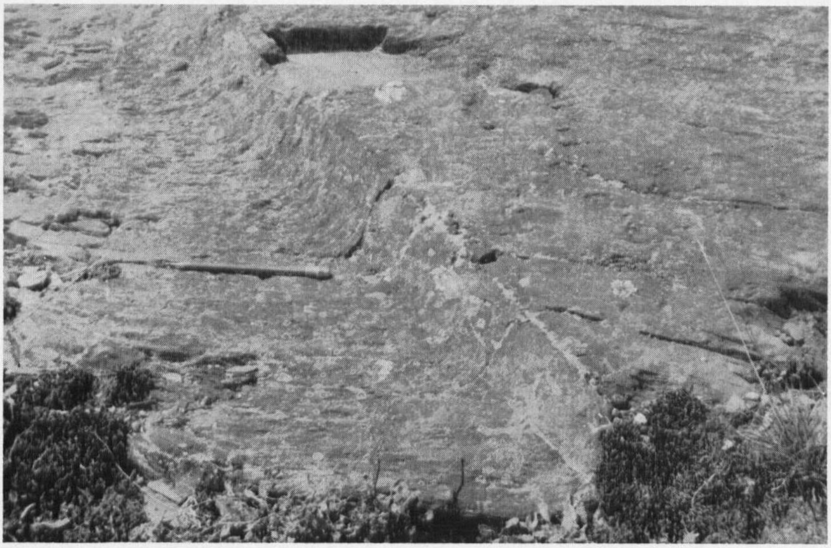


Figure 2. Early sinistral fold in the Waits River formation on Braintree Hill. The bedding, parallel to the pencil, is transected by the earlier schistosity in the nose of the fold.

tent, arenaceous beds, the early folds are more open and have rounded crests. The carbonate-rich rocks within the quadrangle exhibit highly irregular flowage folds (Plate XVII). The shear sense of the earlier folds within the Randolph quadrangle is dominantly sinistral in the latitudes north of Bethel.

Such a drag fold pattern may be interpreted structurally in that the rocks to the east moved up with respect to those on the west, or, stratigraphically, that the rocks to the east are younger.

(d) *Late Folds*

Minor folds in which the earlier schistosity as well as the bedding is folded have been attributed to the later stage of deformation. These later folds are usually more open than the earlier flexures and have a pronounced slip cleavage parallel to their axial planes. The earlier schistosity wraps around the nose of the later folds instead of paralleling the axial planes as in the early folds (Plate XVIII).

The pronounced slip cleavage related to the later deformation is widely distributed and both the early schistosity as well as the bedding are cut by this later cleavage.

The late folds in the Randolph quadrangle are primarily sinistral in pattern.

Major Structural Features

Early Structures

Early minor folds with a sinistral pattern and a constant plunge to the north are common throughout most of the rocks in the Randolph quadrangle.

The rocks in the stratigraphic units west of the Cram Hill formation dip steeply to the east as a homocline on the east limb of the Green Mountain anticlinorium.

East of this homoclinal sequence, the bedding dips steeply to the west becoming more gentle toward the Strafford quadrangle (Plate XIX). The dip of the bedding is consistently steeper than the cleavage and the rocks are all overturned.

It is only in the western band of the Gile Mountain formation in the latitude of North Royalton and to the south, that early dextral folds are prevalent. The beds here consistently dip to the east (Plate XX, Fig. 1) and at a steeper angle than the cleavage. Graded bedding also shows that the Gile Mountain formation is overturned to the west.

PLATE XVII

Flowage folds in the crystalline limestone of the Waits River formation. Outcrop by cemetery just north of South Royalton.

Examples of the dextral folds are figured in Plate XX, Figure 2, and Plate XXI, Figures 1 and 2. A close-up of bedding and cleavage is figured in Plate XXII, Figure 1. Graded-bedding with minor dextral folds and cleavage is demonstrated in Plate XXII, Figure 2.

These relations prevail in the western band of the Gile Mountain formation southward to the vicinity of East Barnard village in the northeastern portion of the Woodstock quadrangle where the formation closes.

That this closure is structural and not due to a facies gradation is indicated by the plunges of the axes of minor folds throughout the western band of the Gile Mountain formation in the Randolph quadrangle. In the vicinity of East Barnard village the plunge is less than 10° to the north and it progressively increases northward to 40° north in the latitude of North Randolph. The strike of the rocks also follows the thinning of the western band of the Gile Mountain formation to the south (Plate II). Finally, the width of the formation to the south is too narrow and the closure too abrupt for any evidence of converging strikes.

The sinistral pattern of the earlier folds dominates throughout

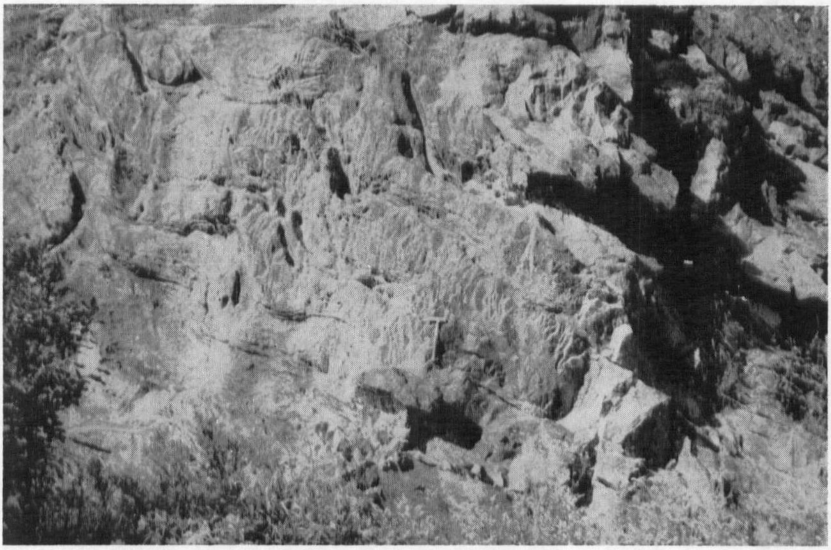


PLATE XVIII

Late dextral folds in the Moretown formation, at the base of Vulture Mountain. Bedding dips to the east in view looking north.

southern Quebec and east-central Vermont (Cooke, 1950; White and Jahns, 1950; Eric and Dennis, 1958; Murthy, 1957; Goodwin, 1959, personal communication; and mapping in the Randolph quadrangle). This indicates that the early stage of deformation was confined to the west limb of a major syncline or the east limb of an anticline (the Green Mountain anticlinorium).

However, a limited number of early dextral folds have been reported. Dennis (1956, p. 63) described early folds in the Lyndonville quadrangle on the west limb of the Willoughby arch as exhibiting "the normal pattern to be expected with an anticline," (that is, dextral). Dennis considered these folds to be "rare" and superseded by later sinistral folds.

In the extreme eastern part of the East Barre quadrangle, Murthy (1957, p. 53) noted dextral folding in bedding. He considered these folds to have developed during earlier folding even though they were affected by the later deformation. According to Murthy (1957), these were rotated early folds.

White and Billings (1951, p. 674) mapped similar dextral folds in the

PLATE XIX

Figure 1. Bedding in the Gile Mountain formation north of Randolph Center dipping approximately 75°W. The cleavage dips 11°W and the beds are overturned.

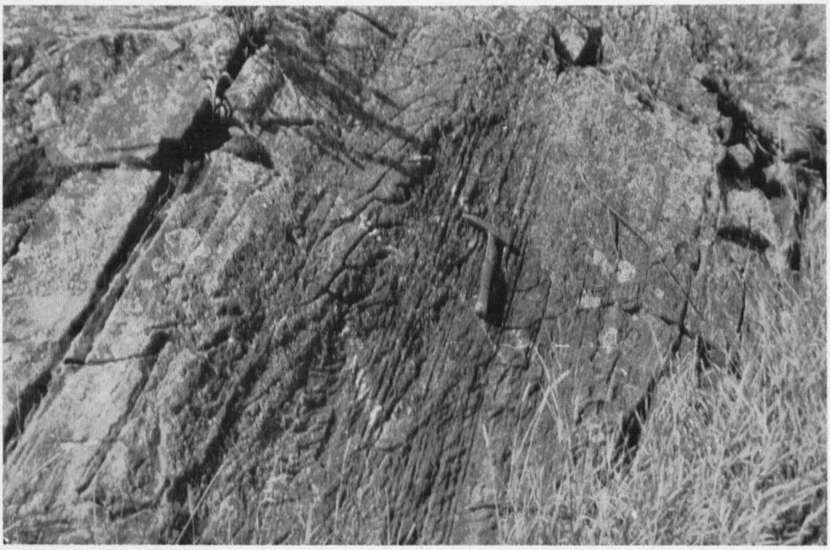


Figure 2. Overturned bedding (54°W) in the Gile Mountain formation by Blaisdell School, Randolph. Outcrop 1.5 miles east of exposure in Figure 1. Note lessening of dip toward the east.

PLATE XX

Figure 1. East-dipping bedding in the exposures north of Royalton. Dextral fold outlined.

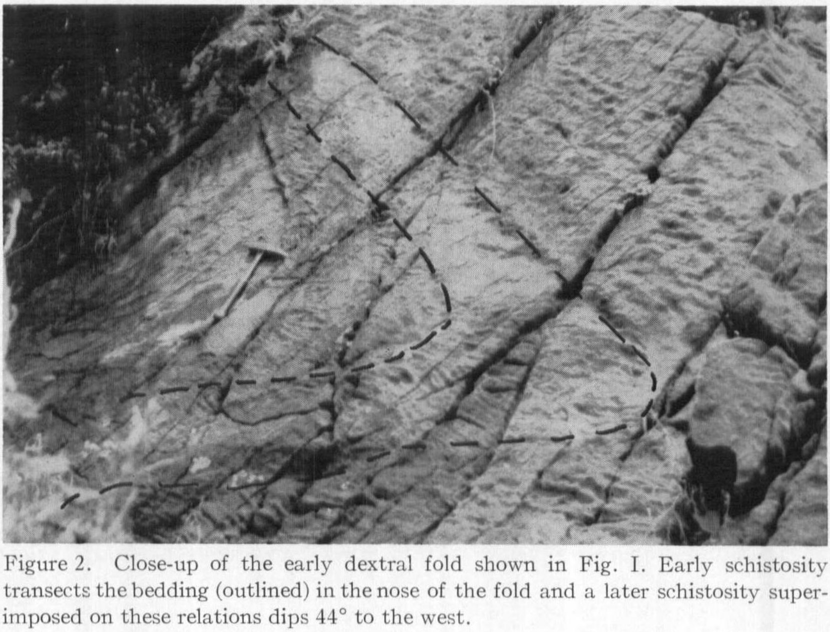


Figure 2. Close-up of the early dextral fold shown in Fig. I. Early schistosity transects the bedding (outlined) in the nose of the fold and a later schistosity superimposed on these relations dips 44° to the west.

Figure 1. Plan view of dextral folding in the Gile Mountain formation, looking north. Exposure in the White River, one mile west of the Route 110-14 junction.

Figure 2. Dextral fold viewed to the south, in the railroad cut one-quarter mile south of exposure in Figure 1.

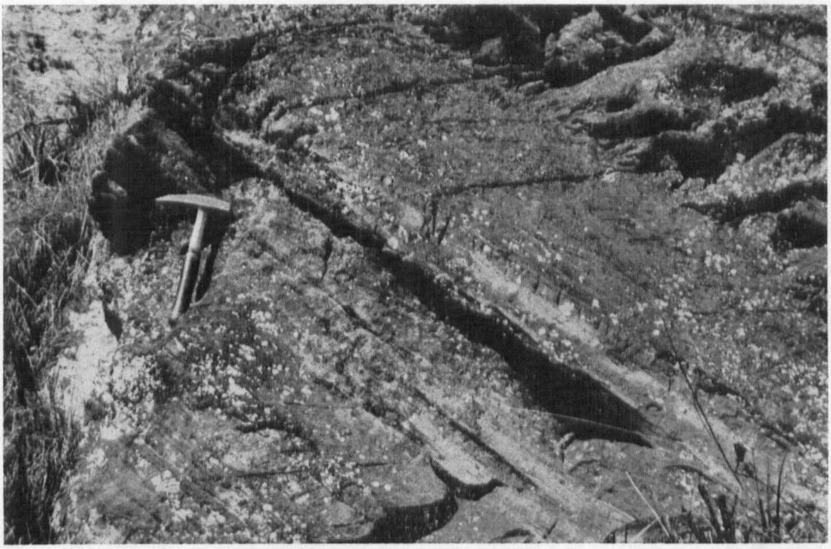


Figure 1. Bedding-cleavage relations looking north at the cliffs of Gile Mountain exposure near North Royalton. Bedding dips 34°E and the cleavage 70°W. Shear sense indicates beds are overturned.

Figure 2. Graded bedding, cleavage, and dextral folds in outcrop less than twenty yards from exposure in Fig. 1. The east-dipping beds, averaging four inches in thickness, grade from coarse to fine (top to bottom) indicating tops to the west.

western portion of the Woodsville quadrangle, but considered them to be related to the later stage of deformation. The writer is led to concur with Murthy's designation because, in the Randolph quadrangle, the large-scale dextral folds similarly involve bedding transgressed by the later deformational effects (see Plate XX, Fig. 2).

A major recumbent anticline is herein proposed to explain the early structural relations. This proposal is based upon a detailed evaluation of the early minor structures known in east-central Vermont and those studied in the Randolph quadrangle. Structural and stratigraphic relations in the Island Pond quadrangle are also best explained by a recumbent anticlinal structure (Bruce K. Goodwin, personal communication, 1959).

Recumbent folds along the trend of the Willoughby arch have been discussed by White and Jahns (1950), Lyons (1955), Billings *et al.*, (1952), and Eric and Dennis (1958). White and Jahns (1950, p. 212) described the north end of the Strafford dome as the noses of two nappe-like structures overfolded from east to west.

In discussing the recumbent folds in the Pomfret dome Lyons (1955, p. 125) stated, "Whether nappe-like overfolds are present west of the Pomfret dome (in the Randolph and Woodstock quadrangles) is not demonstrable on the basis of available field data. Probably, however, the nappe-like structure is non-persistent and dies out on the Strafford dome itself."

The large anticlinal structure presumably was produced by strong compressional components acting from the east which caused thickening and shortening of the sequence in central and eastern Vermont. The root zone of the original anticlinal structure is in the Gile Mountain formation of eastern Vermont, parallel to what is now termed the St. Johnsbury homocline. As deformation continued, the anticlinal structure migrated upward and westward and gradually became recumbent. The core now appears as the western band of the Gile Mountain formation. Under conditions of deformation an anticline normally should show sinistral drag folds on the right flank and dextral drag folds on the left flank. The early dextral drag folds described in the East Barre and Woodsville quadrangles (Murthy, 1957; White and Billings, 1951) correspond to the left flank in the root zone of the anticline. Murthy (1957) explained the early sinistral folds west of and in the west and central parts of the East Barre quadrangle, and the early dextral folds to the east as indicating a synclinal structure as the product of the earlier deformation in the East Barre quadrangle. The writer disagrees with Murthy's interpretation of the early structural setting. Rather, he believes that the formation of the anticlinal structure in eastern Vermont was paramount to the syncline formed west of it.

Early sinistral folds on the east limb of the anticline conform to the folds described by Eric and Dennis (1958). West of the Connecticut River, White and Billings (1951) noted dominantly early sinistral drag folds. This view is substantiated by Eric (1942, p. 47) in the Mt. Cube quadrangle south of Woodsville.

In the Randolph quadrangle, the arch bend (see Fig. 4) and core of the major recumbent fold are present as the western band of the Gile Mountain formation. The plunge of this arch bend is to the north and is known to swing around and join the eastern band of the Gile Mountain formation at the termination of the Willoughby arch in the southwestern portion of the Island Pond quadrangle (B. K. Goodwin, personal communication, 1959).

The east-dipping, dextrally-folded rocks of the western band of the Gile Mountain formation in the Randolph quadrangle would then be the inverted limb but close to the axial plane of the fold in the arch bend of the structure.

The early folds with sinistral drag patterns in the western margin of the Gile Mountain formation in the Randolph quadrangle outline the normal limb of the recumbent fold. Dextral folds are not common along the eastern margin of the formation since the dextral folds along the left flank of the original anticline had to be rotated more than 180° in order to be in their present position. The lower or inverted limb of any recumbent fold is one of extreme shearing with, generally, obliteration of minor structures.

Later Structures

A later deformational episode is imprinted on the rocks in the Randolph quadrangle by the development of later folds and a slip cleavage parallel to the axial planes of these later folds. The later folds in the Randolph quadrangle are sinistral in pattern, dip to the west, and consistently plunge to the north at a variable angle from the axis of the early folds. These second generation features increase in intensity of development eastward across the Randolph quadrangle. The development of the slip cleavage to the east, in central Vermont, has been described by White and Jahns (1950, p. 203).

The later deformation becomes more intense to the west from the Connecticut Valley area where the later folds are predominantly east dipping and have dextral drag patterns (White and Jahns, 1950, p. 208).

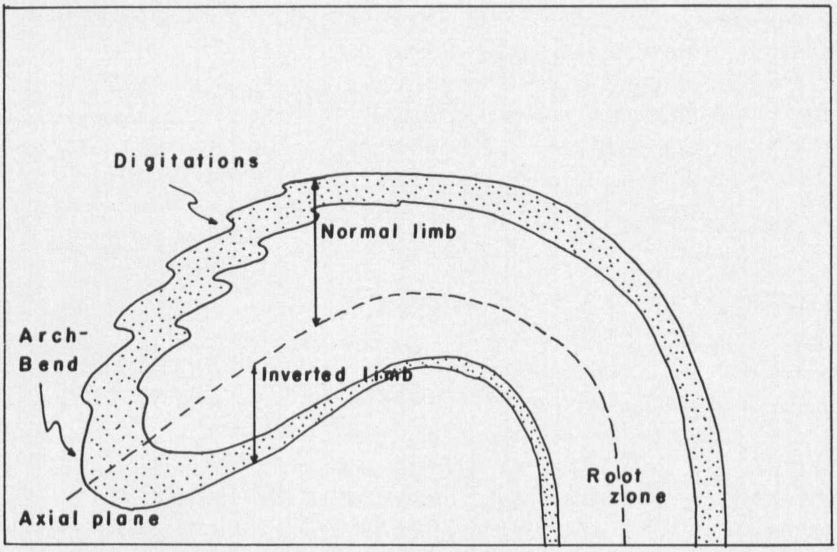


Figure 4. Terminology used with a recumbent anticline.

The later stage of deformation then, is one of both westward and eastward development culminating in the Willoughby arch with its domal structures. The degree of metamorphism also parallels this trend (White, 1949; White and Jahns, 1950; Murthy, 1957). The minor fold patterns east and west of this arch show that it moved upward with respect to the rocks on either side producing drag fold relations opposite to those of a normal anticline.

The doming east of the Randolph quadrangle is, therefore, the mechanism responsible for the later folds and slip cleavage which are superimposed on the earlier structures in the quadrangle.

Doll (1944, p. 22) regarded the structure as a normal anticline with the minor folds on the west limb overturned to the east, and on the east limb overturned to the west. He regarded the structure as having been formed in two stages. In the first stage, an anticline was formed, and in the second, the early anticline was deformed into "zig-zag" folds as outlined by the outcrop pattern of the Standing Pond amphibolites in the Strafford quadrangle.

White and Jahns (1950, pp. 214–219) viewed the formation of the arch as due to compression at depth of earlier folded rocks. The result was a flowage upward of mobile calcareous rocks producing an upward bulge in the cleavage.

In 1953, Bean attempted to relate the gravity anomalies in central and eastern Vermont and New Hampshire to the geology. Each dome studied (Bean, 1953, Pl. 1) showed a negative gravity anomaly. The gravity low within the Strafford and Pomfret domes was attributed by him to a low density rock of granite-like composition underlying the area.

The decrease in the grade of metamorphism away from the crestal area of the dome along with the numerous zones of granitic dikes in the southern part of the East Barre quadrangle were cited by Murthy (1957, p. 65) as evidence for a shallow pluton.

The time lapse between the formation of the west-facing recumbent anticline and the Willoughby arch is unknown, but it is assumed that the rocks in the anticline, perhaps in a near-plastic state, must have attained a nearly recumbent position before the major uplift of the arch. Since the root zone of the recumbent anticline is east of the Willoughby arch, the axial plane of the recumbent fold was arched up over this upwelling concomitant with the thermal peak of metamorphism.

The recumbent folds in the Strafford (White and Jahns, 1950, p. 213) and the Pomfret (Lyons, 1955, p. 124) domes are considered digitations on the inverted limb of the recumbent anticlinal structure.

Structural Evaluation of the Gile Mountain Formation

The structure and stratigraphic position of the western band of the Gile Mountain formation has been one of contention in the correlation of the rocks in the Vermont sequence.

Doll (1951, p. 51), working in the Memphremagog quadrangle, referred to this band as the Westmore formation and postulated that it was in the axial part of a synclinal structure which he named the Brownington syncline. The possibility of the Gile Mountain formation lying in the axial part of a syncline was also discussed by White and Jahns (1950, p. 206) as one structural mechanism to correlate the Gile Mountain (?) formation of their report with the belt of Gile Mountain schists at the type locality farther east. Mapping in the Lyndonville quadrangle by Dennis (1956, pp. 35–36) extends Doll's Brownington syncline to the south.

The most serious objection to the synclinal nature of the western band of the Gile Mountain formation is the fact that the early fold patterns are primarily sinistral on both the east and west margins of the formation in the Barre and East Barre quadrangles and most of the Randolph quadrangle. A synclinal structure should have sinistral drag folds on the western limb and dextral folds on the eastern limb.

The overturned early dextral drag folds just north of Royalton and southward in the Randolph quadrangle are exposed almost throughout the entire width of the western band of the Gile Mountain formation and nowhere indicate a synclinal structure. Bedding-cleavage and drag fold observations along with excellent graded-bedding indicate that the Waits River formation lies stratigraphically above the Gile Mountain formation, refuting a synclinal structure with the Gile Mountain rocks in the core.

The original evidence for the Brownington syncline is scant. Dennis and Doll both described the dip of the bedding on the western margin of the Gile Mountain formation as being vertical to overturned to the east, while on the eastern margin the dips are to the west, "suggesting a synclinal form," (Dennis, 1956, p. 35).

To the north in Quebec, Cooke (1950, p. 31) described a constant overturn of the beds in the St. Francis group which corresponds to the Waits River and Gile Mountain formations of the Vermont sequence. The work of Chang (1950), Murthy (1957), Goodwin (1959, personal communication) and the field relations in the Randolph quadrangle all show comparable overturning.

In addition, Dennis stated that, "the Brownington syncline is one of the very rare east-facing major folds in a region of dominantly west-facing structures," (1956, p. 36). The major recumbent anticline proposed in this report is a west-facing major structure. The relations between the major and minor folds in Figure 4 of Dennis' report (1956, p. 40) are compatible with the structural hypothesis proposed herein.

Murthy (1957, p. 66) and White and Jahns (1950, p. 206) pointed out that the Gile Mountain formation consists of three distinct members. The argillaceous members at either margin differ considerably in thickness. If the Gile Mountain formation were in the axial part of a tight syncline, one would expect the distribution of the lithology to be much more symmetrical than it is.

Murthy (1957) postulated that the Gile Mountain (Westmore formation of his report) represented the western limb of an earlier formed, north-plunging syncline—the east limb of which would correspond to the type Gile Mountain formation in the Strafford quadrangle. The axial part of this syncline would correspond to the rocks of the Waits River formation (type locality) as restricted by Murthy.

Further, he maintained that the formations west of the westernmost band of the Gile Mountain formation (Westmore formation of his report) were all in homoclinal sequence. This would place the calcareous western zone of the Waits River formation (Barton River formation of Murthy) as being stratigraphically older than the western band of the Gile Mountain formation. The bedding-cleavage and primary depositional features in the Randolph quadrangle do not seem to support this interpretation. In the northeastern part of the Woodstock quadrangle, the closure of the western band of the Gile Mountain formation is structural and not stratigraphic as Murthy (1957) postulated.

Constant overturning described throughout the Randolph quadrangle is not in accord with Murthy's proposal that the western unit of the Gile Mountain formation is in a homoclinal sequence.

In summary, neither the tight synclinal structure proposed by Doll (1951) and Dennis (1956) (the Brownington syncline) nor Murthy's (1957) interpretation of the western belt of the Gile Mountain formation as a homoclinal sequence representing the west limb of a very large, north-plunging syncline appear to be tenable.

Tectonic Evaluation and Stratigraphic Implications

The proposed recumbent, nappe-like anticline seems to be the best explanation of the field relations in the Randolph quadrangle and also of those described by other workers in east-central Vermont. If the present structural interpretation is accepted, the stratigraphic sequence proposed by earlier workers (Table I) must be revised.

The rocks in the eastern band of the Gile Mountain formation crop out in the suggested root zone of this anticline in eastern Vermont, while the western belt of the Gile Mountain formation is considered to represent the core and arch bend of this major recumbent fold.

Drag fold analyses by Murthy (1957, p. 54) in the East Barre quadrangle indicate that the rocks in the eastern Waits River formation are younger than rocks of the two belts of the Gile Mountain formation which crop out on either side. In the southeastern part of the Strafford quadrangle and the northwestern portion of the Hanover quadrangle, bedding and cleavage dip to the northwest. Bedding-cleavage relations indicate the beds to be consistently overturned and signify that the rocks become younger to the west (Cady, personal communication, 1958).

The more than two miles of cliffs just north of Royalton in the Randolph quadrangle cut across the strike of the western band of the Gile Mountain formation. Reliable graded bedding along with bedding-cleavage and drag folds denote the western band of the Gile Mountain as older than the Waits River formation.

To the north, the two belts of the Gile Mountain formation structurally unite and have been determined to be stratigraphically equivalent (B. K. Goodwin, personal communication, 1959). Therefore, the Gile Mountain formation lies beneath the youngest unit in the Vermont sequence, the Waits River formation.

However, the western band of the Waits River formation is conformably underlain to the west by the Northfield formation. The stratigraphic units exposed from the Ottauquechee to the base of the western band of the Waits River formation progressively become younger to the east (Currier and Jahns, 1941; Chang, 1950; Thompson, 1950; White and Jahns, 1950; Doll, 1951; Cady, 1956).

Since the Waits River formation is considered the youngest unit in the Vermont sequence in this report, and west of the western belt of the formation it is underlain by the slates and phyllites of the Northfield formation, then, Northfield lithology should also border the Waits River on the arch bend and core of the recumbent anticline.

The western band of the Gile Mountain formation was subdivided by Murthy (1957, p. 28) into three members or zones on the basis of lithologic variation. The central member consists of micaceous quartzite, quartz mica schists and minor argillaceous beds. The eastern and western members are predominantly argillaceous rocks composed of micaceous and phyllitic schists. Murthy (1957, p. 29) has estimated the western member of the western band of the Gile Mountain formation (Westmore, his report) to be 2,000 to 2,500 feet thick with the eastern member ranging between 700 and 1,000 feet in thickness. A similar distribution of the lithologies of the western band of the Waits River formation is evident in the Randolph quadrangle. This writer has estimated the western argillaceous zone to range between 1,200 and 1,400 feet in thickness while the eastern zone is normally less than 500 feet thick.

A part or all of the argillaceous members in the western unit of the Gile Mountain formation on the arch bend in the proposed recumbent fold have been assigned to the Northfield formation. The variable thickness in the two argillaceous members is to be expected on either limb of a recumbent fold due to shearing in the inverted limb.

Since the Gile Mountain formation is in the core of the arch bend and, therefore, underlies the Northfield formation, it should also underlie the Northfield formation to the west. The unconformity which lies above the Cram Hill and Barnard lithologies is very important to the context of the proposed structure. That an unconformity is present at this horizon has been verified (Currier and Jahns, 1941; White and Jahns, 1950; Thompson, 1950; Doll, 1951; Cady, 1956).

This stratigraphic break is herein considered an erosional horizon that removed the Gile Mountain lithology which should overlie the Cram Hill formation.

If the Northfield overlies the Gile Mountain formation as proposed, it should be found on the east limb of the structure in the root zone. The easternmost beds in the Vermont sequence are those of the Meetinghouse slate which conformably lies on top of the eastern band of the Gile Mountain formation. These slates, as originally mapped by Doll (1945, p. 19), were considered by him as the upper member of the Gile Mountain formation.

The youngest formation in the Vermont sequence, the Waits River formation, should then overlie the Meetinghouse slates (Northfield of this report). This is the horizon of the "Monroe line" which separates the Vermont and New Hampshire sequences. The absence of the Waits River lithology is interpreted as due to a major unconformity (Kruger, 1946; Lyons, 1955) at this stratigraphic break. This unconformity may account for the Northfield (= Meetinghouse slate) being in contact with a number of formations in the New Hampshire sequence.

The stratigraphic relations of both the Shaw Mountain formation and the Standing Pond volcanics are uncertain with respect to the proposed structural hypothesis. Both units are intermittently exposed along the strike and have been reported up to 600 feet in thickness. The fact that the Shaw Mountain formation unconformably overlies and is younger than the Cram Hill formation has already been established (ref. cit.). The lithology consists principally of tuffaceous and calcareous sericite schists (White and Jahns, 1950, p. 186), albite-chlorite–calcite schist (Cady, 1956), tuffaceous layers (Doll, 1951), and banded epidote amphibolites (Thompson, 1950).

The Standing Pond volcanics are dominantly amphibolites and occur at the contact of the eastern Waits River and Gile Mountain units in the Strafford quadrangle. However, to the north and south, these volcanics transgress lithologic boundaries and are not restricted stratigraphically. Minor amphibolite beds have been mapped along the eastern margin of the Gile Mountain formation in the Randolph quadrangle, but none were located along its western margin. Murthy (1957, p. 30) reported thin bands of "metasedimentary amphibolite" along the contacts of both margins of the western Gile Mountain formation (Westmore of his report). Whether these amphibolite bands are correlative to the Standing Pond volcanics or whether the amphibolites of the Standing Pond are equivalent to the less metamorphosed greenstones and tuffs to the east (= Shaw Mountain formation) is only speculative.

The evaluation of the structural and stratigraphic evidence as interpreted in this report for east-central Vermont calls for a revision in the stratigraphic column and suggests the following sequence.

Waits River
Northfield (=Meetinghouse)
Shaw Mountain (= ?? Standing Pond volcanics)
Gile Mountain
Cram Hill = Barnard
Moretown
Stowe
Ottauquechee

Diagrammatic cross sections of various interpretations of the regional structure in east-central Vermont are indicated in Figure 5.

The cross sections are drawn at the latitude of Randolph.

PLUTONIC ROCKS

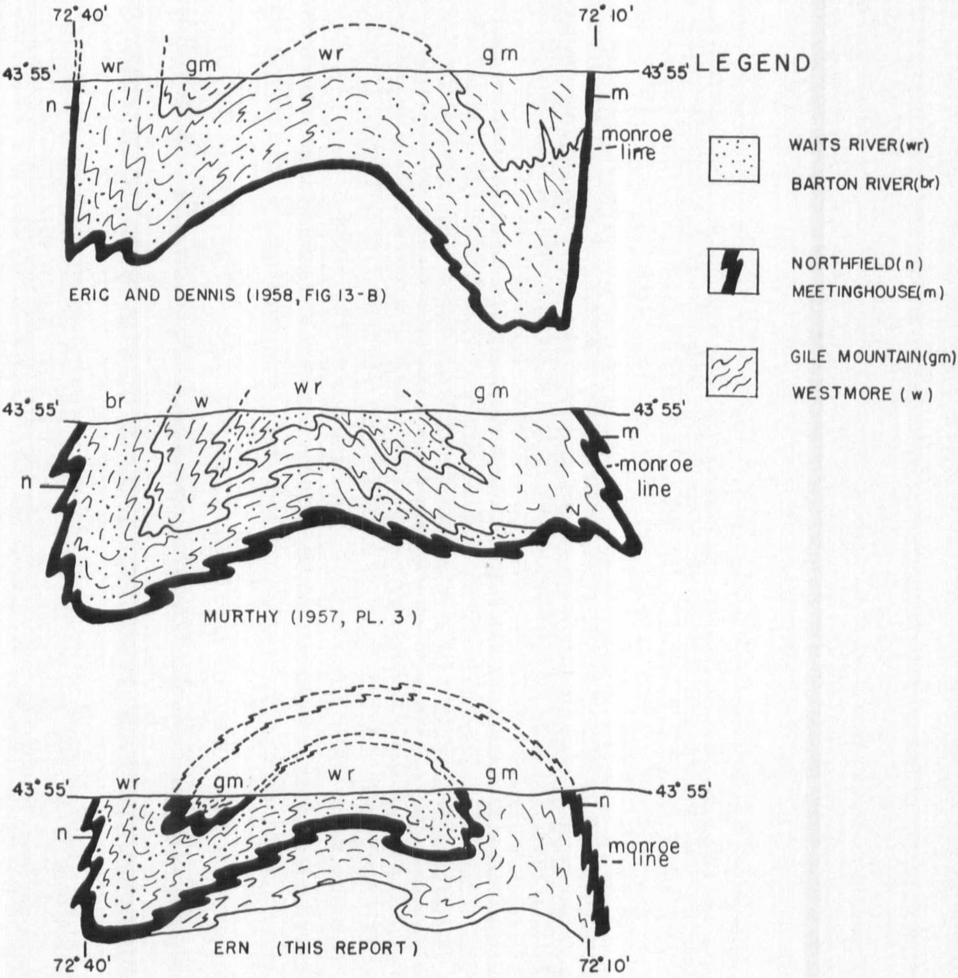
General Statement

Only two plutonic bodies of noticeable extent are evident on the geologic map (Plate I). One is the Bethel granite on Christian Hill in the central part of the quadrangle. The other is north of Braintree Hill in the northwest portion of the quadrangle and is referred to as the Braintree Complex.

Six smaller plutonic bodies, shown in Plate I, are also discussed. Numerous dike rocks crop out within the quadrangle.

The plutonic rocks in the Randolph quadrangle have not appreciably deformed or metamorphosed the metasediments and metavolcanics.

Several ultramafic bodies occur in the western portion of the quadrangle. Plug-like masses of milky white quartz are widely distributed, particularly in the Waits River and Gile Mountain formations.



DIAGRAMMATIC CROSS-SECTIONS OF VARIOUS INTERPRETATIONS OF THE REGIONAL STRUCTURE

FIGURE 5

Granitic Rocks

Bethel Granite

The granitic body at Bethel, known commercially as the "Bethel white granite," is a narrow, elliptical body at the surface. It is located on the crest of Christian Hill, two and one-half miles northeast of the village of Bethel. The outcrop is more than 5,000 feet long from north to south, and approximately 600 feet wide from east to west. The Bethel granite is enclosed completely by the phyllitic rocks of the Waits River formation.

Two quarry operations, the Ellis quarry on the east side of Christian Hill, and about fifty feet north of it, the Woodbury operation, have extracted considerable stone in the past.

Petrographically, the rock is a homogeneous medium- to coarse-grained quartz monzonite. It is composed of quartz, oligoclase, orthoclase, microcline and muscovite with minor quantities of epidote, biotite, apatite, ilmenite and zircon. Oligoclase is partially altered to kaolinite and sericite and the microcline is normally perthitic and fresh. The orthoclase is altered but shows good Carlsbad twinning. Quartz, for the most part, is clear and shows few to no strain shadows.

The main body is surrounded by a much finer grained gray quartz monzonite, ranging from forty to fifty feet in width where exposed.

There is a zone of orbicular granite on the western side of the Ellis quarry. The orbicules parallel the flow structure (Plate XXIII, Fig. 1), but are reported to be smaller than those found in Northfield and Craftsbury (Richardson, 1925). The orbicules are also scattered in lesser amounts in many other zones throughout the quarry (Plate XXIII, Fig. 2). These orbicules are mainly an accumulation of biotite with lesser amounts of feldspar and quartz.

A kerzantite dike approximately five feet thick cuts the area separating the Ellis and Woodbury quarries (Plate XXIV).

For the most part, the contact with the enclosing phyllite of the Waits River formation appears conformable.

The most striking feature of this mass, other than its pure white coloration, is the eastward dipping sheeting (Plate XXV). which, on the average, dips 30°E and is approximately two feet thick.

Two sets of joints, both vertical, cut the rock. One set strikes N85°E, the other N60°E. Pegmatites, quartz veins and aplite follow the nearly east-west set.

A distinct foliation is present, dipping conformably with the enclosing phyllites.

PLATE XXIII

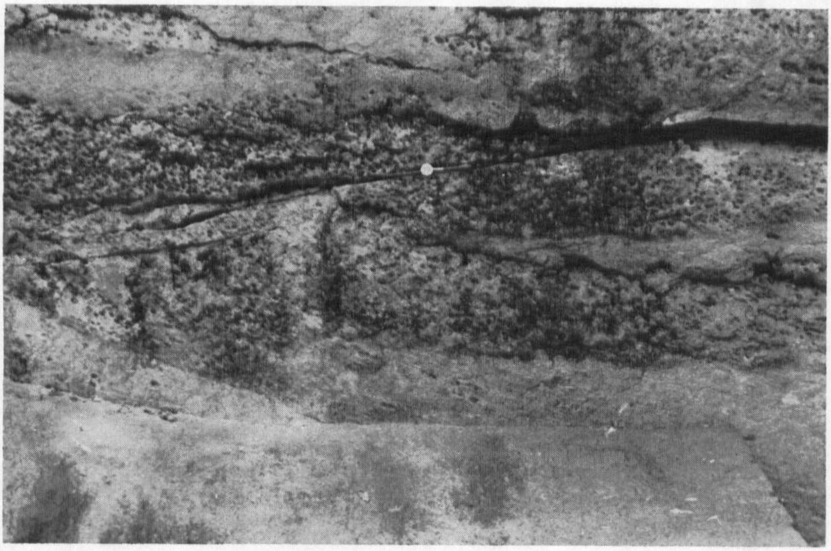


Figure 1. Orbicules paralleling the flow structure on the west wall of the Ellis Quarry, Bethel.

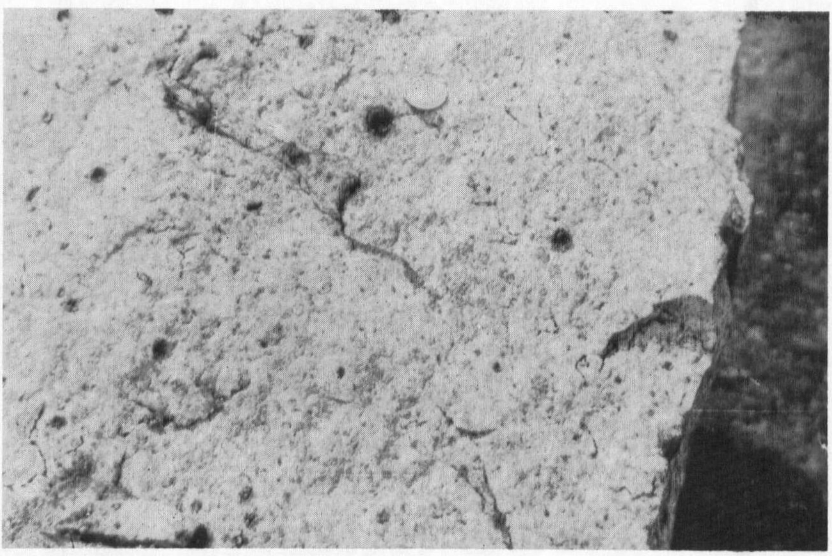


Figure 2. Biotite "chestnuts" common in the Bethel quarry.

PLATE XXIV

Contact of kersantite dike, above the pencil, with the Bethel granite in the area separating the Ellis and Woodbury quarries.

More detailed descriptions of the granite mass are given by Dale (1909, 1923) and Balk (1927).

Other Quartz Monzonite Bodies

(a) *Christian Hill Area*

Smaller outcrops of quartz monzonite are located northeast of and two miles south of Christian Hill. These rocks are not as coarse or white as the Bethel granite. Their composition is about that of the Bethel granite.

(b) *Heap Pinnacle*

Another small body of quartz monzonite is located on Heap Pinnacle west of the village of Bethel. This plutonic body is limited in extent. Its composition and texture are similar to the quartz monzonites of Christian Hill.

(c) *Temple School Area*

A small exposure of quartz monzonite, approximately 360 by 75 feet, is located one mile and one-half south of Temple School. It is intensely

PLATE XXV

Figure 1. East-dipping sheeting, looking north into the Woodbury Quarry.

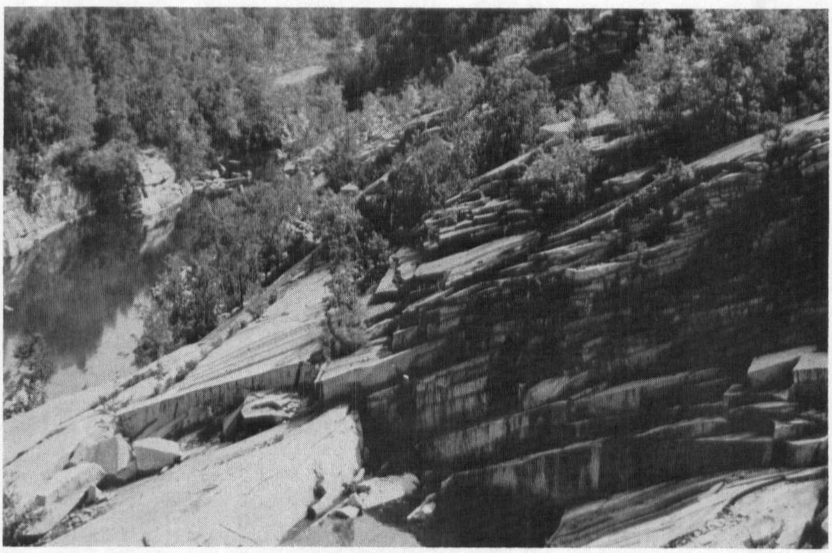


Figure 2. View to the south in the Ellis Quarry showing distinctive jointing and sheeting. Compare with Plate VII of Richardson (1925).

fractured throughout and the fractures are filled with vein quartz (Plate XXVI).

(d) *Beedle's Prospect*

A fine-grained quartz monzonite is located in Randolph, one-quarter mile south of Beanville school. The rock is about the color of the "Bethel white," and is free of mica segregations. The exposed outcrop is approximately 230 feet long and 140 feet wide.

Braintree Complex

General Statement

The Braintree plutonic complex consists of a dioritic and a granitic body emplaced side by side in the northwest part of the quadrangle, just west of Ferry Hill. The greater portion of this complex lies in the Barre quadrangle to the north. Over all, the mass is approximately two miles long and a little less than a mile wide.

Granitic Phase

The granitic body is composed of quartz, orthoclase, microcline, biotite and muscovite with minor quantities of oligoclase, diopside, zircon, apatite and ilmenite.

The rock is a uniform, moderately coarse-grained binary granite. Muscovite is commonly associated with the perthitic microcline and highly sericitized orthoclase and usually borders these minerals. Deep brown biotite is present as large, strongly pleochroic crystals.

No distinct foliation was observed in the granitic portion of this complex in the Randolph quadrangle.

Two sets of joints were observed—one strikes east-west and dips 80° south to vertical, while the other strikes N45°E and dips 62° to 77° southeast. Sheeting, dipping from 21° to 32° west, was observed.

Contacts of the granite with the enclosing Cram Hill formation of the east are sharp, but the southern contact is covered.

Diorite Phase

Mineralogically, the diorite to the west contains major quantities of oligoclase-andesine and hornblende with lesser amounts of chlorite, epidote and sericite. The diorite ranges from fine to coarse grained and contains numerous inclusions of quartzite and dikes of greenstone and granite. The western contact of the diorite mass with the Moretown

PLATE XXVI

Termination of quartz-monzonite exposure, south of Temple School. Fractures filled with milky white quartz.

formation appears conformable. In part, the diorite to the south is porphyritic, with phenocrysts of andesine.

The contact with the granite on the east could not be clearly discerned, but the presence of granite dikes in the diorite substantiates the assumption that the diorite mass is the older.

Origin of the Igneous Rocks

Most of the evidence seems to favor a magmatic source for the plutonic rocks in the quadrangle. The outcrops of the plutonic bodies are elongated about parallel with the regional trend and the contacts with the wall rock are, for the most part, conformable and relatively sharp. Evidence for forceful emplacement is substantiated both in the Braintree and Bethel plutonic bodies by the bulging out of the enclosing formations. In the Braintree complex the Harlow Bridge basal quartzite of the Cram Hill formation is almost completely cut out to the north by this body. Most of the granitic bodies observed contain only minor inclusions of wall rock and evidence for assimilation or replacement is absent.

Age of the Igneous Rocks

Since these bodies occur within rocks of probable Ordovician age, and in view of their assumed intrusion near the close of the second deformational episode, a Lower Devonian age is assigned for their emplacement.

Dike Rocks

Numerous dikes of both acidic and basic composition have intruded the rocks of the Randolph quadrangle. Basic dikes are, by far, the more common. Pegmatites are almost totally lacking. Most of these intrusives are somewhat metamorphosed, but a few appear relatively fresh.

The abundant zones of greenstone in the pre-Shaw Mountain type rocks also occur as cross-cutting dikes. They transect the early deformational features but, in part, are also folded.

In Richardson's reports (1921, 1923, 1924, and 1927) on the townships included in the Randolph quadrangle, granite, diorite, diabase and camptonite dikes are described.

For the most part, the dikes within the quadrangle trend north-south, nearly parallel to the regional trend of the bedding or, on occasion, they follow the east-west joint set. Most dikes are nearly vertical and range from a few inches up to three or four feet thick.

One of the most accessible kersantite dikes crops out three-quarters of a mile northwest of Hewetts Corners in the northeast part of the Woodstock quadrangle. This dike is in the stream on the south side of the road near the junction of the three tributaries of the stream. The dike, approximately eighteen inches in thickness, is composed of subhedral laths of andesine altered to sericite and kaolinite, biotite crystals highly chloritized, corroded euhedral augite, calcite and apatite, with minor amounts of quartz, hornblende and magnetite.

Ultramafic Rocks

The metamorphosed ultramafic rocks in the Randolph quadrangle are confined to the formations west of the Cram Hill formation. Presumably, they antedate the regional metamorphism and are the oldest plutonic rocks in the area. These exposures are part of an extensive belt of ultramafic bodies which has been traced through central Vermont, and is probably a part of the belt extending from Alabama to Newfoundland (Chidester, Billings and Cady, 1951).

The serpentinites have been metamorphosed and altered into steatite, talc-carbonate rocks and verde antique with only a minor amount of the original serpentinite remaining.

A slight zonal distribution of the rocks was distinguished in the locality north of Bethel Gilead. A core of highly altered serpentine or steatite graded outward into a talc-carbonate rock and was bordered by chlorite schists. The other exposures were too small or poorly exposed to show any distribution. The ultramafics are pod-like, usually steeply dipping, and conform to the pronounced schistosity of the enclosing rocks. Large crystals of chrysotile, calcite, actinolite and talc were collected at a number of exposures.

An Early Ordovician age has been postulated for these ultramafic bodies (Chidester, Billings, and Cady, 1951; Cooke, 1937; Bain, 1936).

Quartz Veins

Quartz veins are in all formations within the quadrangle but are most prominent in the rocks of the Gile Mountain and Waits River formations. Richardson (1925) has made particular mention of those north of Mt. Olympus in the western part of the quadrangle.

Perhaps the most conspicuous quartz veins are the large lenticular bodies conformably following the regional strike in the phyllites of both the Gile Mountain and Waits River formations. One vein (by the letter "r" on Hebard Hill on the topographic map) is 120 feet long and about sixty feet wide (Plate XXVII). Approximately 200 yards farther north along the strike, another quartz vein is exposed for eighty-five feet, but is not as wide.

The quartz veins are not restricted to the phyllitic layers. Frequently, they are ptygmatically folded and often show cross-cutting relationships. The quartz veins also follow the bedding, cleavage or schistosity.

The quartz veins, for the most part, are not pure and contain minor quantities of muscovite, pyrite, carbonate and, less frequently, feldspars. In zones of higher metamorphism, kyanite is a common associate.

METAMORPHISM

General Statement

The rocks within the Randolph quadrangle were originally sediments interspersed with minor volcanics. Regional metamorphism has acted on the stratigraphic units from a low to moderately high degree. The effects of contact metamorphism are limited.

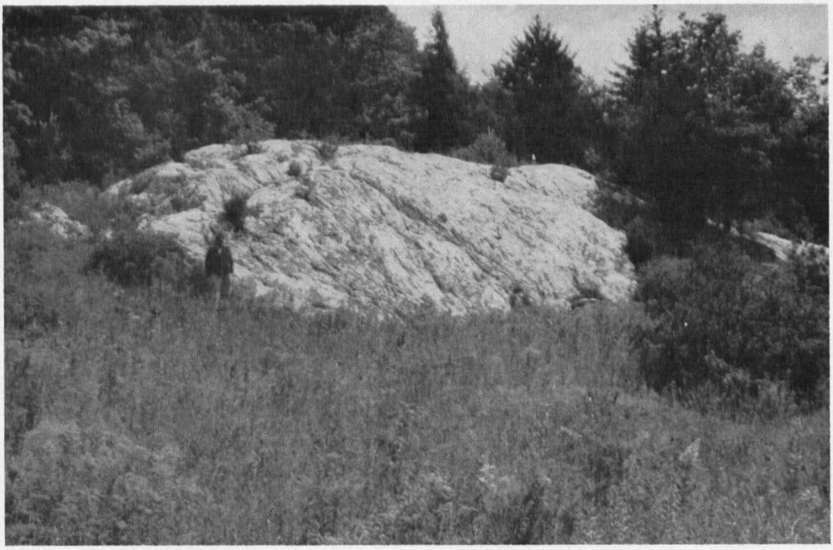


PLATE XXVII

Large outcrop of milky-white vein quartz of Hebard Hill. Exposure over 120 feet in length and 60 feet in width.

Metamorphic zoning is not well defined in the rocks in the Randolph quadrangle. This is due to the wide variance in composition of the interbeds in separate formations and, at times, the indecision of whether this variance was due totally or only partly to the original chemical composition of the rocks or to local diversions in metamorphism.

The facies classification after Turner (1948) is utilized to describe the metamorphic relations.

Greenschist Facies

Rocks placed in the greenschist facies are characterized by an abundance of low temperature hydrous minerals and the absence of garnet. Both the biotite-chlorite and muscovite-chlorite subfacies (Turner, 1948) are probably represented, but due to the interbedding of biotite-free and biotite-rich rocks in most formations, the subfacies could not be distinguished.

The rocks exposed west of the garnet isograd belong to the greenschist facies with the characteristic mineral assemblage of chlorite, muscovite, albite, quartz and biotite in dominance and lesser amounts of epidote, calcite, graphite, magnetite and rare chloritoid. Rocks occurring in this facies, west of the garnet isograd, include a wide range of compositions: graphitic quartz-chlorite schists (Ottauquechee); quartz-chlorite-albite-muscovite schist (Stowe); chlorite-albite-epidote-calcite schists (Brackett member, Cram Hill); quartz-mica granulites (Moretown); micaceous quartzites (Moretown, Cram Hill); sericitic phyllites (Cram Hill, Waits River); quartz-feldspathic schists (Cram Hill, Shaw Mountain); slates (Moretown, Northfield); and siliceous marbles (Waits River and Gile Mountain).

Near the garnet isograd, biotite appears both as disseminated flakes and as porphyroblasts. Biotite cuts across the schistosity and hence the term "cross biotite" is applicable.

No distinctly porphyroblastic chlorite was noted. The mineral is widely distributed throughout the facies as a primary product.

The feldspar in these formations is dominantly albite-oligoclase.

Most of the ultramafic bodies are in this facies and are characterized by the presence of talc, actinolite and chlorite. The appearance of actinolite in these rocks and in the greenstones within the albite-epidote amphibolite facies may be explained in two general ways: (1) reaction of dolomite with quartz, or (2) reaction of excess chlorite with quartz and calcite (Billings, 1937, p. 546). The latter seems more probable since the rocks containing carbonate minerals are composed dominantly of calcite with lesser amounts of ankerite and very minor dolomite.

Albite-Epidote Amphibolite Facies

The majority of the rocks within the Randolph quadrangle are represented by the chloritoid-almandine subfacies (Turner, 1948). This facies embraces the lithologies eastward from the Stowe to the Waits River formation. These rocks are all rich in micaceous minerals, quartz, plagioclase and almandine garnet and to a lesser degree in hornblende, calcite, epidote and magnetite. The biotite, for the most part, shows evidence of having been formed at the expense of the chlorite and, at times, forms about a nucleus of iron oxide or ilmenite. The biotite here and elsewhere (Kruger, 1946; Lyons, 1955; Murthy, 1957) is distinctively darker in color than that found in the greenschist facies. However, Lyons (1955, p. 142) reported no relationship between refractive index, intensity of metamorphism and the nature of the rocks.

The almandine garnet is porphroblastic and generally cuts across slip cleavage planes. Garnets have been observed with perfect crystalline outlines. Some show distinctive zoning and others have corroded

FIGURE 6

METAMORPHIC ISOGRADS AND ECONOMIC LOCALITIES

Um-ultramafics Ap-arsenopyrite Cu-copper

borders. Rotated porphroblasts of garnet are very common in the albite-epidote-amphibolite facies in the Randolph quadrangle indicating an overlap of periods of deformation and metamorphic intensity. Minor unrotated porphyroblasts have been noted (Plate XXVIII).

The plagioclase throughout this facies is dominantly oligoclase although it ranges from albite to andesine.

Chlorite is common in this facies as flakes adjacent to planes of later slippage. It is present as a retrograde product, often totally replacing the garnets. In part, chlorite also replaces biotite and hornblende, particularly that in the Barnard formation.

The presence of minor amounts of tourmaline in the Whetstone Hill member is interesting. MacFadyen (1956) suggests three possible sources for the boron necessary to tourmaline in pelitic sediments. One is the sea water in the geosyncline enhanced by volcanic activity. Second, a source rich in tourmaline such as a granitic area rich in tourmaline-bearing pegmatites. The third possibility suggested was pneumatolytic activity associated with deep seated intrusions—for instance, from the granitic bodies underlying the domes to the east. Since the domes are a later deformational feature, and a source for tourmaline-rich pegmatites is improbable in any area nearby, the first-mentioned probable source for boron seems most reasonable—that of volcanic activity enriching the sea water in the geosyncline and its subsequent enrichment of the sediments.

Calcite, abundant within the Waits River formation, appears to be well recrystallized and shows excellent twinning. On occasion, the calcite crystals are partly replaced by quartz.

Amphibolite Facies

The amphibolite facies is the highest degree of metamorphism attained in the Randolph quadrangle. The area lying within this facies is outlined on the map (Fig. 6) by the kyanite isograd. The mineral assemblages of the staurolite-kyanite subfacies (Turner, 1948) are represented in the garnetiferous quartz-mica schists, phyllites, quartzites and siliceous marbles in the Waits River and Gile Mountain formations, along with the amphibolites and hornblende schists of the Standing Pond volcanics.

The minerals characteristically associated with the metavolcanics of the Standing Pond are hornblende, almandine, oligoclase-andesine, quartz, muscovite, biotite and magnetite. Some of the hornblende is retrogressive to chlorite and sericite.

PLATE XXVIII

Figure 1. Photomicrograph of a rotated garnet porphyroblast in phyllite of the Waits River formation. Note the presence of slip cleavage. (X12)

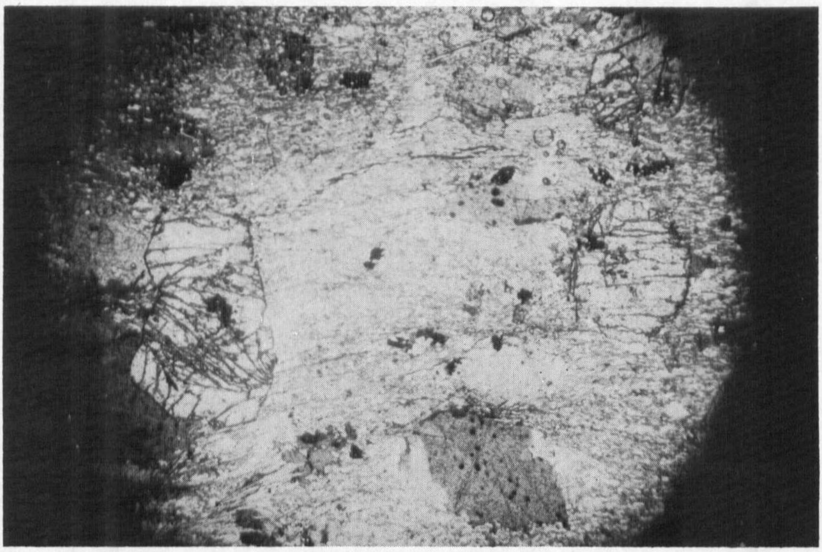


Figure 2. Photomicrograph of a porphyroblastic biotite-garnet schist in the Gile Mountain formation, without any rotational features. (X12)

Muscovite, biotite, albite-oligoclase, almandine and kyanite are the essential constituents of the non-calcareous beds in the Waits River and Gile Mountain formations in this facies.

The minerals characteristic of the calcareous beds are epidote, calcite, oligoclase, biotite and very minor amounts of diopside and sphene. The only aluminous silicate present in the amphibolite facies in the Randolph quadrangle is kyanite. Staurolite is distinctively absent in the quadrangle.

Contact Metamorphism

Contact metamorphic effects are limited within the Randolph quadrangle.

Thermal metamorphism reached a moderate grade in the rocks of the Moretown and Cram Hill formations surrounding the Braintree Complex, but could not be clearly defined in the Randolph area due to poor exposure in its southernmost extension. However, farther north in the Barre quadrangle, a thermal aureole can be clearly substantiated (White and Jahns, 1950, p. 194).

The thermal effect on the dominantly phyllitic rocks of the Waits River formation surrounding the Bethel granite is limited to an extremely narrow zone surrounding this body.

Metamorphic Relations

The metamorphic intensity of the rocks of central Vermont increases toward the east, but grades westward from the Connecticut Valley. The culmination of the metamorphic intensity is in the arch structures and domes which traverse the state from north to south. (White and Jahns, 1950; Thompson, 1950; Chang, 1950; White and Billings, 1951; Lyons, 1955; Dennis, 1956; and Murthy 1957).

The Randolph quadrangle is situated west of the Strafford and Pomfret domes. Therefore, the metamorphic intensity is one of persistent increase in grade to the east.

The porphyroblasts of the second stage of deformation bear a two-fold relationship to the schistosity. In many instances, the garnets and rarely the biotite crystals are rotated or sheared by the later schistosity, whereas in other instances, the porphyroblasts cut randomly across the earlier schistosity. One can deduce from this, that the thermal and deformational episodes in the Randolph quadrangle overlapped to some extent. Similar evidence has been found in the East Barre and Barre areas (Murthy, 1957, p. 111 and White and Jahns, 1950, p. 209). In the

Hanover quadrangle, however, Lyons (1955, p. 138) reported porphyroblasts as relatively uncommon. East of the Willoughby arch evidence of post-crystallization crushing or rotation of porphyroblasts is only a local feature indicating that deformation had ceased before the peak of metamorphic recrystallization (White and Billings, 1951).

The general conclusion of Murthy (1957, pp. 111–112) that "the thermal metamorphism gradually spread outward from the central area of the cleavage arch, whereas the deformation was essentially contemporaneous everywhere" is still appropriate.

The New England crystalline province was compared to the folded Appalachians in Pennsylvania by Barrell (1921). He concluded that neither dynamic metamorphism nor the effects of load metamorphism could cause these metamorphic changes and he atrributed its cause to plutonic intrusions.

In the Randolph quadrangle, the trend of metamorphic intensity is toward an area characterized by a negative gravity anomaly (Bean, 1953, p. 529) and a domal structure, perhaps indicating plutonic activity at depth. In western New Hampshire, Billings (1937, pp. 557–559) noted a progressive increase in metamorphism southeastward which he related to the position of large bodies of the New Hampshire Magma series.

On the whole, the mineral composition of most of the rocks in the area indicates that metamorphic equilibrium was attained. The rocks in which retrogressive minerals are found can be attributed to the overlap of deformation and falling temperature in the close of metamorphic intensity.

ECONOMIC PRODUCTS

General Statement

The natural resources of the Randolph quadrangle include dimension stone, arsenopyrite and copper mineralization, talc and serpentine, and sand and gravel deposits.

The Northfield slate in the Randolph quadrangle is lacking in good fissility so that it is not of economic importance as a roofing material as it is at the type locality farther north.

Dimension Stone

Bethel Granite

The major portion of this industry was centered on the east side of Christian Hill near the town of Bethel where both the Ellis and Woodbury quarries are located. These quarries were opened in 1902 for structural and monumental work and statuary. The distinctive coloration of this rock gave it the commercial name of "Bethel white granite." Some of the more prominent structures erected with this granite are the City Hall and State Library at Hartford, Connecticut; the Capitol Building at Madison, Wisconsin; the Union Station, Post Office and first and second floors of the National Museum in Washington, D. C.

These quaries have been closed and reopened on many occasions. In 1957, the Rock of Ages Corporation again began cutting the "Bethel white granite" on a limited scale for structural replacement stone.

Braintree Granite

The granite in the Braintree Complex in the northwestern part of the quadrangle northwest of Ferry Hill is being quarried on a small scale for monumental rock.

Beedle's Prospect

In the town of Randolph, two-tenths of a mile south of Beanville School, on the east side of the hill is an outcrop of fine white granite very similar to, but not as white as that at Bethel. In the older literature it is referred to as Beedle's prospect. The rock has been used for monumental work.

Heap Pinnacle Prospect

The fine-grained white stone on Heap Pinnacle, two miles west of Bethel, was quarried years ago for construction of the National Bank in Bethel.

Mineral Deposits

Arsenopyrite

Arsenopyrite was first reported by Richardson and Cabeen (1920) near East Braintree village. It occurs in a single vein which parallels the regional strike. The known length of the vein is about two hundred yards. The width ranges from three to four inches. The principal gangue is quartz and an analysis of the arsenic content reported 43.39% (Richardson and Cabeen, 1920, p. 73). Some attempt to develop the vein is indicated by trenching.

Copper

A very small zone of copper mineralization, mainly in the form of bornite, was located in the vicinity of the General Thomas Monument north of Bethel Gilead. A chalcopyrite-pyrrhotite vein, four inches in width, located one-half mile east of Bethel village was ascertained by the presence of a number of pits. Its known length could not be determined.

Talc and Serpentine

The talc and serpentine deposits have been described in the section on ultramafic deposits and known deposits are indicated in Figure 6. None of these deposits show evidence of anything but limited operations.

Sand and Gravel

The glacio-fluvial and alluvial deposits of gravel in the valleys of the Second and Third Branch of the White River have, at times, been used for road construction. In some locales the glacio-fluvial deposits are sufficiently reworked so that sand and fine silts are in low enough proportion, and the remaining pebbles in sufficient abundance to make the exposure useful. The bed of the White River has supplied stream gravels in recent years. Primary and secondary crushers have been set up along the river banks. The crushed stone is adequate for road construction.

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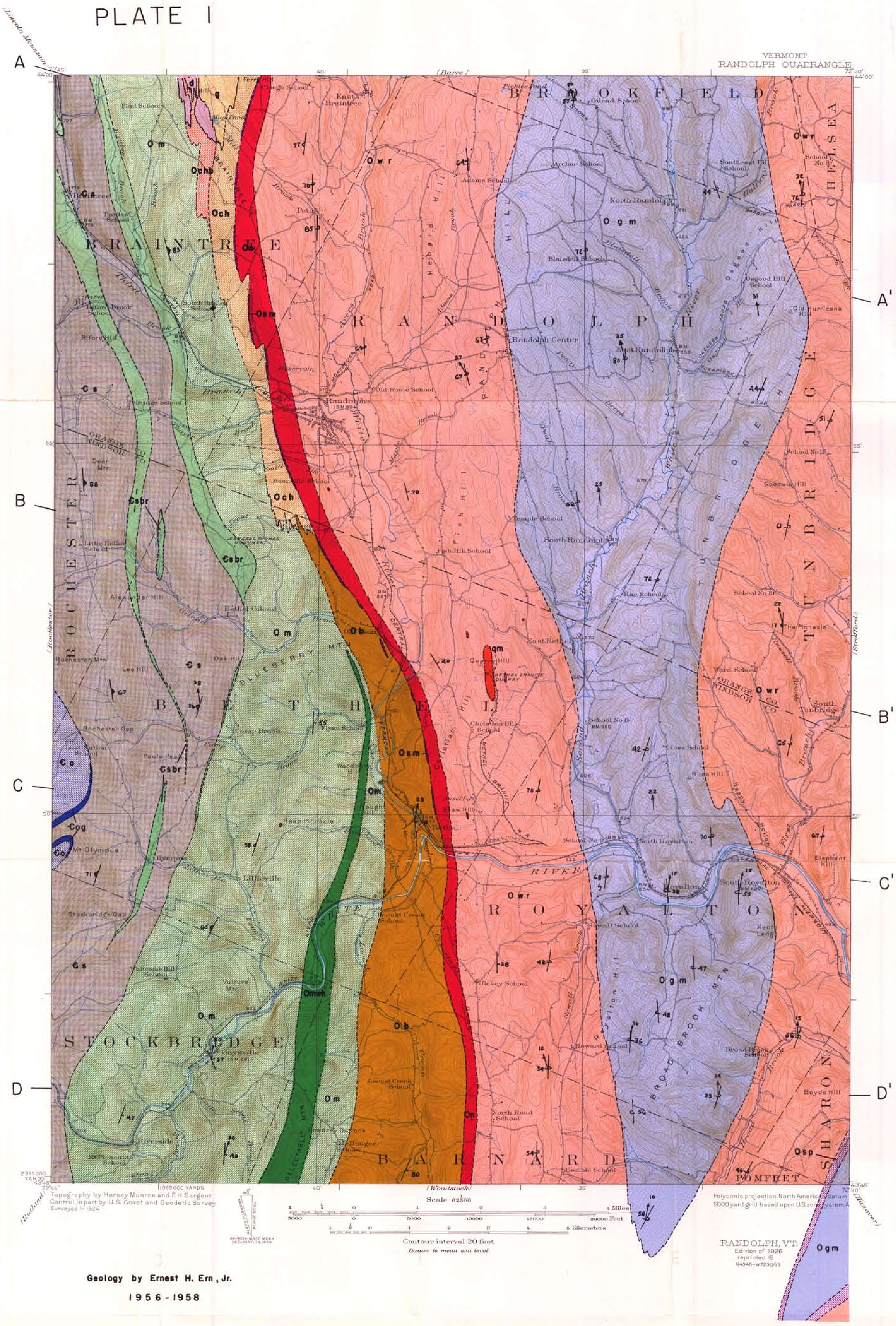
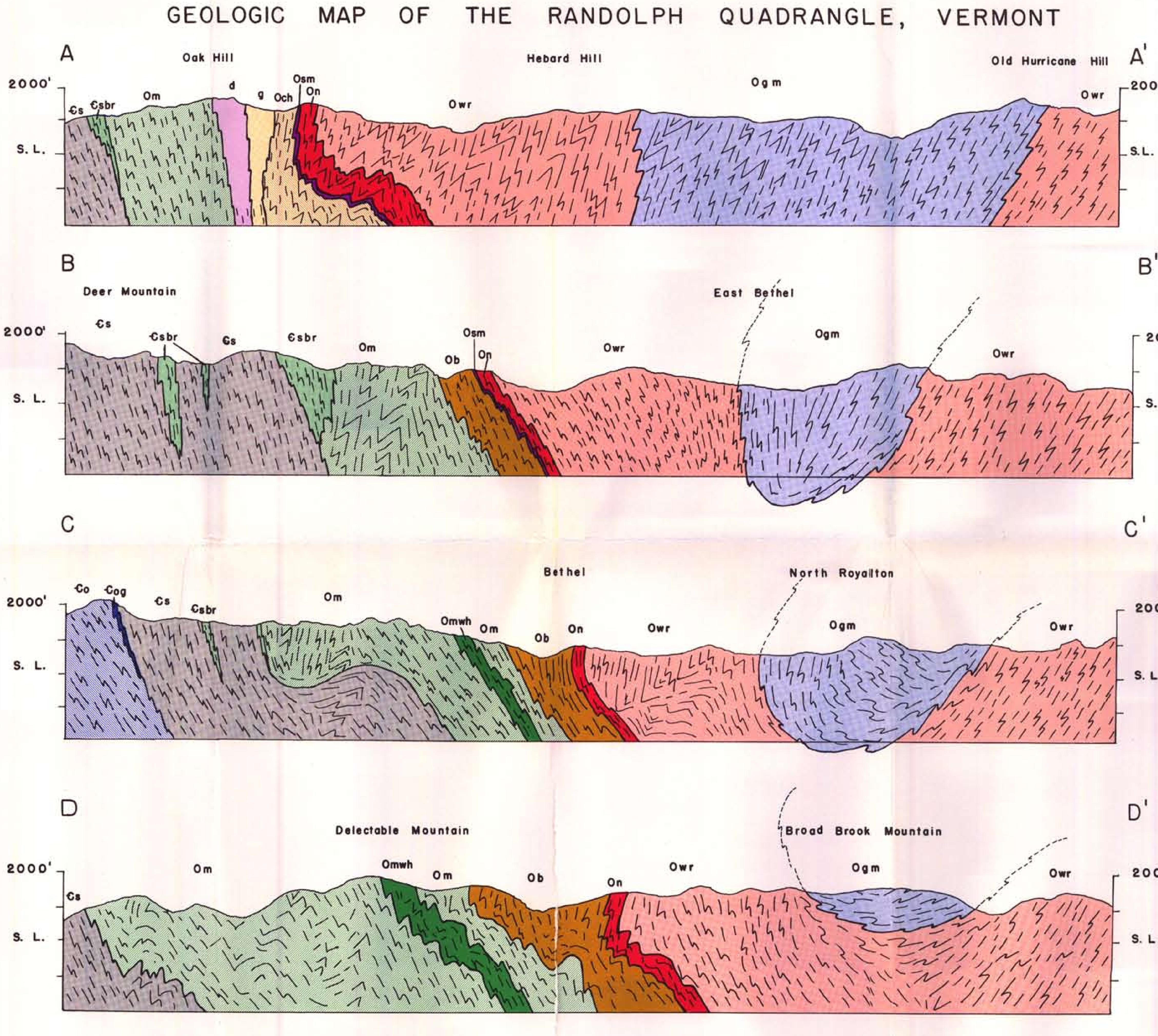
PLATE I



Geology by Ernest H. Ern, Jr.

1956-1958

GEOLOGIC MAP OF THE RANDOLPH QUADRANGLE, VERMONT



LEGEND

d — Diorite

g — Granite

qm — Quartz Monzonite

ORDOVICIAN ?

Owr — **WAITS RIVER FORMATION**

Blue-gray recrystallized impure limestone, highly siliceous, garnetiferous phyllite, tan quartzite, quartz-biotite schist, and quartz-calcite schist.

Ogm — **GILE MOUNTAIN FORMATION**

Quartz-mica schist, garnetiferous phyllite, micaceous quartzite, and minor siliceous marble.

Osp — **STANDING POND VOLCANICS**

Needle amphibolite, garnetiferous amphibolite, and hornblende schist.

On — **NORTHFIELD FORMATION**

Gray slate, phyllite, and minor siliceous marble.

Osm — **SHAW MOUNTAIN FORMATION**

Sericite schist, locally calcareous, and tuffaceous.

- - - - - - - UNCONFORMITY - - - - - - -

Ob — **BARNARD FORMATION**

Biotite gneiss, hornblende gneiss, locally calcareous, garnetiferous hornblende gneiss, greenstone, and amphibolite.

Och, Ochb — **CRAM HILL FORMATION**

Splintery greenish-gray phyllite, greenstone, and feldspathic quartz-biotite-sericite schist. Basal quartzite - Harlow Bridge member, Ochb.

Om, Omwh — **MORETOWN FORMATION**

Pinstriped quartz-chlorite-albite-sericite granulite, micaceous quartzite, greenstone, carbonaceous slate and phyllite. Black sericite-garnet-biotite-quartz schist and phyllite - Whetstone-Hill member, Omwh.

CAMBRIAN ?

Ꞓs, Ꞓsbr — **STOWE FORMATION**

Pale-green quartz-chlorite-albite-sericite schist with distinctive quartz lenses. Quartz-albite-calcite-epidote-chlorite schist - Brackett member, Ꞓsbr.

Ꞓo, Ꞓog — **OTTAUQUECHEE FORMATION**

Graphitic black phyllite, varying to a phyllitic schist, banded quartz-chlorite-albite schist, and interbedded greenstone (Ꞓog).

STRUCTURAL SYMBOLS

- Accurate contact
- Gradational contact
- Inferred contact
- 61 Strike and dip of bedding
- 47 Strike and dip of overturned bedding
- 20 Strike and dip of foliation or schistosity
- 15 Bearing and plunge of lineation

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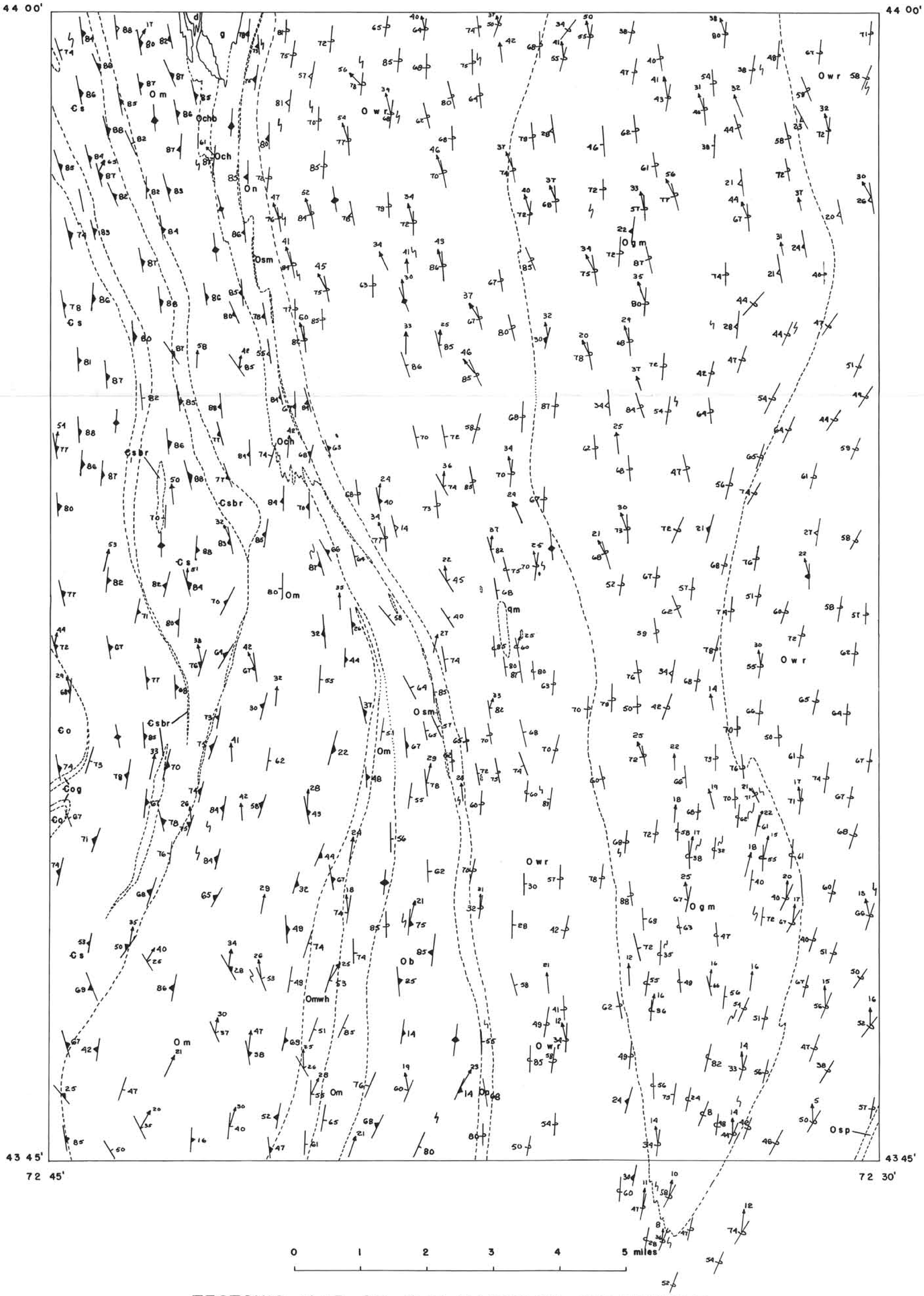
PLATE 2



TECTONIC MAP OF THE RANDOLPH QUADRANGLE, VERMONT

LEGEND

- Accurate contact
- Gradational contact
- Inferred or concealed contact
- Strike and dip of bedding
- Strike and dip of overturned bedding
- Strike and dip of foliation or schistosity
- Strike and dip of vertical foliation or schistosity
- Strike and dip of schistosity with plunge of minor fold
- Strike and dip of slip cleavage
- Sinistral pattern of minor folds
- Dextral pattern of minor folds
- Bearing and plunge of linear element

Formation symbols as shown on the geologic map.

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