BED ROCK GEOLOGY
OF
THE EAST BARRE AREA, VERMONT

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Rock of Ages Quarry seen from its southwestern end. Prominent joint surfaces and a dark dike cutting the Barre granite are seen in the left side of the photograph. Grout piles in the background.

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ABSTRACT

The East Barre area lies on the eastern limb of the Green Mountain anticlinorium in east-central Vermont. Four lithologic units, considered here as formations, are present. West to east they are: The Barton River, the Westmore, the Waits River and the Gile Mountain formations. The Barton River and Westmore formations are continuous with the same formations in their type area farther north. Hitherto, they were included with the unit of calcareous rocks in the central part of the East Barre quadrangle, in an all-too-comprehensive Waits River formation, but the excellent mappability of the individual units and the available structural and stratigraphic evidence justify distinguishing the units as separate formations. I suggest therefore, that the term 'Waits River formation' be restricted to include only the eastern calcareous unit, as the geographic locality, Waits River village, is situated on this unit and excellent outcrops are present northeast of the village.

An analysis of the minor structures, such as plunges and patterns of the minor folds and cleavage-bedding relations, shows that the rocks of the area were subjected to two stages of deformation.

North-plunging minor folds, showing sinistral patterns on the western limb and dextral patterns on the eastern limb, indicate that during the first stage the rocks were folded into a major syncline, the trough of which was occupied by the present Waits River formation. Consequently, the Waits River formation is the youngest in the Vermont sequence. A corollary of this interpretation is the probable correlation of the Westmore formation with the Gile Mountain formation. If correct, the above interpretation calls for a revision of the stratigraphic sequence in eastern Vermont, and as a larger implication helps in the probable correlation of the Vermont and New Hampshire sequences.

In the second stage deformation, the axial part of the early formed syncline was pushed obliquely upwards, possibly by the rise of a plutonic

body at depth. This resulted in the rotation of the early folds and early schistosity and in the formation of a cleavage arch—recorded in the second stage schistosity.

Petrographic studies of the two major groups of granite plutons in the above area indicate significant mineralogical differences between them. Evidence of several sorts shows that the Barre granite is a magmatic granite and that it has been emplaced as a passive intrusion, space being provided partly by pushing aside of the country rocks and partly by stoping.

The age of the Barre granite is 330 ± 25 million years, as determined by the Rb/Sr method, using the biotite in the rock.

Two stages of metamorphism, corresponding to the two stages of deformation, are noted. In the first stage, the rocks were metamorphosed to a low grade. In the second stage, regional metamorphism attained an intensity corresponding to the amphibolite facies. The Barre granite produced some contact metamorphism at its margins. The spatial relations of metamorphic facies to the plutonic bodies indicate a genetic relation between them.

The Barre granite, copper ore from the Pike Hill area, and gravel from the Pleistocene alluvial deposits, are of economic importance and are briefly discussed.

INTRODUCTION

Location and Area

The East Barre quadrangle is located in the northern portion of Orange County in east-central Vermont (Fig. 1). It lies between the 44° 00′ and 44° 15′ north latitude and 72° 15′ and 72° 30′ west longitude, and includes the towns of Orange and Washington, much of Corinth, Topsham, Groton, Barre, Plainfield, and Chelsea, and the eastern portion of Williamstown. The area of the quadrangle is about 210 sq. miles.

Regional Geologic Setting

The eastern limb of the Green Mountain anticlinorium consists of a thick homoclinal sequence of Cambro-Ordovician eugeosynclinal sediments and metasediments of essentially calcareous and arenaceous character, interspersed with volcanics. These rocks unconformably overlie the Precambrian crystalline complex in the core of the Green Mountains, and become progressively younger to the east. This thick

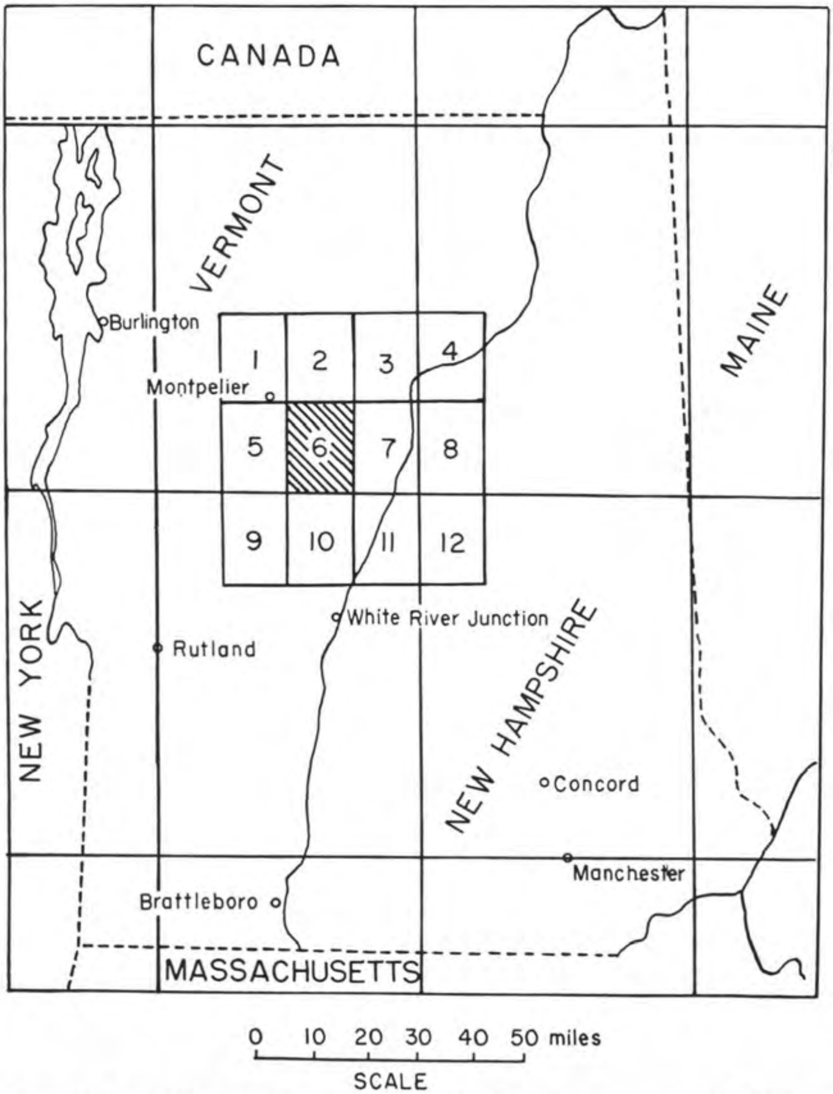


Figure 1. East Barre quadrangle is shaded. Quadrangles are numbered as follows:

1. Montpelier
2. Plainfield
3. St. Johnsbury
4. Littleton
5. Barre
6. East Barre
7. Woodsville
8. Moosilauke
9. Randolph
10. Strafford
11. Mt. Cube
12. Rumney

Paleozoic section is separated from the New Hampshire sequence by the Monroe line. The exact relation of the Vermont sequence to the New Hampshire sequence is controversial.

The east-dipping beds of the eastern limb of the anticlinorium steepen progressively, and some 20 to 30 miles west of the East Barre quadrangle, they pass into a tight syncline. East of this syncline, the structural setting is rather complex and evidences of several stages of deformation are shown in the cleavage domes of east-central Vermont and west-central New Hampshire.

The area of the present study is directly north of the Strafford quadrangle (Doll, 1944, p. 14–28) and the rocks that crop out on the sides of the Strafford dome in this quadrangle continue into the East Barre quadrangle from both sides of the dome. Structurally the East Barre area forms a part of the eastern and central tectonic belts of White and Jahns (1950, p. 198).

Previous Work

The earliest geological studies were those of Edward Hitchcock (1861), C. H. Hitchcock (1912), and C. H. Richardson (1902, p. 61–98; 1906, p. 63–115). Of these the first two were mainly reconnaissance surveys, and are now much modified and elaborated upon by subsequent investigations. Richardson's papers are in greater detail and include descriptions of the stratigraphic sequence overlying the eastern limb of the Green Mountain anticlinorium, and chemical and petrographic studies of the granites of Bethel, Danby, and Woodbury.

In addition to regional geologic studies many other investigations were focussed on the various granite localities in the state, of which the Barre area is pre-eminent. The earliest detailed description of the petrographic and structural features of the Barre granite is that of Finlay (1902, p. 46–60). Subsequently, T. N. Dale (1909, 135 pp; 1923, 488 pp.) published his comprehensive work on the granites of New England, in which a prominent place was given the Barre granites. Robert Balk (1925, p. 39–96) made a detailed study of the structural relations of the granites of Bethel, Barre and Woodbury, Vermont, and more recently Maynard (1934, p. 146–162) studied the composition of the quartz-bearing plutonic rocks of Vermont, and Shimer (1943, p. 1049–1066) conducted a series of spectrographic analyses of New England granites, including some from the Barre area.

In the past few years the staff of the U.S. Geological Survey made a very detailed geologic map of the granite area on a scale of 1000 feet to the inch. The work was aimed at elucidating the mode of emplacement of the granitic rocks, evaluating their various structural characteristics, and solving numerous technical problems that have arisen during the course of the quarrying operations (Jahns, 1956, personal communication). But none of this work has yet been published.

Chayes, F. (1950, p. 52–66; 1952, p. 207–254) studied the variation in the modal analyses of several specimens from the Barre granite and came to the conclusion that the Barre granite is possibly of magmatic origin.

The main stratigraphic studies made in the area are those of Currier and Jahns (1941, p. 1487–1512); Doll, C. G. (1943, p. 57–64; 1944, p. 14–28) and Cady, W. M., (1949, p. 488–497). Currier and Jahns's discovery of crinoidal limestones at a horizon lower than the base of the Northfield slate proved that the Cambro-Ordovician boundary of earlier authors is only a horizon in the Ordovician. They also formally named two new formations, the Shaw Mountain formation and the Cram Hill formation, both underlying the Northfield slate.

Doll (1943, p. 57–64) reported crinoids, cystoids, and brachiopods in the phyllitic beds of the Waits River formation and accordingly gave a Middle Silurian or Early Devonian age to the Waits River formation. Also, Doll (1944, p. 14–28) has mapped the Strafford quadrangle, an area of structural importance directly south of the East Barre area.

Cady (1949, p. 488–497) found fossil cup corals in phyllitic beds of the Waits River formation near Montpelier and on the basis of these fossils ascribed a Middle Ordovician age to this part of the Waits River formation. The most comprehensive recent work on the structure of this part of the state is that of White and Jahns (1950, p. 179–220). They have found evidence for two periods of deformation each characterized by a cleavage and schistosity, and minor folds, readily distinguishable from each other in the field. Based on the mutual field relations of these minor structural features, and their relation to the bedding, they came to the conclusion that the Strafford dome is a cleavage dome and not a simple anticline as postulated by Doll (1944, p. 14–28). White and Jahns have also outlined the problem of the stratigraphic status of the belt of phyllites and schists occurring immediately east of the town of Barre, and suggested some alternative explanations.

Present Study

The present work was undertaken to study mainly the following aspects of the geology of the East Barre quadrangle:

1. Major structures in the area and their implication on the stratigraphic sequence in eastern Vermont.

2. Stratigraphic and structural relations of the belt of phyllites and schists east of Barre City, in the western part of the quadrangle.

3. Petrology of the granites and their origin.

4. Regional metamorphism and its relation to structural deformation.

Method of Work

The field work occupied two field seasons during which the quadrangle was mapped geologically. Emphasis was laid on a detailed study of the minor structural features which were mapped on a scale 2 inches to a mile. The contact relations of the granites to the country rocks, and detailed sampling of the granites for modal analyses was done subsequently. A good part of two academic years at Yale University went into the laboratory study of the rock specimens and other investigations.

The map used in the present work for the areal mapping of the quadrangle was the 15 minute U.S.G.S. topographic map of the East Barre quadrangle, published in 1948. For some detailed mapping around the granite quarries larger scale maps were used. Aerial photographs have been used very sparingly, since the dense vegetation in most areas makes them very difficult to read.

Acknowledgments

I am greatly indebted to Professors Bateman and Rodgers under whose general supervision this work was carried out; both of them gave freely of their time and advice and visited me in the field.

Dr. Charles G. Doll, State Geologist of Vermont, kindly arranged for the employment of the author by the Survey during the two field seasons. I sincerely acknowledge my pleasure in working for the Vermont Geological Survey under his supervision. Dr. Doll visited me in the field several times and supervised the work.

To Dr. W. M. Cady and Dr. A. Chidester of U.S. Geological Survey I am very grateful for familiarizing me with the regional geology, for the many suggestions and instructive criticisms, and for visiting me in the field several times.

It is a pleasure to acknowledge the help of fellow geologists working in nearby areas for the several discussions and field trips into their areas. Particular mention must be made of Ronald H. Konig, Ernest H. Ern, Jr., Leo Hall, and Stephen P. Averill. The last named assisted me in the field for one month during the second field season.

To several companies in the granite industry I express my gratitude for the help given in the field work and laboratory investigations on the granites. Chiefly to the Rock of Ages Corporation, I am particularly indebted for giving me free access to all their quarries, for supplying me with large-scale maps of the granite area, and for other invaluable help. Financial help received from the D. F. Hewett Fund, and the Alan M. Bateman Fund is gratefully acknowledged.

The two summer seasons in the field have been made particularly pleasant by the kind hospitality of Mr. and Mrs. Earl A. Rinker of East Barre village.

It is my pleasure to record here the keen interest shown by Governor Joseph B. Johnson in the present program of the Vermont Geological Survey in getting the whole State of Vermont geologically mapped and studied. Governor Johnson personally visited me in the field and spent a day going over the more critical areas in the East Barre quadrangle. The State of Vermont is fortunate indeed that its Chief Executive should take such an active interest in the development program of the Geological Survey.

Topography and Drainage

The topography of the East Barre quadrangle includes two distinct types. The northwestern corner of the area is characterized by flat topped hills with gently undulating slopes. To this category also belongs the topography of the southeastern corner of the map area. The topography of the rest of the quadrangle, in contrast to the above, is typically hilly to mountainous, with steep rugged slopes on the narrow valley sides. In some places, a relict glacial topography modified to some extent by the action of running water and frost as well as other mass wasting processes is seen.

In a general way, the relief of the area is related to the bed rock. The conspicuous divide that trends approximately northeast in the northern half of the quadrangle is composed of granitic rocks. The lowest point at the extreme southern margin of the area is underlain by the relatively more erodable limestones and calcareous schists of the Waits River formation. The overall relief of the quadrangle is well over 2400 ft.

The major topographic features are the granite mountains, of which the highest is Signal Mountain with an elevation of 3348 ft. above sea level. Other prominent granite mountains are Burnt Mountain (3116 ft.), Spruce Mountaiu (3137 ft.), Butterfield Mountain (3166 ft.), St. Cyr Mountain (2346 ft.) and the Knox Mountains. At the western margin is a conspicuous granite knob, called Cobble Hill (1776 ft.), and 1½ miles southwest of it is a flat-topped, dome-shaped hill, Millstone Hill.

A striking topography consisting of steep cliffs and narrow valleys occurs in the southwestern corner of the quadrangle. The origin of these valleys is not clear. It is surmised that downcutting of easily erodable limestone by streams running parallel to the trend of the local schistosity, may have given rise to these features.

The drainage of the area can be divided into two systems. The streams of the northwestern portion of the quadrangle drain into the Jail Branch which is a main tributary of the Winooski River. The general direction of flow is toward the northwest, into Lake Champlain. The Winooski and its drainage is one of the best examples of superposed streams. Its major tributaries are subsequent streams, and form a trellis pattern with the main stream.

The First Branch White River, Waits River and the Hart Hollow stream flow generally southeast and drain into the Connecticut River. The First Branch White River and Waits River are inferred (Meyerhoff, 1929) to have been superimposed from the Connecticut River sediments that at one time covered the entire area. The divide between the two drainage systems is the Knox Mountain granite belt that trends in a northeasterly direction through the middle of the quadrangle. At its western margin, the topographic high immediately south of Washington village separates the headwaters of the Jail Branch from those of the First Branch White River.

The influence of structure of the bed rock on the drainage pattern is best exemplified in the southern half of the quadrangle. The stream courses are generally parallel to the cleavage or schistosity which strikes northeast in the western part, east-west in the central part, and northwest in the eastern part.

Climate and Water Supply

The climate of the region is moist continental to humid temperate. The winters are cold with abundant snowfall and minimal temperatures about 20 to 25 degrees below freezing. The summers are warm and humid, and the temperature seldom exceeds 90° F. The average annual rainfall, distributed evenly throughout the year is about 30–35 inches.

Wells and artificial reservoirs are the two major sources of water supply. The ground water table is close to the surface and wells dug to about 20 ft. depth yield water throughout the year.

Industries and Accessibility of the Area

The major industry of the area centers around the granite that is worked for monumental purposes. Granite from Millstone Hill is quarried in several places, mainly by the Rock of Ages Corporation and the Wells-Lamson Granite Company. This industry employs a large percentage of people in East Barre and nearby little towns.

The main towns in the area are connected by good state highways. The William Scott Memorial highway runs east-west through the middle of the quadrangle, and to the east it branches off into Route 302 that goes northeast, and Route 25 that runs southeast to join U.S. highway 5.

A network of unsurfaced graded and dirt roads provide access to the western and southwestern parts of the quadrangle. The mountainous north central and northeastern portions are practically devoid of passable roads and in many places can be reached only by foot.

STRATIGRAPHY

General Statement

In central Vermont, lower Paleozoic rocks on the eastern flank of the Green Mountain anticlinorium trend generally north-northeast with comparatively straight contacts, except for a few localities where they outline domal structures. Metasediments of similar age are found in western New Hampshire, but their stratigraphic relation to the sequence in eastern Vermont remains a controversy. It was considered, until recently, that a major fault, known as the Monroe fault separated the two sequences. The sequence west of the fault was called "the Vermont sequence" and that east of it, "the New Hampshire sequence" (White and Jahns, 1950, p. 182). However, the existence of such a major fault is doubtful in view of more recent and extended field work in nearby areas. The great lithologic similarity between the two sequences and indirect structural evidence suggest some probable correlations between them. Until the true nature of the 'Monroe line'—whether structural or stratigraphic—is known, however, and until more information about the regional structure is available, correlations between the two sequences will remain, at best, probable.

Despite the marked structural disturbance undergone by these rocks in central Vermont, no major repetitions of formations occur except in the extreme eastern part of the Vermont sequence. Complicated domal uplift and isoclinal folding repeat the Waits River and Gile Mountain formations in southern Vermont (Thompson, in Billings, et al, 1952; Doll, 1944, p. 21–26; Lyons, 1955, p. 122–125). The possible repetitions of the Gile Mountain formation in the East Barre area by a large-scale synclinal structure is discussed below in the chapter on structural geology.

Stratigraphic Units

In the present report the metasedimentary rocks of the East Barre quadrangle are divided into four mappable units. Previously, the western three units were included in one formation called the "Waits River formation" (Currier and Jahns, 1941, p. 1491). My geologic mapping in the East Barre area and recent work in the areas to the north showed that two of the units must be considered as separate formations. Consequently I propose that the term "Waits River formation" be redefined and the stratigraphic sequence modified as follows:

Gile Mountain formation (type locality—Strafford quadrangle)
Waits River formation (as newly restricted-type locality this area)
Westmore formation (type locality—Memphremagog quadrangle)
Barton River formation (partly exposed in this area)
Northfield slate (exposed in the Barre quadrangle)

The full reasons for this modification of the stratigraphic column are given later in the chapter.

If the structural interpretation offered in this report is accepted however, the Westmore formation may be correlated with the Gile Mountain formation and the stratigraphic column will have to be modified as follows:

Waits River formation (as restricted here)
Gile Mountain formation (= Westmore fm.)
Barton River formation
Northfield slate

Stratigraphic Relations

The problem of determining the proper sequence and the thickness of formations in this area presents many difficulties. Bedding in the western part of the quadrangle dips steeply west. In the southern and eastern parts of the quadrangle bedding is rarely observed, having been obliterated by intense deformation that produced secondary schistosity and slip cleavage. However, four lines of evidence, obtained from adjacent areas and cited in previous literature, indicate that the formations in the Vermont sequence become progressively younger eastward from the Green Mountain anticlinorium.

1. A conglomerate at the base of the Northfield slate in the Barre quadrangle contains pebbles derived from the Shaw Mountain and Cram Hill formations. These formations crop out to the west of the Northfield slate. (Currier and Jahns, 1941, p. 1502).

2. Ripple marks and cross-bedding in the quartzite beds of the Braintree-Northfield Range indicate that the rocks are younger to the east (White and Jahns, 1950, p. 183).

3. Fossil evidence, meagre and sometimes disputable, is consistent with evidences 1 and 2 above. The Cram Hill formation, correlated with the graptolitic slates of Magog, Quebec, (Clark, 1934; Ambrose, 1942) is of Trenton or Middle Ordovician age. Crinoids of Middle Ordovician or younger age have been found in the Shaw Mountain formation (Currier and Jahns, 1941, p. 1502). Fossil cup corals reported to be of Middle Ordovician age were found in the lower part of the Waits River formation (Barton River formation of the present report) by Cady (1950, p. 488), but they may be possibly Lower Silurian in age (Cady, personal verbal communication, 1956). Doll (1943, p. 57–64) reported crinoids, cystoids, and gastropods assigned to Middle Silurian or Lower Devonian age from the Westmore formation of the Memphremagog quadrangle. Thus it can be seen that the available fossil evidence is in agreement with the other lines of evidence in suggesting that the rocks become younger to the east.

4. If the north-plunging minor folds in the western part of the East Barre quadrangle are interpreted as drag folds, their sinistral pattern suggests that they lie on the west limb of a large syncline with its axis in the east-central part of the East Barre quadrangle, and thus that the rocks become younger to the east.

Definitions of Formations

Westmore Formation

The belt of micaceous schists and quartzites in the northwestern corner of the East Barre quadrangle poses certain structural and stratigraphic problems. The rocks of this belt are very similar to those of the Gile Mountain formation in the southeastern ninth of the East Barre quadrangle, and in the Strafford quadrangle. Because of their lithologic similarity, White and Jahns (1950, p. 189) tentatively correlated the two units. In areas where fossil evidence is very meagre and non-diagnostic, exact correlations can be made only on positive structural evidence and these authors discussed several structural interpretations that might explain the repetition (White and Jahns, 1950, p. 206–207).

This belt of arenaceous and argillaceous schists has been mapped continuously for more than 50 miles along the strike, connecting to the north with the Westmore formation of the Memphremagog quadrangle (Doll, 1951, p. 33). Dennis's (1956, p. 35) conclusion that the Westmore formation extends no farther south than the northern part of the St. Johnsbury quadrangle appears to be incorrect, and recent mapping in progress in the Plainfield and St. Johnsbury quadrangles (Ronald H. Konig and Leo Hall, 1956, personal communication) shows that it extends into the belt of schists in the East Barre quadrangle. It is therefore proposed that the name "Westmore formation" be used for this belt of schists and phyllites in the East Barre quadrangle.

Barton River Formation

Recognition of the belt of schists in the northwestern portion of the East Barre quadrangle as the Westmore formation necessitates the use of the term "Barton River formation" (Doll, 1951, p. 25) to include the essentially calcareous lithology west of the Westmore formation in the latitude of East Barre and Randolph quadrangles. Thus, the term "Barton River formation" will include the rocks above the Northfield slate and below the Westmore formation. This unit also is traceable continuously into the Barton River formation of the Memphremagog quadrangle, where it was originally named by Doll (1951, p. 22, 25). In the Barre and East Barre quadrangles, prior to this study, both the Barton River and Westmore formations were included under the Waits River formation as defined by Currier and Jahns (1941, p. 1491).

Central and East Central Vt. (Currier & Jahns, 1941; and White & Jahns, 1951.)	Memphremagog Quadrangle (Doll, 1951)	Hanover Quadrangle (Lyons, 1955)	Vermont - New Hampshire Stratigraphic Column (Billings, 1956) Standard	Vermont - New Hampshire Stratigraphic Column (Billings, 1956) Alternative		Montpelier Quadrangle (Cady, 1956)	EAST-BARRE QUADRANGLE AND ADJACENT AREAS (Murthy, 1957, This Report)	
		LITTLETON	LITTLETON					
		FITCH	FITCH					
		CLOUGH	CLOUGH					
		AMMONOOSUC VOLCANICS	AMMONOOSUC VOLCANICS					
		ALBEE	ALBEE					
		ORFORDVILLE	ORFORDVILLE				WAITS RIVER (AS RESTRICTED HEREIN)	
		MEETING HOUSE SLATE	MEETING HOUSE SLATE	MEETING HOUSE SL			STANDING POND	
GILE MOUNTAIN (=GILE MOUNTAIN?)	WESTMORE = GILE MOUNTAIN	GILE MOUNTAIN	GILE MOUNTAIN	GILE MOUNTAIN	= LITTLETON	GILE MOUNTAIN	WESTMORE	GILE MOUNTAIN
			STANDING POND	STANDING POND				
WAITS RIVER	BARTON RIVER	WAITS RIVER	WAITS RIVER	WAITS RIVER		WAITS RIVER	BARTON RIVER	
	AYERS CLIFF							
NORTHFIELD SLATE	NORTHFIELD SLATE		NORTHFIELD SLATE	NORTHFIELD SLATE		NORTHFIELD SLATE	NORTHFIELD SLATE (?)= MEETING HOUSE SL.	
SHAW MOUNTAIN	SHAW MOUNTAIN		SHAW MOUNTAIN	SHAW MOUNTAIN (=CLOUGH & FITCH)		SHAW MOUNTAIN	SHAW MOUNTAIN	
CRAM HILL	CRAM HILL		CRAM HILL	CRAM HILL (=PARTRIDGE & AMMONOOSUC)		SERPENTINITES TALC-CARBONATE ROCK & STEATITE		
ARENITES OF BRAINTREE-NORTHFIELD RANGE						MORETOWN		

Table 1.

CHART SHOWING EVOLUTION OF THOUGHT ON EQUIVALENCE OF STRATIGRAPHIC UNITS IN EAST-CENTRAL VERMONT AND NEW HAMPSHIRE.

——— INDICATES ORDOVICIAN-SILURIAN BOUNDARY

Waits River Formation

Since the above two units are defined as two separate formations, the use of the term "Waits River formation" to include all the rocks above the Northfield slate and below the Gile Mountain formation of the Strafford and Woodsville quadrangles is no longer valid. Therefore, I suggest that the term "Waits River formation" be redefined and restricted to include only the calcareous rocks in the central part of the East Barre quadrangle. The type locality, Waits River town, is in this belt, and excellent exposures are present, ¾ miles east of the town. The outcrop of this newly defined Waits River formation extends for a width of 12 to 15 miles, from the eastern contact of the Westmore formation to the western contact of the Gile Mountain formation in the Woodsville quadrangle. Stratigraphically, it is younger than the Westmore formation. The structural evidence for this statement is discussed in the chapter on structure.

Barton River Formation

Distribution

The Barton River formation crops out in a belt about 1½ miles wide in the northwestern corner of the map. The beds strike north-northeast and dip 55 to 70 degrees west. Only the upper part of the formation is exposed in the East Barre quadrangle; but to the west, in the Barre quadrangle, it extends west to the contact of the Northfield slate, a total width of about 6½ miles. Previously this unit was mapped as part of the Waits River formation (Currier and Jahns, 1941, p. 1491), and as the western outcrop belt of the Waits River formation (White and Jahns, 1950, p. 187).

Lithology

Thick- and thin-bedded limestones with interspersed quartz-calcite schists and quartz-mica schists are the main rock types in the Barton River formation. The limestones are bluish gray on an unweathered surface, but outcrops are mostly dark brown because of iron stain. Most of the limestones are actually marbles; and where appreciable amounts of mica are developed, a schistose structure is generally present. Pure limestones are the exception; in mild grades of regional metamorphism, the limestones contain some low-grade calc-silicate minerals such as tremolite and diopside.

The mica schists and impure quartzose rocks occur as thin beds, which stand out in relief on weathering. The differentiation into calcareous and arenaceous bands, though appearing sharply demarcated in outcrops, is only gradational, the carbonate gradually decreasing from the limestone beds to the quartz-calcite schists and mica schists. The mineralogy of the main lithologic types in the Barton River formation is summarized in Table No. 2 which gives the modal analyses of the rock types.

The individual limestone beds range in thickness from about 6 inches to 5 feet or more, though generally they are about one to two feet thick. The noncalcareous beds are much thinner in general, their average thickness ranging from a few inches to a foot. However, since only the top part of the formation is exposed in the East Barre quadrangle, generalizations about the thickness of beds in the whole formation cannot be made here.

Thickness

Since only the top few hundred feet of the Barton River formation are exposed in the East Barre quadrangle, its total thickness cannot be given for this area. However, the maximum thickness of the part of this formation present in this area can be given. The average dip of the beds is about 45 degrees to the west. Assuming that repetition of beds due to minor isoclinal folds is compensated by tectonic thinning, the approximate thickness of the widest part of the Barton River formation exposed in the quadrangle is about 5,000 feet. The general absence of minute and complicated folds, and the low grade of metamorphism, may indicate, on the other hand, that the original thickness of the beds has been changed very little. In either case, the given thickness would hold good.

Correlation

The Barton River formation of the East Barre area can be directly correlated with the Barton River formation of the Memphremagog quadrangle (Doll, 1951, p. 25), by continuous mapping. Doll (1951, p. 22) considered the Barton River formation equivalent to the middle part of the Waits River formation. In this report, however, his correlation is not considered valid, as the type Waits River formation is here shown to include only rocks stratigraphically younger than the Barton River formation.

North of the International Boundary, the Barton River formation

Table 2

ESTIMATED MODES OF BARTON RIVER FORMATION

Rock	1	2	3	4
Quartz	26.6	22.8	31.1	30.5
Calcite	59.8	44.5	6.8	
Muscovite	6.1	14.6	32.6	27.1
Biotite	2.1	8.7	21.9	21.8
Chlorite		4.6	3.8	4.6
Actinolite	—	—	—	—
Epidote	1.9	—	—	—
Garnet	—	—	—	9.7
Magnetite	2.2	1.2	1.8	3.9
Other accessories	2.3	3.6	2.0	2.5
No. of Sections	1	2	2	1
Total Counts	1239	2848	2492	1461

1. Siliceous limestone
2. Quartz-calcite-mica schist
3. Quartz-mica schist
4. Garnetiferous phyllite

has not been traced out, but the impure limestones in the bottom part of the undifferentiated St. Francis group may be correlative with the Barton River formation. Southward, at the latitude of South Royalton in the Randolph quadrangle, the Barton River formation unites with the lithologically similar Waits River formation because the Westmore formation pinches out.

Age

The age of the Barton River formation is controversial. No fossils were found in this formation in the East Barre quadrangle. In the Memphremagog quadrangle Doll (1951, p. 26) reported some doubtful graptolitic markings, which bear a close resemblance to the markings associated with other easily identifiable graptolites from the Castle Brook locality in Canada. The age of these graptolites is considered to be Ordovician. However, Doll (1951, p. 32–33) is of the opinion that the Irasburg conglomerate indicates a major break in the stratigraphic column and may possibly be between Ordovician and Silurian. Accordingly, he assigned a Silurian age to the Barton River formation. Also, in his opinion, "this assignment is based upon the position of the formation stratigraphically below strata yielding fossils of Silurian age or younger."

Cady (1950, p. 488) reported fossil cup corals from phyllites of the Barton River formation, and these were identified as probably of Middle Ordovician age. However, he is at present of the opinion that they may possibly be of Silurian age, and in his latest work, he considers the Waits River formation of the Montpelier quadrangle (the Barton River formation of the present report) to be essentially Silurian (Cady, W. M., 1956). The St. Francis group in Canada, as defined by Cooke (1950, p. 29) is correlated with the Northfield, Barton River, Westmore, Waits River and Gile Mountain formations in Vermont. Recently, Morin (1954, as quoted in Dennis, 1956, p. 28) ascribed a Siluro-Devonian age to the St. Francis formation on the basis of its strike alignment with the Devonian in Gaspe. This would also support a Silurian age for the Barton River formation.

Most of the earlier workers advanced an Ordovician age for the Barton River formation. Until 1951, the Barton River formation of the Barre and East Barre quadrangles was included in the all-too-comprehensive Waits River formation, and arguments put forth for the age of the Waits River formation were applied to the Barton River formation also. Thus, Hitchcock (1861, p. 447–451) assigned an age older than the Upper Helderberg to his 'calciferous mica-schist'. Ells (1887, p. 16–17) described 'Llandeilan' graptolites from the Castle Brook area and accordingly gave an Ordovician age to all the rocks of the Memphremagog area. The graptolites from Castle Brook were identified by Ruedemann as both Deepkill and Normanskill in age. Clark (1934, p. 1–20) and Ambrose (1943) consider the Waits River formation at least in part equivalent to the Tomifobia formation of Southern Quebec, which is regarded as Ordovician in age. White and Jahns (1950, p. 192) doubted the organic nature of the fossil finds of Doll (1943, p. 7–14) from the Waits River formation, and adopted an Ordovician age for at least the lower part of the Waits River formation (Barton River formation of the present report).

From the above discussion, it is evident that the fossil evidence for the age of the Barton River formation is insufficient and conflicting.

Westmore Formation

Distribution

Southeast of the dominantly calcareous rocks of the Barton River formation is a belt of phyllites and schists that lacks intercalated limestone beds. The outcrop belt of this formation is about 1¾ to 2 miles wide, and the average trend of beds is N20°E. The dip of the beds varies from 40 to 70 degrees west, and progressively lessens to the east. The formation as a whole has gradational contacts with both the Barton River formation below and the Waits River formation above. The western contact with the Barton River formation is a zone about 100 to 200 feet wide, best seen half a mile northwest of Cobble Hill School in the northwestern part of the East Barre quadrangle. The transition zone contains thin grayish-black, fine-grained limestone beds 2 to 6 inches thick, which gradually disappear to the east, being replaced by entirely argillaceous rocks. The eastern contact with the Waits River formation is poorly exposed; but east of Mt. Pleasant and farther south along the strike, the contact is quite sharp and well defined. In spite of the gradational contacts, the belt as a whole is a distinct mappable unit, practically devoid of carbonate rocks in its entire width. This belt has been mapped continuously for a strike length of about 10 miles in the East Barre quadrangle, and work in progress in surrounding areas indicates that it can be continuously traced to join the Westmore formation of the Memphremagog quadrangle (Doll, 1951, p. 33.) Hence the name Westmore formation is adopted here for this belt of schists. In the past these rocks were mapped as a part of the Waits River formation by Currier and Jahns (1941, p. 1491) and as Gile Mountain (?) formation by White and Jahns (1950, p. 189).

Lithology

A variety of argillaceous and arenaceous schists are the main rock types of the Westmore formation. The thickness of individual beds ranges from a few inches to nearly a foot (Pl. 4). Many outcrops show clear bedding because of the color contrast between the argillaceous beds, which are generally dark gray, and the arenaceous schists, which are light gray to light brown. A few thin bands of dark gray to bluish gray fine-grained limestone beds are present near the contact with the Barton River formation, but otherwise no calcareous rocks are found anywhere in the unit.

The rocks of the Westmore formation become progressively more quartzose to the east. However, both the lower and upper beds are predominantly argillaceous. On the basis of these lithologic variations, the Westmore formation is divided into three members. The western

Plate 4. Bedding in the Westmore formation, in outcrop about 1½ miles N25°E of Cobble Hill School. Alternation of argillaceous and arenaceous lithology. Thicker beds are more quartzose. Schistosity parallel to bedding.

member is predominantly argillaceous, composed essentially of dark-gray mica-schists with local porphyroblasts of biotite and garnet. Impure micaceous quartzites of light tan and gray color are present only to a minor extent. The thickness of the western member is about 2000 to 2500 feet. The central member is composed of rocks rich in arenaceous materials. The main rock types are light fawn or gray colored micaceous quartzites and quartz-biotite schists with minor amounts of argillaceous beds. Garnet porphyroblasts are quite common in the argillaceous rocks that are interbedded with the more arenaceous lithologies. In the field, the arenaceous beds contrast with the argillaceous beds because of their lighter color. The average thickness of the beds ranges from a couple of inches to a foot or more. The total thickness of this member is about 1000 to 1500 ft., on the same assumptions as those made for the Barton River formation.

The upper member of the Westmore formation is once again composed of argillaceous rock types. Predominantly the rocks are garnetiferous biotite schists and mica schists. The rocks in general show a higher grade metamorphism than the other two members. Thin quartzitic beds occur sparingly in this member. The thickness of this unit is approximately

700 to 1000 ft. Dark gray muscovite schists with porphyroblasts of garnet and biotite are common in this formation. These rocks are typical of the bottom and top members of the Westmore formation, and contain a variety of minerals in contrast to the more simple rock types of the quartz-rich central member. The porphyroblasts of biotite and garnet occur in an anhedral fine-to-medium-grained groundmass of quartz, sericite, muscovite and a little sodic plagioclase. Accessory minerals are magnetite, rutile, and a little zoisite and sphene (Table 3).

TABLE 3

ESTIMATED MODES OF WESTMORE FORMATION

Rock No.	1	2	3	4
Quartz	81.6	67.6	42.3	30.9
Plagioclase	—	6.8	2.0	6.2
Muscovite	7.6	11.2	20.6	14.4
Biotite	4.9	9.1	19.8	24.6
Chlorite	—	—	4.9	6.6
Garnet	—	—	5.1	12.4
Magnetite	5.4	2.8	3.4	3.7
Other accessories	0.5	1.5	1.9	1.2
Number of sections	2	3	4	3
Number of counts	2036	3736	4981	3464

1. Quartzite
2. Micaceous quartzite
3. Quartz-mica schist
4. Garnetiferous mica schist

Mention must be made of sparce, thin bands of metasedimentary amphibolites present both at the lower and upper contacts of this formation. About half a mile northwest of Cobble Hill school, thin bands of dark green to black medium- to coarse-grained amphibolites are found intercalated with garnetiferous mica schists and quartz biotite schists.

The argillaceous rocks are metamorphosed to biotite and garnet grades regionally, and to sillimanite grade locally around the granitic intrusives. The various aspects of metamorphism are dealt with later in the chapter on metamorphism.

Most of the metamorphosed argillaceous rocks show well developed schistosity that is subparallel to the bedding. In outcrops about a mile south of Mt. Pleasant on the eastern contact of the Westmore formation, the schistosity dips less than the bedding and strikes somewhat more to the east than the bedding. In the northwestern corner of the area, the schists show a pronounced lineation of mineral streaming on the bedding or plane of schistosity, with an average rake of 65°–70°, N 25°W. The minerals are aligned porphyroblasts of biotite and garnet. These porphyroblasts appear to be later than the regional deformation as they lie athwart the schistosity. However, this may also be due to the greater idioblastic nature of these minerals.

Micaceous quartzites occur commonly in the central member of the Westmore formation. They consist of bedded, light-colored quartzites containing both white and dark micas. Pure quartzites are rare and occur as thin beds of medium-grained rocks with gray color. Some argillaceous material is undoubtedly present in these quartzites, as indicated by the presence of biotite and muscovite, and the porphyroblasts of garnet. There is, however, an overall predominance of arenaceous lithology in this member, in comparison with the members above and below (Table 3). The change from argillaceous to arenaceous lithology is rather sharp in many beds.

Thickness

The width of outcrop of this formation in the East Barre quadrangle ranges from about 9,000 to 12,500 feet. Assuming the average dip of the beds to be approximately 45 degrees, and assigning a factor of 2 for repetition of beds by folding, the average thickness of this formation is 3700 to 5100 feet.

Correlation

Like the Barton River formation, the Westmore formation in the East Barre quadrangle is directly correlated with the formation of the type locality in the Memphremagog quadrangle (Doll, 1951; p. 33). In view of its stratigraphic position above the Barton River formation, which Doll considered as equivalent to the Waits River formation, and its lithologic similarity with the Gile Mountain formation of the Strafford quadrangle, Doll (1951, p. 34) correlated the Westmore with the Gile Mountain formation. However, in my opinion, 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. The Barton River formation is considered here as distinctly older than the Waits River formation. The synclinal structure in the East Barre quadrangle has the Westmore formation on the west limb and the Gile Mountain formation on the east limb, and it is very tempting to correlate the two on the basis of this structural relationship, the more so because of their identical lithologies. But, since no positive evidence for this correlation has been obtained from the East Barre quadrangle, the correlation of the Westmore formation with the Gile Mountain formation is considered only as probable. As shown below, however, such a correlation integrates much of the available field evidence into one coherent interpretation, and hence the idea appears reasonable.

The southwest portion of the Island Pond quadrangle is most critical for the evaluation of the above idea. Here, the eastern contact of the Westmore formation appears to swing around the outcrop of the Waits River formation and join the western contact of the Gile Mountain formation. Clearly, if this swinging is structural, the two units, Westmore and Gile Mountain formations are one and the same and are repeated by a major fold. On the other hand, if the contact between Westmore and Waits River in that area is a facies change, it is likely that Westmore and Gile Mountain are two facies tongues separated by a calcareous tongue, the Waits River formation (Fig. 2).

Another critical area is the southeastern portion of the Randolph quadrangle. Available information at present indicates that the outcrop of the Westmore formation pinches out within carbonate rocks like those of the Barton River and Waits River formations. The nature of this closure of the Westmore formation near South Royalton is very important in the present context (Fig. 3). If it is one of facies change, in which the non-carbonate rocks of the Westmore are replaced by the carbonate rocks of the Waits River formation, then the Westmore formation is nothing but a stratigraphic tongue in a huge thickness of carbonate lithology. However, if it is a structural closure, the contentions of Doll (1951, p. 51) and Dennis (1956, p. 35, 37) that the Westmore formation lies in the axial part of a syncline may be borne out. Cursory examination in this area suggests that it is more likely a facies change, but the area needs critical study.

Age

The age of the Westmore formation is uncertain. Doll (1943, p. 57–64; 1951, p. 34) reported some cystoids and crinoids from this formation

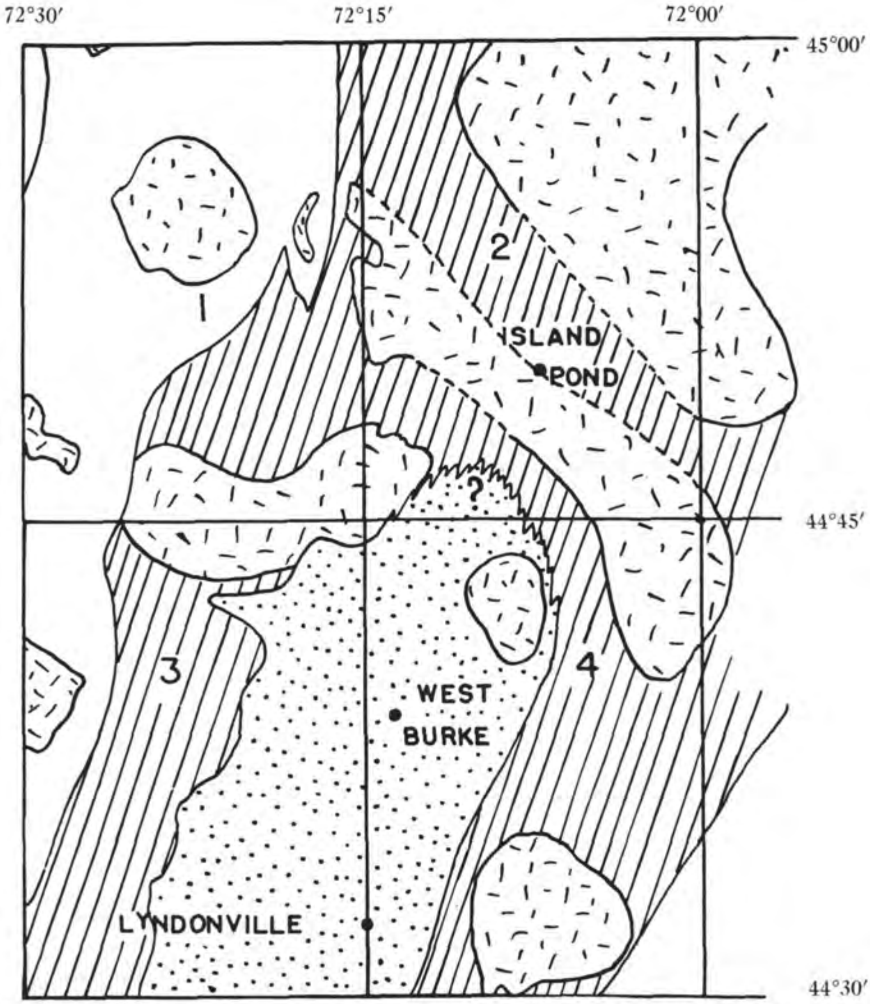
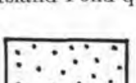


Figure 2. Geologic sketch map showing the pinching out of the Waits River formation by a facies change.

1. Memphremagog quadrangle
2. Island Pond quadrangle
3. Lyndonville quadrangle
4. Burke quadrangle



Waits River formation

Westmore and Gile Mountain formations

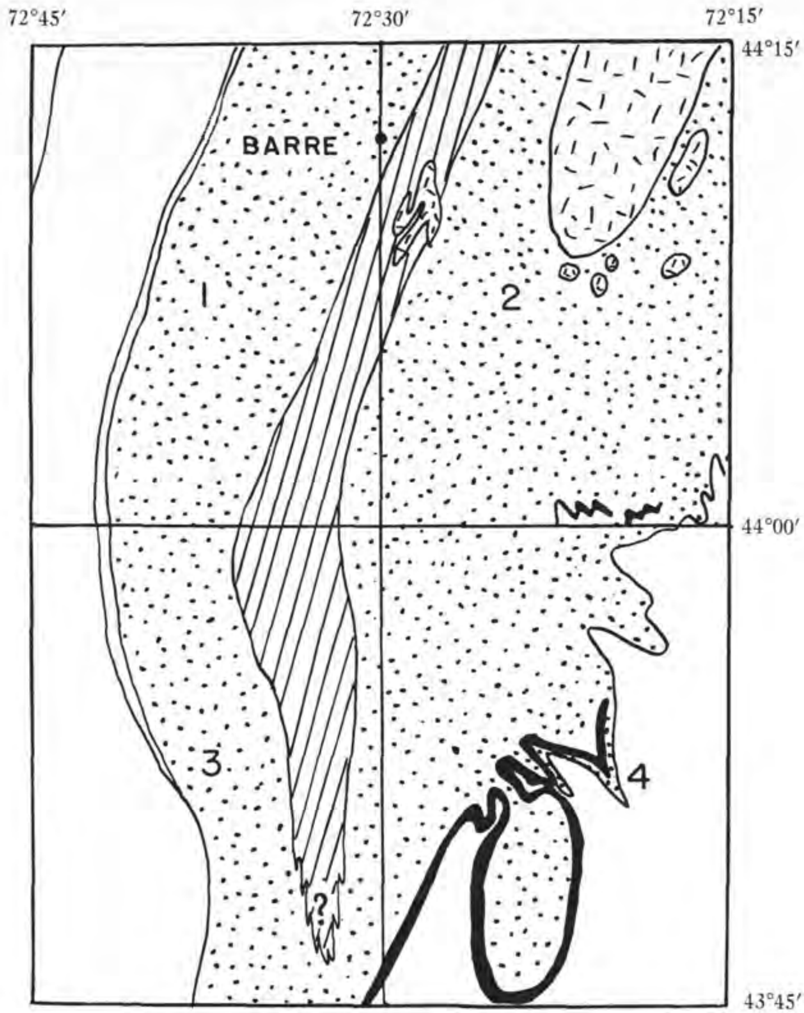
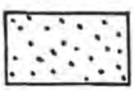


Figure 3. Geologic sketch map showing the pinching out of the Westmore formation by a probable facies change.

1. Barre quadrangle
2. East Barre quadrangle
3. Randolph quadrangle
4. Strafford quadrangle



Barton River and Waits River formations

Westmore formation

in the Memphremagog quadrangle that were identified as Middle Silurian or Lower Devonian forms; but the organic nature of these forms is controversial. Furthermore, his correlation of the Westmore with the Gile Mountain formation of Strafford quadrangle would give it a Lower Devonian age; but such correlation is still unproved. In any case, the Westmore formation is younger than the Barton River as indicated by cleavage-bedding relations and minor folds. On this basis, the Westmore is apparently at least no older than Silurian.

Waits River Formation

General Statement

The term "Waits River formation" is restricted in this area to the essentially calcareous rocks in the central and eastern parts of the East Barre quadrangle. The formation occurs as a belt about 12 to 15 miles wide with an approximate north-northeast trend. By far the greater part of the East Barre quadrangle is occupied by rocks of this formation. Stratigraphically it is considered to be younger than the Westmore and Gile Mountain formations on the basis of evidence discussed elsewhere in this report.

History of the Name

The name "Waits River" is of considerable antiquity in the stratigraphic literature of eastern Vermont. Inasmuch as the term 'Waits River' is restricted here, it is considered desirable to trace out the history of the name.

The first mention of a huge thickness of interbedded limestones, phyllites and mica schists in eastern Vermont was by C. B. Adams (1845, p. 49, 62) who gave the whole group the name "calcareo-mica slate." Subsequently, the same group of rocks was included under the title "calciferous mica-schist" by Edward Hitchcock (1861, p. 475–488). Richardson 1898, 1906) subdivided the calciferous mica-schist and named the essentially calcareous rocks as the Waits River limestone. However, since the unit included both phyllites and schists as well as limestones, the name 'Waits River limestone' was considered unsuitable, and Currier and Jahns (1941, p. 1491) substituted the term "Waits River formation." As defined by them, the formation included all the rocks stratigraphically above the Northfield slate and below the Gile Mountain formation.

Doll (1951, p. 22), in his study of the Memphremagog quadrangle, subdivided the belt of interbedded limestones and schists into the Ayers Cliff and Barton River formations. He correlated these formations with the Waits River formation and proposed that the all too comprehensive term "Waits River formation" be discarded. However, mapping in the Lyndonville, Plainfield, Montpelier, Barre, and East Barre quadrangles showed that the Ayers Cliff and Barton River formations are in strike continuity with only the lower part of the Waits River formations. Dennis (1956, p. 16), for reasons of precedence, retained the name Waits River formation and regarded the Ayers Cliff and Barton River units as members of the Waits River formation.

On the basis of the structural evidence available in east central Vermont, it is my opinion that the Barton River and Westmore formations and the calcareous rocks east of the Westmore formation are in a homoclinal sequence and the synclinal axis beyond which these beds repeat lies in the eastern part of the East Barre quadrangle. Consequently, these three mappable units of rocks are defined separately. Waits River, the geographic locality after which the formation is named, is located in the eastern calcareous sequence and excellent exposures of the calcareous schists are present in the neighborhood of the village. Hence, the term "Waits River formation" is restricted in the present study to include the essentially calcareous sequence east of the Westmore formation.

Lithology

Calcareous rocks interbedded with mica schists are the main rock types of the Waits River formation. Thus, the formation is strikingly similar to the Barton River formation, except that its rocks are metamorphosed to a higher degree. Impure limestones and calcareous rocks constitute approximately 60 to 75 percent of the whole formation. The limestones are bluish gray when fresh, but most of the outcrops present a characteristic rusty-brown color due to iron stain. The non-calcareous rocks are mostly dark-gray biotite-muscovite schists, quartz-biotite schists and garnetiferous-biotite schists. Quartzites or micaceous quartzites are rare. In spite of every effort, subdivision of the formation on the basis of the lithology was not possible, because the calcareous beds are intercalated with the non-calcareous beds in all proportions. In some places, as around Riders Corners, massive limestone beds of 3 to 4 feet thickness crop out almost to the exclusion of the noncalcareous beds. The thickness of both the calcareous and noncalcareous beds is highly variable, however, and their separation is impossible. The grain size of most of the rocks of this formation ranges from medium to coarse and in some places metamorphism has produced a very coarse-grained garnetiferous mica schist. It is quite evident that the present grain size of the rocks is entirely due to metamorphism. Mineralogically, most of the rocks are composed of quartz, calcite, biotite, and muscovite. Accessory minerals include diopside, epidote, and plagioclase. The amount of these minerals differs very markedly in the individual rock types, as shown by the modal analyses in Table 4.

TABLE 4

ESTIMATED MODES OF WAITS RIVER FORMATION

Rock	1	2	3	4
Quartz	23.9	60.1	10.6	12.6
Plagioclase	8.6	17.0	31.8	2.1
Calcite	53.4		7.2	72.3
Biotite	4.0	6.8	14.6	4.0
Muscovite	7.8	5.2	2.3	6.4
Hornblende		1.9	23.8	
Chlorite		3.5		
Magnetite			6.0	1.2
Other accessories	2.2	5.5	3.7	2.4
Number of thin sections	2	2	3	2
Number of counts	4682	3961	5841	3646

1. Calcite—Quartz schist
2. Quartz—mica schist
3. Metasedimentary amphibotite
4. Siliceous marble

In the southeastern part of the quadrangle, metamorphism and extreme structural deformation have produced mixed rock types. The rocks are essentially calcareous micacaeous schists with great amounts of recrystallized quartz that occurs as stringers, veins, and elongate lenses along bedding and schistosity planes, and locally with no consistent relation at all.

THICKNESS

Intense structural deformation of the beds (Pl. 7, 14) of the Waits

River formation makes it very difficult to estimate the thickness of the formation. Complicated minor folds in the entire width of the formation have caused large scale repetition of beds. Plastic flowage (Pl. 12) of calcareous rocks introduces an additional complication. Only part of the eastern contact of the formation is exposed in the East Barre quadrangle. The total outcrop width of the formation measured across the regional trend is about 60,000 feet. Since the width represents the two limbs of the major syncline, the apparent thickness of one limb would be of the order of 30,000 feet. In the past, a factor of two has been applied to compensate for the repetition due to minor folds. In the present study, however, it is felt that a factor of two is inadequate and that a factor of three might be more nearly correct. Making the above corrections, and assuming an average dip of beds about 40 degrees, the true thickness of the formation would be 4,750 to 6,500 feet approximately. But, in view of the many basic assumptions made, the thickness given above may be in error by many hundreds of feet.

Correlation

Rocks corresponding to the newly restricted Waits River formation have been mapped as a continuous belt from the northern portion of the Strafford quadrangle (Doll, 1944, pl. 1) to the southern part of the Island Pond quadrangle. In the Lyndonville quadrangle, the eastern belt of the Barton River member of Dennis (1956, p. 17) corresponds to this unit.

Age

In my interpretation of the structure of the area, the Waits River formation is considered the youngest stratigraphic unit in the Vermont sequence. It overlies the Westmore and Gile Mountain formations, whose age from available fossil evidence is considered to be Lower Silurian to Lower Devonian (?). So, the age of the Waits River formation may be lower Devonian (?).

Another line of evidence for the age of the Waits River and Westmore formations is provided by the Rb-Sr age determination of the Barre granite that intrudes these rocks. The age of this granite is 330 ± 25 million years. This would be compatible with a Silurian age for the Westmore and Waits River formations.

Table 5

ESTIMATED MODES OF STANDING POND VOLCANIC MEMBER OF WAITS RIVER FORMATION

Rock	1	2	3
Quartz	14.6	8.2	3.6
Plagioclase	26.6	13.9	43.4
Calcite	5.9	6.6	2.8
Biotite	11.3	3.4	21.6
Hornblende	25.8	43.6	—
Chlorite	10.6	4.1	6.4
Muscovite	—	—	8.4
Magnetite	4.8	4.6	2.9
Garnet	—	12.9	9.4
Other accessories	1.7	2.7	1.5
Number of thin sections	1	2	1
Number of counts	1891	3396	1607

1. Metavolcanic hornblende schist
2. Metavolcanic garnetiferous amphibolite
3. Metavolcanic garnetiferous feldspathic schist

Thickness

The outcrop width of the amphibolite and the garnetiferous schist, taken together, ranges from 1000–2500 feet. Assuming an average dip of 45 degrees and the correction factor 3 for thickening by minor folding, the true thickness of this unit would be between 250 and 600 feet.

Gile Mountain Formation

Name

The name "Gile Mountain formation" was first given by Doll (1944, p. 18) to a group of micaceous and quartzose schists exposed at the type locality, Gile Mountain in the Strafford quadrangle. This belt of schists continues north into the southeastern portion of the East Barre quadrangle, and hence the name Gile Mountain formation, as used in this report, includes the same rocks.

Richardson (1906, p. 115) subdivided the all too comprehensive term "calciferous mica schist" (Hitchcock, 1861, p. 475–488), and named the noncalcareous schists the Vershire schist. In an earlier report, he included the same rocks under the name "Bradford Schist" (1898) but later abandoned it—as the name was preoccupied. The rocks of the Vershire schist are in strike continuity with Doll's Gile Mountain formation of the Strafford quadrangle.

The Gile Mountain formation is mapped in a continuous belt extending as far north as Quebec, where it is equivalent to the upper part of the St. Francis formation, and as far south as Ascutney in southern Vermont.

In the Memphremagog quadrangle, Doll (1951, p. 33) named the rocks above the Barton River formation as the Westmore formation and because of its lithologic similarity with the Gile Mountain formation, correlated the two. However, until the stratigraphic and structural relations of the Waits River contact in the southern part of the Island Pond quadrangle are known, no such correlation is proved.

Distribution

Rocks of the Gile Mountain formation occupy the southeastern corner of the East Barre quadrangle and only part of the western contact of the formation is exposed. Here the contact outlines a few north plunging folds, but farther northeast it runs in a general north-south direction in the western part of the Woodsville quadrangle (White and Billings, 1951, Pl. 1).

Lithology

The Gile Mountain formation is similar to the Westmore formation previously described. For the most part the rocks are dark-gray micaceous schists with some light-gray micaceous quartzites. In the extreme southeastern corner of the area two lenses of calcareous rocks are present in this formation. Each of these lenses is about 200 feet thick, and the rocks are mostly dark-brown (gray when fresh) quartzose limestones interbedded with mica schists. These lenses bear a striking similarity to the rocks of the Waits River formation and, but for their stratigraphic position in the Gile Mountain formation, would be indistinguishable from the Waits River formation. Another difference noted by White and Billings (1951, p. 655–656) in the Woodsville quadrangle is that these calcareous lenses in the Gile Mountain formation contain a greater proportion of micaceous quartzite rather than mica schists interbedded with the limestones. This distinction was not clearly noted in the East Barre quadrangle.

The schistose rocks vary from almost pure mica schists to quartz-mica schists and impure micaceous quartzites. Quartzitic beds in general are rather less abundant in this formation than in the Westmore formation. Individual beds of mica schists commonly range in thickness from a fraction of an inch to 2 to 4 inches.

The minerals of the rocks are mainly quartz and muscovite, with lesser amounts of chlorite and biotite. Plagioclase is almost always present in small amounts. Garnets are found in some of the schistose rocks, but in general their occurrence is limited. The micas are well developed and parallel, giving rise to good schistosity. Quartz occurs as granular aggregates and stringers between the mica foliae.

The micaceous quartzites exhibit a rather well developed foliation due to flattening of the quartz grains in the plane of the prevailing schistosity and due to parallelly oriented mica flakes.

The relation of the porphyroblasts of garnet and staurolite to the schistosity in these rocks is noteworthy. The porphyroblasts are randomly oriented with reference to schistosity and cut across it. This is interpreted as indicating that the main pulse of thermal metamorphism postdated the regional deformation.

The modes of the various rock types of the Gile Mountain formation are summarized in Table 6.

TABLE 6

ESTIMATED MODES OF GILE MOUNTAIN FORMATION

	1	2	3	4	5
Quartz	66.1	21.3	36.8	14.8	34.4
Plagioclase	3.9		4.9	26.1	4.8
Muscovite	10.1	10.8	16.1	3.1	17.1
Biotite	15.4		26.6	12.9	24.7
Chlorite	1.2		5.8	6.1	7.1
Garnet			4.1	5.1	11.2
Calcite		64.9			
Hornblende				25.6	
Magnetite	1.2	1.6	2.0	4.2	2.6
Other accessories	2.5	1.4	3.7	1.1	3.1
Number of thin sections	2	1	2	1	1
Number of counts	3866	1498	3301	1291	1407

1. Micaceous quartzite
2. Calcite—quartz schist
3. Arenaceous mica schist
4. Hornblende schist
5. Garnetiferous mica schist

Thickness

Since only the western part of the formation is exposed in the East Barre quadrangle, an estimate of the total thickness of the formation is not relevant here. The thickness of that part of the formation exposed in this area, however, is of the order of 1000 to 1500 feet. White and Billings (1951, p. 656) have estimated the total thickness of the formation to be of the order of 6,000 to 7,000 feet, using an appropriate correction for the tectonic thickening of beds.

Correlation

The Gile Mountain formation has been continuously mapped from the East Barre quadrangle to the type locality in the Strafford quadrangle, where Doll mapped the same unit as the "Gile Mountain schist" (1944, p. 18–19). This belt of schists has been traced farther south and north for many miles.

Age

As for the other stratigraphic units of the area, the age of the Gile Mountain formation is controversial. Doll (1943, p. 676–679) reported a brachiopod from the Gile Mountain formation near South Strafford and on this basis ascribed a Lower Devonian age to the formation. Likewise, his discovery of cystoids and crinoid calyces (1951, p. 34) in the Westmore formation of the Memphremagog quadrangle supports a Middle Silurian or possibly Lower Devonian age, on the assumption that the Westmore and Gile Mountain formations are one and the same. In this report, the Westmore and Gile Mountain formations are considered definitely younger than the Barton River formation and hence their age may be between Lower Silurian and Lower Devonian (?).

Relationship Between Westmore and Gile Mountain Formations

If the very similar Westmore and Gile Mountain formations lie on either limb of a major syncline, as postulated in the present study, a correlation between the two is strongly suggested. The attempt to correlate these two units is by no means a new one. White and Jahns (1950, p. 189) mapped the Westmore formation of the East Barre quadrangle as the Gile Mountain (?) formation and tentatively correlated it with the Gile Mountain formation. They postulated and discussed several tentative hypotheses (1950, p. 206–207) to explain the repetition of this unit. Doll (1951, p. 33–35), who was the first to designate the Westmore

Standing Pond Member of Waits River Formation

General Statement

In the southeastern corner of the East Barre quadrangle, a group of dark-green amphibolites and associated garnetiferous felspathic schists have been mapped as the Standing Pond member. Doll (1945, p. 17) first reported rocks of similar lithology from the Strafford quadrangle, and gave them the name Standing Pond amphibolite. The stratigraphic position and lithology of the amphibolite and associated garnetiferous schists in the East Barre quadrangle justify their inclusion under the same name, even though the unit is not continuously mapped to join the Standing Pond amphibolite at the type locality. The unit occurs here as a highly folded, thin but distinct band roughly along the boundary of the Waits River and the Gile Mountain formations. This relationship is best exemplified in the Strafford quadrangle (Doll, 1944). In the East Barre quadrangle, the Standing Pond amphibilite does not have a stratigraphic position strictly between the Waits River and Gile Mountain formations. (Pl. 1). It is transgressive in its relation to formational contacts; and in the south-central part of the East Barre area lies in the Waits River formation considerably above its contact with the Gile Mountain formation.

Similar rocks in approximately the same stratigraphic position have been reported at considerable distances both north and south of the present area. In the Saxtons River and Claremont quadrangles, and in the southern portion of the Hanover quadrangle, several amphibolite bands have been mapped as Standing Pond amphibolite (Billings, Thompson, Rodgers, 1952, Pl. 4). Recent detailed studies of some of this area indicate that the distribution and structural relations of these amphibolites are considerably more complex than was thought, and that even the correlation of these amphibolites with the Standing Pond member of the type locality is by no means certain (Thompson, verbal communication, 1956). Dennis (1956, p. 22, Pl. 3) mentioned the occurrence of pillow lavas near the contact of the Barton River (Waits River of my report) and Gile Mountain formations and even though it was lithologically different from the type Standing Pond unit, gave it the same name.

In eastern Vermont metavolcanic rocks occur at several horizons in the stratigraphic column. In view of the structural complexity of the areas correlation of these rocks with one another, even if based on lithologic similarity and apparently identical stratigraphic position, may be proved incorrect when the areas are studied in detail. Thus, it is with some hesitation and misgivings that the name Standing Pond member is used here to designate the metavolcanic rocks of the East Barre quadrangle.

Lithology

Several rock types are found in the Standing Pond member. Fine-grained, dark-green needle amphibolites and coarse-grained hornblende schists are by far the most prevalent, but garnetiferous amphibolites and feldspathic garnetiferous schists are present in discontinuous bands. A prominent schistosity is imparted to the rocks by the parallel orientation of the amphiboles. The garnets occur for the most part as porphyroblasts. Locally they are as much as 1 to 2 inches across, and both rolled and undeformed varieties are quite common. This is taken to indicate that the thermal metamorphism and deformation are synchronous in part, and overlap each other in individual areas. Slip cleavage parallel to the axial planes of tiny minor folds is strongly developed in some outcrops. (Pl. 8).

The detailed mineralogy of the various rock types of the Standing Pond member is shown in Table 5. Plagioclase is almost universally present, and may form up to half of the rock in the feldspathic schists. Quartz is normally present in subordinate amounts and possibly results from the liberation of silica in the process of conversion of the original pyroxenes to hornblende. But part of the quartz may be contributed from the intercalated metasedimentary beds, which occur in several outcrops. Epidote occurs as irregular knots and thin streaks, and is commonly associated with the contacts of plagioclase and hornblende. Other accessories include calcite, biotite, chlorite, apatite and magnetite.

Associated with the black and dark green amphibolites in places, is a light-colored garnetiferous feldspathic schist that is also an excellent key bed. It is not a continuous bed like the amphibolite, but crops as discontinuous, elongate bands in close proximity to the contacts of the amphibolite. Typically it is an extremely micaceous and feldspathic rock with porphyroblasts of almandine garnet averaging ¼ to ½ inches across. Many of the garnets of this rock are intensely sheared, rolled, and riddled with numerous inclusions of quartz.

formation in the Memphremagog quadrangle, correlated the two on the basis of the stratigraphic position of the Westmore above the Barton River formation and the lithologic similarity between the Westmore and Gile Mountain formations. However, this was under the assumption that the Barton River formation is the same as the Waits River formation, and that the Westmore formation occurs in the axial part of a very tightly folded syncline. According to his interpretation then, the Westmore and the Gile Mountain formations are repeated by a major anticline, the axial part of which is occupied by the calcareous rocks of the Waits River formation (of this report). The field evidence in this area contradicts the above hypothesis and, in my opinion, neither the synclinal structure of the Westmore formation nor the repetition of the Westmore and Gile Mountin formations by a large-scale anticlinal structure is tenable. This is discussed in detail in the chapter on structure.

In the southern part of the Island Pond quadrangle (Fig. 2) the western contact of the Gile Mountain formation swings around to the west and joins the eastern contact of the Westmore formation. The determination of the nature of this contact is very critical to the evaluation of the relationship of the Westmore formation to the Gile Mountain formation. Clearly, two possibilities exist—a facies change or a structure involving the two lithologies. Until this point can be settled by a detailed study of the southern part of the Island Pond quadrangle, no definitive statements about the relationship between the Westmore and Gile Mountain formation can be made.

If the change from non-calcareous to calcareous rocks in the southern part of the Island Pond quadrangle were actually a facies change, then both the Westmore and Gile Mountain formations should be interpreted as two large facies tongues of the St. Francis formation of Southern Quebec (Cooke, 1950, p. 29). These two tongues would be separated by a carbonate tongue, termed here the Waits River formation. The Waits River formation would merge with the Barton River formation at the latitude of South Royalton where the Westmore formation pinches out as shown diagrammatically in Figure 3. From a reconnaissance study of the area, I feel that the Westmore formation terminates at the latitude of South Royalton by a facies change but this will have to be borne out by detailed work that is now in progress in the Randolph quadrangle (Ernest H. Ern, Jr., personal communication, 1956).

If, however, the nature of the contact in the southern part of the

Island Pond quadrangle were structural, it would be possible to correlate the Westmore with the Gile Mountain formation. The two formations, then, would be actually one and the same, repeated by a large scale syncline, the axis of which has a general northeast trend in the eastern part of the East Barre quadrangle. All the field evidence from the East Barre area (cited in the chapter on structure, in this report), and the data that Jahns (1956, personal communication) obtained from detailed studies in areas west and southwest of the East Barre quadrangle are fully compatible with the above interpretation.

The absence of rocks corresponding to the Barton River formation on the east limb of the syncline postulated above can be explained in either of two ways. One obvious possibility is that this unit was cut out by the Monroe fault. But the existence of the Monroe fault itself is controversial, though no such thing is explicitly mentioned in the published literature on the geology of eastern Vermont. Also, a major synclinal structure for the sequence of the rocks in this region suggests the correlation of the Northfield slate with the Meetinghouse slate, which occurs west of the Monroe fault (White and Billings, 1951, p. 656, Pl. 1). If so, the Barton River formation should crop out immediately west of the Meetinghouse slate, and the Monroe fault east of the outcrop of the Meetinghouse slate could not have eliminated the eastern outcrop of the Barton River formation. Hence, it is my opinion that the Barton River formation pinches out at depth by a facies change, as shown in the structural cross sections on Plate 3.

STRUCTURE

General Statement

The structural geology of the East Barre quadrangle is very complex because two or more stages of deformation have produced mixed structural elements, both on megascopic and microscopic scales. The area lies directly north of the Pomfret and Strafford domes and west of the complexly folded and faulted rocks of the Woodsville quadrangle. To understand the structure, conventional methods of studying dips and strikes of bedding are inadequate. A study of minor structural features like cleavage, attitude of minor folds, and direction and plunge of linear elements is of great importance in delineating the structural history of the area. There is an integral relationship between the minor and major structures, and analysis of the minor structures leads directly to inferences about the major structure.

Terminology

To avoid any misunderstanding of the meaning of structural terms used here, a brief explanation of the terminology is included.

Bedding

Any primary compositional banding. It does not include the banding due to metamorphism in metasediments. However, metamorphism may accentuate the primary compositional banding.

Schistosity

Any metamorphic planar element, caused by a parallel orientation of the tabular surfaces of minerals. Most commonly the minerals belong to the mica group. Schistosity may or may not parallel the bedding.

Cleavage

Any metamorphic planar element by virtue of which a rock can break along essentially parallel surfaces spaced from microscopic distances to a few millimeters apart. Essentially, it is a surface of fracture. Unlike the schistosity planes, the cleavage surfaces do not necessarily show parallel minerals, but mimetic recrystallization along the cleavage planes may give rise to a cleavage closely simulating schistosity.

The term "slip cleavage" is used to indicate planes of dislocation parallel to the axial planes of minor folds. It generally post-dates and transects the schistosity in this area, and in an advanced stage of development, may pass into a second generation schistosity that cuts across the earlier schistosity.

Syncline and Anticline

In areas that have undergone more than one stage of deformation, the use of dips of beds to infer the structure might lead to an erroneous interpretation. As used here, the term "syncline" denotes any structure which has younger beds in the core and the term "anticline" denotes any structure with older beds in the core.

Trend of Bedding

Because most of the rocks of the quadrangle are folded into numerous minor folds, the strike of undeformed bedding can rarely be measured. The only measurement that can be made is the average direction in which the bedding "trends." The term "trend," as used by Balk (1936,

p. 702) and as used here, is the direction of strike of a plane that is tangential to the noses of minor folds in the bedding (Fig. 4).

Dextral and Sinistral Patterns of Minor Folds

In describing the pattern of asymmetrical minor folds, the terms "dextral" and "sinistral" are used here as used by White and Jahns (1950, p. 197). In a dextral pattern (Fig. 4), if one stands on the long limb of a minor fold and traces the bedding away from oneself, the next long limb is offset to the right. In a sinistral pattern (Fig. 4), it is offset to the left. These patterns are considered to be a "function of one component of the differential movement that formed the folds" (White and Jahns, 1950, p. 197).

Structural Features

Minor structural features have been of utmost importance in studying the major structural relations of the stratigraphic units in this area. These structural features include minor folds, planar features like schistosity and slip cleavage, and linear features like crinkling and fold axes.

A study of the minor structural features of the area indicates two distinct stages of deformation. The word 'stage' of deformation is used with caution. Necessarily, it implies only a certain time interval between the formation of structures belonging to one stage and the other, and two genetically separate deformations are not postulated. The two stages might be integral elements of a single orogeny, though no such relationship can be proved by the evidence available in the limited area of one quadrangle. Evidence for two stages of deformation appears also in contiguous areas and has been described in the literature. In the western part of the Woodsville quadrangle, White and Billings (1951, p. 675–686) describe a schistosity predominantly parallel to the bedding and sinistral north plunging minor folds in the bedding, and assign them to the early stage deformation. In the later stage, these earlier structures were transected by a slip cleavage or schistosity parallel to the axial planes of series of dextral minor folds. White and Jahns (1950, p. 198–206) reported that in a major part of the Barre quadrangle and adjacent areas, later structural features that include slip cleavage, folds and minor faults are superimposed on the earlier bedding schistosity and minor folds. In many cases the later slip cleavage is parallel to the axial planes of folds in which the earlier schistosity itself is folded. The structural

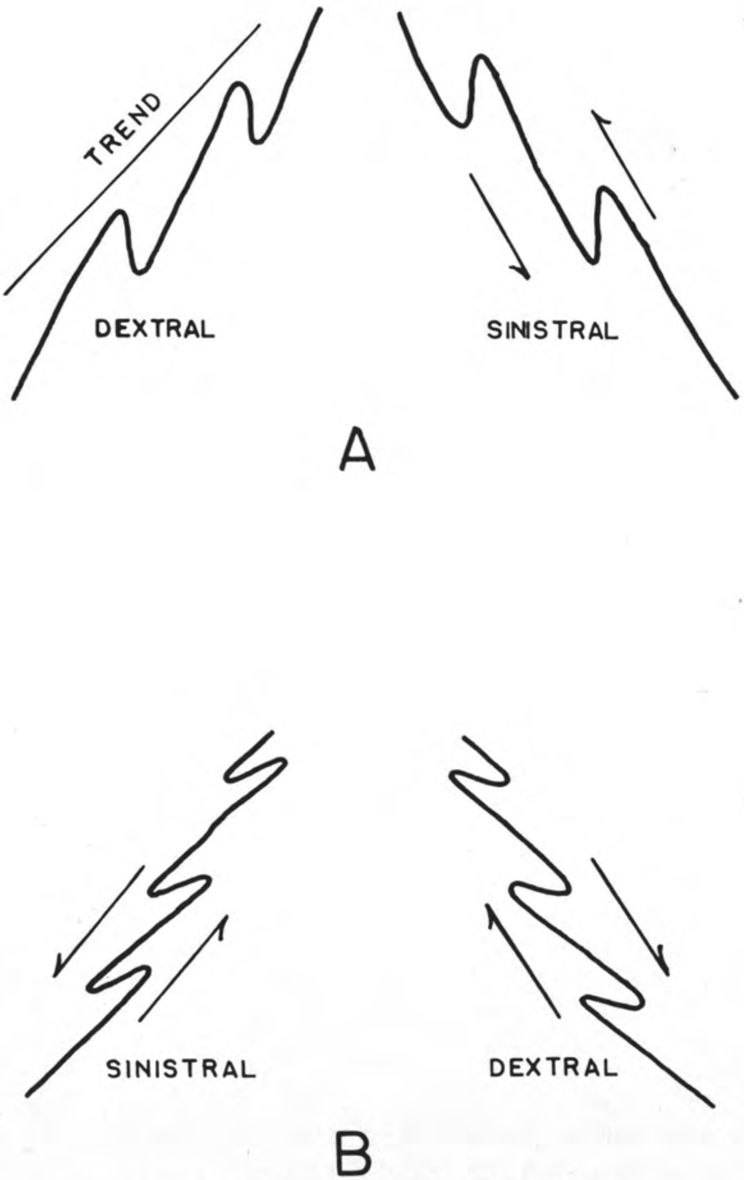


Figure 4. Dextral and sinistral patterns of folds.
A—Normal drag folds
B—Reverse drag folds

history of the area is here discussed in terms of these two stages of deformation.

Early Structures

The major difference between the early and later stages is that in the early stage, the beds of the stratigraphic units were deformed and a series of minor structural features were developed, whereas in the later stage, the early minor structures themselves were deformed to give rise to superimposed later structures.

Early Schistosity

The most prevalent early structure is a schistosity subparallel to the bedding of the rocks, and is best seen in the argillaceous rocks of the Westmore formation, and the phyllitic beds of the Barton River and Waits River formations. This schistosity is due to the formation of micaceous minerals and, in non-micaceous rocks, to quartz, feldspar and calcite in parallel orientation. Mineralogic control of the development of the schistosity is clearly seen in the rocks of the Westmore formation. The argillaceous rocks, now predominantly mica schists, show excellent schistosity, whereas in the more quartzose rocks that are interbedded with the mica-schists the schistosity is markedly poorer.

In most outcrops, the early schistosity and bedding are so nearly parallel to each other, that for purposes of terminology the schistosity can be termed the bedding-schistosity. This schistosity is parallel to the axial planes of early minor folds and transects the bedding in the noses of the minor folds. Transection of schistosity and bedding is observed in some outcrops both in plan and in cross-section. East of Mt. Pleasant, in the western part of the quadrangle, the schistosity dips slightly less to the west than the bedding. About half a mile south of East Hill, the schistosity strikes slightly more to the east and dips more gently to the west than the bedding. Although such differences in the attitude of schistosity and bedding are noted in some outcrops, the two are essentially parallel on a regional scale, and the angular discordance is so small as to be negligible.

The early schistosity is easily recognized only in the outcrops of the western half of the quadrangle. In other parts of the area, recognition of clearcut early schistosity is difficult, because a later stage deformation affected the early schistosity, and in some places altogether obliterated and replaced it by a second generation schistosity.

Early Folds

The early minor folds, like the early schistosity, are well exhibited by the schistose rocks of the Barton River, Westmore and Waits River formations in the western half of the quadrangle (Pl. 5,6). For the most part, these folds in the bedding are tightly compressed and isoclinal. Calcareous beds of both the Barton River and Waits River formations show considerable plastic flowage, which in some cases produces irregular geometric relations in the folds. Folds in the mica schists and micaceous quartzites consistently plunge 10° to 25° north; their axial planes strike north to north-northeast, and dip 40° to 75° west. The schistosity described as the early schistosity is parallel to the axial planes of these early folds and transects the bedding in the noses of the folds.

Lithologic variation in rocks influences the tightness of the folding. In general, folds in arenaceous beds are more open and show rounded crests whereas the associated folds in the argillaceous rocks are small, tightly folded, chevron folds. Folds of the early stage are conspicuously shown by the deformed quartz veins in the schistose rocks of the Westmore formation on top of Mt. Pleasant and a mile farther south along the strike (Pl. 5). Similar folds in the calcareous rocks of the Waits River formation are present on the steep east-facing cliffs about half a mile west of Newman School, in the west central part of the quadrangle.

The early minor folds in the southwestern and south-central parts of the quadrangle are far more complex, for they were affected by the later stage of deformation. In the southwestern corner of the area, the folds are sinistral in pattern with northeast plunges and their axial planes dip to the west in conformity with the early minor folds described previously. But farther to the east, they have been considerably rotated and deformed by the disturbance that caused the domal structure in the later stage. The rotated early folds, even though they were formed in first stage deformation, are considered in detail in the discussion of the later structural features.

Minor folds in all but the extreme southeastern and eastern parts of the quadrangle are considered here to belong to the first stage of deformation. This is contrary to opinions previously held (White and Jahns, 1950, p. 210; White and Billings, 1951, p. 680), which assign them to the later stage of deformation. The present view is based on the field evidence that they are essentially sinistral folds in the bedding, and on the gradual transition in the trends of their axial planes from a northeast strike in the western part to a northwest strike in the eastern part is

Plate 5. Sinistral folds shown by deformed quartz veins in the Westmore fm. on top of Mt. Pleasant.

Plate 6. Sinistral minor folds in the bedding, on the eastern flank of Mt. Pleasant, 150 yds. NE of the summit. Outcrop of the Westmore fm.

clearly defined in the field in the southern part of the East Barre quadrangle. The change in the direction of strike and dip of their axial planes, the overall sinistral pattern being preserved, is attributed to the deformation of the second stage in which the domal structure was formed. White and Billings (1951, p. 680) mentioned the possibility that these so called 'later folds' may well be rotated early folds, and that the schistosity parallel to their axial planes, which they termed the 'later schistosity,' may in part represent early schistosity that has been rotated. This is precisely the opinion held by me in view of the field evidence available in the southern half of the East Barre quadrangle.

Most of the minor folds in the southeast part of the quadrangle plunge gently to the north and northeast. The magnitude of the plunges generally increases to the north. Axial planes of these folds, parallel to which is a schistosity that defines the domal structure, strike northwest and dip about 30° to 35° northeast. The size of the folds varies from a few inches to a few feet from limb to limb (Pl. 7). The tightness of these folds decreases away from the crest of the domal structure, which also confirms the idea that they were affected by the deformation attendant on the formation of the domal structure. Slip cleavage, seen in some outcrops, is parallel to the axial planes of the folds (Pl. 8).

On the question of the patterns of early folds in the east-central part of the quadrangle, caution is needed. In some outcrops, two orders of drag folds are present; on the limbs of the first order drag folds second order drag folds show the usual relations of minor folds to major folds (Fig. 5). Such folds can be well seen a mile northeast of East Orange village, where the first order drag folds have an overall sinistral pattern but the second order drag folds on one limb are dextral and on the other, sinistral. If in such an area, outcrops were poor and far apart, then some might show sinistral minor folds and others dextral, depending upon their spatial relation to the first-order drag folds. Clearly, for deciphering any major structure, only the first order folds are reliable, and a mistake in the identification of the order of the minor folds might lead to an erroneous interpretation.

In the western two thirds of the quadrangle, the early minor folds are consistently north plunging and sinistral in pattern. However, in the extreme east-central and southeastern parts of the East Barre quadrangle, folds of a dextral pattern are observed in bedding, notably on the western flank of Pierson Hill and about half a mile northeast of Waits River village. These folds plunge 20° to 30° northeast, and their

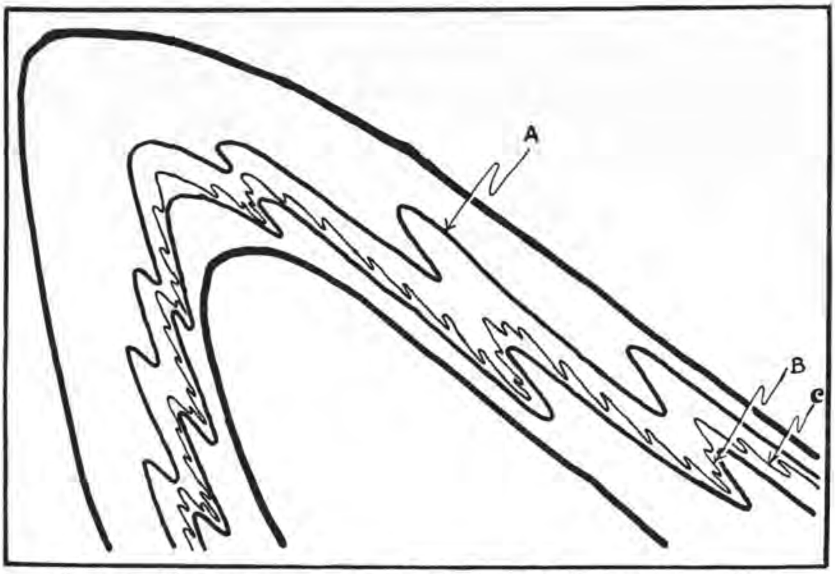


Figure 5. First and second order drag-folds on the limbs of a major fold.
A—First order sinistral drag-fold
B—Second order dextral drag-fold
C—Second order sinistral drag-fold

axial planes strike north to northeast. White and Billings (1951, p. 674, Fig. 10) show several such dextral folds in the adjacent part of the Woodsville quadrangle, but considered them to be of the later stage. Once again, it may be mentioned that these folds clearly involve primary bedding, and that even though they were affected by the later stage deformation, are still considered here as belonging to the first stage. The contact between the Waits River and Gile Mountain formations in the southeastern corner of the East Barre quadrangle is involved in large-scale dextral folds which plunge gently north or northeast (Pl. 1). Their axial planes strike northwest or north-northwest. These folds likewise are considered to be of the early stage but rotated to some extent by the later stage disturbance.

The patterns of the early minor folds, sinistral in the western part of the quadrangle, and dextral in the easternmost part, indicate that a synclinal structure was the major product of the first-stage deformation in the East Barre quadrangle. Of course, the assumption made is that these minor folds are drag folds on the limbs of the major fold. The

Plate 7. Early stage sinistral folds in calcareous schist of the Waits River formation. Size of the minor folds varies from a few inches to a few feet. Outcrop 1½ miles south of Pike Hill school.

Plate 8. Slip cleavage parallel to axial planes of small chevron folds in the Standing Pond amphibolite. Outcrop 1¼ miles N70°E of Eaton School.

Waits River formation, as restricted in the present report, occupies the trough of this syncline, the axis of which lies in the eastern part of the East Barre quadrangle.

Another line of evidence buttressing this view comes from the extreme northeastern part of the Hanover quadrangle and the southeastern corner of the Strafford quadrangle, down strike from the southeast corner of the East Barre quadrangle. Both the beds and cleavage in these two areas dip consistently northwest, but the cleavage dips steeper than the beds, which indicates that the beds become younger to the west (Cady, personal verbal communication, 1956). But, as mentioned earlier in the chapter on Stratigraphy, several lines of evidence in the western part of the East Barre quadrangle show that the beds become progressively younger to the east. This can only mean that there is a synclinal axis somewhere between the western and eastern parts of the East Barre quadrangle—supporting the interpretation arrived at by the use of the minor-fold patterns.

The above interpretation of the early stage structure calls for a major change in the stratigraphic column of the Vermont sequence, as discussed in detail in the chapter on stratigraphy.

Later Structures

General Statement

The most conspicuous major structural feature of the area is a broad arch-shaped structure that occupies the southern half of the East Barre quadrangle. This structure has been variously regarded as an anticline (E. Hitchcock, 1861, p. 254; C. H. Hitchcock, 1912; Doll, C. G., 1944, p. 22, and Lyons, 1955, p. 24) and as a cleavage arch (White and Jahns, 1950, p. 209–219). Whatever is the genetic nature of the arch, it is not only exposed in the southern half of the East Barre quadrangle but extends into the Strafford quadrangle, where it is known as the Strafford dome. The outcrop pattern of the Standing Pond amphibolite (Pl. 3) in the southern part of the Strafford quadrangle displays the structure best; but the structure is by no means confined to that area. It extends all the way through the East Barre quadrangle, but paucity of outcrops and extensive igneous rocks in the northern part of the East Barre quadrangle render its demarcation difficult.

In a controversial issue like the origin of this dome, I think it is best to segregate field evidence from interpretative statements, so that any one interested in the area can always obtain the relevant field data and yet steer clear of the interpretation.

Field Data

In the southern half of the East Barre quadrangle, the structure under consideration is defined by a schistosity that trends northeast in the western part, east-west in the central part, and northwest in the eastern part. The schistosity always dips away from the domal structure, very gently in the crestal part but somewhat more steeply in the marginal parts. In all cases, the schistosity that defines the dome is parallel to the axial planes of prevalent minor folds. Such folds are present in great numbers all through the southern part of the East Barre area.

Along an east-west traverse across the structure in the southern part of the quadrangle (Pl. 2), the field evidence is as follows: Along the western margin of the dome many isoclinal sinistral folds plunge gently northwest to west-northwest; their axial planes strike north-northeast and have an apparent dip 35° to 55° west, the amount of dip becoming progressively less eastwards. These minor folds are in the bedding and the axial plane schistosity cuts the bedding only in the noses of the folds, but is parallel to the bedding in the limbs of the folds. Much farther to the west, outside the East Barre quadrangle, White and Jahns (1950, p. 201) reported sinistral folds with north-northeast plunges and axial plane schistosity that dips 45° to 50° west. Eastward, these folds become more and more recumbent, and slightly to the west of the crestal part of the arch they are more or less horizontal, their axial planes dipping gently north (Pl. 9, 10, and 11). A gradual transition from northeast plunging folds at the western margin of the area to northwest or north-northwest plunging recumbent folds in the crestal part of the arch is very clearly seen along an east-west traverse a mile north of the southern border of the quadrangle. On the crestal line, the deformation of the folds is very intense, as attested by the tightness and recumbency of the folds, and by the plastic flowage in many limestone outcrops giving rise to irregular folds (Pl. 12, 13).

Still farther east, in the southeastern part of the quadrangle, the Waits River formation is crumpled by numerous folds, all having essentially sinistral pattern, and with their axial planes locally dipping 20° to 35° northeast (Pl. 14,15). All these folds have a gentle north or northeast plunge. The mechanism by which this type of folds is produced is discussed on p. 82–84. In micaceous rocks, a schistosity developed

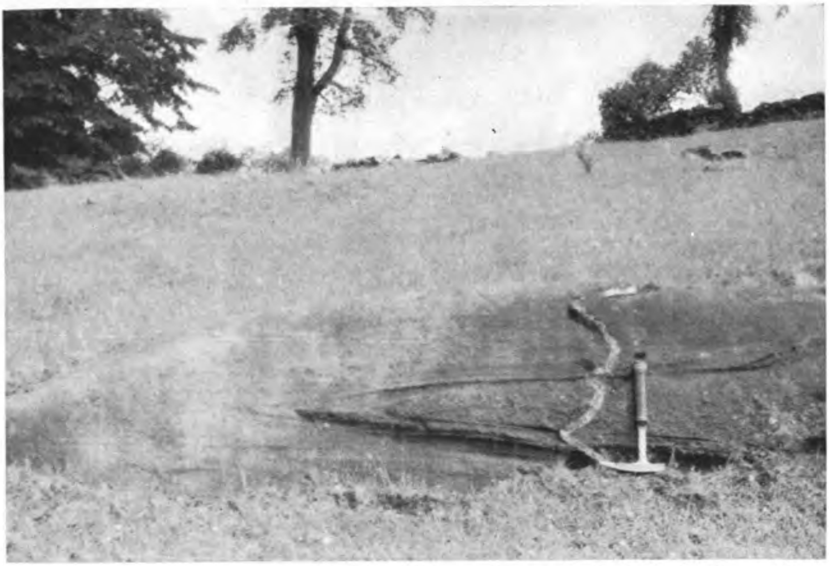


Plate 9. Completely recumbent acute fold in a limestone bed of the Waits River formation. Outcrop 1½ miles S20°E of South Washington village.

Plate 10. Acute recumbent fold in limestone beds of Waits River formation. Picture taken obliquely to include the cross-section and longitudinal section. Axial plane dips 20° due north. Outcrop 1½ miles south of South Washington village.

Plate 11. Sinistral recumbent folds in limestone beds of the Waits River fm. Outcrop back of a farm house 1½ miles S10°E of South Washington village.

parallel to the axial planes of these folds defines the pattern of the domal structure in this part of the quadrangle.

Origin of the Structure

A controversy exists on the nature of this domal structure. Doll (1944, p. 22) in his work in the Strafford quadrangle, considered it as a conventional anticline involving the beds. He thought that the schistosity that defines the dome is parallel to bedding, and that in the Strafford dome minor folds in the west limb are overturned to the east and those on the east limb are overturned to the west. Accordingly, he postulated two stages of evolution for the Strafford dome, the first, during which the anticline was formed, and the second, in which the earlier formed anticline was deformed into complex zig-zag folds, best shown by the outcrop of Standing Pond amphibolite near South Strafford village (Pl. 3).

White and Jahns (1950, p. 209–219), on the other hand, considered the structure as a dome in the cleavage formed parallel to the axial planes of minor folds. They postulated two stages of deformation; in the first stage, the rocks were folded and schistosity developed nearly parallel to the bedding; in the second stage, the earlier schistosity in turn was

Plate 12. Plastic flowage deformation in calcareous beds of the Waits River fm. Folds plunge west, and the axial planes of folds dip 35° due NW. Outcrop 1½ miles N45°W of South Washington village.

Plate 13. Rotated sinistral folds of the early stage, on the crestal part of the cleavage arch. Outcrop of calcareous schist of the Waits River formation 1½ miles SE of South Washington village.

Plate 14. Sinistral folds of the early stage deformation in the Waits River formation. Outcrop 1 mile SE of Waits River village.

Plate 15. Sinistral folds in limestone bed of the Waits River formation. Outcrop in road cut on Rte. 302, ¾ mile NW of Fuller Hill.

folded and slip cleavage formed parallel to the axial planes of the second-stage folds. According to their concept, the cleavage arch is a flexure in the axial planes of these later stage folds.

From the discussion above, it is clear that the present structural makeup of the area is the result of superimposition of structural elements belonging to two distinct stages of deformation. Available evidence indicates that the early stage deformation produced a large scale syncline with a general north-south axis somewhere in the eastern half of the East Barre quadrangle. Minor folds in the western limb of this syncline are predominantly sinistral and are clearly seen in the field.

The early-stage sinistral folds in the southern half of the East Barre quadrangle have been affected very strongly by the later stage deformation. Minor folds in the south-central part of the area have been rotated in a counter-clockwise direction and made recumbent. Transition of north-plunging early sinistral folds into west- or northwest-plunging recumbent folds is well seen in the southwest corner of the quadrangle, notably around South Washington village. The rotation and deformation of the folds indicate a strong upward and northward movement.

The minor folds in the southeast corner of the area are considered here to be rotated early folds and not later folds as postulated by White and Jahns (1950, p. 210). The main reason for this is that most of these folds, even though located on the eastern side of the arch, are sinistral in pattern and have essentially northeast plunges. No wrapping around of earlier schistosity has been noted in the noses of the folds. Also, their gradual transition to their present attitude from the attitude of the undoubted early minor folds from the western part of the area can be followed in the field. The axial planes of these folds in the southeastern and east-central part of the quadrangle trend northwest and dip 20° to 40° northeast. The present orientation of these folds is due, in my opinion, to the clockwise rotation of their axes and tilting of their axial planes. Such a rotation of the fold axes and tilt of the axial planes is compatible with an upward and northward movement of a central block in the second stage of deformation. The direction of rotation of a fold in response to such a movement is entirely dependent upon its location with respect to the area of domal uplift.

This mechanism of rotation is diagrammatically shown in Fig. 6. The lines AB and CD are the traces of the axial planes of the northeast plunging early folds prior to the second stage deformation. During the second stage deformation, the northward horizontal component of the obliquely

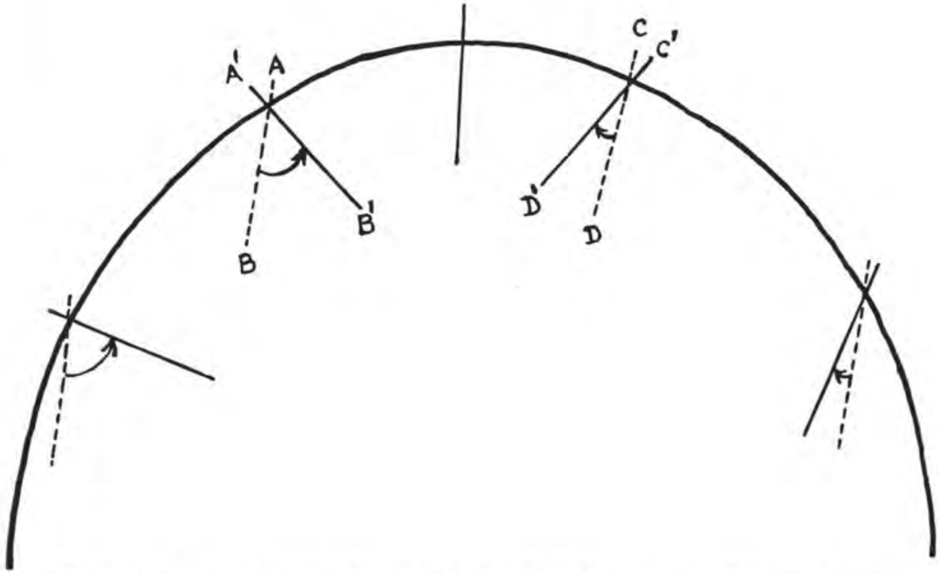


Figure 6. Diagram showing the rotation of early fold axes during the second stage deformation.

rising mass outlined by the semicircular line, rotated the folds into their present orientation, indicated by the lines A'B' and C'D'. On the crestal part of the dome, outcrops show a local strike and dip due to the rotation of the early minor folds during the second stage disturbance. Confusion between the true trend and dip and this local strike and dip of beds in the crestal part of this domal structure has, in part, been responsible for the controversy on the nature of this domal structure, mentioned above.

The relationship between this local attitude of bedding and the true trend and dip are shown diagrammatically in Fig. 7. The original strike and dip of the bedding involved in early sinistral minor folds are shown by the dashed lines. In the second stage deformation, the vertical component of the deformation, lifted up these folds and made them acutely tight and recumbent. Inasmuch as the component of uplift was greatest close to the dome and decreased farther away, the axes of these folds plunge gently away from the dome. Now, the attitude of the beds in these folds, seen in an east-west section, most common in the outcrops of the area, is horizontal and might be mistaken for the trend of the beds.

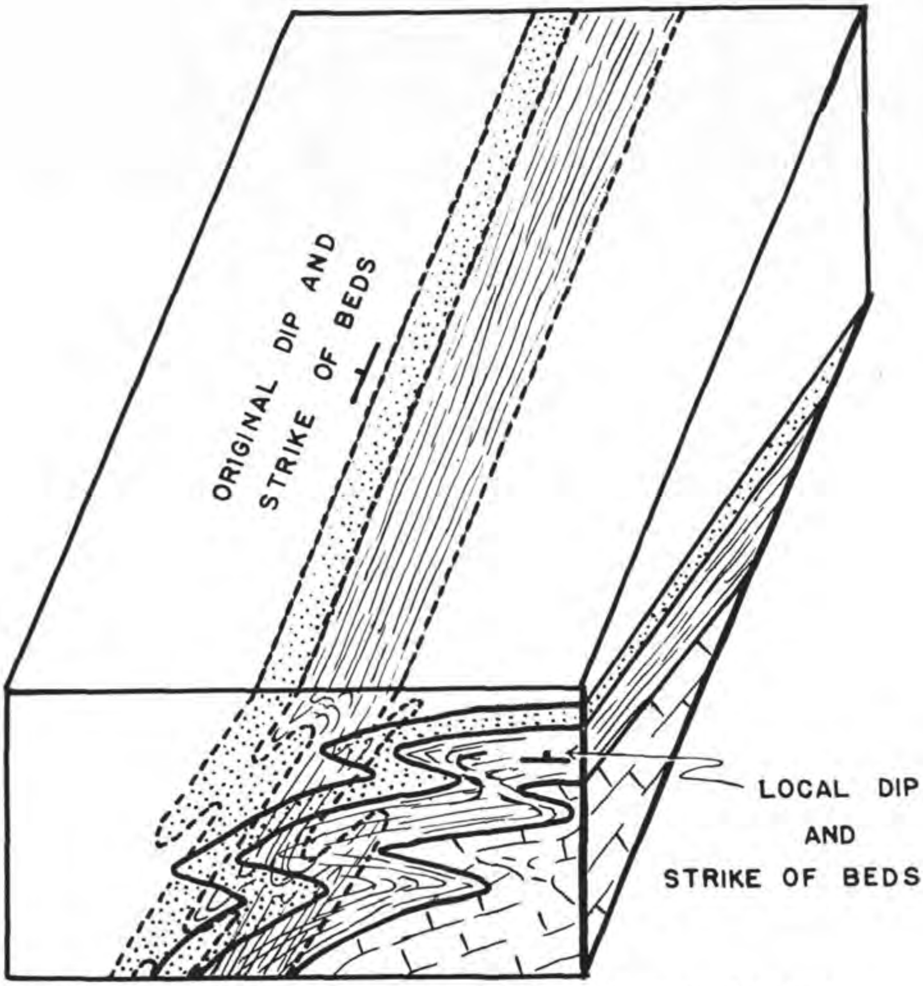


Figure 7. Diagram showing the rotation of early folds and the relation of the local dip and strike of beds to the regional dip and trend.

Similarly, in a north-south section, the beds give a false sense of dip due to the north plunge of the folds. In actuality, the true trend of the beds is in the direction of plunge, in this case to the north. The cleavage in the crestal part of the dome is parallel to the axial planes of these accordion folds, strikes east-west, and dips away from the dome to the north.

Where it is intensely developed it passes into a schistosity (the later schistosity of White and Billings, 1951, p. 679–680), and is the main feature that defines the arch structure in the area. Hence the term 'cleavage arch' (White and Jahns, 1950, p. 209) is retained to designate the structure here.

Independent evidence for an upward and northward movement of the central area of the dome comes from White and Jahns' (1950, P. 204) study of regional structure in east-central Vermont. The plunges of the sinistral minor folds in the rocks east of the Braintree-Northfield Range indicate a northward displacement of the rocks on the east, and the prevailing sinistral and dextral patterns of the later minor folds (outside of the East Barre quadrangle) on either flank of the domal structure indicate a strong upward movement of the rocks in the center of the cleavage arch.

The axis of the cleavage arch does not coincide exactly with the axis of the first-stage syncline; but in the latitude of the East Barre quadrangle, is slightly to the west of it. Consequently, rocks on the western limb of the first stage syncline are involved in the second stage deformation to a much greater extent than those on the east limb of the first-stage syncline. This explains why the early-stage sinistral folds are so conspicuously rotated, tilted and otherwise deformed on the flanks and crest of the cleavage arch.

The cause of the upward movement of the rocks that gave rise to the cleavage arch is not known. White and Jahns (1950, p. 214–219) ascribed this upward bulge to the extreme mobility of the calcareous rocks of the Barton River and Waits River formations under deep-seated deformation of initially folded schists and limestones. Study of gravity anomalies by Bean (1953, p. 528–533) however, indicated a definite negative gravity anomaly associated with the Strafford dome. This calls for the presence of a low density rock in the central part of the dome, and Bean calculated that the Strafford area is underlain by a mass of rock of approximate granitic composition at a depth of about 2500 feet below the surface. Several suggestive evidences also point to this as the possible origin of the cleavage arch. The grade of metamorphism decreases away from the crestal area of the dome towards either side. In the southern part of the East Barre quadrangle, large areas are intruded by numerous granitic dikes and this may indicate the existence of a pluton not far below the surface. Analogy with other domes in nearby areas also favors the idea of the existence of a pluton at depth in the center of the cleavage dome. The uprise of such an igneous body would satisfactorily explain all the complicated minor structures associated with the cleavage arch in addition to explaining the higher grade of metamorphism at the center of the cleavage arch.

Structure of the Westmore Formation

A synclinal structure termed the Brownington syncline was postulated by Doll (1951, p. 51) for the rocks of the Westmore formation in the Memphremagog quadrangle. Following Doll, Dennis (1956, p. 35-36) extended the structure into the Lyndonville quadrangle. Dennis (1956, Pl. 3) however thought that the outcrop of the Westmore formation pinched out in the northern part of the St. Johnsbury quadrangle, and postulated that the proposed syncline plunges north in the Lyndonville and St. Johnsbury quadrangles. Based on his reconnaissance work, he extended the Gile Mountain (?) formation of White and Jahns (1950, p. 189), the Westmore formation of the present report, into the Plainfield quadrangle and closed the outcrop in the southern part of the Plainfield quadrangle (Dennis 1956, Pl. 3). He postulated a synclinal structure for this band of schists too, and suggested that "there is no reason why this could not be a continuation of the Brownington syncline" (Dennis, 1956, p. 35). Thus, in his interpretation, the belt of schists variously mapped as Westmore formation and Gile Mountain (?) formation occurs in the axial part of a doubly plunging syncline, and the areas where it was supposed to be absent in the Plainfield and St. Johnsbury quadrangles would be a saddle or culmination.

Evidence of several sorts from the present field work renders a synclinal structure for the Westmore formation highly improbable.

1. All the minor linear structures of the Westmore formation in this area, including the plunges of minor folds, crinkling and mineral streaming along cleavage planes plunge consistently north, thus repudiating the idea of south plunging structure.

2. Lithologically, the belt shows three distinct members (Pl. 1), a western belt of dominantly argillaceous rocks, a central belt of dominantly arenaceous rocks, and an eastern belt of, once again, argillaceous rocks. The two belts of argillaceous rocks on either margin are distinctly different in thickness however, which is difficult to explain unless very quick facies and thickness changes are assumed over very short distances.

3. The relationship of slip cleavage to bedding on both the western and the eastern margins indicates consistently that the beds on both

margins are overturned, and that the rocks are younger to the east progressively. North of the Memphremagog quadrangle, (Cooke 1950, p. 31; fig. 2) describes a consistent overturn of the beds much farther to the east and does not mention any synclinal structure corresponding to the Brownington syncline.

4. The pattern of the minor folds is sinistral on both margins of the Westmore formation. A syncline should show sinistral drag folds on the western limb and dextral folds on the eastern limb.

5. Recent mapping in progress in the St. Johnsbury and Plainfield quadrangles (Leo Hall, Ronald Konig, 1956, personal communication) has shown that this belt of schists is continuous with the Westmore formation of the Memphremagog quadrangle (Doll, 1951, p. 33), and that there are no closures of outcrop in the Plainfield and St. Johnsbury quadrangles as shown by Dennis (1956, Pl. 3; p. 35–36). Thus there is no reason to believe that this belt forms a doubly plunging syncline with an inversion in the direction of plunge in the central part of the Plainfield quadrangle.

6. There is no major change in the width of the outcrop of this belt for a considerable distance along the strike. In the southern part of the Randolph quadrangle, where the belt pinches out (Fig. 3), reconnaissance study suggests that there is a facies change. Thus the closure in the outcrop of this formation in the latitude of South Royalton in the Randolph quadrangle may be stratigraphic rather than structural.

7. In the Plainfield quadrangle, the contact between this formation and the Barton River formation to the west is completely gradational, and is probably a gradual facies change in a regimen of continuous deposition. Farther south, in the East Barre quadrangle, the western contact is gradational, but the eastern contact is rather sharp. One would expect a close similarity of the contacts on either limb of a syncline.

At this point a re-evaluation of the evidence put forth to support the postulated syncline is in order. Doll (1951, p. 51) in his report on the Memphremagog quadrangle first mentioned the structure and named it the Brownington syncline. Beyond mentioning that the beds show a pronounced overturn on the western margin and a normal sequence on the eastern margin, he cited no other evidences. As already stated, Cooke's map (1950, fig. 2) of southeastern Quebec shows a consistent overturn of beds and no synclinal structure along the strike immediately north of the International Boundary.

Dennis (1956, p. 35) thought that "the synclinal form . . . could be fully substantiated in the Lyndonville and adjacent quadrangles by two lines of evidence:

1. The band of Gile Mountain formation (Westmore formation in the present report) in the area has nearly vertical dips in the west and very shallow westerly ones in the east, suggesting a synclinal form.

2. The trough of the syncline is exposed and can be traced out in the Danville and Walden townships (St. Johnsbury quadrangle)."

The first evidence is far too weak to be conclusive, and the second statement is disproved by recent mapping in the St. Johnsbury and Plainfield quadrangles (Leo Hall and Ronald Konig, 1956, personal communication).

In view of the above discussion, a synclinal structure for this belt is no longer tenable. I believe that this formation is a unit in a homoclinal sequence, lying above the calcareous rocks of the Barton River formation.

Structural Synthesis

The interpretation of a synclinal structure for the belt of schists included under the Westmore formation, as postulated by Doll (1951, p. 51) and Dennis (1956, p. 35), is considered highly improbable in view of the overwhelming evidence against it. Instead, this unit is thought to be part of a homoclinal sequence that constitutes the west limb of major syncline, involving rocks stratigraphically above and below the Westmore formation.

The analysis of minor structures reveals at least two distinct stages of deformation in the area. In the early stage, a major synclinal structure with a nearly north-south axis was formed in the eastern part of the East Barre quadrangle. The calcareous and schistose rocks in the central part of the East Barre quadrangle belong to the trough of the syncline. Drag folds of a sinistral pattern on the western limb of the syncline, shown very clearly in the argillaceous rocks of the Westmore formation and the calcareous rocks of the western part of the Waits River formation, indicate a movement in which the rocks on the east have moved up. On the eastern limb of the syncline, the early stage dextral folds are scarce, except in a few localities. This may be because the early dextral folds have been affected by the second stage deformation, merging with second-stage dextral folds. In any case, distinction between first-stage and second-stage dextral folds is quite difficult in the eastern part of the quadrangle.

The major tectonic element of the second-stage deformation is the domal structure that extends from the southern part of the East Barre quadrangle south into the Strafford quadrangle. The early sinistral folds on the western limb of the syncline were lifted up and rotated in a counter-clockwise direction. Consequently, many of them are now recumbent, with their axial planes dipping north and their axes plunging gently to the west or northwest. The early dextral folds on the east limb of the syncline were affected to a much lesser degree, but they have been rotated in a clockwise direction. From the direction of rotation of these folds, it is inferred that the main tectonic stress of the second stage was upwards, but had a pronounced northward horizontal component. The rotated early folds on the crest and flanks of the arch are the result of this northward horizontal component, whereas the extremely compressed recumbent folds on the crest of the arch are due mainly to the vertical component.

Bean's (1953, p. 509–538) gravity survey of east-central Vermont indicated residual negative anomalies associated with the domal structures. The gravity anomaly under the Strafford dome was interpreted by him as due to the presence of a low density rock under the comparatively denser metamorphic rocks. Lyons (1955, p. 125), following along the lines of Bean's work, suggested that the lower density rock may be granite, locally rising up vertically as a plunger. While there is no indisputable field evidence to support the presence of granite at depth, the presence of numerous granitic dikes in the southern part of the quadrangle, and the high grade of metamorphism attained in the central part of the domal structure, make the suggestion very plausible. Also, the kinematics associated with a plunger rising up from depth are thoroughly compatible with the field evidence provided by the minor structures.

PLUTONIC ROCKS

General Statement

Plutonic rocks, located in the northwestern and north-central parts of the East Barre quadrangle, occupy approximately one eighth of the area of the quadrangle. Two major outcrops are present, and the larger of the two, in the north-central part of the quadrangle, is fringed with a group of small granite bodies. These small bodies may in fact be connected to a large body underneath the thick cover of glacial and alluvial deposits that separate them from the main body.

The two major outcrops are separated at their closest by a mile-wide stretch of the Waits River formation. The western granite body has long been known as the Barre granite, both in early geologic literature and commercial nomenclature, and this name is used in the present work. The much larger body of granite in the north-central part of the quadrangle has been referred to as the Knox Mountain granite (Richardson, 1902, p. 99), and this name is also retained in the present report.

Early Work

Mention of the granite plutons in this area dates back to the early works of Richardson (1902, p. 61, 98, 1906, p. 63–115). Detailed studies of these rocks were made by Finlay (1902, p. 46–60). Dale (1924, p. 104–108, 113–118, 121–143) conducted an exhaustive study of the commercial granites of New England, and gave a wealth of data on the Barre granite. Balk (1925, p. 39–96) studied the internal structural features and structural relations of the Barre granite with the host rocks and came to some interesting conclusions as to the origin and emplacement of the granite pluton. In his classic memoir "Structural behavior of igneous rocks" (1937) he discussed the Barre granite and its structural relations at some length. Maynard (1934, p. 146–162) made a petrographic study of the quartz-bearing plutonic rocks of Vermont, and on the basis of modal analysis of a few specimens of Barre granite suggested that the rock was a granodiorite instead of a granite. Shimer (1947, p. 1049–1066) analyzed the Barre granite spectrographically, and found some interesting trends in concentrations of minor elements and their association with the major elements. Finally, Chayes (1950, p. 22–36; 1952, p. 207–254) made a very careful modal analysis of the Barre granite and discussed some important points bearing on the composition of granites, mutual relations between the minerals, and mineralogic and compositional evidence for the origin of the granite.

The Barre Granite

The Barre granite is an elongated, oval-shaped body that crops out in the northwestern and west-central parts of the East Barre quadrangle. The outcrop has a north-south length of over four and a half miles and an east-west width of about two miles. Its long axis trends north-northeast, in close parallelism to the regional trend of the rocks of the area.

The outcrop of the Barre granite is confined to the Westmore formation, except at the eastern margin, near East Barre village, where it extends a short distance into the Waits River formation. The two prominent hills in the northwestern part of the quadrangle, Cobble Hill and Millstone Hill, are made up of this granite. All quarrying of monumental granite is at present restricted to Millstone Hill.

PETROGRAPHY

In its megascopic appearance, the Barre granite is a light to medium gray, even-textured rock of predominantly medium grain size. The uniformity of color and grain size over large areas is quite striking and, of course, is well attested to by the extensive use of the granite for monuments. Along the joint planes, cracks and other openings in the rock, percolating ground water has altered the biotite and other iron-bearing minerals, producing a faint yellowish brown stain, familiarly known as "sap" in the quarryman's language. Abrupt variations in color, in places knife-edge sharp, are found where the granite contains partly absorbed xenoliths or where dikes of late granite cut earlier granite (Pl. 16). Variations of grain size also are noted in such circumstances, but do not definitely correlate with the color, though at first glance it might appear that the coarse-grained varieties are somewhat lighter shades of gray.

Chayes (1950, p. 22–36; 1952, p. 207–254) has made an exhaustive mineralogic study of the Barre granite. I felt, therefore, that detailed mineralogic work on this granite would be repetitious and would contribute little new to subject; so emphasis in the present study has not been on detailed mineralogic description, but rather on the discussion of the data available—both from previous literature and from my work. For the sake of completeness, however, a brief mineralogic description of the granite is given below.

Quartz, potash feldspar (predominantly microcline), and plagioclase (oligoclase) are the chief light-colored minerals in the Barre granite. Biotite is the prevalent mafic mineral and the color of the granite is mostly due to this mineral. The darker the granite the greater the amount of biotite present in the rock. Muscovite is present in almost all the Barre granites studied; in many specimens it equals or exceeds biotite in amount. A variety of accessory minerals are present; the list includes epidote, apatite, sphene, and less commonly calcite, magnetite, and tourmaline. Zircon is rare—in fact so rare that a program of separating zircon from the granite for age determination had to be abandoned in favor of an alternative method of age determination, namely the Rb/Sr method using biotite separated from the granite.

Typically, the Barre granite is a two-feldspar, two-mica granite. The

Plate 16. Sharp contact between 'dark' and 'light' granite. Faint banding observable in the dark granite. Exhibition (polished) slab Rock of Ages quarry.

two main feldspars are microcline and oligoclase to sodic oligoclase. Orthoclase may be present, and can be distinguished from the microcline by its alteration. Most commonly, the orthoclase is kaolinized, but the microcline with its cross-hatched twinning remains clear and unaltered. The plagioclase occurs as irregular subhedral grains, some twinned on the albite law. Plagioclase is replaced almost exclusively by aggregates and small intergrowths of muscovite. Quartz in the Barre granite occurs in the interstices between the plagioclase and potash feldspar. Quite commonly it shows effects of strain such as undulatory extinction and irregular cracks.

Biotite in the Barre granite occurs as well formed large flakes and aggregates evenly distributed throughout the rock. It is a deep brown, iron-rich variety. In places it is altered to chlorite with a concomitant release of leucoxene, but on the whole most of the biotite is remarkably fresh. Pleochroic haloes are quite common in many of the biotite flakes.

Muscovite occurs in quantities comparable to the biotite in almost all the thin sections studied. It is almost always closely associated with the plagioclase, which it replaces in poikilitic aggregates or fine intergrowths. In places, it rims the plagioclase. Very minor quantities of muscovite replace the potash feldspar and some muscovite occurs as bladed intergrowths with biotite. The significance of the close association of the plagioclase and muscovite is discussed in a later part of this chapter.

Paragenetic relations of the major minerals of the Barre granite derived from the study of thin sections are as follows: plagioclase was the first light-colored mineral formed, with a great part of the biotite crystallized simultaneously with it. A small part of the biotite appears to be earlier than some plagioclase. Microcline and orthoclase followed next. Quartz was the last mineral to crystallize, for it is xenomorphic and fills the spaces between the feldspar grains. Muscovite is definitely a reaction product between the end liquids of the magma and the early-formed plagioclase.

In commercial and early geologic literature this rock has been included under the omnibus lithologic name 'granite.' Classifications being what they are, the term granite means different things to different people. It would be perhaps more precise to give the rock a name and specify the system of classification or nomenclature adopted. For this report it was considered best to follow the classification of Johannsen (1955 ed., p. 141–161) inasmuch as modal analysis was the chief technique used in the quantitative study of the granites. Accordingly, under this classification the so-called Barre granite is really a granodiorite, as clearly stated long ago by Maynard (1934, p. 154).

Modal Analysis of the Barre Granite

Chayes (1952, p. 207–254) arrived at significant conclusions about mineralogic abundances and variations by a statistical study of the modes of the various major constituents in the Barre granite. One of the main points he brought out was the very small range of variation of the major constituents in any one given body of New England granite. His collection included specimens taken from the major quarries in the Barre granite; namely, Wells Lamson, Wetmore-Morse, Smith Granite Company, Pirie Estate, and Rock of Ages Quarries. Many of them were taken from inside the quarries where fresh specimens could easily be obtained and some were collected from the grout piles at the derrick sites. Care was taken to guard against suppressing the variability in composition by too close a sampling. Even with such precautionary steps in the sampling procedure, his analysis indicated a remarkable invariance in the modal composition of the Barre granite.

During the present study, I decided to extend Chayes' study by taking a number of samples over a wider area than he covered and determining mineralogic modes by his method, in order to see if the modal composition of these specimens differed from that of his collection. In all, 36 samples were collected. As a pilot project nine thin sections were cut from samples, the locations of which were as distant as possible from the sites from which Chayes selected his samples. If significant differences were noted, then thin sections could be cut from all the 36 samples and their modes determined, so that the variations could be studied on a statistical basis. If no significant differences showed up, these nine samples would serve the purpose of extending the area of granite for which his conclusions hold good.

The modes of the nine thin sections of the Barre granite are given in Table 7. The opaque accessories in the Barre granite are negligible in

TABLE 7

ESTIMATED MODES OF THE BARRE GRANITE

Specimen number	Quartz	Potash Feldspar	Plagio-clase	Biotite	Muscovite	Non opaque accessories	Number of counts
13	25.8	15.3	35.2	7.97	13.25	2.30	3864
34	28.7	15.06	36.6	7.15	10.52	2.2	4000
12	23.43	24.56	31.04	12.27	7.92	0.8	3611
82	21.11	30.34	39.8	8.75	7.2	2.4	4384
10	25.14	17.6	32.2	11.46	9.2	2.05	3699
6	20.7	19.0	30.62	16.97	10.65	2.05	5032
88	19.66	27.89	38.1	7.24	6.63	0.5	4282
36	27.24	15.71	33.96	9.73	11.53	1.80	4213
23	26.83	15.83	35.05	8.73	11.13	2.32	3916
Mean	24.29	20.143	34.73	9.84	9.78	1.82	4111.2

amounts and hence were omitted from my calculations. The result of Chayes' analysis of 21 thin sections of the Barre granite (1952, p. 248) are given in Table 8 for comparison.

As may be seen from the tables, no major differences are evident between the modes of my samples and those of Chayes. This means that the Barre granite, over wide areas in its outcrop, is remarkably homogeneous in composition.

TABLE 8

MODAL ANALYSES OF 21 THIN SECTIONS OF BARRE GRANITE BY CHAYES (1952).

Specimen number	Quartz	Potash Feldspar	Plagio-clase	Biotite	Muscovite	Opaque accessories	Non-opaque accessories	Number of counts
1	26.6	18.2	38.6	6.3	8.5	0.1	1.7	1406
2	31.2	17.6	32.4	9.3	8.0	0.2	1.3	1350
3	31.6	17.3	35.2	9.1	4.5	0.1	2.2	1464
4	32.7	20.0	32.1	8.0	5.8	0.1	1.3	1491
5	24.7	23.5	32.3	8.5	8.9	n.d.	2.1	1358
6	22.5	18.7	39.7	7.0	9.7	0.1	2.3	1415
7	26.4	23.8	33.5	6.2	8.1	0.3	1.7	1446
8	29.2	21.1	33.9	6.4	8.2	0.2	1.0	1294
9	20.8	23.8	38.8	7.9	6.9	0.1	1.7	1459
10	30.8	17.7	32.6	9.4	8.3	0.2	1.0	1341
11	25.1	18.8	36.1	9.4	9.4	0.1	1.1	1450
12	24.8	19.7	35.8	9.6	8.3	0.3	1.5	1433
13	28.0	15.4	38.3	7.5	9.1	n.d.	1.7	1466
14	29.0	18.8	33.0	9.1	8.1	0.2	1.8	1475
15	27.4	24.8	36.6	0.2	9.8	0.1	1.1	1486
16	25.8	21.2	32.6	7.1	11.2	0.4	1.7	1427
17	25.4	20.4	30.3	16.0	6.8	0.1	1.0	1429
18	27.9	17.6	37.6	6.3	9.3	0.1	1.2	1281
19	28.6	18.5	33.5	7.7	9.1	0.3	2.3	1480
20	24.3	18.3	35.9	11.1	8.0	0.5	1.9	1521
21	27.9	12.5	40.4	8.7	7.9	0.4	2.2	1375
Mean	27.2	19.4	35.2	8.1	8.3	0.2	0.8	1421

The implication of such a remarkable homogeneity in the modal composition of the Barre granite, using samples collected as randomly as possible, are amply discussed by Chayes (1952, p. 239–244). His plot of the modes of Barre granite in a ternary diagram whose apices are quartz (Q), orthoclase (Or), and plagioclase (Pl) consistently points to a rectangular area corresponding to the thermal valley in the system nepheline-kaliophilite-silica, investigated by Bowen (1937, p. 1–21). This, of course, is highly significant, for experimental evidence at hand shows that for any liquid whose composition lies within the triangle crystallization proceeds in the direction of the thermal valley. In other words, "granites form by crystallization of magmas (liquids) of granitic composition."

Relationship between Muscovite and Biotite

The relation between the amounts of muscovite and biotite present in the calc-alkaline granites of New England has also been investigated by Chayes (1952, p. 216–217). His results, indicating a definite lack of correlation between the two types of mica, are not surprising. Indeed, it would be surprising to find a correlation between the two, in view of the very different roles played by the two types of mica in crystallization of granitic magmas. Biotite, on the one hand, is a straight magmatic mineral and crystallizes from the magma either with or before the feldspar; muscovite in the Barre granite, on the other hand, is a late magmatic product, the result of a reaction between the residual liquids of the crystallization process and the early formed plagioclase. Its immediate ancestor is the potash-enriched liquid of the 'residual' system of Bowen. Thus there should not be any direct correlation between the amounts of biotite and muscovite in the granite.

Relationship between Muscovite and Plagioclase

An important characteristic of the Barre granite is that over 90 percent of the muscovite replaces the plagioclase, whereas the amount of microcline replaced by muscovite is insignificant. This raises the question: Why should the end residues of the magma neglect the potash feldspar and seek out the plagioclase for reaction and pseudomorphous replacement? There seem to be two possible answers to this question.

(1) According to this the bulk of the potash feldspar formed later than the muscovite, so that the potash-enriched residual liquids could replace only plagioclase and not microcline. However, two definite lines of evidence contradict this hypothesis. First, the evidence from the microscopic study of the Barre granites does not indicate that the potash feldspar is later than the muscovite. In fact, some sections show microcline being replaced by small amounts of muscovite. Second, our knowledge of systems with hydrous phases and their behavior during crystallization indicates that it is improbable, if not impossible, that formation of a hydrous phase of a compound should precede that of an anhydrous phase.

(2) An alternative hypothesis invokes the kinetics of reactions. If the rate of the reaction

$$\text{K–feldspar} + K^+ \text{ in } H_2O \longrightarrow \text{K–mica} + K^+ + OH^-$$

is insignificant compared to the rate of reaction of

$$\text{Na–feldspar} + K^+ \text{ in } H_2O \longrightarrow \text{K–mica} + Na^+ + OH^-$$

then for a given length of time in which the reacting liquids are in contact with the two feldspars, more plagioclase than potash feldspar would react with the liquids rich in potash.

Chayes (1950, p. 22–36) has argued that the muscovite of the Barre granite is a 'late magmatic' product. By his definition, this means that the reaction between the residual liquids and the plagioclase occurred before the residues were expelled from some parts of the chamber and concentrated in others. If so, the amount of replacement mineral (muscovite) formed would be roughly proportional to the amount of original mineral available for reaction (plagioclase). This proportional relation would be independent of time, and there should be a positive correlation between the replacement mineral and its host. The Barre granite shows this correlation. Thus, when once the late magmatic nature of the muscovite is established, it is implicit in the argument that the residues were still evenly distributed in the partly crystallized magma at the time of the formation of muscovite, and thus had access to both the plagioclase and the microcline. The only factor governing the amounts of plagioclase and microcline that would react with the liquid would be the rates of the two reactions. To my knowledge, no quantitative information is available on the kinetics of the above reactions, but the question is certainly well worth investigation.

The answer to the question on hand depends on thermodynamic considerations. The reaction between the feldspars (plagioclase or microcline) and the magmatic residue that ultimately results in the formation of muscovite proceeds through an intermediate product, which might conveniently be called here the 'proto-mica.' Essentially, in this intermediate step the cation of the feldspars is replaced by a hydrogen ion (H^+). In a K-feldspar, the K^+ ion is directly replaced by the H^+ ion. But in the case of the plagioclase, the proto-mica is far more complex. In the presence of a hydrous phase that contains the K^+ ions, some of the Na^+ ions are replaced by K^+ ions and some by H^+ ions. The potash rich solutions required in the reactions may be residual, or some of the plagioclase containing small amounts of potash may become unstable, the potash entering the hydrous phase. The reactions may be visualized as follows:

$$\text{K–feldspar} + H^+ + K^+ \longrightarrow H^+ \text{ proto-mica}(_1) + K^+ + OH^- \quad \ldots . 1$$

$$\text{Na–feldspar} + H^+ + K^+ \longrightarrow K^+, H^+ \text{ proto-mica}(_2) + Na^+ + OH^- \quad \ldots 2$$

The next step is the conversion of this proto-mica to muscovite by substitution of K ions for H ions.

The free energy change of the reactions may be of a similar order of magnitude for the two feldspars. But once the proto-mica is formed on the surface of the feldspars, the second stage of the reaction involves not free energy changes, but surface phenomena and surface energy relations. In other words, for the reaction to proceed to muscovite, a certain amount of activation energy has to be supplied to the surface layer. It may be that the activation energy required for the conversion of proto-$mica_2$ to muscovite is much less than that required for the conversion of proto-$mica_1$ to muscovite. For one reason the atomic framework of the proto-mica formed from the plagioclase, as explained above, would be much more highly disturbed than that of the proto-mica formed from the microcline. And it is common knowledge in physical chemistry that a highly random state requires the lowest activation energy to change to the ordered form. If the conversion of proto-$mica_2$ to muscovite is of this type, then, by and large, under any one set of given energy conditions, this reaction will be favored.

Experimental work by Garrells (from a lecture given at the Geology Dept., Yale Univ., 1956) (unpublished) indicates another point. The reaction

$$3\,K\,Al\,Si_3\,O_8 + 2\,H_2O \rightarrow KAl_3\,Si_3\,O_{10}\,(OH)_2 + 2K^+ + 2\,(OH)^- + 6\,Si\,O_2$$

$$\text{or, K–feldspar} \xrightarrow{H_2O} \text{Muscovite} + \text{Silica}$$

is strongly hindered by the presence of K^+ ions in the water. In fact, the strongly alkaline solution produced when K-feldspar is added to water can be titrated with a KCl solution. This may be taken to indicate that the conversion of K-feldspar to muscovite is less significant, or more improbable, with solutions having free K^+ ions, . . . and these are precisely the solutions postulated for a late magmatic stage of the Barre granite.

In an answer to the same question, Chayes (1952, p. 245–246) mentions that, as crystallization of the magma progresses a stage is reached in which plagioclase becomes unstable; thus some of the potash that might otherwise have formed potash feldspar replaces the unstable plagioclase and forms muscovite. Admittedly, the stability fields of the three minerals, potash feldspar, highly sodic plagioclase, and muscovite overlap. Chayes suggestion does not make it clear at all, then, why the muscovite should replace the plagioclase so exclusively.

Knox Mountain granite

A large densely wooded mountainous area in the north-central part of the East Barre quadrangle is occupied by granite. This is the Knox Mountain granite—named after the Knox Mountains within the quadrangle (Richardson, 1902, p. 91).

The outcrop area of the Knox Mountain granite extends northward into the Plainfield and St. Johnsbury quadrangles. Although a separate name is given to this granite, the Knox Mountain granite and the Barre granite may be separate outcrops of a single plutonic body. No positive evidence to attest such a relationship was obtainable. In fact, some indirect lines of evidence seem to suggest the contrary. This matter is taken up at length below.

It may be mentioned that this granite crops out very poorly except at the very tops of the mountains. Hence observation and sample collection had, of necessity, to be sporadic and uneven. All the area was covered by traverses, however, and in the time available no more detailed mapping could be undertaken.

Petrography of the Knox Mountain Granite

The Knox Mountain granite is a medium-grained, light gray granite, and an unweathered specimen is apt to resemble the Barre granite rather closely, even though the granite is invariably lighter in color than the average Barre granite. However, the homogeneity in composition and color so characteristic of the Barre granite are lacking in the Knox Mountain granite and in many places it shows wide variations in color and grain size; areas with many pegmatitic dikes and quartz veins are not uncommon. These can be seen well on top of Spruce Mountain and on the western slopes of Knox Mountain where the granite is exposed on glaciated and exfoliated surfaces.

Mineralogically, the Knox Mountain granite is made up of quartz, potash feldspar, plagioclase (oligoclase), biotite and muscovite.

The most important mineralogic difference from the Barre granite is that the muscovite is not as closely associated with the plagioclase as in the case of the Barre granite. In almost all the thin sections studied, the muscovite occurs close to potash feldspar, in places rimming it or replacing it.

Potash feldspar occurs both as microcline and orthoclase, and commonly, the orthoclase is selectively sericitized in preference to the microcline. Grains of potash feldspar and quartz form anhedral aggregates, indicating that they crystallized at a somewhat later stage than the plagioclase.

Biotite in the Knox Mountain granite is sporadically distributed throughout the body of the granite and is remarkably fresh. It is present in well formed flakes and, in places, is intergrown with muscovite. Biotite is not related to any other mineral in the rock in its mode of distribution.

Accessory minerals include sphene, apatite, epidote and magnetite. Magnetite occurs in much lesser amounts than in the Barre granite.

The modes of 9 thin sections of the Knox Mountain granite are given in Table 9.

TABLE 9

ESTIMATED MODES OF THE KNOX MOUNTAIN GRANITE

Specimen number	Quartz	Potash Feldspar	Plagio-clase	Biotite	Muscovite	Total accessories	Number of counts
$5M_7Gr$	52.86	34.60	5.17	8.05	2.02	0.37	3269
$3H_6Gr$	43.33	25.82	19.06	5.01	5.59	1.17	3254
$3D_{14}Gr$	48.2	33.3	9.4	1.5	6.80	0.8	2660
$5K_{10}Gr$	43.02	25.67	18.08	4.87	1.34	0.35	6484
$2L_{11}Gr$	59.5	20.62	5.60	10.1	33.65	0.56	2303
$2H_9Gr$	61.24	16.8	6.22	9.96	4.79	1.00	2108
$3F_{14}Gr$	44.72	25.67	17.6	5.03	5.69	1.31	3359
$1H_{15}Gr$	46.71	27.23	12.6	7.86	4.89	0.71	3256
$6F_4Gr$	45.20	21.36	16.71	9.90	5.79	1.04	2891
Mean	49.42	27.9	12.293	6.92	4.506	0.812	3542.8

The main differences between the mineralogic make-up of the Knox Mountain and Barre granite is quite apparent from a comparison of Tables 7 and 9. The chief characteristics of the Knox Mountain granite as contrasted with the Barre granite are:

1. its greater quartz content,
2. significantly higher amounts of potash feldspar,
3. decidedly lesser amounts of plagioclase,
4. lower total mica content.

The quartz content of the Knox Mountain granite is very high, and though this is quite apparent in a hand specimen it could not have been foretold from hand specimens that the mean quartz content of the Knox Mountain granite is about twice that of the Barre granite. In every thin section studied the quartz content is over 40 percent and in one specimen collected from a granite dike on the top of Colby Hill, the quartz content reaches an anomalously high value of over 60 percent. The same specimen shows the lowest amount of total feldspar. The rock is clearly a variant in composition from the usual Knox Mountain granite and perhaps belongs to a much later stage in the crystallization of the magma.

The rocks of the Knox Mountain granite are decidedly richer in potash feldspar and poorer in plagioclase than the Barre granite. Table 9 shows that the mean potash feldspar of the Knox Mountain granite is about 30 percent higher than that of the Barre granite, while the mean of the plagioclase in the Knox Mountain granite is about one-third the value of the plagioclase in the Barre granite.

Qualitative spectrographic analysis of the granites

When it became certain that the modal analyses of the Barre and Knox Mountain granites differed significantly, it was thought that a spectrographic analysis for trace elements might disclose more subtle differences in the two rocks. As an initial step, a total of 30 specimens, 20 from the Barre granite and 10 from the Knox Mountain granite were analyzed, using the "total energy" method without internal standards, and arcing the sample (5 mg.) to completion. The main idea behind this pilot project was to see if any differences in trace element chemistry in the two granites could be detected; if so, then the number of samples for analysis could be increased and the trace elements determined quantitatively. The results of the initial investigation, however, failed to show any distinctive differences in the trace elements of the two granites. All the samples were low in Cu, Cr, Pb and Ni; Sr was low in the Barre granite specimens and was present in small quantities in some, but negligible in other specimens of the Knox Mountain granite. Ba was almost uniformly present in all of the granites studied.

The Sr content of the granitic rocks is known to be directly related to calcium content (Goldschmidt, 1954 Ed., p. 244–245; Turekian and Kulp, 1956, p. 276–284). The main host mineral for strontium in the Barre granite then is the plagioclase, which is a major constituent of the Barre granite. Some strontium, of course, is contributed by the potash feldspar.

The lower strontium content of the Knox Mountain granite may be ascribed mainly to the significantly lesser amount of plagioclase present, only about one third that in the Barre granite. Also, it is known that the strontium content is higher in early formed potash feldspar crystals and lower in late crystals. Perhaps the potash feldspar of the Knox Mountain granite belongs to a later stage in the crystallization of the magma than that of the Barre granite.

Relations of the granite with the host rocks

The presence of a great thickness of glacial and alluvial debris along the contacts of the Knox Mountain granite makes it difficult to decipher the exact structural relations of this body of granite to the country rocks. In fact, even the true map extent of the granite outcrop is difficult to determine. Under this heading, therefore, the structural relations discussed pertain mostly to the Barre granite body, unless otherwise mentioned.

On a small scale map of the quadrangle, the first noticeable feature is the general concordance of the Barre granite. The outcrop is elongated parallel to the regional trend of the country rocks, and the contacts follow broadly the regional trend of the rocks.

The contacts of the Barre granite with the country rocks are extremely sharp. Closer examination of the contacts reveals its discordant nature (Pls. 17, 18). The granite cuts sharply across the schistosity of the rocks of the Westmore formation in many places. Knife-edge contacts prevail both at the margins of the granite body and at the contacts with the xenoliths within the body of the granite (Pls. 19, 20). Evidence of assimilation or a zone of reaction is conspicuously absent, except around some very small xenoliths. Only two even moderately extensive zones of replacement are found, one at the border of a large block of country rock deep in the granite in the Rock of Ages quarry (Pl. 21), and the other at the western contact of the granite body (Pl. 22). Even in these cases, the zone of reaction or replacement only locally exceeds a few inches in width. At places, the schistosity of the country rocks is contorted, indicating the application of some pressure at the time of emplacement of the magma.

The contacts between the country rock and the granite dip steeply west or are almost vertical on both the western and eastern margins.

The host rocks at the contacts seem very little disturbed. No faults, fractures or other indications of extreme disturbance are seen along the contacts. Balk (1937, p. 126–129) points out that such disturbance of the

Plate 17. Barre granite cutting across the schist foliae of the Westmore formation. Knife edge contacts prevail for the most part. Outcrop in an abandoned quarry half a mile southwest of Quarry School.

Plate 18. Contact of a dike of Barre granite with schist of the Westmore fm. Sharp contacts are the general rule. Outcrop in an abandoned quarry half a mile southwest of Quarry School.

Plate 19. Inclusions of large blocks of schist of the Westmore fm. in the Barre granite, at a depth of about 150–175 ft. from the present surface. Rock of Ages quarry.

Plate 20. Large inclusion of schist of the Westmore fm. in the Barre granite, approximately at a depth of 150 ft. from the surface. Rock of Ages quarry.

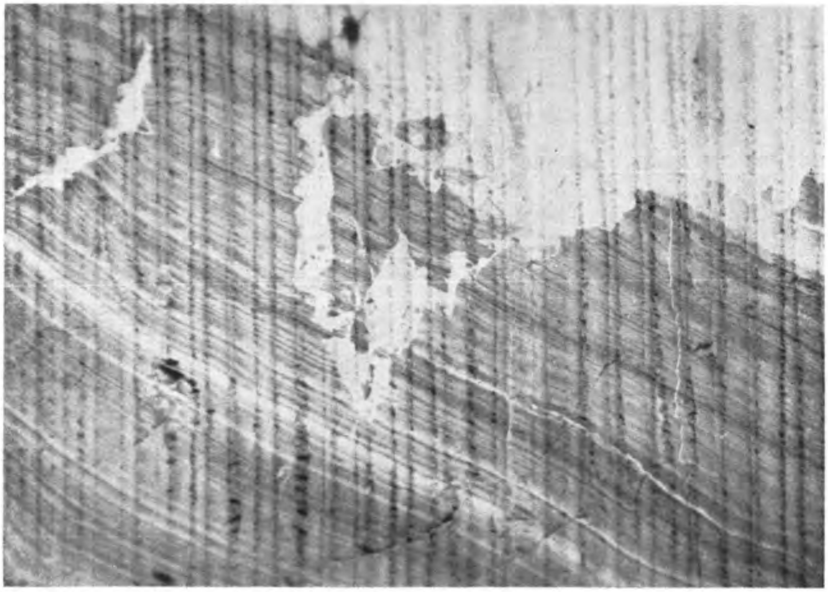


Plate 21. Replacement of the country rock xenolith by granite. A faint banding parallel to that of the xenolith is seen in the granite, in the upper right part of the photograph. Rock of Ages quarry.

Plate 22. Contact of a dike of Barre granite with schist of the Westmore formation. Note partial absorption and reaction of schist with the granite, near the hammer head. Outcrop in an abandoned quarry half a mile southwest of Quarry School.

country rocks may not necessarily be confined to the immediate vicinity of the contacts, but may occur farther out. A search for disturbance of such has been fruitless in the area. With the prevailing steep contacts, one would normally expect to find marginal fissures and upthrusts, but none were found.

Internal structural features of the Barre granite

Much information exists in the literature on the internal structural features of this granite body (Dale, 1923, p. 125–143; Balk, 1937, p. 13, 28, 73–76 and 106; Jahns, 1956, unpublished work, personal communication). My own work has not been in sufficient detail to modify or substantiate earlier data, so a brief resume of the main features is given here for completeness.

Flow Structures

Linear parallelism of both feldspar and quartz grains in the Barre granite has been reported (Balk, 1937, p. 13). The lineation thus produced trends approximately north-south, and is in general parallel to the regional trend of the country rocks. These flow lines form several arch-like structures as indicated by their plunges. In each such arch, the plunge of these flow lines is gently to the north in the northern portion, roughly horizontal in the central part, and to the south in the southern portion.

Jahns (1956, personal communication) reports the presence of flow lines around the xenoliths in the Rock of Ages quarry. According to him, these flow lines indicate a downward movement of blocks broken loose from the roof. It may be mentioned that these flow structures in the Barre granite can be detected only by very careful search and are not very clearly visible on the surface.

The presence of flow-line arches in the Barre granite was interpreted by Balk (1937, p. 122–123) to indicate an upward surge of the magma. This is discussed below in connection with the mode of emplacement of the granite.

Joints

Several systems of joints are found in the Barre granite. Their orientation is clearly related to the trends of the flow lines, the regional trend of the country rocks, and the long axis of the granite body.

Plate 23. Major joints in the Barre granite—strike N50–70°E, dip 55–80° SE. View on a south-facing wall of the Rock of Ages quarry.

Longitudinal Joints

The most conspicuous joints in the Barre granite belong to a longitudinal set that trends approximately north 20 degrees east, parallel to the regional trend. Dips of the individual joints range from 45 to 80 degrees to the west, once again in conformity with the dip of the country rocks (Pl. 23 and Frontispiece). The joints are also parallel to the rift direction and to the trend of the flow lines. Spacing between the joints is not uniform, and ranges from a couple of inches to several feet. The surfaces of joints are mostly coated with secondary minerals, such as chlorite, and sericite, and are stained with limonite.

Cross Joints

By definition, these are the joints oriented normal to the flow lines, or other types of lineation, in plutonic bodies. The system of cross-joints is not particularly well developed in the Barre granite body. At places, however, as in the Wells-Lamson quarry on Millstone Hill, they are well shown. They strike approximately east-west and dip steeply either north or south. Their surfaces, like the surfaces of the longitudinal joints, are covered with hydrothermal minerals.

Flat-lying Joints

More or less horizontal or very gently dome-shaped joints are present in the quarries on top of Millstone Hill. These, together with the longitudinal and cross joints, control the maximum size of the blocks that can be quarried. These joints may not be primary, however. The spacing between them increases with depth, and the surfaces of most are not coated with secondary minerals, like those of the other types of joints. Hence, they may actually be secondary exfoliation surfaces.

In the Knox Mountain granite two sets of joints are well shown. The more prevalent set strikes N 20°–40° E; the other strikes E–W. Dips of both are very steep to vertical. At places, the NE-striking joints contain thin pegmatite veins, but more commonly the surfaces of joints in both sets are coated with such secondary alteration minerals as chlorite and iron hydroxides.

Origin of the Barre granite

Any geologic work on granites customarily ends in a discussion of the origin of the granite. Conformity to this convention has resulted in much abstruse and philosophic writing, and only a few works provide a clear cut discussion of the field evidence and its implications for the origin of a particular granite. Hence, it is with some misgivings that a discussion of the origin of the granites of the East Barre quadrangle is attempted here, although care is taken to be very conservative in the interpretation of the evidence.

The problem of the origin of the granite, as discussed herein, really includes a consideration of two individual but connected questions: first, whether or not the body of the rock as seen now was ever a magma; and, second, if it were a magma at any time in its history, how it was emplaced. Needless to say, the answer to one question immediately raises the other; that is, if it can be proved that a magma once existed, one is immediately confronted with the problem of explaining its mode of emplacement. If, on the other hand, the problem of emplacement is unanswerable, then doubts may have to be entertained that a magma existed at any time in the history of the granite.

Two types of evidence are available for the evaluation of the questions on hand, one petrologic and the other structural. They are taken up in that order.

Petrologic Evidence

The remarkable homogeneity in composition and especially the very small variations in the quartz and feldspar content of the Barre granite has been interpreted by Chayes (1952, p. 239–244) as indicating a magmatic parentage for the granite. Quantitative estimates show how large, not to say unreasonable, would be the transfers involved in converting the country rocks by any process of granitization. The petrologic heterogeneity of the country rocks is great, and even very thin individual beds differ greatly in composition, as can be well seen in the photographs of the inclusions in the Rock of Ages quarry (Pls. 24–27). That some process could work on such heterogeneous material and produce a rock of so uniform a composition as the Barre granite over areas as large as a single quarry or as small as a thin section is incredible indeed.

More positive evidence already briefly mentioned is supplied by the quantitative relations of the major constituents of the granite, quartz, potash feldspar, and plagioclase. The quantities of these minerals, when plotted in a ternary quartz-orthoclase-plagioclase diagram (Fig. 8), fall in an area corresponding to the thermal valley of the system nepheline-kaliophilite-silica (Bowen, 1937, p. 1–21).

The huge blocks of country rock deep in the body of the granite (Pls. 19, 20) pose some interesting problems. The contacts of these blocks with the granite are generally knife-edge sharp. Reaction between the granite and xenoliths is negligible. Mutual transfer of materials is insignificant and the granite shows no effect whatsoever except a chilling against the country rocks producing a finer grained variant of the granite (Fig. 9). Evidence of replacement of the xenolith is rare and minor. What sort of process granitizes sediments so heterogeneous in composition and yet stops short so abruptly at the contact of the xenoliths so deep in the body of the granite? If ichors, ions or solutions, permeate the country rock, add and remove materials to make it over to granite, what sort of physical or chemical barriers prevent them from doing the same with the inclusions?

The absence of any appreciable number of pegmatite dikes, quartz veins or aplites along the margins of the granite may be taken to indicate that there was no appreciable introduction of alkalies and alumina into the country rocks. Neither does the granite show any appreciable volume of basic variants or hybridized rocks due to reaction with the country rocks. This will mean that the granite had more or less its bulk composition before it got there—directly implying the existence of a liquid of granitic composition. Is it improper to call this a magma?

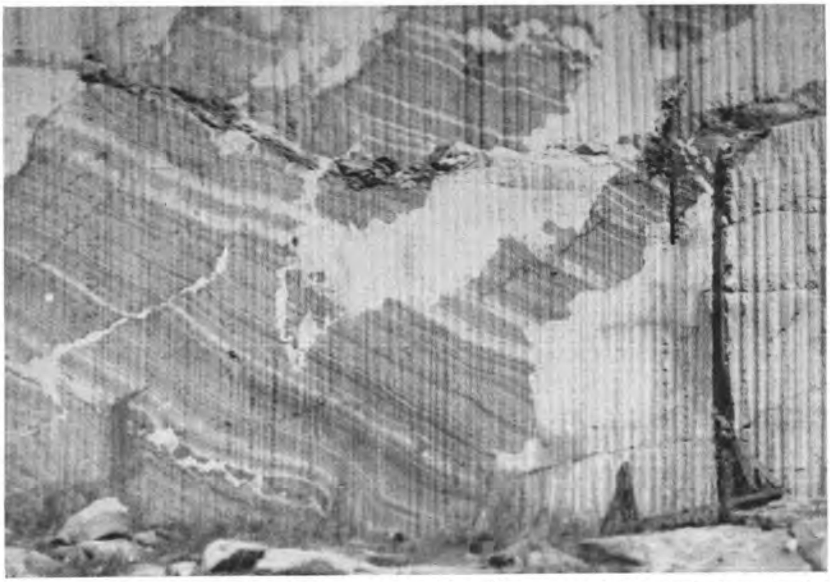


Plate 24. Close view of an inclusion of schist (Westmore formation) deep in the granite body. The banding in the schist is compositional. Vertical furrows are due to drill holes.

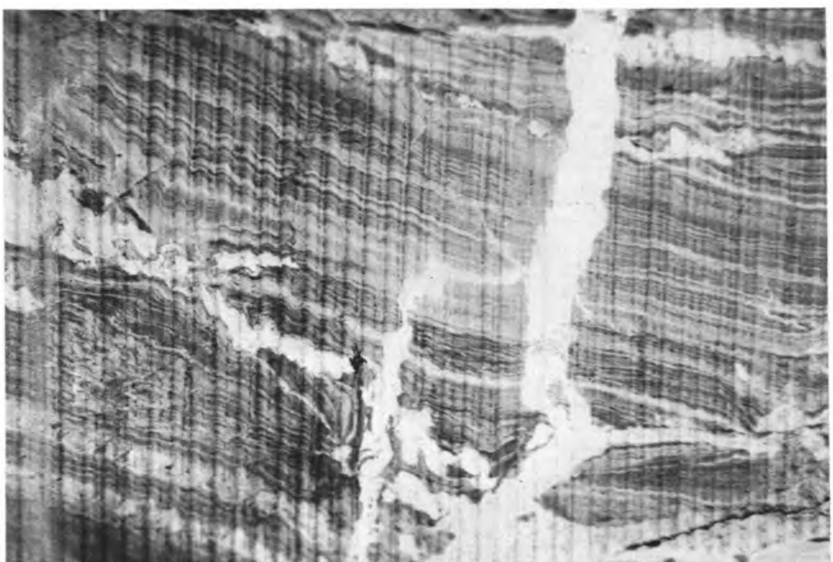


Plate 25. Close view of a xenolith in the Barre granite, Rock of Ages quarry. Granite dike cuts sharply across the foliation of the schist.

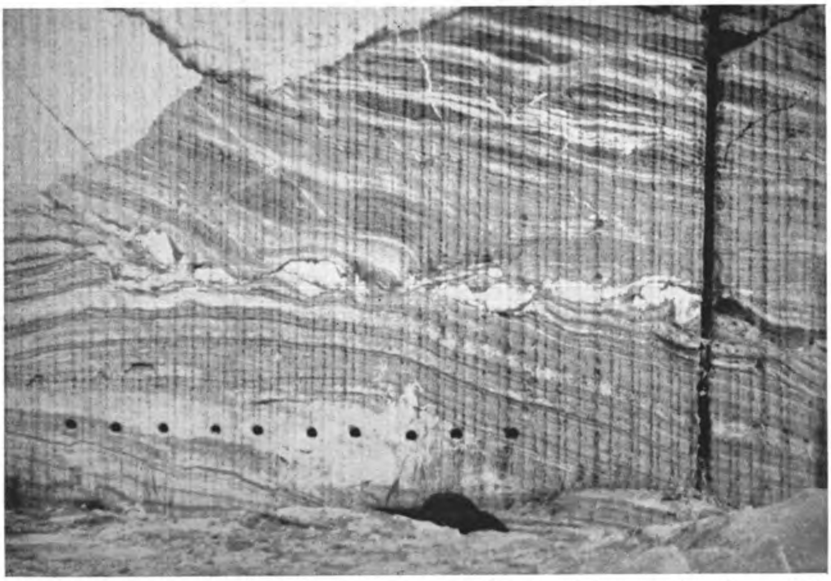


Plate 26. Sharp contact between massive granite (top left corner) and xenolith. Rock of Ages quarry.

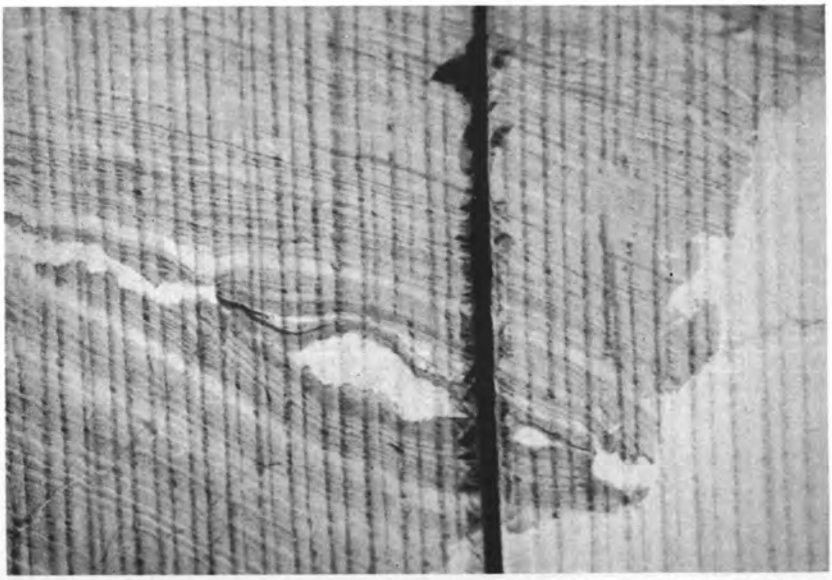


Plate 27. Granitic lens in the schist folia. Close view of a xenolith in the Barre granite, Rock of Ages quarry.

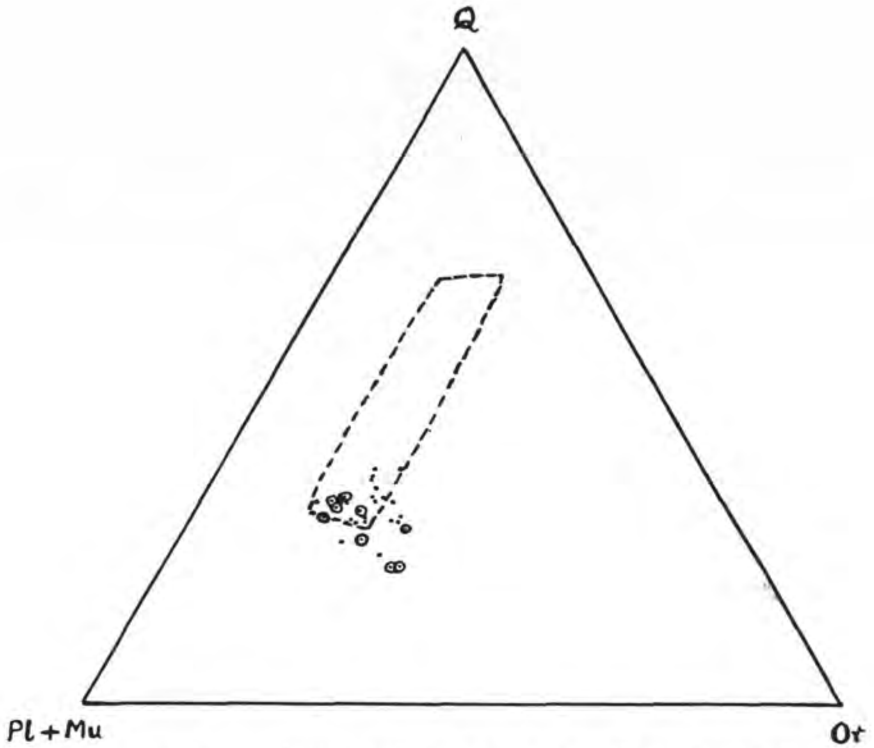


Figure 8. Quartz-Plagioclase-Orthoclase diagram for the Barre granite. Dotted line shows the area corresponding to the 'thermal valley' of Bowen (1937).

⊙ Modal analysis by the present writer.

• Modal analysis by Chayes (1950).

Structural Evidence

Structural evidence of several sorts is available to prove the existence of a dominantly liquid phase of the granite at one time in the history of the rock. Since such evidence has been discussed in detail elsewhere in this chapter, only a brief summary is given here. The evidence includes the presence of flow lines, fractures that can be related to the mechanics of emplacement of a magma, rotation of huge xenoliths of the country rock that are suspended in the body of the granite, cross-cutting granitic dikes and chilled margins of the granite around some xenoliths. All this shows that the Barre granite is magmatic in origin.

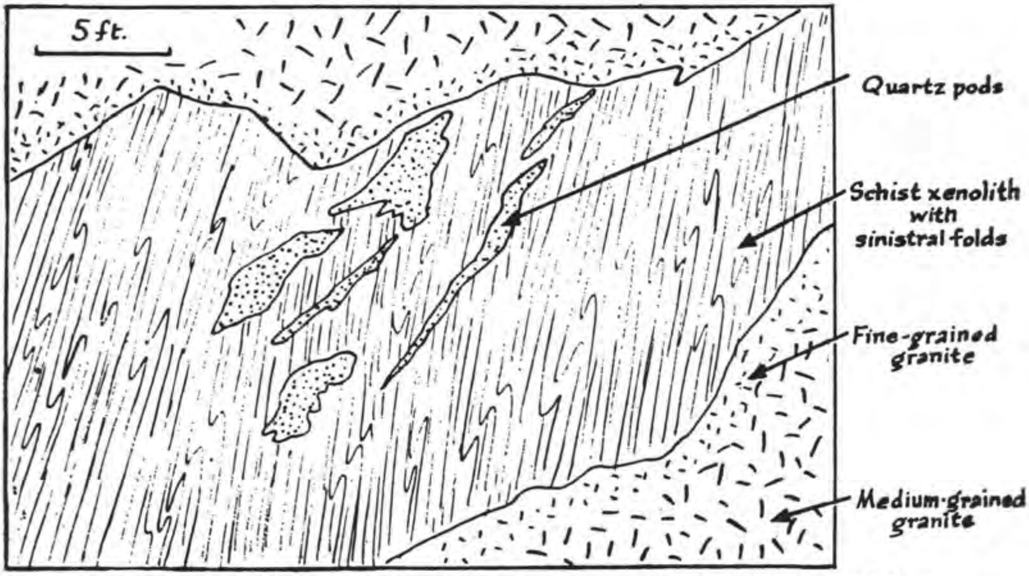


Figure 9. Chilled fine-grained granite at the contact with xenolith in Rock of Ages quarry.

Mode of emplacement

The establishment of the magmatic origin of the Barre granite leads us directly to the next question. The Barre granite in the East Barre quadrangle occupies a volume of several cubic miles. If the granite is not a result of the in situ conversion of the country rocks, then the question of space for the emplacement of the magma enters. The fact that the Barre granite is concordant on a regional scale but discordant on a closer examination of the contact relations is very significant. If it were an altogether concordant body, there would be no drastic room problem, for by definition, room has to be provided for concordant bodies by flexing or bulging aside of the country rocks. If, on the other hand, it were altogether discordant, then, the alternatives for the mode of emplacement are limited to two, namely, magmatic stoping or forcible injection. Actually these two modes of emplacement are not mutually exclusive but may be complementary. Forcible intrusion can pave the way for the upward rise of the granite magma, and the problem of space can be effectively solved by the stoping process. To determine which process was more effective quantitatively, one must turn to the critical field evidence.

1. The presence of large blocks of country rock some tens of feet in dimensions (Pls. 19, 20) at depths of 100 to 200 feet in the body of the granite has been mentioned earlier. These blocks are tilted and rotated and in their orientation do not parallel the country rock. They may be interpreted either as stoped blocks or as blocks broken away from the roof as mechanical intrusion took place. The general absence of evidence of a highly disturbing mechanical intrusion, such as marginal faults, fracture zones etc.; and the general concordant nature of the body, however, indicate that the intrusion was submissive and hence the blocks are more likely due to stoping.

2. Balk (1937, p. 73–76) has described the presence of several flow-line arches in the granite. These are generally discernible, but his conclusion that each arch is independent and belongs to a separate granite body is questionable. My mapping in the area and that of Jahns (1956, personal communication) indicate that the body is one elongate mass interspersed with some schist septa. One such major septum traverses the granite body roughly along the middle with a north-south trend (Pl. 1). Several minor septa are undoubtedly present in the eastern and southeastern portion of the granite body. None of these septa show any notable disturbance, once again indicating that the magma was injected somewhat submissively and took advantage of existing weaknesses in the rocks rather than tearing them apart or drastically disturbing them.

The arches indicated by the linear parallelism of minerals and their orientation are no doubt due to flow of the magma before its solidification. The formation of the arches would certainly be controlled by the original roof configuration of the granite, which undoubtedly was not a plane. Thus, Balk's refutation of the idea of magmatic stoping, with the contention that these individual arches represent individual loci of magmatic injection seems to lose its validity. In any case, the presence of arched flow lines is not strong enough evidence to refute the hypothesis of stoping. All that their presence establishes is the once molten nature of the granite body.

Detailed field work by Jahns (1956, personal communication) in the granite area indicates that about one fifth of the space now occupied by the igneous rocks is provided by lateral spreading of the country rocks. This shows that the magma has not forcibly punched its way up, but that it took advantage of the weakness in the direction of the regional trend, and to some extent wedged its way up by pushing the country rocks aside.

The flow lines around the xenoliths in the Barre granite in the Rock of Ages quarry indicate a rotational and downward movement of the blocks after their dislodgment from the roof (Jahns, 1956, personal communication). This clearly calls for a stoping mechanism, and Balk's objection (1937, p. 125) that some of these xenoliths may have been passively carried by the magma and hence that there is no necessity to invoke a stoping mechanism, is not valid.

The Knox Mountain granite, especially its contact with the country rocks, is not well enough exposed to provide critical information as to its origin.

Age of the Barre granite

The age of the Barre granite was fixed as Devonian by the early workers in the area. Thus, Richardson (1908) assigned a Devonian age to it, and Foyles and Richardson (1929) in their correlation chart of the rocks of Vermont included the Barre granite in the Devonian. The main reason for this age assignment was that the Barre granite intrudes the old Waits River formation which was considered to be Ordovician.

In the present report, the old Waits River formation is subdivided and the newly restricted Waits River formation (as of this report) is assigned a Lower Devonian age. In view of this change in age assignment of the sedimentary rocks, it was felt that an absolute age determination of the Barre granite would throw some light on the problem.

An attempt to separate zircon from the granite and to determine the age using the zircon sample had to be given up because so little zircon is present in the Barre granite. Consequently, the Rb/Sr method using the biotite in the granite had to be employed.

A pure sample of biotite was separated from the granite powder by a mechanical process using heavy liquids, in a device built along the lines described by Fairbairn (1955, p. 458–468). The sample obtained in this device was further concentrated by a Franz isodynamic separator and finally by hand picking under a binocular microscope.

The Rb/Sr age was determined at the Geochemistry Laboratory of the Massachusetts Institute of Technology by Cormier. The result gives the age as 330 ± 25 million years (Pinson, 1956, personal verbal communication). Offhand this suggests a Silurian age for the granite, but it is only slightly higher for Middle Devonian.

Dike Rocks

Granitic Dikes

Apart from the major plutonic bodies, many dikes of granite, pegmatite and vein-quartz are present in several parts of the quadrangle. Pegmatite dikes and quartz veins occur in groups of all sizes and diverse orientation so that it is not possible to map individual dikes or the boundaries of the areas containing many dikes on the scale of the map used in this report. Hence, areas with many granitic dikes are shown by an overlay (Pl. 1).

Many of these dike swarms have no apparent relation to exposed parts of the granite plutons, and their distribution is irregular with respect to that of the plutons. They may, of course, be related to granitic bodies that are not yet exposed. This may be true especially of the many pegmatite and granite dikes in the southern part of the quadrangle. Gravity anomalies determined by Bean (1953, p. 528–533) indicate the probable existence of a granite mass at depth in that area, hence the granitic activity represented by these dikes may be a surface manifestation of the subjacent body.

In addition to these irregular dike swarms unrelated to the plutons, there are many pegmatite dikes seemingly related to the Knox Mountain granite, either irregularly cutting the country rocks immediately around the granite, or showing definite structural trends within the granite itself. By their very nature of occurrence, these pegmatites seem genetically connected to the granite pluton.

Structural Trends

The pegmatite swarms unrelated to the granite bodies do not show any regular trends; but those that cut the granite show systematic orientation, mainly because they are to some extent controlled by the planes of structural weakness in the granite, such as joints. For example, the pegmatites cutting the granite in the western part of the Knox Mountains follow two sets of steep joints trending N 30°– 50°E, and E–W. The pegmatites occurring in the E–W joint set are later than those in the other set, as they offset and cut across them. Similarly, the granite in the flat area west of Colby Hill shows two sets of joints trending N 40°–50°E and E–W, and a number of pegmatites are located in the northeast system of joints. Joints in the granite of Spruce Mountain trend N 40°– 60°E and the pegmatites have a trend of N 35°–50°E. Both the joints and the pegmatites are steeply dipping or vertical. It is evident from the above examples that the trend of pegmatites cutting the granite is closely controlled by the orientation of the joints in the granite.

Mineralogy of the Pegmatites

The pegmatites connected with the Barre granite are 'simple' pegmatites. In almost all cases, they consist of quartz and feldspar with minor amounts of biotite and muscovite. Both plagioclase and potash feldspar are present. Biotite occurs as small booklets about ½ to 1 inch across. Muscovite is present in flakes of small size closely associated with the feldspars, particularly the plagioclase.

The pegmatites associated with the Knox Mountain granite are a little more complex in their mineralogy. They contain pink, semi-transparent garnets, black, prismatic tourmaline, and muscovite in addition to the usual quartz and feldspars. Biotite is much less common than in the pegmatites associated with the Barre granite.

Basic Dikes

Basic dikes are far less common in the East Barre quadrangle than granitic dikes. Dale (1923, p. 128) reports the occurrence of basic dikes in seven of the granite quarries on Millstone Hill, but I could not locate all of them—presumably they have been quarried away since he mapped the area.

A basic dike is very conspicuously exposed cutting the Barre granite in the northeastern part of the Rock of Ages quarry. The dike, about 5 feet wide, is located in one of the major longitudinal joints, trending N45°E, and dipping 75°SE. The dike shows chilled edges about half an inch wide at both the contacts, and close to the contact the granite is jointed parallel to the walls of the dike.

Mineralogy

The dike rock is dark brownish black, fine grained and compact. Microscopic examination reveals that it is composed of plagioclase (oligoclase-andesine), augite, dark green hornblende, biotite, and magnetite. A faint semblance of poikilitic structure is shown at places between the plagioclase and the dark minerals. Many of the grains are remarkably idiomorphic in their crystal outlines. Secondary minerals are quite abundant; sphene, epidote and chlorite formed by the alteration of the pyroxene and the amphibole. The rock is a lamprophyre of kersantite-spessartite composition.

METAMORPHISM

General Statement

The sedimentary and volcanic rocks of the East Barre quadrangle show the imprint of regional metamorphism of medium to high grade. Mineral assemblages characteristic of thermal metamorphism occur locally at the contacts of the plutonic bodies, but on the whole, thermal metamorphism is quite subordinate to regional metamorphism. Consequently, the regional metamorphism, the mineral assemblages produced by such metamorphism, and the relation of structural deformation to metamorphism, form one of the main objects of this study.

Paucity of outcrops in critical areas, and the irregular distribution of granitic and quartz dikes which cause high grades of metamorphism locally, make it impossible to define distinct zones of metamorphism by using index minerals and isograds. the rocks vary in composition greatly even in one formation, and no constant index minerals are formed. Despite the lack of index minerals, it may be generalized that the metamorphism is most intense in the central portion and falls away from the central area, with one exception: the grade of metamorphism in the south-central part of the quadrangle is high, even though no major plutonic bodies are exposed in the area. In several localities in that area, numerous granitic dikes and pegmatite veins cut across the rocks of the Waits River formation, and these by themselves may be responsible for the high grade of metamorphism, or they may indicate the close proximity of a subjacent pluton that is responsible for the metamorphism.

The facies classification of metamorphic rocks (Eskola, 1915; 1920) rather than the zone classification (Barrow, 1893; 1912) is followed in this report. Needless to say, the two concepts are not mutually exclusive; they emphasize different points, however. In the zone classification, the chemical composition of the rocks is considered invariant, and the mineral assemblages are classified according to the P-T conditions under which they were formed. In the facies classification, however, the variable chemical composition of the rocks is taken into consideration, and several assemblages are recognized under identical P-T conditions. It can be seen, therefore, that an interfacies boundary is the same as a zonal boundary, as both of them are formulated on P-T conditions. The lithologic types in any one of the formations in the East

Barre quadrangle are intimately interbedded, and hence the facies classification is more suitable.

From the standpoint of metamorphic geology, the rocks of the East Barre quadrangle may be divided into three types: (1) The calcareous rocks of the Barton River and Waits River formations, (2) the argillaceous rocks of the Westmore and Gile Mountain formations, and (3) the basic volcanic rocks of the Standing Pond member of the Waits River formation. Each of these types is taken up individually below, and the effect of metamorphism in various facies and the mineral assemblages produced are considered.

Argillaceous Rocks

The argillaceous and arenaceous rocks in the quadrangle are metamorphosed from the green schist to the amphibolite facies as the result of regional metamorphism. Several sub-facies and mineral assemblages reflect the original differences in lithology. Some special assemblages are produced at the contacts with the granite plutons which are described below under the heading contact metamorphism.

Green Schist Facies

Mineralogic assemblages belonging to the biotite-chlorite sub-facies of the green schist facies are represented in a limited area in the northwestern corner of the map area. These apparently represent the lowest grade of metamorphism exposed in the area. The rocks include sericitic and chloritic schists of the Westmore formation in which porphyroblasts of biotite have just started to form.

Bedding in the rocks is still well preserved, and in some outcrops the orientation of micaceous minerals produces a schistosity subparallel to the bedding.

The most characteristic minerals of these rocks are biotite, chlorite, muscovite, and quartz. There are minor amounts of calcite, clinozoisite, magnetite and, at places, a garnet of spessartite-almandine composition. Quartz along with muscovite and chlorite forms a fine-grained groundmass in which porphyroblasts of biotite occur. These grains of biotite have just started to form at the expense of the chlorite and muscovite (sericite). From the beginning the biotite has a tendency to form porphyroblasts, and is seldom seen in the ground mass. In some specimens, many of the porphyroblasts of biotite show a nucleus of magnetite and the biotite is darker in color close to the magnetite.

Garnet with some spessartite content is present at places even in rocks of the lowest grade of metamorphism. It also has a tendency to grow in euhedral porphyroblasts. The porphyroblasts contain inclusions of chlorite and quartz in continuous orientation with the chlorite and quartz of the ground-mass. This indicates that the chlorite in the garnet is not an alteration product, but the original material from which the garnet has been formed.

Albite-epidote-amphibolite facies

Rocks belonging to the albite-epidote-amphibolite facies are by far the most prevalent in the western half of the quadrangle. The mineral assemblage muscovite-biotite-almandine-quartz is particularly well represented by the rocks of the Westmore formation and the quartz-mica schists in the western half of the Waits River formation. The rocks are mostly quartz-biotite schists with appreciable amounts of muscovite, plagioclase, and garnet of almandine composition.

Biotite is mostly porphyroblastic, but as the grade of metamorphism increases, the rocks show biotite distributed in well formed flakes throughout the rock. It shows clear evidence of having been reconstituted at the expense of chlorite, and the amount of biotite bears an inverse relation to the original chlorite. Some chlorite in the rocks is secondary, having been produced as an alteration product, but this should not be taken into account in considering the inverse relation between the modes of the biotite and chlorite. The biotite in these rocks is somewhat darker in color than that of the rocks in the green schist facies. Kruger (1946, p. 199) found that in the metamorphic rocks of the Bellows Falls quadrangle, N.H.-Vt., the refractive indices of biotites do not vary significantly from the middle- to high-grade rocks. Similarly, Lyons (1955, p. 142) found that the refractive indices of biotite showed no evident relation either to the petrographic nature of the rock in which they occur or to the intensity of metamorphism. This may be true of the biotites in the middle and high grades of metamorphism, but in the passage from low to medium grade the biotite does seem to increase in refractive indices and darken in color. No specific determinations of refractive indices, however, were made in the present study, and the above statement can be considered only qualitative.

Muscovite occurs in these rocks as well formed grains somewhat evenly distributed in the quartz that makes up the general matrix of the rock.

Garnet is abundantly present and widely distributed in rocks of this facies. Many porphyroblasts are perfectly euhedral; many show inclusions of quartz, chlorite, and opaque iron oxides. The inclusions are either randomly oriented or aligned conformable to the general direction of the schistosity in the rocks. Where the inclusions are random, the garnet shows a well developed poikiloblastic structure. Many of the grains of garnet and some porphyroblasts of biotite show pressure shadows on two sides; these shadow areas are occupied by recrystallized quartz.

Amphibolite Facies

Rocks of this facies represent the highest intensity of metamorphism attained by the argillaceous units in the quadrangle. The argillaceous beds of the Waits River formation in the south-central parts of the quadrangle, and locally the rocks of the Westmore formation, show this facies of metamorphism.

Two types of assemblages are represented, depending on the original composition of the sediments. If in the original sediments chlorite was considerably in excess of sericite, the mineralogical assemblage includes muscovite, biotite, plagioclase and almandine; if, on the other hand, sericitic material exceeded in amount the ferro-magnesian impurities, the typical assemblage represented is muscovite, biotite, plagioclase, and microcline. Quartz is present in all the rocks. Except for the presence of almandine garnet in one assemblage and of small amounts of microcline in the other, the two assemblages give rise to the familiar quartz-mica schists. The general absence of the aluminous minerals kyanite and staurolite in these rocks, although they are stable in this facies, can be attributed to original compositional deficiencies. The feldspars occur in small amounts in these rocks.

Calcareous and Impure Calcareous Rocks

The rocks of the Barton River and the Waits River formations are mostly calcareous mica schists and limestones. The intercalation of calcareous material is irregular and the rocks, apart from the distinct beds of phyllites and schists, can be considered *in toto* as impure calcareous rocks.

Green Schist Facies

Calcareous rocks belonging to the green schist facies are very rare; only the rocks of part of the Barton River formation in the northwestern corner of the quadrangle fall in this category. The biotite-chlorite sub-facies is represented. Recrystallized calcite is the most common mineral and occurs in irregularly segregated patches and lenticles. In rocks originally rich in lime, calcite occurs evenly distributed throughout the rock. Chlorite and biotite are almost always present. In the lower grade rocks, chlorite is more abundant than biotite; in such cases, muscovite is present to some extent. The muscovite is fairly well reconstituted from the original sericitic material. As the intensity of metamorphism increases, the amount of biotite increases and the amount of chlorite dwindles, showing that the biotite is formed by the reaction of chlorite and muscovite. Some epidote is formed as a by-product of this reaction. (Harker, 1950 ed., p. 53, 215–216) stressed the importance of the original ratio of chlorite to sericite or muscovite in affecting the trend of metamorphism. In calcareous mica-schists like these, in which both biotite and muscovite are present, the original chlorite was subordinate to sericitic material, and the muscovite now present is the excess sericite left over after the formation of biotite used up all the chlorite. Similarly, actinolite is generally absent in these rocks in the low grade of metamorphism, because actinolite is formed only by the reaction of excess chlorite with quartz and calcite.

Albite-epidote-amphibolite Facies

The calcareous rocks of the Waits River formation in much of the southern half of the quadrangle belong to this facies, and to its chloritoid-almandine subfacies. The typical mineral assemblage contains calcite, epidote, and actinolite. In addition, minor amounts of plagioclase, biotite and retrograde chlorite are commonly present. As in the greenschist facies, calcite occurs in irregular, recrystallized grains and provides the ground mass in which clusters of epidote are present. Epidote formed by the reaction of original chlorite and sericitic material to yield biotite. Alumina liberated in the reaction reacted with the calcite of the rock to give rise to zoisite or epidote. Minor amounts of sphene and magnetite are present as accessories.

The presence of biotite, chlorite, and actinolite, and the deformation of the calcite imparts a definite foliation to these rocks; and many of them show tiny crinkles and folds like those so characteristic of the argillaceous rocks in the same area.

Amphibolite Facies

The highest intensity of regional metamorphism of the calcareous rocks belonging to the Waits River formation is shown by mineral assemblages corresponding to the staurolite-kyanite sub-facies of the argillaceous rocks. The rocks of this facies are not as widespread as those of the albite-epidote-amphibolite facies, but are developed near the central parts of the cleavage dome, and locally wherever the deformation was most intense.

Diopside, epidote, calcite, oligoclase, and biotite are the common minerals in the rocks of this facies. Sphene is present in considerable amounts as an important accessory. Diopside and epidote occur as clusters and irregular aggregates in a general matrix of calcite with small amounts of biotite. The rocks show well developed schistosity and minute folds, although the grain size and the textures indicate the high grade of metamorphism attained.

Metavolcanics

Under this group are included the amphibolites and the hornblende schists of the Standing Pond member of the Waits River formation. The rocks belong to the amphibolite facies, and the plagioclase-hornblende-almandine-quartz assemblage of the staurolite-kyanite subfacies is well represented (Turner and Verhoogen, 1951, p. 452–454).

Hornblende is the most important mineral in these volcanic rocks, and occurs as long prismatic crystals, and in the so-called needle amphibolites, as fine acicular needles. There are no traces of original pyroxene from which the hornblende is derived, and the hornblende itself shows alteration to chlorite due to retrograde metamorphism. At places, the hornblende shows a sieve structure, having been replaced by clear irregular grains of oligoclase.

Associated with the hornblende in these rocks is plagioclase. The calcic plagioclase of the original rock was unstable under the P-T conditions represented by the amphibolite facies, and broke down to sodic plagioclase releasing material of anorthite composition. Some of the alumina so released reacted with the original pyroxene of the volcanics to produce hornblende. The lime and the rest of the alumina went into epidote. Thus the alteration of the original pyroxene to amphibole was not simply a paramorphic change, but involved a reaction between the original pyroxene and the plagioclase (Wiseman, 1934). Some of the lime released may also have been incorporated into sphene which is quite commonly present in the amphibolites of the Standing Pond volcanics.

The presence of large porphyroblasts of almandine garnet and the association of oligoclase and dark-green hornblende with insignificant amounts of epidote and actinolite clearly label the grade of metamorphism as the amphibolite facies.

CONTACT METAMORPHISM

The rocks of the Westmore and, to a lesser extent, the Waits River formation are involved in high-grade thermal metamorphism at the contacts of the Barre granite. The eastern contact of the granite with the Waits River formation is poorly exposed, and the contact metamorphism cannot be observed clearly. But excellent outcrops along the western margin of the Barre granite in the abandoned quarries, and the many inclusions found deep in the body of the granite in the Rock of Ages quarry (Pls. 19, 20), show the metamorphism very clearly.

The contact metamorphism at the borders of the Knox Mountain granite is difficult to study because outcrops are scarce and contacts are hidden.

It is shown below that the two periods of deformation in the area were accompanied by at least two periods of regional metamorphism. The regional metamorphism of the second period rises in grade symmetrically around the igneous bodies in the area, suggesting that it was caused by an uprise of the magma that formed the igneous rocks. Thus the contact effects of the granite bodies are, as it were, the culmination of the metamorphic activity concomitant with the intrusion and emplacement of the magma into the sediments. The sediments had already been metamorphosed to some extent by the first period of metamorphism, however, and hence the contact metamorphism may be considered as thermal metamorphism superposed on an earlier, low-grade regional metamorphism.

Amphibolite Facies

The mineral assemblages found in the contact metamorphic rocks indicate the amphibolite facies of metamorphism. The cordierite-anthophyllite subfacies is represented by the mineral assemblages muscovite-biotite-plagioclase-microcline and muscovite-biotite-cordierite-plagioclase; quartz is ubiquitous. The original potash content of the sediments controlled the assemblage formed; rocks with sufficient potash gave rise to the first-mentioned assemblage and rocks deficient in potash to the second. Judging from the regional metamorphism of the argillaceous rocks of the Westmore formation, they are typically richer in iron and magnesium than in potash, for biotite is always more important and in greater amount than muscovite. Thus the observed predominance of the muscovite-biotite-cordierite-plagioclase-quartz assemblage in the contact metamorphic rocks is what might reasonably be expected. However, cordierite occurs only in very small amounts indicating only a slight original deficiency of the potash in these rocks.

The small amount of sillimanite in the hornfelses needs special mention. Sillimanite can be produced by several reactions, but the most probable mode of formation here is by the partial breakdown of muscovite to orthoclase and sillimanite.

A remarkable feature of these thermally metamorphosed rocks is the preservation of the original foliation of the rocks. This may be interpreted as indicating that the stress was insignificant, that migration of material was of minor importance, and that there was little or no internal differential movement at the contacts of the granite; and thus that the intrusion of the granite was more or less passive—a point substantiated by several other lines of evidence.

Distribution and mode of occurrence of important minerals

Chlorite is present mostly in the groundmass of the low-grade schists of the Barton River and Westmore formations. It occurs in small clusters of flakes, the size of which increases with the intensity of metamorphism. In the higher grade rocks, the chlorite is replaced by biotite.

Chlorite produced by alteration of higher-grade metamorphic minerals is ubiquitous. Most of this may be retrograde, having been produced at a time of waning temperatures after the maximum of thermal metamorphism. Obviously, this chlorite is not in equilibrium with the mineral assemblages in which it is found. It should be understood, however, that the inclusions of chlorite that occur in porphyroblasts of biotite and garnet and are conformable to the schistosity of the rocks, are not retrograde, but were caught in the process of being reconstituted into the higher grade minerals.

Chlorite is found in many areas where slip-cleavage is prominent. It occurs as irregular flakes along the slip planes and is formed by mimetic recrystallization along them. No porphyroblastic chlorite, like that described by White and Billings (1951, p. 691) in the Woodsville quadrangle, has been found. High alumina content of the sediments is necessary for the formation of such chlorite, and it is absent in the rocks of the East Barre quadrangle probably because of their moderate to low alumina content.

Calcite is a predominant mineral in the rocks of the Barton River and

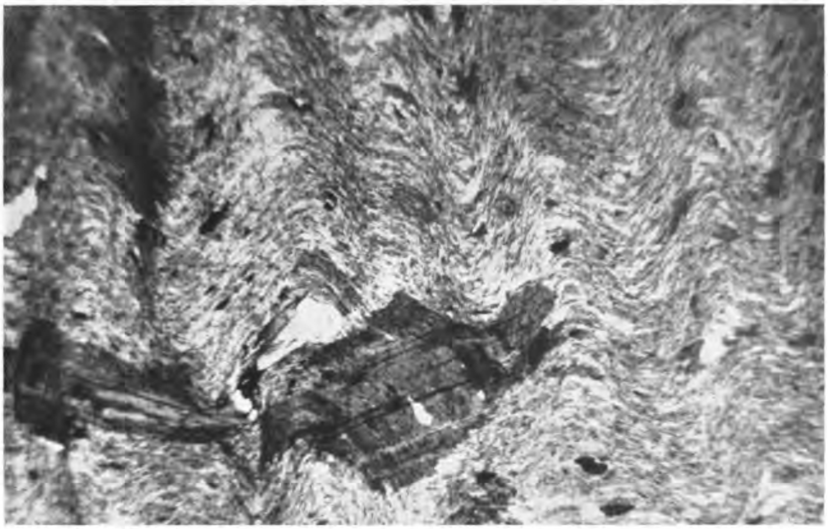


Plate 28. Porphyroblast of biotite cutting across schistosity and slip-cleavage. Specimen from outcrop 1½ miles south of Mt. Pleasant.

Plate 29. Porphyroblast of biotite formed around a nucleus of opaque iron oxides. Specimen from outcrop on south side of East Hill.

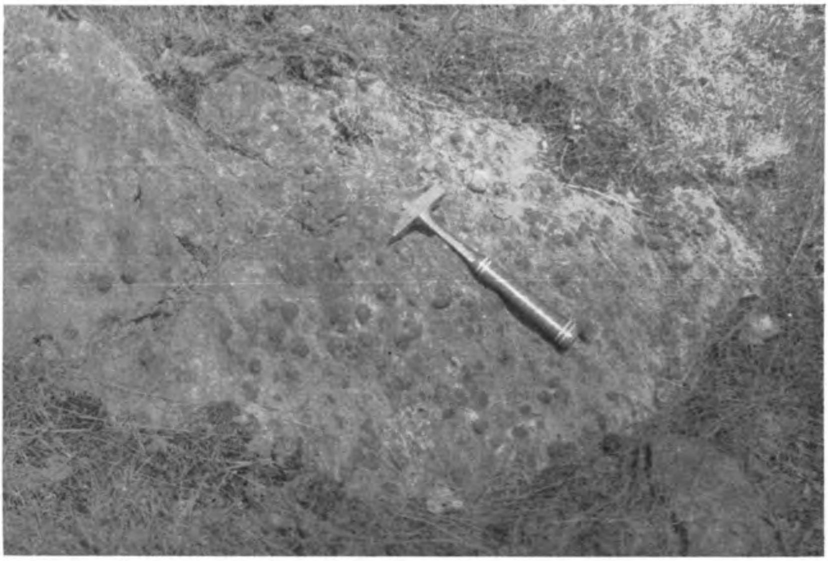


Plate 30. Large size porphyroblasts of garnet in impure calcareous rocks of the Waits River formation, 1½ miles S10°E of Pike Hill school.

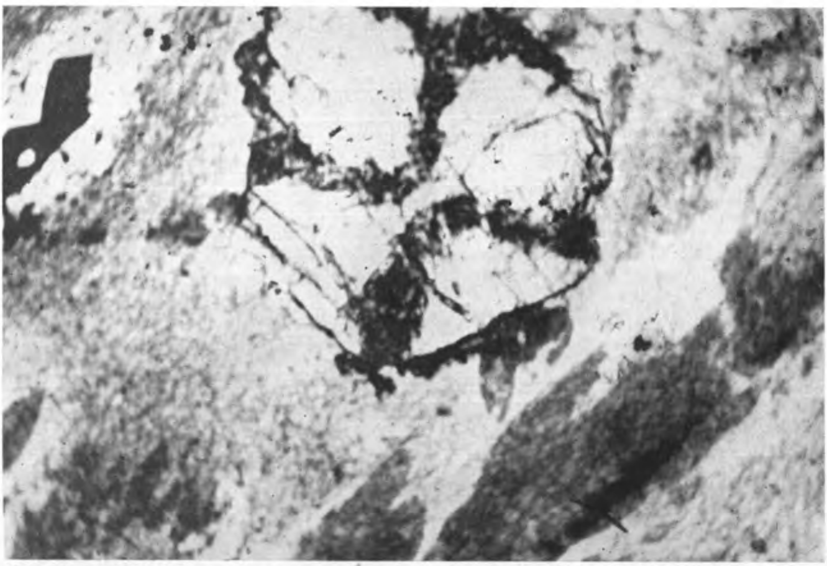


Plate 31. Cross-shaped inclusions in garnet. Specimen from the Waits River formation, 1 mile NW of Center School.

Waits River formations. It has survived through the highest intensity of metamorphism attained in the quadrangle, remaining stable even in the quartz-calcite schists. In calcareous rocks that contain enough impurities, such as chlorite, a reaction between calcite and chlorite gave rise to some actinolite or epidote and diopside. But the chlorite in such rocks was so small in amount that it was all used up in the very early stages, leaving a large excess of calcite.

Biotite is the most common micaceous mineral throughout the quadrangle. It is almost invariably present in the schists of the Westmore and the Gile Mountain formations in all metamorphic facies. It is produced by the direct reconstitution of the argillaceous material in the rocks. Biotite always has a tendency to form porphyroblasts or discrete, well-formed flakes, with a sub-parallel orientation cutting across the foliation of the schists—whence the descriptive term 'cross-biotite' (Pl. 28). The meaning of such 'cross-biotite' in the time-sequence of deformation and thermal metamorphism is discussed later in this chapter. Many of the biotite porphyroblasts have formed around a nucleus of opaque iron oxides or ilmenite (Pl. 29).

Garnet is widely distributed in the argillaceous rocks throughout the quadrangle. In a general way the garnets increase in size eastward and in the south-central part of the quadrangle, where locally they are as much as 2 to 3 inches across (Pl. 30). The garnet porphroblasts in the western half of the quadrangle grow across the schistosity of the rocks and hence are later than the deformation that produced the schistosity. Many of the garnets are zoned or show a cross-shaped distribution of inclusions (Pl. 31), an arrangement ascribed by Harker (1950 ed., p. 44) to distribution of the inclusion along the traces of the edges of a growing dodecahedral crystal of garnet.

The garnet of the amphibolites of the Standing Pond member is almandine in composition, and is associated with dark-green hornblende, plagioclase, and minor amounts of chlorite (retrograde in origin) and iron oxides. At some places the garnets cut across the foliation (Pl. 32) and at others are deformed by the schistosity (Pl. 33), showing that the time of formation of the garnets (height of metamorphic P-T conditions) considerably overlapped the structural deformation.

Actinolite in the East Barre quadrangle is confined to the albite-epidote-amphibolite facies of the calcareous rocks, and it is rarely abundant. Actinolite can be produced in many ways in regional metamorphism. In the rocks described here, it seems most likely that it is due to the reaction of chlorite and calcite. Billings (1937, p. 546) men-

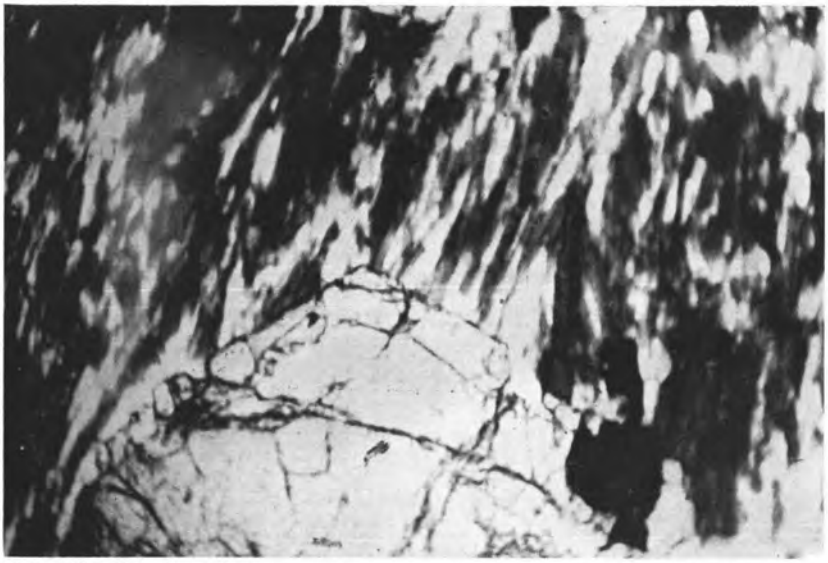


Plate 32. Porphyroblast of garnet cutting across the foliation—Standing Pond amphibolite ½ mile N of Eaton School.

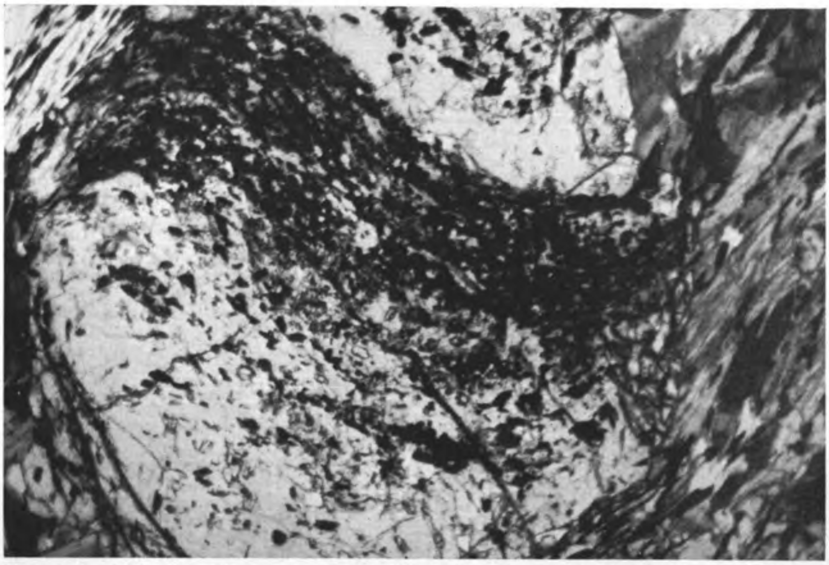


Plate 33. Rotation of garnet porphyroblast during growth shown by the S-shaped train of inclusions. Specimen from the Waits River formation 1 mile NW of Center School.

tions that a quartz-dolomite reaction may give rise to an amphibole of tremolite-actinolite composition. As the calcareous rocks of the Waits River formation are almost devoid of dolomite and contain appreciable amounts of chlorite, it is more likely that the actinolite here was produced by the chlorite-calcite reaction.

Actinolite is present in some of the specimens of amphibolite from the Standing Pond volcanics, but is in disequilibrium with the mineral assemblages in these rocks.

Hornblende of a dark green variety occurs in the meta-sedimentary amphibolites and in the Standing Pond volcanics. In the metasediments it occurs as long, acicular needles of actinolitic hornblende or in well formed blades or long prisms of common hornblende.

In metavolcanic rocks, the type of amphibole that is stable depends on the intensity of metamorphism attained (Wiseman, 1934, p. 354–417). Since the Standing Pond volcanics belong to the amphibolite facies of metamorphism, hornblende rather than actinolite is stable.

Diopside is present in the amphibolite facies of the calcareous rocks of the Waits River formation. It was formed either by the reaction of the earlier formed actinolite with calcite and quartz, or by the reaction of dolomite and quartz under the P-T conditions of medium-grade metamorphism (Billings, 1937, p. 546). The first reaction is the more likely one in this area, since the rocks are very poor in dolomite.

Sillimanite is confined to the thermally metamorphosed argillaceous rocks of the Westmore formation near the contacts with the Barre granite, where it is typically associated with biotite, orthoclase, cordierite and quartz. Sillimanite in these rocks is neither due to the breakdown of biotite, for biotite remains stable in the highest grade of metamorphism reached in the area, nor to the inversion of the low temperature form andalusite, for no andalusite has been found in the lower grade metamorphic rocks. Thus, it probably forms from excess alumina released in the breakdown of muscovite to potash feldspar.

Cordierite is present only in the contact-metamorphic hornfelses near the Barre granite and is closely associated with sillimanite. It occurs as irregular small xenoblastic grains with minute inclusions of opaque matter. Its other associates are biotite, potash feldspar, and quartz.

Plagioclase Feldspar is present both in the metasediments and in the metavolcanics of the Standing Pond member of the Waits River formation, but its origin and mode of occurrence is quite different in the two types of rocks. In the argillaceous schists the plagioclase is more anorthitic in composition and is probably formed by reaction of chlorite and calcite in the presence of silica. The role of chlorite may be taken by epidote in some cases. Hornblende is a typical by-product, hence the assemblage hornblende-calcic plagioclase, with epidote, chlorite, and magnetite in minor amounts, giving rise to the metasedimentary amphibolites.

The plagioclase feldspar of the metavolcanic rocks, is a sodic oligoclase. It occurs as clear, irregular blebs formed by the breakdown of the original calcic plagioclase in the volcanic rocks. Its typical associates are the by-products of this breakdown; namely, epidote and some calcite, in addition to hornblende and iron oxides.

Relation between deformation and regional metamorphism

As shown previously (p. 89–90), the structural features of the East Barre quadrangle indicate at least two important stages of deformation. Here the relation between these stages of deformation and the regional metamorphism is considered. Important evidence is furnished by the textures, structures, and parageneses of the minerals in the metamorphic rocks.

During the early stage deformation, the more active element in metamorphism was stress; and the result was the widely prevalent schistosity that is more or less parallel to the bedding in most parts of east-central Vermont. At present the rocks in this quadrangle show no evidence that high grades of metamorphism were ever attained in the early metamorphism.

The present distribution of regional metamorphic mineral assemblages is closely related to the cleavage arch and the deformation associated with the arch. In almost all cases the porphyroblasts of garnet and biotite formed during this metamorphism cut across the schistosity of the first stage metamorphism. Their relation to the second stage schistosity is not so uniform. In some places they cut across this later schistosity (Pl. 32); in others the porphyroblasts are rolled and otherwise deformed by the second stage schistosity (Pl. 31). Clearly enough, thermal metamorphism and structural deformation overlapped to a considerable extent in the second stage. White and Jahns (1950, p. 209) reached a similar conclusion for this area, but farther east in the Woodsville quadrangle they described porphyroblasts that were unaffected by the second stage deformation and presumably were formed later than those in the East Barre area. In other words, the thermal metamorphism gradually spread outwards from the central area of the cleavage arch whereas the deformation was essentially contemporaneous everywhere.

Cause of Metamorphism

It is evident that the intensity of metamorphism of the rocks in the East Barre quadrangle is highest in the central and south-central parts of the quadrangle and falls away both to the east and to the west. The distribution of metamorphism around the domes in Strafford and Hanover quadrangles is similar (Doll, 1944; Lyons, 1955, p. 138). Thus whatever the factors that caused the metamorphism, they must have been more intense in the central area and lessened gradually outwards.

Two such factors fit this pattern and seem important in considering the causes of metamorphism. First, if the structural history of the area has been correctly interpreted, a major syncline formed in the early stage of deformation, its trough occupied by the rocks of the Waits River formation. These rocks should be more metamorphosed than those on the limbs of the syncline. The first period of low-grade metamorphism may have occurred at this time.

The second factor is the distribution of major plutonic bodies in the central belt. As already mentioned, the intensity of regional metamorphism progressively increases toward the plutons and finally culminates in the contact metamorphism in their aureoles. The contact metamorphism, however, is only a special and insignificant effect of the granite intrusives. The stresses associated with the emplacement of large bodies of magma subjected the surrounding rocks to an environment not only of elevated temperatures but also of severe directional stresses. The result is the regional metamorphism, which, for obvious reasons, was most intense where the stresses and the temperatures were most intense—i.e., close to the plutons and in the central parts of the cleavage arch or dome.

It is also evident that load, or depth of burial, is not a cause of metamorphism in this area. Otherwise, the older rocks in the stratigraphic sequence, having been under greater load, would be more intensely metamorphosed. On the contrary, the youngest unit of the sequence, the Waits River formation, shows the highest grade of metamorphism in the quadrangle.

The heat supplied by the plutonic bodies may have been transported in two ways—by conduction through the solid rock, and by volatiles and permeating fluids. Evidence of activity of the latter is not abundant except for the numerous granitic and pegmatitic dikes in the south-central part of the quadrangle. Doubtless, water is always present in sediments and metamorphism of the intensity reached in this quadrangle would certainly drive much of it out of the rocks; but the role played by water in carrying heat to the sediments is difficult to evaluate.

ECONOMIC GEOLOGY

There are only three materials of economic importance in the East Barre quadrangle. One of them is the granite that provides the major industry of the area. Another is copper ore that has been won in the past from a few mines in the Pike Hill region, but these were closed some time ago and renewed interest in them is just being shown. The third material is gravel from the quaternary alluvial deposits that occur in several parts of the quadrangle. This material is used in road-building.

Granite

The granite industry in the Barre area is one of the most flourishing industries of the area and provides employment to much of the population of the town of Barre and neighboring villages. The Barre granite is the one used most in the industry, and extensive quarrying operations at present are confined to Millstone Hill.

The granite of Millstone Hill is used for several types of monuments. Only the choicest stone is utilized, and the waste rock is dumped into enormous piles, locally called 'grout piles,' near each quarry. Several attempts have been made to use the granite from the grout piles, but efforts have been unsuccessful due to the high cost involved in handling the material and processing it for use, either as road-metal or as a fertilizer in powdered form.

Factors Affecting the Value of the Granite

Homogeneity in color and texture of the granite is the most important factor in fixing its value. For delicate carvings an even texture of the rock is necessary, while fine polishing work demands a rather rigid flawlessness in color. By flaws in color are meant those spots, knots, bands and other local characteristics that spoil the evenness of the color. Any shade of gray is acceptable in the granite as long as it is homogenous, but the darker shades of gray bring better prices.

Size of the blocks is also an important consideration in quarrying the granite. Areas with closely spaced joints that divide the granite into small blocks are avoided in the development of the quarries. Assuming there are no flaws in the granite, the larger the block the more valuable it is.

Flaws in the granite are of several kinds, such as inclusions of country rock, dark mineral segregations, dikes or veinlets of quartz, pegmatite, or granite of a later age, variations in grain size or composition, and staining by percolation of ground water. Several of the discarded blocks appear flawless to the uninitiated, but the practised eye of the quarrymen can detect even microscopic flaws.

Economic Classification of the Granite

The Barre granite is classified by the 'shade' of gray color it exhibits on a polished surface. As Dale (1923, p. 14) points out, the term 'shade' is used to indicate the degree of blackness apart from the color. This blackness is perhaps due to the smokiness of the quartz or the amount of the biotite present in the rock. The rock that was previously marketed as the "Barre dark" was unusually rich in biotite. Apart from that variety, which is no longer available, the various other shades described as "light" or "medium gray" do not indicate mineralogic differences. A geologist might never be able to classify them in an unpolished sample, and yet, most experienced quarrymen can separate them easily. Similarly, the word "fine" is used not so much in reference to the grain size but to refer to an evenness of grain in the granite, which makes it particularly amenable to fine polishing and intricate carving.

Copper deposits

In the southeastern part of the East Barre quadrangle, several abandoned copper workings are present. Some of them around Corinth are small mines and prospect pits; somewhat larger mines exist about a mile northwest of Pike Hill village.

In eastern Vermont, the various copper mines are located in a north-south trending mineralized zone about 20 miles long and 5 miles wide at its maximum (Jacobs, 1944, p. 2). The mineralized zone itself is located on the eastern flank of the cleavage arch described elsewhere in the report. The trend and dip of the ore bodies, which occur as elongate lenses, indicate that ore deposition post-dated the latest regional deformation in the area.

History of the Mines

The early operations in the Pike Hill area date back to the 1860's.

They were in active production until 1919, when the mines were closed due to the slump in copper prices immediately after the close of the war. This is important to remember—the closing of the mines was not due to a pinching out of the mineralized zone or fall in the tenor of the ore but was due wholly to external circumstances. Should the market prove favorable and demand rise, the re-opening of the mines might be worth investigation.

Three mines were in active operation in the Pike Hill area. These were the Union, Eureka, and the Smith mines. The Union was the northernmost and the Smith southernmost. The Eureka Mine was the first one to be opened, about 1860, followed shortly afterward by the Union Mine. The mines were in production intermittently until 1906, when the property was acquired by the Pike Hill Mines Company which consolidated the mines and worked them as a unit.

The three mines were purchased by the Vermont Copper Company, Inc., in 1942.

Geology of the Mines Region

The country rocks in the mineralized area belong to the Waits River formation. Rock types include quartz-calcite-mica schists, garnetiferous mica-schists, minor quartzites and limestones. All of these lithologies are intimately interbedded. Structural deformation, described in detail in the chapter on structure, has produced complicated minor folds in the bedding and has given rise to a well defined schistosity that trends north 20–30 degrees west and dips northeast. Many of the minor folds have gentle north or slightly northeast plunges.

Mineralogy of the Ore

The main ore minerals are pyrrhotite, chalcopyrite, and pyrite. Pyrrhotite is the most abundant and constitutes the groundmass in which chalcopyrite occurs. Pyrite is always present in appreciable quantities. The gangue minerals are quartz, mica, and calcite, and in places, garnet of almandine composition.

Paragenetic relations observed in polished specimens are as follows:

Pyrite was the first mineral to crystallize; pyrrhotite followed pyrite and to some extent overlapped the last stage of formation of the pyrite. It surrounds and occupies the space between the grains of pyrite, and at places is moulded around the grains of pyrite. Chalcopyrite was the last mineral to crystallize. It replaces pyrrhotite or occurs disseminated in a matrix of pyrrhotite.

Origin of the Ore

An exhaustive geological investigation of the Elizabeth mine in South Strafford village had been conducted by White (1952) and White and Eric (1944). Detailed study of the underground workings of the Pike Hill mine was not possible, mainly because of the collapsed condition of the entrances. The conclusions as to the origin of the ore given below are mainly those indicated in the study of White and Eric (1944) at the Elizabeth mine. Inasmuch as the Elizabeth Mine is located in the southward strike extension of the mineralized belt of the Pike Hill area, and since no contradictory data was obtained at the Pike Hill Mines, it is assumed that the same origin holds good for the ore in the two mines.

The ore occurs in medium to high grade metamorphic rocks. High temperature gangue minerals like almandine garnet, hornblende and plagioclase in the Elizabeth Mine were interpreted by White (1952, p. 1313) as indicating that the rock temperature was still high when the ore deposits were formed. In the Pike Hill Mines hornblende is not present, because of the absence of the rocks belonging to the Standing Pond volcanic member, which are closely associated with ore in the Elizabeth Mine. The general grade of metamorphism as indicated by the mineral assemblages of garnet and biotite in the schistose rocks is perhaps only a little lower than at the Elizabeth Mine. In the Pike Hill area, no low-temperature alteration such as kaolinization, sericitization or chloritization is present.

The consistent northward plunge of the minor structures of the area provide a means of restoring the structure above the present surface. This indicates that ore deposition must have taken place at considerable depth; evidence consistent with the other lines of evidence indicating that the ore was formed at high temperatures.

The controls of ore deposition could not be observed in the Pike Hill region, because of the poor outcrops on the surface and the inaccessibility of the underground workings. No faults or shear zones are seen on the surface. The general trend of the vein and its pitch indicates a certain structural control by the pre-existing schistosity of the country rocks. The early operations in which miners followed the outcrop of the gossan indicates that, at least near the surface, the vein more or less parallelled the schistosity.

It may be surmised that ore deposition at Pike Hill was more likely to have been controlled by folds or flexures in the schistosity than by shear zones. This is quite different from the type of control that exists in the Elizabeth Mine, where the ore occurrence is controlled by faults or shear zones.

A close genetic relationship of the copper ores with the granite bodies in nearby areas had been postulated by Weed (1911, p. 20), and by White and Eric (1944). In the Pike Hill region a few granitic dikes and pegmatites are present; and a little farther south in the Cookville area, numerous granitic and pegmatitic dikes and several quartz veins are perhaps indicative of the close proximity of a subjacent granite pluton. The genetic relationship between the copper ore and the granites can hardly be proved with the information on hand.

Gravel deposits

Cenozoic alluvial and glacio-fluvial deposits of gravel, sand and fine silts are found in several localities, particularly in the northern half of the quadrangle. In places where a deposit is composed of material of predominantly pebble size with a minimum of other admixed sizes, the deposits are excavated, and the material, after some preliminary screening, is used for road-building purposes. Good-grade gravel is rather rare, but material of mixed sizes can be obtained from the southwestern foot of Knox Mountains, near the Orange Reservoir, from the gravel banks about three quarters of a mile northwest of Washington Heights, and from many other small pits.

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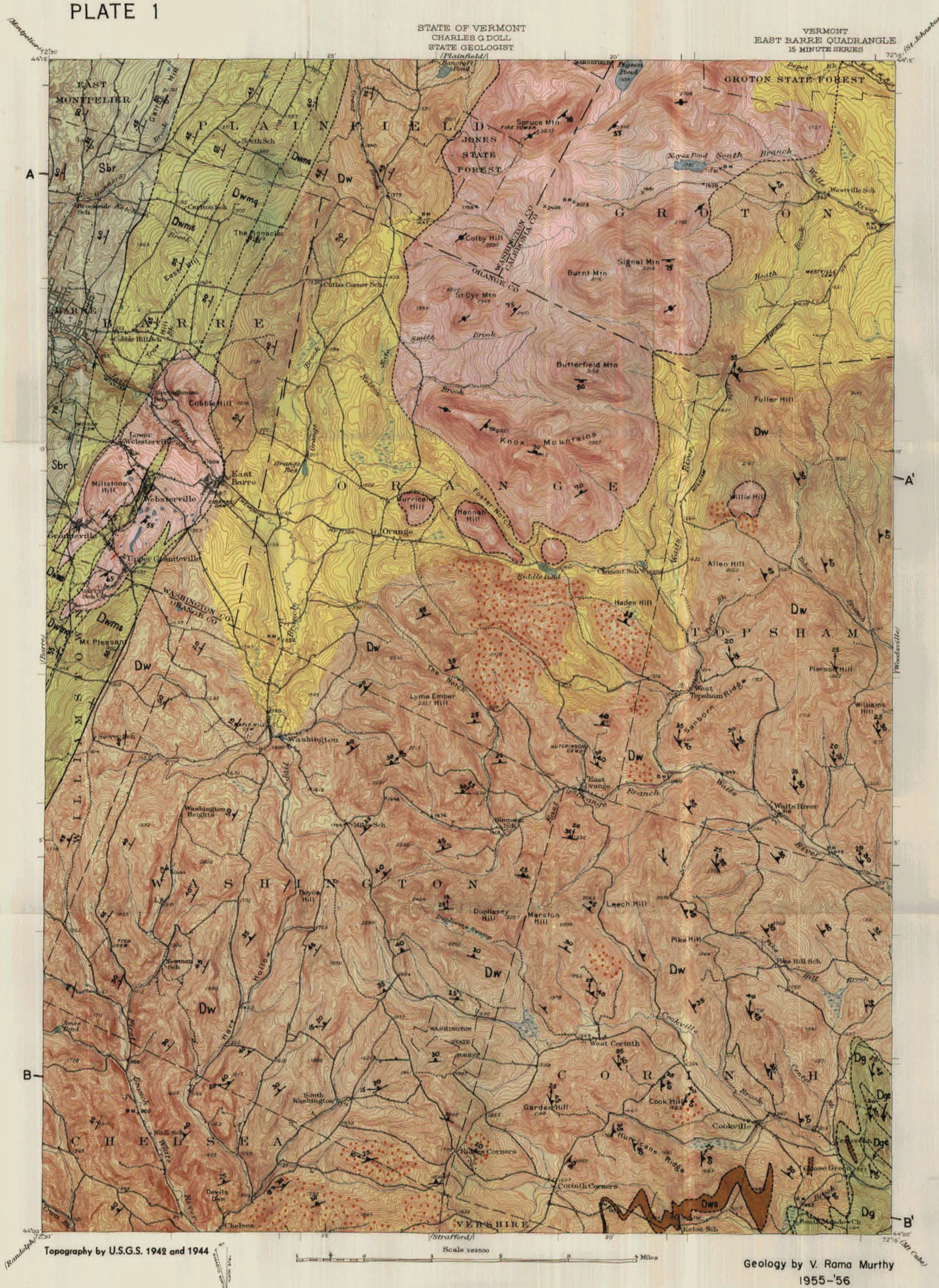
PLATE 1

STATE OF VERMONT
CHARLES G. DOLL
STATE GEOLOGIST

VERMONT
EAST BARRE QUADRANGLE
15 MINUTE SERIES



Topography by U.S.G.S. 1942 and 1944

Scale 1:62500

Geology by V. Rama Murthy
1955–'56

EAST BARRE, VT
Edition of 1948

LEGEND

Undifferentiated glacial drift and alluvium

Mafic dike rocks

Medium- to coarse-grained grey biotite-granite, granodiorite, quartz-monzonite, composed of microcline, oligoclase, quartz, biotite, muscovite.

Areas with numerous granitic dikes

DEVONIAN ?

Dw

WAITS RIVER FORMATION

Impure calcareous mica schist, thick-bedded dark-tan limestones, quartz mica schists, and quartzose marbles—Dw; dark-green needle amphibolites, medium- to coarse-grained garnetiferous hornblende gneiss—the Standing Pond volcanic member, Dws.

Dwm

WESTMORE FORMATION (?GILE MOUNTAIN FORMATION)

Dark-grey phyllites, quartz-mica schists, and micaceous quartzites—Dwm; dark-grey schists with subordinate quartzite and quartz-mica schists—Dwms; quartz-mica schists and micaceous quartzites—Dwmq; Gile Mountain formation—Dg; locally dark tan limestones interbedded with schists—Dgc.

SILURIAN ?

Sbr

BARTON RIVER FORMATION

Interbedded grey phyllites and bluish-grey limestones with a dark rusty color on weathered surface, calcareous mica schists—Sbr.

STRUCTURAL SYMBOLS

Accurate and well-defined contact

Indefinite and gradational contact

Concealed or inferred contact

Dip and strike of bedding

Dip and strike of overturned bedding

Dip and strike of foliation or schistosity

Dip and strike of foliation or schistosity parallel to bedding

Dip and strike of foliation or schistosity with plunge of lineation

Dip and strike of joint plane

Strike of vertical joint

GEOLOGIC MAP OF THE EAST BARRE QUADRANGLE, VERMONT

VERMONT GEOLOGICAL SURVEY

Charles G. Doll, State Geologist

Published 1957

(Bulletin No. 10)

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Published 1957
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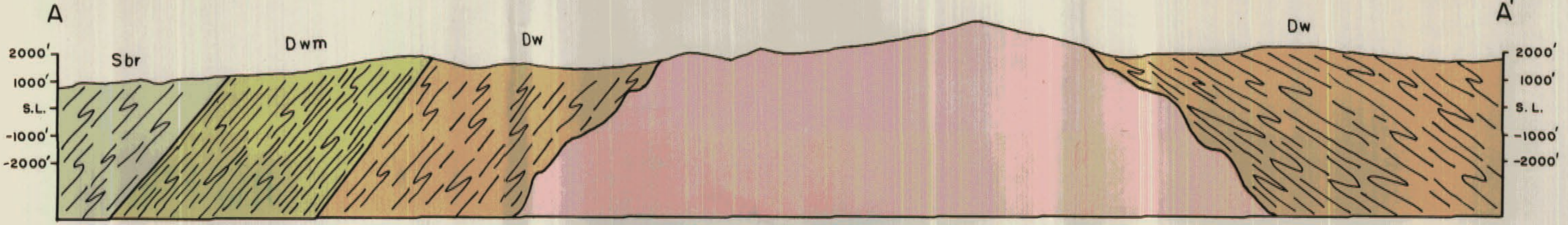
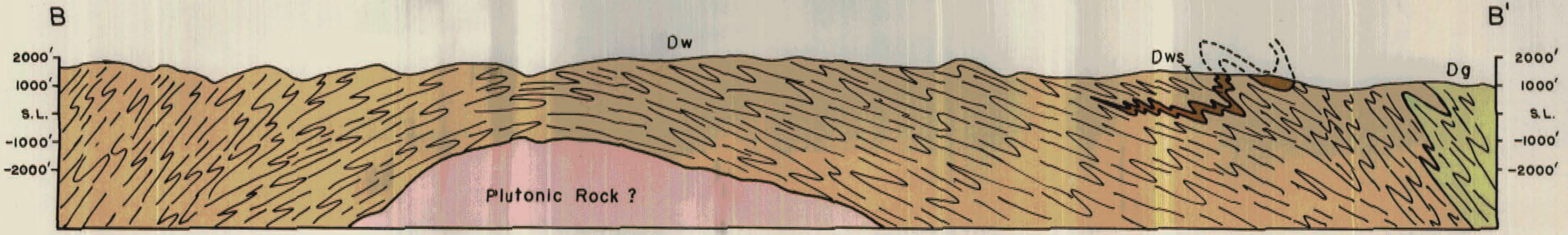
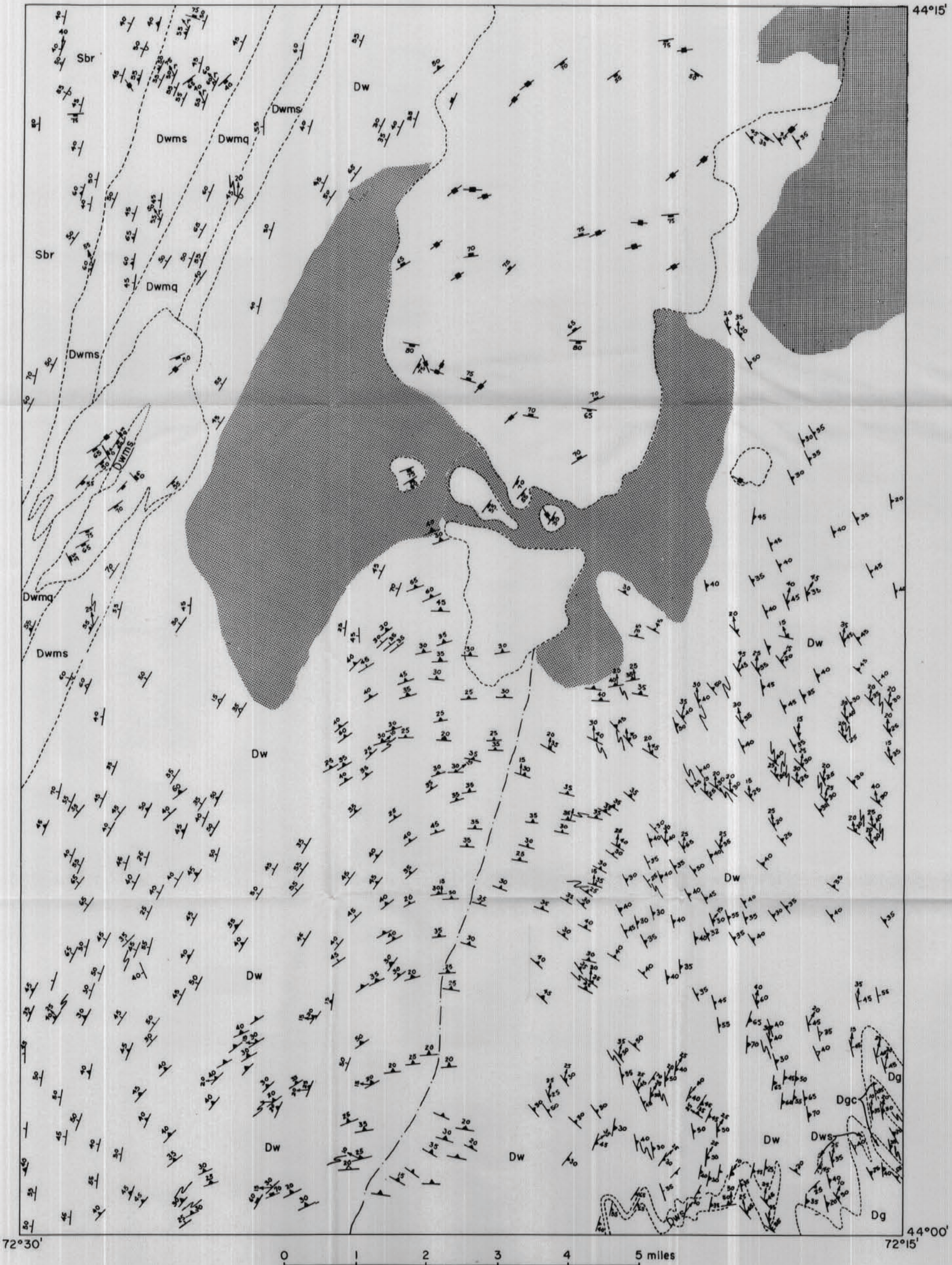


Section A-A'



Section B-B'

PLATE 2



LEGEND

Dip and strike of beds

Dip and strike of overturned beds

Dip and strike of schistosity

Dip and strike of beds and schistosity

Dip and strike of schistosity with plunge of minor fold

Dip and strike of schistosity with rake of lineation

Dip and strike of slip cleavage

Sinistral pattern of minor folds

Dextral pattern of minor folds

Dip and strike of joint plane

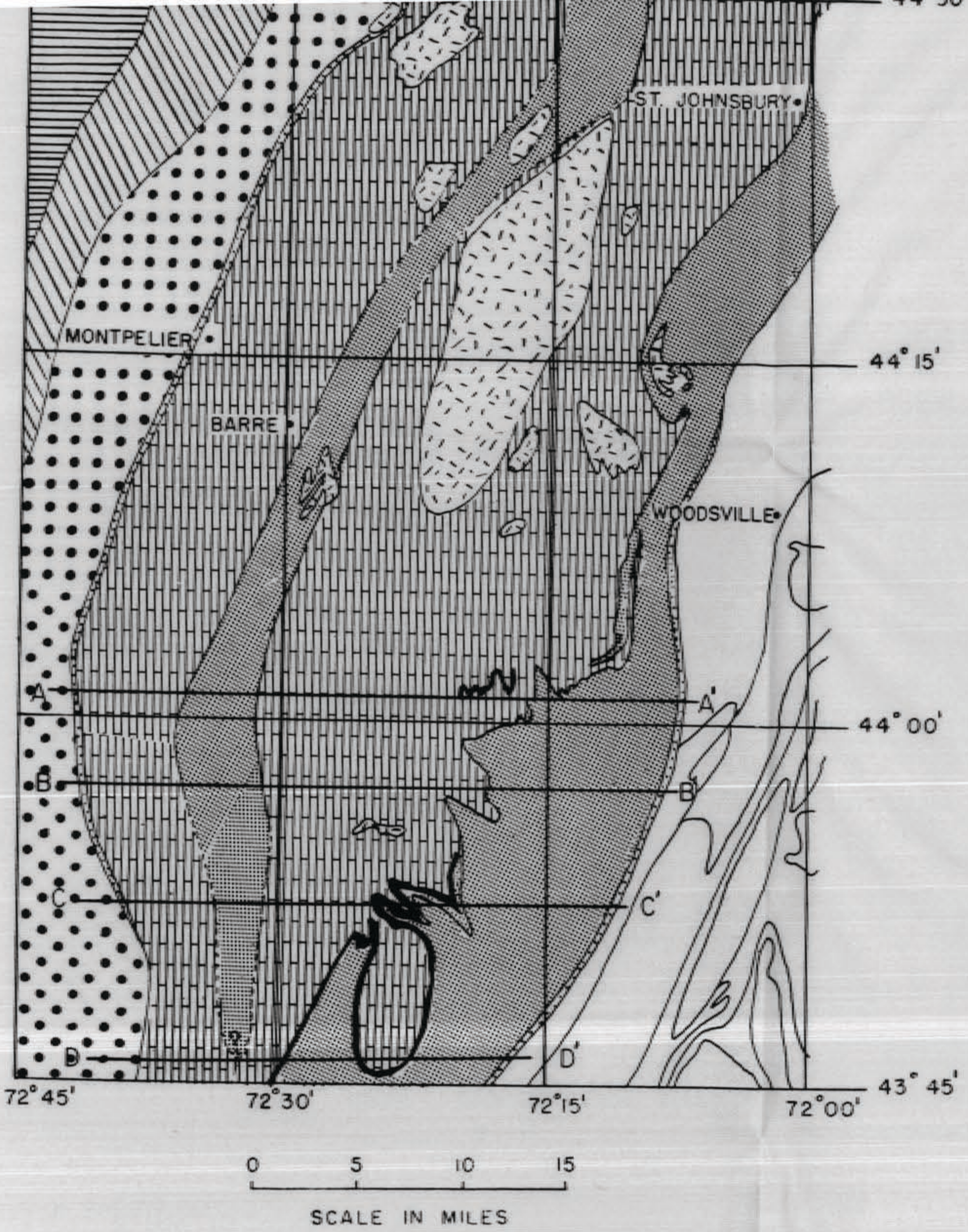
Strike of vertical joints

Axis of the cleavage arch

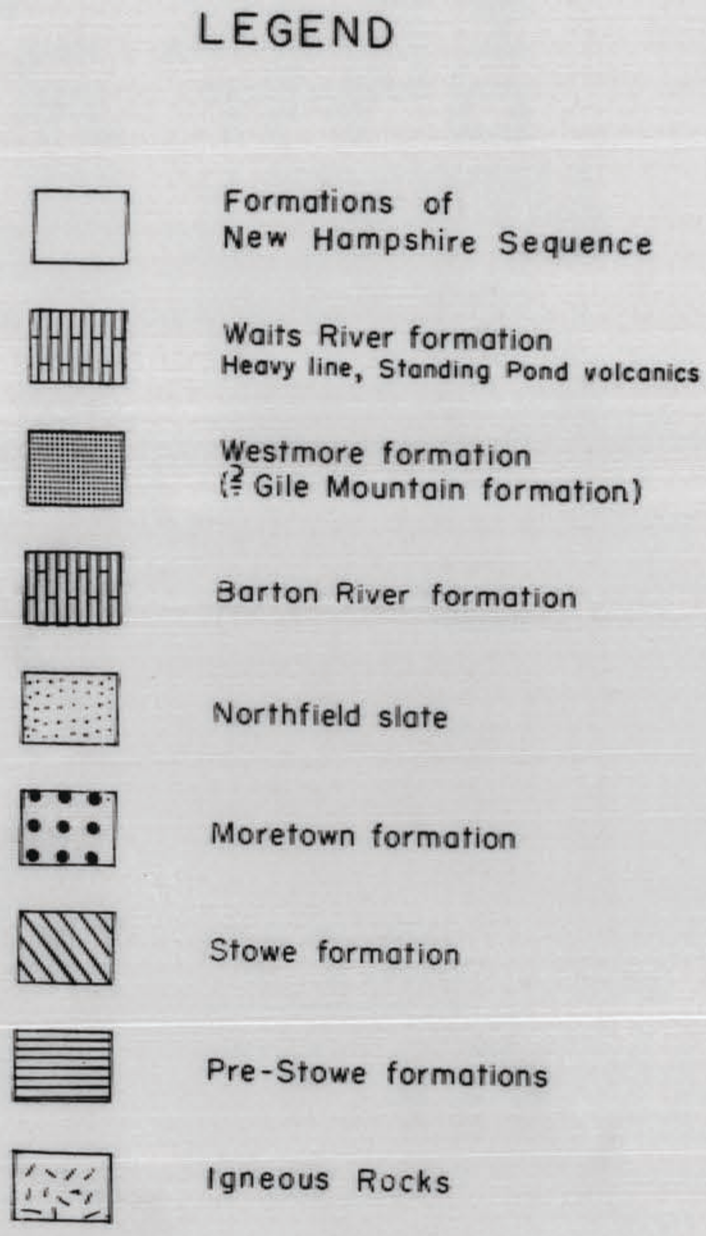
Formation symbols as shown on the geologic map.

Shaded area—glacial and alluvial deposits.

STRUCTURAL MAP OF THE EAST BARRE QUADRANGLE, VERMONT

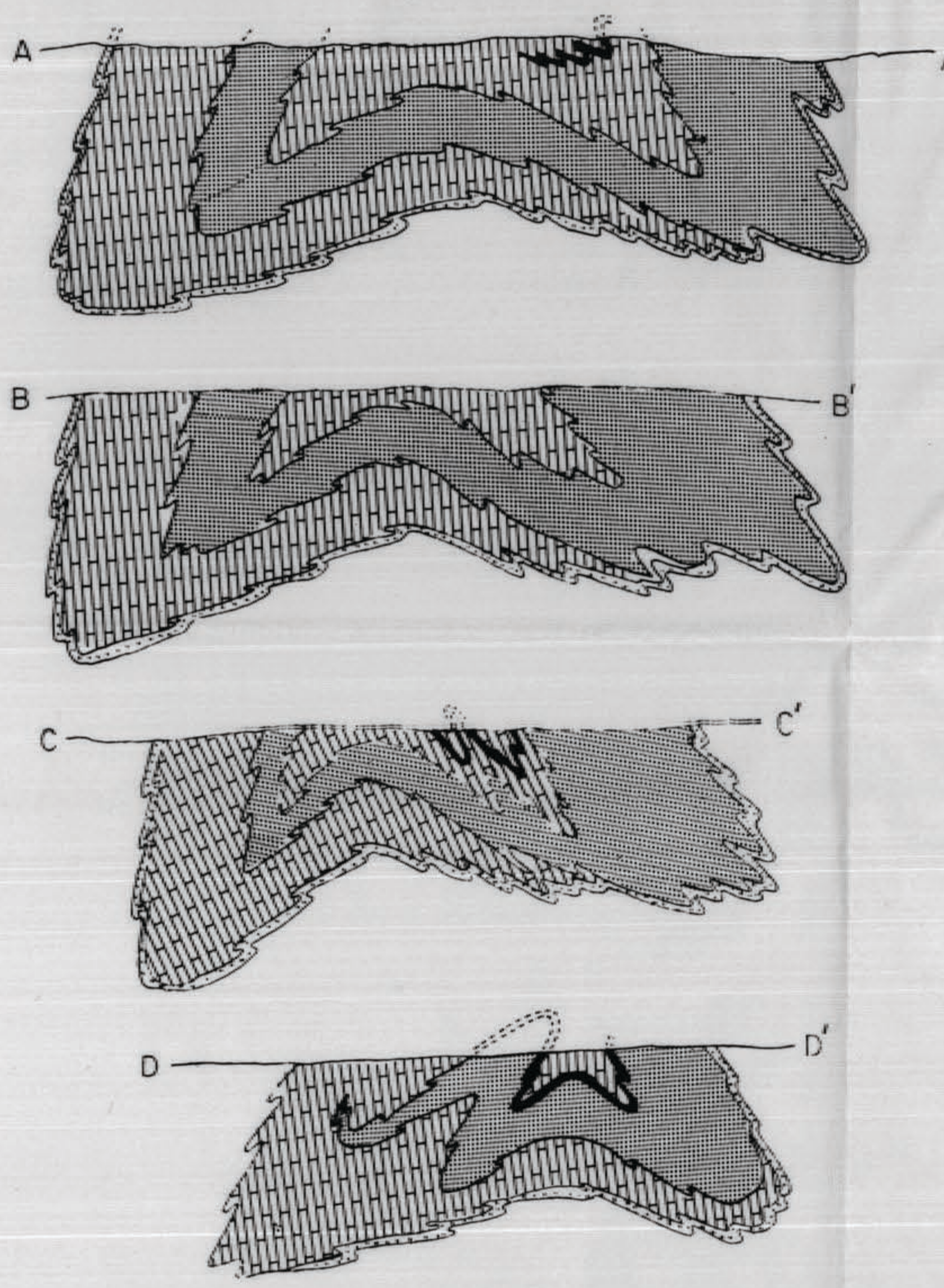


ST. JOHNSBURY
MONTPELIER
BARRE
WOODSVILLE
44° 15'
44° 00'
43° 45'
72° 45'
72° 30'
72° 15'
72° 00'
A
A'
B
B'
C
C'
D
D'
0 5 10 15
SCALE IN MILES



LEGEND
Formations of New Hampshire Sequence
Waits River formation
Heavy line, Standing Pond volcanics
Westmore formation
(? Gile Mountain formation)
Barton River formation
Northfield slate
Moretown formation
Stowe formation
Pre-Stowe formations
Igneous Rocks

PLATE 3



A
A'
B
B'
C
C'
D
D'