GEOLOGY OF THE BRADFORD - THETFORD AREA

ORANGE COUNTY, VERMONT

By

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Abstract

This report describes the geology of an area of about 80 square miles west of the Connecticut River in the northwest part of the Mt. Cube quadrangle, Vt.-N. H. Bedrocks exposed in the area are highly folded and metamorphosed sedimentary and volcanic rocks and minor intrusives, all of Ordovician or probable Devonian age. The Ordovician metasedimentary rocks represent part of a thick geosynclinal accumulation of carbonaceous sand and mud, intercalated with dominantly basic lavas and some tuffs (Orfordville formation), overlain by lighter colored feldspathic sandstone and shale (Albee formation). The Devonian (?) rocks represent thick-bedded feldspathic sandstone and shale in part calcareous (Gile Mountain formation) overlain by thinner-bedded, dark, dominantly shaly rocks (Meetinghouse slate). The original thickness of strata deposited during each period was several thousand feet. None of the rocks were found to contain recognizable fossils.

The Ordovician rocks were probably subjected to gentle folding near the close of the Ordovician period, although no evidence of this folding was found in the area. A much more vigorous disturbance toward the end of the Devonian period (Acadian orogeny) produced the vast number of large and small folds now visible in all the metasedimentary rocks of the area. Regional metamorphism accompanying this deformation has changed the sedimentary rocks into slate, phyllite, schist, and feldspathic quartzite; and the various kinds of volcanic rocks have become greenstone, amphibolite, felsitic or muscovitic schists. In this process most of the original features of these rocks have been destroyed. Of the two prominent faults in the area, the older (Monroe fault) separates

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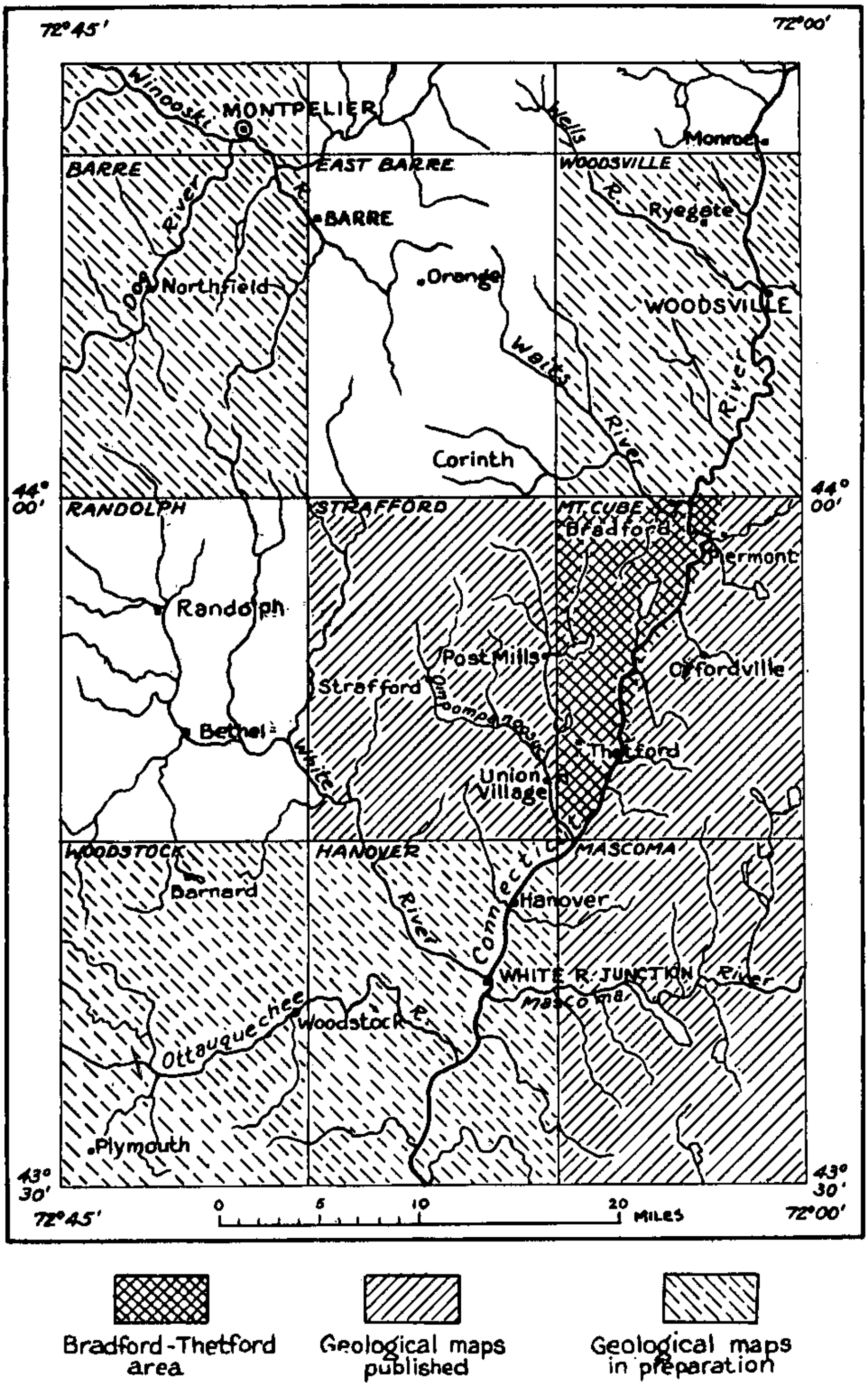

FIG. 1. Index map of east-central Vermont, showing location of the Bradford-Thetford area and adjacent quadrangles.

the Ordovician from the supposedly Devonian rocks and is older than the regional metamorphism. The younger fault (Ammonoosuc thrust) lies within the Ordovician rocks but is younger than the folding and metamorphism.

The Devonian (?) rocks particularly show systematically folded schistosity, which is interpreted as indicating a second stage of deformation following regional low-grade dynamothermal metamorphism. Porphyroblastic development of minerals indicating higher metamorphic temperatures seems to have followed the second deformation. Both stages of deformation and both stages of metamorphism probably took place in one diastrophic cycle near the close of the Devonian period.

The only large intrusive body (Fairlee quartz monzonite) intrudes the Ordovician rocks and is thought to be of late Ordovician age (Highlandcroft magma series of Billings). Intrusives associated with the Acadian orogeny include basic dikes and sills abundant in the Devonian (?) rocks, as well as dike-like bodies of granodiorite and granodiorite porphyry. A unique body of olivine gabbro porphyry near Thetford has been located by tracing glacially dispersed boulders and by geophysical methods. It is probably of Mississippian age.

During most of Mesozoic and Cenozoic time, about 200 million years, the rocks of the Bradford-Thetford area have been subject to erosion. The land forms produced during the first three-quarters of this time have vanished; but during the last 60 million years the present form of the landscape and its drainage lines have gradually become established. The advance and disappearance of the continental ice sheet during the last million years has contributed the rounded upland profiles, the lakes, ponds, and small swamps, and the stony or sandy subsoil material characteristic of the area today.

INTRODUCTION

The Bradford-Thetford area, in southeastern Orange County, Vermont, includes all of the township of Fairlee, together with considerable parts of the townships of Bradford, Thetford, and West Fairlee, and smaller parts of Corinth, Vershire, and Norwich. The area as a whole comprises the northwestern third of the Mt. Cube (Vt.-N.H.) fifteen minute quadrangle of the U. S. Geological Survey's Topographic Atlas of the United States (Fig. 1).

The area described is part of a region of hills and valleys of moderate relief traversed from north to south by the valley of the Connecticut, New England's largest river. Here the valley, a mile to a mile and a half wide, is 400 to 500 feet above sea level; from the valley floor the hills on either side rise irregularly to altitudes ranging from 800 to 1,800 feet. Two principal tributaries enter the river within the area: the Waits River, which joins the Connecticut at the village of Bradford, and the Ompompanoosuc River, which drains most of the western part of the mapped area and joins the Connecticut a few miles north of Hanover, New Hampshire.

Between two-thirds and three-fourths of the area is now covered by second-growth forest, which is most continuous in the high country immediately west of the river. Most of the cleared lands in the hilly part of the area are pastures, some of which on the highest summits, afford fine distant views. Much of the bottom land, especially along the Connecticut River, is cultivated.

The principal occupation of people living in the area is farming, but providing for vacationers is an important activity in the summer months. The Bradford-Thetford area is one of the largest centers of children's camps in New England, and more than a score of such camps are located along the shores of the larger lakes and ponds of the area.

The geological field work on which this report is based was done largely during the summer of 1938, although brief additional visits were made in 1940 and in 1947. Most of the petrographic study and the preparation of the report were done in 1947 and 1948 under the auspices of the Geological Survey, U. S. Department of the Interior. The writer wishes to express his gratitude to Richard Story for valued assistance in the field; and to Walter S. White of the Geological Survey and Richard H. Jahns of the California Institute of Technology, whose extensive work in eastern Vermont was being carried on at about the same time as the writer's, for much helpful information about areas to the north and west, and for many stimulating discussions of the stratigraphic and structural problems of this complicated region. Permission granted by the Department of Geology, Dartmouth College, to make use of unpublished material relating to the olivine gabbro porphyry at Thetford is gratefully acknowledged.

PHYSIOGRAPHIC HISTORY

The drainage of the Bradford-Thetford area is controlled by the Connecticut River, its larger tributaries, the Waits River and Ompompanoosuc River, and their lesser tributaries. These streams were at work during most of Tertiary time cutting deeper into the bedrock and widening their valleys. However, the deepening and widening do not appear to have proceeded at the same rate throughout the area nor throughout the erosional history of the region. Instead, there may have been periods of relatively rapid deepening of the larger stream channels followed by periods during which the streams widened their valleys by eroding the walls more than the bottoms. The dramatic interruption of stream erosion by the onset of glaciation has obscured much of the evidence for such periodic changes in stream erosion throughout New England. Nevertheless, evidence for such changes along the Connecticut River in southeastern Vermont has been described by Meyerhoff and Hubbell (1928), and similar features may be seen in the Bradford-Thetford area and its vicinity. Relatively gentle upper slopes of hills, breaking to steeper lower slopes at altitudes between 1,000 and 1,200 feet, are common for some distance east of the Connecticut River in the Mt. Cube quadrangle and west of the river in the Woodsville quadrangle. Viewed from State Highway No. 10, a few miles north of Piermont, New Hampshire, the upper slopes in the Woodsville quadrangle appear to merge into a gently rolling surface in marked contrast to the higher country on either side. This rolling surface may represent a broad valley floor, which, if restored, would lie at about 1,200 feet altitude. More doubtful evidence of a lower surface exists in Fairlee on the hill on which the Palisades cliffs are located. The relatively flat summit of this hill, beveling diverse rocks, may be a remnant of a former flat valley floor at about 820 feet altitude. Unfortunately no other remnants of this supposed floor have been found. Several smaller hills somewhat below the level of the Palisades in the Mt. Cube quadrangle may represent such remnants, but the near accordance of their summit levels may also be fortuitous.

In more recent times the Connecticut River has cut a canyon in bedrock 500 feet below the top of the Palisades, and the river was flowing in this canyon when the Pleistocene ice sheet arrived. Much of the canyon was filled with glacial deposits, which have not been entirely removed by the river. Borings near Hanover and at the Comerford hydroelectric plant north of Woodsville (Crosby, 1934) indicate that the bottom of the canyon is buried by glacial sand and gravel and lies 50 to 60 feet below the present level of the river.

A remarkable feature of erosion during the period of canyon cutting in the Bradford-Thetford area was the natural diversion of a former tributary of the Connecticut River near Ely, Vt., leaving a wind gap now occupied by the road from Ely to Lake Fairlee. This gap, 700 feet deep, is the only large gap in the western wall of the Connecticut River valley between the Waits River and the Ompompanoosuc River. It is particularly striking as seen from the upper slopes of the 1,500-foot hill north of the road. No stream now flows through this gap, and it is clear that the stream that once carved it has disappeared. Moreover, a study of the drainage in the eastern part of the Strafford quadrangle and the western part of the Mt. Cube quadrangle strongly suggests that the North Branch of the Ompompanoosuc River, which now joins the West Branch in the southeastern part of the Strafford quadrangle, formerly flowed eastward through the gap as an independent tributary of the Connecticut River. Some time early in the period of canyon cutting, a smaller tributary of the West Branch of the Ompompanoosuc, working rapidly northward, intersected this independent stream, which we may call the Ely River, near Post Mills, thus capturing it and diverting its water into the Ompompanoosuc drainage system. This act of piracy not only took all the water of the Ely River above Post Mills, but eventually caused Middle Brook and Blood Brook, whose waters originally joined the Ely River below the point of capture, to flow westward into the Ompompanoosuc.

GLACIAL FEATURES*

The Bradford-Thetford area shows abundant evidence of having been glaciated during the Wisconsin or fourth glacial stage. Many features are found which resulted from glacial erosion and a variety of unconsolidated deposits have been left by the ice and its meltwater.

Outcrops of bedrock showing the characteristically rounded shapes that result from abrasion by ice are very common in the area. Much less common are original, ice-smoothed surfaces with their more delicate grooves and scratches parallel to the direction of ice movement at the time the abrasion occurred. These surfaces, along with a shell of rock an inch or less thick, have been removed by weathering from most outcrops in the relatively short time they have been exposed. Measurable grooves or striations, seen on about twenty outcrops in various parts of the area, indicate that the ice moved more-or-less directly from north to south, at least during the later part of the glaciation. Additional evidence of the southward movement of the ice is found in the distribution of distinctive boulders of olivine gabbro porphyry removed from a now-concealed source in Thetford. These boulders are found in fields and stone walls within a narrow, fan-shaped area that extends southward for a mile and a half from the source (Chivers, 1938).

* A systematic study of the glacial geology of the Bradford-Thetford area was not attempted. However, some general observations based on this and nearby areas are given here.

In addition to such boulders of local origin, a great quantity of loose material has been moved from sources in and north of the area and deposited as a blanket over practically the entire area. This material now appears as bluish-gray or yellowish-gray more or less bouldery till, locally covered by thin deposits of washed and stratified sand and gravel (outwash). Stratified deposits below 600 feet altitude in the valley of the Connecticut River are commonly rather fine sand, silt, and clay laid down in ponded water adjacent to the melting ice. According to some geologists (Goldthwait, 1925; Lougee, 1935), this ponded water formed a sizable lake, dammed by glacial deposits south of the Bradford-Thetford area and fed by melt waters in and north of the area. The lake, which extended for a brief period over much of the valley, was drained by erosion of its natural dam some thousands of years ago. Delta deposits of sand and gravel built by the larger streams along the margins of the lake, as at Lyme, N. H., and elsewhere, remain and mark its upper limit.

The origin of Lake Fairlee and Lake Morey are closely related to the later stages of the melting of the ice sheet. Lake Fairlee appears to fill a large kettle hole once occupied by a body of stagnant ice in the valley of the now-vanished Ely River. The western end of the lake is held in place by sand and gravel piled around the ice by neighboring streams before it melted away. The hole that was left when the ice finally disappeared has not yet been filled with sediment carried by the small streams now entering the lake. Lake Morey occupies a similar depression in what may be an abandoned preglacial channel of the Connecticut River between the Palisades and Sawyer Mountain. During glaciation, that part of the channel now occupied by the lake was probably widened and possibly somewhat deepened. The present lake, however, appears to be confined at its southern or outlet end by stratified glacial deposits on the Connecticut valley floor. A few small kame deposits along the west side of the lake indicate that an isolated mass of ice lingered in the depression after most of the sheet had disappeared.

BEDROCK UNITS

Beneath the surficial mantle of glacial and alluvial deposits, most of the Bradford-Thetford area is underlain by hard crystalline rocks of sedimentary and volcanic origin, which have been metamorphosed by deep burial in the earth's crust and by the heat and pressures developed during the deep earth movements of a former geologic era. These rocks have lost many of their original features and are known in their present condition as slates, phyllitic schists, quartzites, greenstones, and felsitic schists. They are layered according to the order of their deposition on the ancient earth surface, and they still appear in more or less definite sequences, considerably obscured, it is true, by intense wrinkling or folding of the layers. Tracing the original sequence of strata is made more difficult by the complete absence of fossils and by the presence of through-going breaks or faults, by which segments of the crust have been sheared apart and the segments displaced from each other by distances estimated in miles. Two such faults, the Ammonoosuc thrust fault and the Monroe fault, pass along the eastern side of the Bradford-Thetford area near the Connecticut River.

In addition to the metamorphic rocks just mentioned, several kinds of igneous rocks are present. They invaded the area in part during the earlier phases of the geologic history and in part after the other hard rocks had been more or less thoroughly metamorphosed. Most of these igneous rocks are readily recognized by their distinctive mineralogical composition and texture, and by the size, shape, and relations of the bodies in which they are found.

METASEDIMENTARY AND METAVOLCANIC ROCKS

Metamorphosed sedimentary and volcanic rocks constitute by far the larger portion of the bedrock in the area; their total thickness amounts to many thousands of feet. For convenience in mapping and description they are divided into four units: the Orfordville formation and Albee formation both of Ordovician age, and the Gile Mountain formation and Meetinghouse slate possibly of Devonian age.

ORDOVICIAN

Orfordville Formation

In the belt of rocks passing through Sawyer Mountain between the Ammonoosuc and Monroe faults and herein called the Sawyer Mountain belt, five members of the Orfordville formation are present. These members, named from exposures just across the Connecticut River in New Hampshire (Hadley, 1942), are, from youngest to oldest:

Sunday Mountain metavolcanic member
Upper black slate member
Hardy Hill quartzite member
Lower black slate member
Post Pond metavolcanic member

Post Pond metavolcanic member.—The oldest part of the Orfordville formation in the Bradford-Thetford area consists of variously textured greenstones and green chloritic schists commonly interbedded with schistose felsite and quartz-feldspar-sericite schist. This assortment of rocks, largely of volcanic origin, was named from outcrops of the same unit in the vicinity of Post Pond in the town of Lyme, N. H., east of Thetford, Vt. The rocks of the Post Pond metavolcanic member in Vermont occupy most of the zone between the Monroe and Ammonoosuc faults southwest of Ely, Vt. The most extensive exposures in this zone are in partly wooded pastures west of the road from Thetford village to Pompanoosuc and north of the Orange County line; other good exposures may be seen in a road cut on U. S. Highway No. 5, one-half mile north of North Thetford.

At all places where the Post Pond member is well exposed, greenstone is the dominant rock, although chlorite schist or chlorite-sericite-quartz schist is also a common type, and east of the Connecticut River, north of North Thetford, chloritic schists with abundant small grains of bluish quartz and white feldspar are exposed. The greenstone and green schists generally lack bedding although thin, indistinct, light-colored layers can be seen in some places. The greenstones are less foliated than the schists, and in some of them diabasic texture is preserved. They are generally composed of albite or albite-oligoclase feldspar, epidote, and chlorite, with various amounts of calcite, sphene, and magnetite. Small amounts of quartz may be present, as well as traces of sericite or muscovite. Several types have abundant pale-green amphibole partly altered to chlorite.

Thin sections of the greenstones and green schists show that they have been profoundly altered with the development of an entirely new set of minerals and textures. Thus it is difficult to tell just what type of rocks they were. Nevertheless, judging from their mineral composition, the greenstones are chemically similar to basalts. The lack of bedding or fragmental texture suggests that many of them represent lava flows. Some of the more schistose types, however, may have been tuffs, blown out of volcanic vents along with extrusion of the more abundant flows. A considerable amount of the greenstone in the southwest corner of the quadrangle has a texture that seems too coarse for basalt. Such rock may represent small intrusive bodies of metadiabase or metagabbro.

The lighter-colored rocks in the Post Pond member occur generally as layers from 3 to 5 feet or more in thickness intercalated in green schist or greenstone. The most typical rock in these layers is a white or buff-colored felsite, weakly to moderately schistose, with abundant small grains of white feldspar and bluish quartz ranging from 1 to 6 millimeters in diameter. The color of weathered felsite surfaces is commonly orange brown because of the oxidation of finely divided sulfides scattered through the rock. Other layers of the lighter-colored rocks are similar to the felsite in color and texture but are more thoroughly foliated and contain more quartz, therefore they are classed as quartz-feldspar-sericite schists. In a few places these layers contain beds of dark sandy slate.

Under the microscope the felsites and sericitic schists are seen to have similar mineral contents. The larger feldspar grains are generally oligoclase or albite, although orthoclase is abundant in some specimens. The grains are more or less rounded with little trace of crystal outlines. Quartz grains are also rounded and are severely strained, which probably accounts for their bluish color. Both quartz and feldspar grains may represent broken crystals in a crystal tuff. The more abundant groundmass of these light-colored volcanic rocks consists of very fine grained quartz and alkali feldspar, probably sodic plagioclase. Small or moderate amounts of sericite are always present, and smaller quantities of chlorite, spene, or leucoxene. Secondary calcite, epidote, and muscovite appear in some samples.

Upper and lower black slate members.—The greater part of the Orfordville formation in the type area consists of fine-grained metasediments characterized by dark color due to the presence of finely divided carbon and iron sulfide. These rocks are represented in the Bradford-Thetford area by dark slate, such as that exposed along the east side of Lake Morey and along the road north from the lake. The slate is generally dark gray or sooty black in color, generally without much luster on the cleavage surfaces although locally a phyllitic sheen is present. Weathered outcrops are commonly rather fissile, splitting into thin chips and outcrops stained yellow or yellowish brown are common. Thin sandy beds can be seen here and there in the slate, but generally bedding is absent. At several places in the upper part of the formation on Sawyer Mountain and east of the Connecticut River northwest of Piermont Station, the darker slate contains thin beds of lighter-gray slate or dense-textured feldspathic quartzite; locally all the beds are lighter-colored and sandy.

Thin beds of conglomerate were found in the black slate in two places in the area. One is near the west side of the road from Thetford village to North Thetford, 0.4 mile northeast from the corner marked 677 on the topographic map; the other is in a railroad cut a little more than a mile northeast of Ely. At each of these places, rounded pebbles of dark-gray sandstone and smaller fragments of light-colored quartzite are embedded in dark slate. Individual conglomerate beds are less than 5 feet thick, but conglomeratic zones, including the interbedded slate, may reach 25 feet or more in thickness.

In general no lithologic distinction can be made between the upper and lower black slate members of the Orfordville formation. Where the intervening Hardy Hill quartzite member is absent the two units are indistinguishable, hence they are not shown separately on the geologic map.

Hardy Hill quartzite member.—A layer of quartzite and quartz conglomerate, known from exposures near Lebanon, N. H., as the Hardy Hill quartzite (Chapman, 1939), occurs near the middle of the dark metasediments of the Orfordville formation. Five outcrops of this quartzite occur within the dark slates of the Sawyer Mountain belt; the most prominent of these is found on the low hill one-half mile N. 25° E. from the bridge over the Connecticut River between Bradford and Piermont, N. H. Here the Hardy Hill member is about 60 feet thick. In parts of this outcrop abundant quartz pebbles about 1 inch in average dimensions are embedded in white, sericitic quartzite. The pebbles in this, as well as in the other outcrops to the southwest, have been much flattened parallel to the foliation of the matrix and are not conspicuous. The other outcrops are all smaller and more difficult to find; their locations are shown with some exaggeration in size on the geologic map. They appear to represent a thin, possibly discontinuous, layer which has been broken into separate lenses as a result of the intense folding and shearing that has taken place in the enclosing rocks.

Sunday Mountain metavolcanic member.—The uppermost part of the Orfordville formation everywhere contains rocks of volcanic origin similar to those in the Post Pond metavolcanic member. They were named from Sunday Mountain in Orford, N. H., on which they are well exposed.

In the vicinity of Lake Morey and northward, two belts of the Sunday Mountain member flank the dark slates just described. One belt is exposed on the Palisades and Sawyer Mountain and continues across the Connecticut River into Piermont, N. H. The other begins at the north end of Lake Morey, continues northeast as a zone a few hundred feet wide between the dark slates and the Monroe fault, and crosses into New Hampshire near Piermont Station. Good exposures of the various rock types within the member can be seen on the upper west slope of the Palisades, on Sawyer Mountain, and on the unnamed hill 1 mile east of Bradford village.

As in the Post Pond member, felsite and sericite-feldspar schist commonly contain abundant distinctive grains of quartz and feldspar in a groundmass of much finer grains. Otherwise the rocks are generally uniform in appearance, without bedding or conspicuous fragments. In a few places, however, the light-colored rocks are distinctly stratified; and at one place on the northeast slope of Sawyer Mountain, small angular fragments of other rocks appear in the felsite.

Under the microscope these rocks are essentially similar to comparable types in the Post Pond member. As a whole they appear to represent rhyolite and dacite tuffs and possibly some flows.

Dark metavolcanic rocks, also abundant in the Sunday Mountain member, include indistinctly stratified chloritic schist with conspicuous bluish quartz grains, and a variety of greenstones, some porphyritic, others distinctly fragmental. Characteristic sooty, black, siliceous slate is interbedded with the darker metavolcanics on the low ridge just north of Lake Morey and on the previously mentioned hill east of Bradford. The uppermost green schists may contain thin beds of light-colored quartzite similar to those in the overlying Albee formation, and a few layers or lenses of sericitic schist and green schist occur in the upper part of the black slates below the Sunday Mountain member proper.

A study of thin sections of the greenstones and green schists indicates that these rocks are composed largely of albite feldspar and chlorite, with abundant calcite, epidote, and sphene. Quartz is abundant in some types and green hornblende occurs in others. The volcanic types represented appear to be greatly altered andesitic and basaltic flows and tuffs.

*Area southeast of the Ammonoosuc thrust.**—Rocks of the Orfordville formation exposed southeast of the Ammonoosuc thrust in the southeast part of Thetford and the northeast part of Norwich are more highly metamorphosed than elsewhere in the area. The metasedimentary rocks consist of feldspathic quartzite and staurolite-kyanite-bearing quartz-mica schists. The metavolcanic types, corresponding to the Post Pond member in the Sawyer Mountain belt, are exposed in many knobs and hills in the vicinity of Wilmot Mountain and Blood Mountain. Amphibolite and hornblende gneiss are the principal metavolcanic rocks in this area, corresponding to the greenstones in the Sawyer Mountain belt. These rocks are intercalated with light-colored, quartz-feldspar-mica gneisses, which are the equivalents of the sericitic schist and felsite described above.

* The rocks in this area are more fully described in a previous report (Hadley, 1942, pp. 171-173).

Thickness of the Orfordville formation.—Very little idea can be gained of the stratigraphic thickness of the black slate members and the Post Pond metavolcanic member in the narrow, faulted Sawyer Mountain belt. The present width of the Sunday Mountain member in this belt ranges from 500 feet east of Bradford to more than 1,000 feet at the Palisades. Some of this breadth of outcrop is due to repetition by folding; but the original thickness of the member was probably several hundred feet. Elsewhere in the Mt. Cube quadrangle, the original thickness of the Post Pond member is estimated between 2,000 and 4,000 feet and that of the metasedimentary part of the formation between 1,000 and 3,000 feet (Hadley, 1942, p. 119).

Albee Formation

Rocks of the Albee formation are exposed largely east of the Connecticut River in the northernmost part of the Sawyer Mountain belt, although two narrow tongues extend into Vermont on either side of the Orfordville formation just south and east of Bradford village. Good exposures of these rocks are found from 0.3 to 0.6 mile south-southwest of Piermont station in Bradford and on the hill a mile east of Bradford village. The rocks seen here are greenish-gray to light-gray phyllitic slate interbedded with many even layers of sugary, fine-grained white quartzite, generally less than 1½ inches thick. At several places the slate is definitely quartzose or feldspathic, showing a mixture of sandy or volcanic material, and appears to grade into impure quartzite or slaty felsite.

Age of the Albee and Orfordville formations. The Albee and Orfordville formations are everywhere unfossiliferous. Their age is suggested by relations in western New Hampshire, where they lie unconformably beneath rocks with middle Silurian fossils (Billings, 1937, p. 475). These relations indicate that the two formations are older than the middle Silurian, and it seems probable that they are largely of Ordovician age (Hadley, 1942, pp. 124-127).

DEVONIAN (?)

Meetinghouse Slate

The Sawyer Mountain belt of rocks just described is bordered on the west by a second zone of dark slate. This zone, ranging in width from 0.75 mile at Lake Morey to less than 0.1 mile at the southwestern boundary of the quadrangle, has been mapped in the adjacent Strafford quadrangle by Doll (1944, p. 19), who has named it the Meetinghouse slate from exposures on Meetinghouse Hill in the southeast corner of the Strafford quadrangle (not to be confused with Meetinghouse Hill in Thetford in the Mt. Cube quadrangle). The slate is well exposed at many places along the steep escarpment that borders the Connecticut River valley on the west between Lake Morey and Thetford village. Especially good and easily accessible exposures are to be found at Glen Falls, on Glen Falls Brook, reached by a foot path from the road along the west side of Lake Morey; and in two road cuts on U. S. Highway No. 5, one just north of its junction with Highway No. 113 and the other 0.2 mile south of the bridge over Roaring Brook between Ely and North Thetford. Typical slate of this unit may also be seen in an abandoned quarry at the base of the escarpment about 1,000 feet west-northwest from the same bridge.

The Meetinghouse slate is typically a dark-gray, lustrous, fissile slate. Its color is bluish or iron gray when compared with the greenish or sooty black color of much of the adjacent slate of the Orfordville formation; nevertheless, the two units are commonly difficult to distinguish from each other. Thin beds of white quartzite appear in all but the easternmost outcrops of the Meetinghouse slate. In outcrops washed clean by the streams descending the western side of the valley, the white quartzite layers make a striking contrast with the darker slate. The layers are generally few, less than 1/8 inch wide, and inconspicuous along the eastern side of the slate belt, but toward the west they increase markedly in thickness and abundance and form a transition into the more quartzitic Gile Mountain formation. This westward increase of quartzite beds is well shown in Glen Falls Brook. At the lower falls, about 700 feet west of Lake Morey, the dark gray slate contains a few quartzite layers. One hundred feet upstream, quartzite layers one-fourth inch to 2 inches thick appear in the slate, and at the upper falls under the foot bridge the dark slate contains many quartzite layers 1/12 to 1/5 inch wide, all considerably folded. Above the falls a series of good outcrops in a rocky gorge are about half quartzite in layers 1 to 3 inches thick. Two hundred feet northwest of the upper falls, grayish quartzite is the dominant rock but it contains interbeds of slate. In the next 1,000 feet upstream are abundant outcrops of quartzite with slate interbeds and of slate with interbeds of quartzite, the quartzite beds reaching 5 inches or more in thickness. Still farther upstream quartzite is much more abundant but contains sporadic interbeds of slate; these predominantly quartzite beds are assigned to the Gile Mountain formation.

Microscopical study of the Meetinghouse slate indicates that it consists of very fine-grained quartz, sericite, and chlorite in various proportions, together with minutely dispersed, black, opaque material.

The light-colored layers contain abundant quartz, much smaller amounts of alkali feldspar, and traces of muscovite. Tiny knots are commonly found on the cleavage surfaces of the slate; in thin sections these are seen to be "eye structures"—consisting of small clusters of leucoxene surrounded by secondary quartz and chlorite—around which the foliation of the slate is bent.

The thickness of the Meetinghouse slate can be determined only within wide limits. The beds have been intensely folded and no key beds could be found which would indicate how much of the present width of the belt is due to repetition of beds by folding. The original thickness of beds exposed in the area may have been between 1,000 and 2,000 feet; this requires a two-fold to four-fold increase in thickness in the widest part of the belt.

Gile Mountain Formation

By far the greater part of the Bradford-Thetford area is underlain by a thick sequence of interbedded feldspathic quartzite and phyllitic schist. These rocks are also widely present in the Strafford quadrangle to the west, where they were named the Gile Mountain schists by Doll (1944, pp. 18-19). In the northwestern part of the Bradford-Thetford area beds of calcareous sandstone and sandy limestone are prominent in the formation. To the north and west, in the Woodsville and Strafford quadrangles, the Gile Mountain formation is bounded by calcareous schists of the Waits River formation (White and Eric, 1944). The gradation between the Gile Mountain formation and the overlying Meetinghouse slate on the east has already been described.

The rocks of the upper part of the Gile Mountain formation adjacent to the Meetinghouse slate are well exposed on the summit and eastern slopes of Houghton Hill and in open pastures on the ridges just north of High Peak in Thetford. These rocks are light-colored to moderately dark chloritic phyllite or fine-grained quartz-mica schist interbedded with light greenish-gray feldspathic quartzite. They are, on the whole, well bedded; quartzite beds range from less than an inch to a foot or so in thickness although somewhat thicker beds occur locally. Phyllite beds range from a fraction of an inch to several feet in thickness. Thinner phyllite beds tend to be more micaceous, whereas thicker beds contain more admixed quartz and feldspar, some of which may be concentrated in thin, lighter-colored bedding laminae about a millimeter thick. In much of the phyllite, however, bedding is lacking and in parts of it the content of uniformly distributed quartz may approach that of the quartzite. A few beds of dark gray slate are intercalated with quartzite beds adjacent to the Meetinghouse slate, but such slates are absent elsewhere in the upper part of the Gile Mountain formation. All of the rocks except the most quartzose have well-developed cleavage, commonly caused by paper-thin films of mica separating somewhat thicker laminae of less foliated rock.

Under the microscope the sandier beds are seen to be composed largely of fine granular quartz and smaller amounts (20 percent or less) of alkali feldspar, probably sodic plagioclase. Both chlorite and muscovite are present in various amounts, although muscovite is generally more abundant. These micaceous minerals, especially muscovite, are much more abundant in the phyllite and schist, whose pronounced cleavage and shining lustre are produced by myriads of tiny mica flakes arranged parallel to one another. Somewhat larger crystals (porphyroblasts) of brown biotite, more rarely of green biotite or chlorite, are seen megascopically with some difficulty in the easternmost part of the formation, but they become larger and more abundant westward, where they may stand out rather conspicuously as more or less randomly oriented grains in otherwise foliated rock. Ilmenite and zircon, apparently of detrital origin, are present throughout the formation, and some secondary tourmaline is also found.

Somewhat thicker beds of feldspathic quartzite and quartz-mica schist and the coming in of thin beds of dark-colored phyllite mark the lower part of the Gile Mountain formation as exposed in the northwestern part of the Bradford-Thetford area. Such rocks are well-displayed on Spaulding Hill and the high ridge immediately east of it; also on Old Buffalo, on Narrow Hill, and on the east-west ridge just north of Rowell Brook in Bradford. In these outcrops, uniform beds of fine-grained, gray, feldspathic quartzite generally a foot to 5 feet thick, more rarely 8 to 15 feet thick, are interbedded with phyllitic quartz-mica schist, in which biotite, or biotite and garnet, are conspicuous. Tiny flakes of muscovite and biotite, generally recognizable in the quartzite beds, are mostly well oriented but are insufficient in quantity to produce more than a weak schistosity. Quartz-mica schist, the most abundant rock type, forms beds ranging from 1 to 5 feet thick. It usually consists of alternate thin layers of more quartzose and more micaceous rock in which the bedding, perhaps originally indistinct, is now further obscured by cleavages and recrystallization. Larger grains of biotite are distinctly visible, but muscovite generally retains the smaller size and lepidoblastic arrangement characteristic of the phyllite. Dark-colored beds ranging from an inch or less to a foot in thickness are present in most of these outcrops; they rarely amount to more than 5 or 10 percent of the rock seen at any one place, although a few outcrops contain as much as 50 per cent of dark beds. These beds are composed of iron-gray phyllite, thickly studded with metacrysts of biotite and garnet. Staurolite is sparsely distributed in such beds in the northwest corner of the quadrangle. The original cleavage of this phyllite is nearly everywhere intensely folded or crinkled, which, together with the abundant metacrysts, gives the rock a more or less coarse-textured and nonschistose aspect. Beds of dark gray, sandy limestone are associated with the dark phyllite here and there in the Gile Mountain formation in the north-central part of the area. Generally these isolated beds are only a foot or so wide, but wider zones of dark limestone apparently occur without much exposure on the west slopes of Spaulding Hill. also in a north-south trending swale 0.75 mile north of Blood Brook School, and on the ridge north of Rowell Brook 0.45 mile southeast of School No. 7.

North of Bear Notch and Old Buffalo, in the extreme northwest corner of the quadrangle, calcareous beds are common. These rocks range from gray sandy limestone and calcareous sandstone to calcite-quartz-mica schist and are interbedded with noncalcareous schists and quartzite.

As seen in thin section, quartzite and quartz-mica schist of the upper part of the Gile Mountain formation consists largely of granular quartz with indeterminate but probably small amounts of andesine feldspar, along with muscovite, biotite, and traces of detrital magnetite, ilmenite, zircon, and apatite. Some specimens contain considerable calcite. The dark phyllite beds are characterized by abundant muscovite, with quartz and feldspar similar to that in the quartzites. Brown biotite forms large ellipsoidal grains, also smaller flakes parallel to the foliation. Abundant opaque dustlike material, presumably composed of carbon particles, is characteristic of the dark phyllite, and traces of ilmenite or sphene are present.

The thickness of the Gile Mountain formation as a whole cannot be measured anywhere in the area because of the diverse attitudes of the strata and the absence of any key beds by means of which the formation could be divided into more easily measurable parts. The formation is at least several thousand feet thick.

Age of the Meetinghouse Slate and Gile Mountain Formation.—No direct evidence of the age of the Meetinghouse slate and Gile Mountain formation could be obtained in the Bradford-Thetford area. They are separated from the Ordovician and younger rocks to the east by the Monroe fault. To the west, a succession of very thick units on the eastern flank of the Green Mountain anticline has the Gile Mountain formation and Meetinghouse slate as its easternmost, therefore presumably uppermost, units (White, W. S., personal communication). Next older units in east-central Vermont are the Waits River formation, Northfield slate, and Shaw Mountain formation. Crinoid remains in the Shaw Mountain formation indicate that it is Middle Ordovician or younger (Currier and Jahns, 1941, pp. 1500-1501). According to Doll (1943-a), other less well preserved fossils suggest a Silurian or Devonian age for the Waits River formation (Doll, 1943-a). Doll has also collected a specimen, believed to be a poorly preserved brachiopod, from quartz-mica schist near Strafford village just west of the Bradford-Thetford area (Doll, 1943-b) and suggests that the Gile Mountain formation may be Devonian.

INTRUSIVE IGNEOUS ROCKS

A variety of intrusive rocks, including quartz monzonite, quartz diorite, granodiorite porphyry, amphibolite, greenstone, and olivine grabbro porphyry, occur in the Bradford-Thetford area. With one exception, these rocks form small dikelike bodies, many of which are too small to be shown individually on the geologic map. The only large mass, extending from Fairlee, Vt., to Piermont, N. H., is quartz monzonite believed to be of late Ordovician age. The granodiorite porphyry and amphibolite and greenstone are probably of late Devonian age; the olivine gabbro porphyry is probably Mississippian.

Fairlee Quartz Monzonite

A coarse-grained granitic rock, relatively resistant to erosion, forms several prominent hills within the Connecticut Valley in Bradford, Vt., and Piermont, N. H., and is strikingly exposed in the cliffs known as the Palisades in Fairlee. This rock was studied by C. H. Richardson and referred to by Foyles (1928, chart opp. p. 288) as the Fairlee granite gneiss of Upper Cambrian age. Later studies have shown that the rock probably belongs to the late Ordovician Highlandcroft series of plutonic rocks in western New Hampshire (Billings, 1937, pp. 499-500; Hadley, 1942, p. 136). The rock is coarse-grained and greenish gray with local pink tinges. Its essential minerals are bluish-gray quartz, perthitic microcline, and saussuritized oligoclase or andesine, accompanied by chlorite, sericite, and green sagenitic biotite. The effects of intense deformation under conditions of low-grade metamorphism are seen in the strained and fractured quartz grains, sheared and sericitized potash feldspar, and greatly altered plagioclase. The rock is generally more or less crushed and foliated, and locally at the margins of the body it has been mashed to a dark slaty rock (phyllonite) containing remnants of less-crushed granite.

Basic Intrusives

Sill-like or dike-like bodies of more-or-less schistose greenstone and amphibolite are found in nearly all parts of the Bradford-Thetford area, and are very abundant in some places. They are mostly not well-exposed and undoubtedly many more are present than were seen during the field work. Together they amount to a large-scale igneous invasion, comparable in volume to a much larger single mass such as the Fairlee quartz monzonite. In general, these basic rocks form lenses 20 to 100 feet wide and as much as several hundred feet long. In a few places where they are sufficiently exposed, they are found to lie nearly parallel to the strike of the enclosing rocks and to have been deformed with them. The central parts of these intrusives are commonly not foliated; their margins however are well foliated with a distinct schistosity parallel to that in the surrounding rocks.

Although present more or less throughout the area, the basic intrusives are concentrated in two places. The first is a zone in the upper beds of the Gile Mountain formation, extending from Big Brook, near the north end of Lake Morey, southwestward nearly to Thetford village (Pl. 1). The zone narrows from a width of about 4,000 feet opposite Lake Morey to less than 2,000 feet south of the road from Ely to Lake Fairlee. The intrusives are most abundant in the northern and wider part of the zone, where in some places half the outcrops are greenstone. Quartzite and slate beds in the neighborhood of these bodies are commonly soaked with an iron-bearing carbonate, which on weathering leaves abundant spots of brown limonite. Similar limonite spots are very common in the intrusives themselves. The carbonate, which is the source of the limonite, appears to have been liberated from the greenstones during regional metamorphism. Although basic intrusives themselves are not so abundant in the southern part of the zone, carbonate and limonite marking its position can be traced a long distance.

The basic intrusives in the eastern zone are composed of albite or albite-oligoclase feldspar and various amounts of chlorite, epidote, carbonate, ilmenite, and leucoxene. Small phenocrysts of albite are fairly common, and some specimens contain pale or colorless amphibole. In others secondary green hornblende is present along with small amounts of biotite of metamorphic origin. The carbonate, which is commonly ankerite, gives the weathered rock a characteristically porous, iron-stained surface.

Only one of these greenstone intrusives is large enough to show on the geologic map (Dh, Pl. 1). This body, 200 feet wide and at least 1,000 feet long, is well exposed on a rocky wooded ridge 20 to 30 feet high ¾ mile north of the north end of Lake Morey. The marginal parts of this body are highly altered amphibolitic greenstone similar to that found in the smaller ones. The central part, exposed along the crest of the ridge, is medium-grained hornblende diorite; it is much less altered and shows a marked diabasic texture.

The other zone in which basic intrusives are concentrated lies along the west boundary of the area a short distance north of Lake Fairlee. The most abundant rock in the intrusives of this zone is amphibolite, containing blue-green hornblende and andesine feldspar, generally accompanied by considerable calcite.

Both amphibolite and greenstone were probably diorite or diobase originally, but they show evidence of profound alteration since they were intruded, and they have undoubtedly been metamorphosed along with the surrounding rocks. The present differences in mineralogical composition have resulted mainly from higher temperatures prevailing during metamorphism in the western part of the area.

Quartzdiorite and Granodiorite Porphyry

Several dikes of granodiorite porphyry occur in the Meetinghouse slate along the face of the escarpment west of the Connecticut River in the vicinity of Ely, Vt. They range from dikes a foot or two thick and a few tens of feet long, to larger bodies at least 100 feet thick and 2,000 feet long. The most typical rock contains conspicuous small phenocrysts of quartz and albite feldspar in an aphanitic, light-gray groundmass. Some of the quartz and albite phenocrysts have crystal outlines and measure as much as 2½ millimeters across; a few phenocrysts apparently of a ferromagnesian mineral have been altered to chlorite. Phenocrysts in the smaller dikes are commonly either smaller and less abundant, or they have been more completely altered, with the result that the porphyritic character of the rock is less noticeable. The groundmass of both large and small dikes is composed principally of very fine-grained (0.03 to 0.05 millimeters) quartz and albite or albite-oligoclase. It also contains considerable deuteric muscovite, small amounts of sericite and chlorite of metamorphic origin, and traces of magnetite, apatite, sphene, leucoxene, rutile, and ilmenite.

All the dikes lie parallel to the strike of the cleavage in the surrounding slate, and their few apophyses follow cleavage and transverse joints in the slate for short distances from the dikes. Small inclusions of slate occur here and there at the margins of some of the larger dikes. Most of the larger dikes consist of nearly massive rock without foliation or flow structures; but the rock at their margins and throughout the smaller dikes is somewhat foliated parallel to the contacts with the adjacent rocks. Slickensided surfaces indicating small fault movements are common in the marginal parts of the dikes and along the dike walls.

At the north end of the zone of porphyry dikes, just west of the southern end of Lake Morey, is a body of moderately coarse grained, non-porphyritic quartz diorite similar in size and shape to the larger porphyry dikes. This rock is composed of quartz, albite, secondary chlorite, sericite and calcite. The albite is full of minute scales of muscovite and grains of calcite, both of which are probably secondary. A small amount of coarser muscovite may be magmatic in origin. Some chlorite appears to have replaced an earlier dark mineral, probably biotite. The rock at the margin of this body is considerably foliated parallel to the contacts with the country rock, but the central part of the body is not foliated.

Two small dikes of fine-grained, subporphyritic granodiorite were found in the quartz-mica schist and quartzite of the Gile Mountain formation near the Waits River in the northwest part of the quadrangle. The mineral composition of one of these dikes is, approximately: quartz, 45 per cent; albite, 45 per cent; muscovite, 5 per cent; biotite, 5 per cent; and traces of calcite and sphene.

The smaller granitic bodies in the Bradford-Thetford area have undergone some metamorphism, yet they were obviously emplaced after the schistosity and even some of the joints in the Meetinghouse slate had formed. They are probably not older than Devonian and may belong to the late Devonian intrusive epoch.

Olivine Gabbro Porphyry

Dikes of dark ferro-magnesian rocks clearly younger than the regional folding and metamorphism, although fairly common in western New Hampshire, are relatively scarce in eastern Vermont (Main, 1942). No outcrops of such rocks in the Bradford-Thetford area are known to the writer; however the so-called "limburgite" or olivine gabbro porphyry at Thetford village belongs to this group.

Long known from erratic boulders found during the middle of the last century along the roads southeast of Thetford village, no outcrop of this rock has ever been found. The source of the boulders, however, appears to lie beneath a covering of till 2,000 feet due east from the crossroads at Thetford village. This spot is at the northern apex of a train of boulders displaced from the original outcrop by moving ice (Chivers, 1938). F. H. Main of the Department of Geology, Dartmouth College, using a dip needle in the area of the apex of the boulder train, concluded that the boulders came from a body 20 to 40 feet wide and about 900 feet long, trending N. 30° E. (Main, 1942).

Boulders of the porphyry are typically more or less rounded and have dark brown somewhat pitted surfaces suggestive of stony meteorites. Freshly broken surfaces are dull, nearly black, and marked by abundant green spots composed of wholly or partially serpentinized olivine grains. Cleavage surfaces of dark gray augite phenocrysts are also conspicuous.

According to E. O. Hovey (1894, pp. 162-163) the rock is composed of unusually large, rounded and embayed masses of olivine and augite set in a fine-grained groundmass consisting mainly of augite and calcic plagioclase. Magnetite, ilmenite, apatite, brown hornblende, and pyrite are accessory minerals, whereas serpentine, chlorite, and calcite are alteration products. Some finer-grained types associated with the olivine-bearing boulders are similar to camptonite found elsewhere in eastern Vermont and in New Hampshire. These rocks and similar ones throughout New Hampshire have been correlated with a group of intrusives known as the White Mountain magma series, probably of Mississippian age (Billings, 1937, p. 517).

STRUCTURE

The rocks of the western part of the Mt. Cube quadrangle are divided into three structurally distinct belts by two major faults, the Ammonoosuc and Monroe faults (Pl. 2). As the Ammonoosuc fault and the belt of rocks immediately east of it have been described (Hadley, 1942, pp. 154-158), principal attention will be directed herein to the Monroe fault, the Sawyer Mountain belt between the two faults, and the area west of the Monroe fault.

AMMONOOSUC THRUST FAULT

The fault that bounds the Sawyer Mountain belt on the southeast has been traced from the valley of the Ammonoosuc River near Littleton, N. H., southwestward to the northeast part of the Bradford-Thetford area (Billings, 1937, map; also geologic map of part of the Woodsville quadrangle, unpublished). The movement on this fault, which amounted to at least three miles, (Billings, 1937, pp. 528-529), took place after regional metamorphism, bringing less metamorphosed rocks on the west side of the fault into contact with more highly metamorphosed rocks on the east side. Features associated with the fault in the Bradford-Thetford area include brecciated and silicified rock, crumpled and contorted cleavage, and at a few places ultramylonite (Hadley, 1942, pp. 154-158). An unusual exposure of silicified rock at the fault surface may be seen immediately northeast of a tiny pond 0.6 mile due west of the summit of Wilmot Hill in the southeastern part of Thetford township. The west-dipping surface of this mass of silicified rock is believed to represent approximately the dip of the fault at this point.

MONROE FAULT

The Monroe fault, which separates the rocks of the Orfordville formation from the Meetinghouse slate in the Bradford-Thetford area, is a fundamental break in the rocks of western New Hampshire and eastern Vermont. It has been traced from its type area near Monroe, N. H., a few miles north of Woodsville, southward through the Woodsville, Mt. Cube, and Strafford quadrangles to the north border of the Hanover quadrangle, a distance of more than 70 miles (Eric, White, and Hadley, 1941; Doll, 1944). Throughout its length the fault separates a group of formations widespread in western New Hampshire from other formations equally widespread in eastern Vermont.

Throughout the Bradford-Thetford area, the Monroe fault separates the Meetinghouse slate on the west from the Albee and Orfordville formations which successively abut against it on the east. For 3½ miles north of Lake Morey the rocks on either side of the fault are well-exposed. Detailed mapping in this area at a scale of 750 feet to an inch shows that the fault follows a somewhat sinuous course between dark slates with local thin quartzite beds on the west side, and rocks of the Albee formation and the Sunday Mountain member of the Orfordville formation on the east. On a low knoll just north of the farm road, 2,000 feet S. 40° W. from the railroad crossing at Piermont Station, dark gray slate with abundant thin quartzite layers (Meetinghouse) abuts discordantly against light greenish-gray sandy slate and feldspathic quartzite of the Albee formation. Although the fault strikes nearly north-south at this point, cleavage and closely folded bedding in the rocks on both sides strike N. 30° E.

At two places along the fault about a mile north of Lake Morey, small outcrops of quartz conglomerate (not shown on map, Pls. 1 and 2) were found in the expected position of the fault. These are thought to represent blocks of the Hardy Hill quartzite member of the Orfordville formation torn from the east side of the fault.

South of Lake Morey, black slate of the Orfordville formation and, in the southern part of the area, greenstone of the Post Pond metavolcanic member lie against the fault. Where the fault crosses the Ompompanoosuc River a few feet north of the bridge at Union Village (Strafford quadrangle), the greenstone is well exposed, and the fault passes through a concealed interval about 30 feet wide separating it from an unusually sandy phase of the Meetinghouse slate.

No exposure of the fault itself was found, although at several places outcrops within a few feet of the fault were seen. At none of these places is there evidence of unusual contortion of beds or cleavage, brecciation, or slickensiding resulting from movement on the fault. Foliation surfaces in the nearby rocks remain undisturbed. It seems, therefore, that most of the fault movement occurred before the regional metamorphism. About 2 miles north of Lake Morey, a westward deflection in the course of the fault is accompanied by an aberrant northwest trend in beds of the Albee formation and by northeast-trending slip cleavage and shear folds in the rocks on both sides of the fault. From this it seems certain that both the fault and the beds on either side have been affected by late-stage shear-folding movements cutting diagonally across the fault. The dip of the fault is not definitely known, but it must be fairly steep. Unfortunately, deviations in the strike of the fault make its topographic expression unreliable as an indication of dip.

Thus the Monroe fault appears to have been established before the metamorphism of the adjacent rocks, and to have been involved in at least the later stages of the folding. Because the stratigraphic relations of the rocks west of the fault to those on the east are not known, the amount and direction of displacement on the fault is likewise not known. However, the presence in the Bradford-Thetford area of blocks of the Hardy Hill quartzite member of the Orfordville formation along the fault suggests that the rocks to the west were brought upward relative to those on the east. Accordingly the fault may represent a thrust from the west, developed relatively early in the tectonic history of the region.

SAWYER MOUNTAIN BELT

At the northern end of the Sawyer Mountain belt is a well defined anticline, in which dark slates and metavolcanic rocks of the upper part of the Orfordville formation plunge northeastward under highly folded beds of the Albee formation. Minor folds in these rocks are more or less isoclinal, and both bedding and cleavage dip with steep to moderate angles toward the southeast. As far south as Lake Morey, the Sunday Mountain metavolcanic member of the Orfordville formation appears on both limbs of this fold; but farther south the member is cut out by the Monroe and Ammonoosuc faults. The two northernmost outcrops of the Hardy Hill quartzite member apparently lie on the east limb of the anticline; but the southernmost outcrop, in the vicinity of North Thetford, must lie on the west limb, as probably do the two isolated outcrops west and north of Sawyer Mountain. The absence of outcrops of the Hardy Hill on the west limb north of Piermont Station is interpreted as indicating a thrust fault, by which a part of the west limb including the Hardy Hill member is cut out.

South of Lake Morey the anticlinal character of the Sawyer Mountain belt is hardly recognizable, for almost the entire east limb is cut out by the Ammonoosuc thrust fault. On the west limb, also, most of the units present farther north are cut out by the Monroe fault, leaving only the Post Pond member between the two faults at the southern boundary of the quadrangle. Bedding and cleavage in this southern part of the belt are generally vertical or dip steeply eastward, although a few erratic northeast and northwest dips were also noted.

AREA WEST OF THE MONROE FAULT

West of the Monroe fault, the well-bedded rocks of the Gile Mountain formation appear in numberless minor folds ranging from a few inches to many feet across. These folds are visible in most outcrops of the formation but are especially well displayed in cross section on the surfaces of steeply dipping transverse joints (Figs. 2 and 3).

The attitude and the amount of compression of the minor folds differ considerably from place to place. South of Lake Morey and Lake Fairlee (Pl. 2), the axial planes strike more or less north and dip 50° to

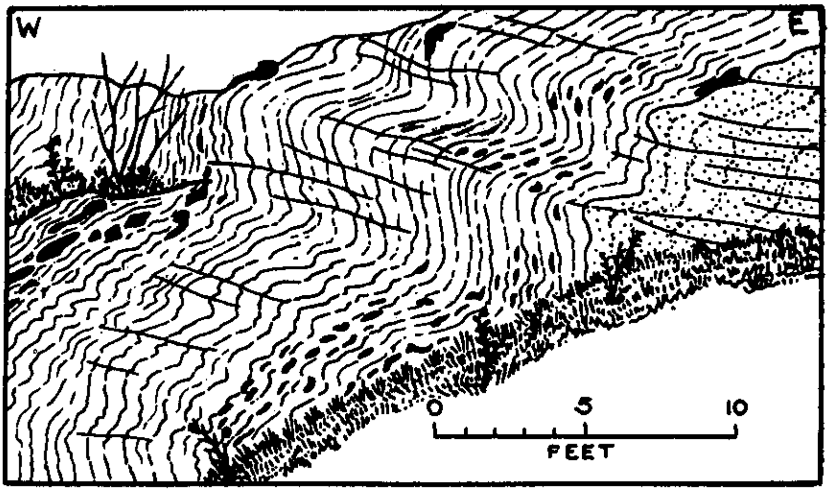

FIG. 2. Folded quartzite and quartzose schist of the Gile Mountain formation seen on south-sloping joint face on Narrow Hill (sketched from photograph). Older schistosity is parallel to bedding; slip cleavage is parallel to axial planes of folds. Shear joints concentrated in the more quartzose layers; quartz pods in the more micaceous ones.

80° E. In the northeastern part of the area, north strikes and moderately steep easterly dips (40° to 65°) prevail; northwest strikes and gentler northeast dips (20° to 50°) are found in the northwestern part. The folds are less compressed in the eastern and southern parts of the area, where the angle between the limbs is commonly 90° or more and

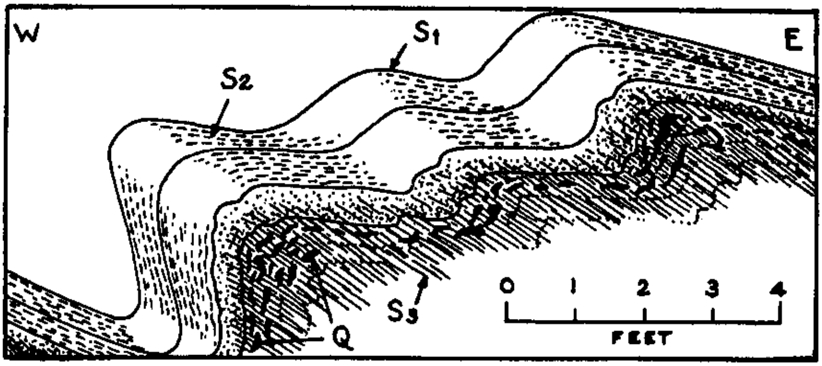

FIG. 3. Shear folds in quartzite and schist of the Gile Mountain formation, north end of Wormwood Hill, West Fairlee (sketched from outcrop). S_1 = bedding; S_2 = older schistosity in quartzite beds; S_3 = younger slip cleavage in schist beds. Q = quartz pods following folded older schistosity in schist beds. Note absence of older schistosity in the apical regions of folded quartzite beds.

is rarely less than 60°. In the northwest corner of the quadrangle, however, this angle decreases to as little as 20° in some folds.

The axes of the minor folds in the Gile Mountain formation plunge nearly due north with remarkable uniformity throughout the area. Plunges between 5° N. and 20° N. are the rule in the western part; they are somewhat steeper (25° N. to 50° N.) in the eastern and southern parts.

The abundance of these minor folds, especially in the absence of any key beds within the Gile Mountain formation, effectively conceals the gross or regional attitude of the formation. Nevertheless, a careful survey of the overall attitudes of folded beds in the larger outcrops in the eastern and southern parts of the formation shows that north or northwest dips between 10 and 60 degrees prevail. Therefore it seems likely that the formation here has a regional northwest dip in the neighborhood of 30 or 40 degrees. In the northwest part of the area, similar overall dips apparently range from 10° to 35° N. (see Pl. 2, section A-A′).

A remarkable structural feature of the Gile Mountain formation is that the dominant schistosity or slaty cleavage antedates the observed folds, for it is generally more or less parallel to bedding and the two are folded together. In the phyllite beds, where the schistosity is best developed, it is commonly intensely crinkled. Moreover, the crinkles are highly systematic in their attitudes and their plunge is always parallel to that of the axes of the minor folds. They are, in fact, minute folds developed in the original schistosity surfaces where these surfaces are cut by a series of closely spaced shear planes essentially parallel to the axial planes of the minor bedding folds. Movement along the shear planes has bent some of the mica flakes away from the original schistosity surfaces and toward the new shear planes. Where a considerable amount of such bending has occurred and a sufficient number of mica flakes have been rotated into the new planes, a new schistosity or *slip cleavage* has resulted. In other places, where the amount of bending is less, a closely spaced fracture cleavage results, rather than a slip cleavage; and in some places no cleavage at all results, although the subparallel planes containing the axes of the crinkles are well enough defined to be measurable. This slip cleavage or its equivalent is easily recognized in the more micaceous beds of the Gile Mountain formation. Where it can be so distinguished it is shown by a special symbol on the structure map (Pl. 2). Because of the systematic relation between slip cleavage and minor folds, these symbols also constitute an accurate representation of the attitude of the axial planes of minor folds in this part of the area, and the attached arrows indicate the plunge of these folds.

A rather weak schistosity, fairly common in the quartzite beds of the Gile Mountain formation in the extreme western part of the area, is nearly parallel to the bedding and, like the slaty cleavage of the phyllite, belongs to an earlier stage of deformation (Fig. 3). It is folded along with the quartzite beds and is preserved only on the limbs of these folds, for in the apical parts of the folds the older mineral alignments seem to have been destroyed. Not enough mica is present in the quartzite beds to permit the formation of slip cleavage; but shear fractures parallel to the axial planes of the folds are common in the more quartzose beds (Fig. 2).

Although the older schistosity and younger slip cleavage are clearly distinguishable throughout the central part of the area west of the Monroe fault, this is not true of the eastern and westernmost parts, of this area. Along the west edge of the quadrangle, south of Wormwood hill, only one foliation is commonly seen. This appears to be a result of more intense folding and accompanying recrystallization there than elsewhere, whereby phyllites have been converted to schists and all trace of their older schistosity has been destroyed by transposition and growth of micas in the new foliation planes.

In the eastern part of the area, minor folds in quartzite beds in the Meetinghouse slate are commonly very tight or isoclinal, and slip cleavage, if present, is not distinguishable from the normal slaty cleavage. At many places, however, these closely folded rocks are unusual in that they break along the bedding, yielding remarkable S-shaped specimens of folded beds. Close examination shows that this unusual parting results from the presence of a folded schistosity, which is more or less parallel to the bedding and serves as a parting plane. Very closely spaced slip-cleavage planes crossing this schistosity can be seen with a hand lens and under the microscope in thin sections taken from the apical regions of small folds. Throughout much of the slate, however, shearing movements essential to the formation of slip cleavage probably took place along the surfaces of the previously formed slaty cleavage; therefore no second cleavage appeared.

The widespread presence of folded schistosity in the area west of the Monroe fault indicates that the beds there have undergone an earlier stage of deformation, in which the phyllitic cleavage or schistosity was developed, and that they have subsequently been refolded in accordance with a very different arrangement of stresses. It would thus be logical to find in the area some folds related to the earlier stage of folding. Although such folds were found at very few places west of the fault, they are common in the Sawyer Mountain belt, which seems to have been little affected by the later deformation. Schistosity in this belt is generally not crinkled and remains parallel to the axial planes of simple folds formed during the earlier stage.

METAMORPHISM

Much of the bedrock in the Bradford-Thetford area represents sedimentary and volcanic rocks that have been profoundly metamorphosed by heat and pressure deep within the earth's crust. The effect of heat has been to develop new minerals such as biotite, hornblende, garnet, and staurolite (not ordinarily abundant in sedimentary or volcanic rocks), and that of pressure has been to form the parallel alignments of micaceous minerals which result in schistosity, slaty cleavage, slip cleavage and other foliated structures. Cleavage and foliation are well developed throughout the area; the effects of heat, however, are not uniformly distributed.

It has been shown in many areas that a gradual rise in the temperature of argillaceous or shaly rocks during metamorphism is accompanied by the development of an orderly sequence of minerals, each of which requires a higher temperature than the last for its formation from the materials present in the rock. The most common sequence in order of increasing temperature is: chlorite, biotite, garnet, staurolite and kyanite, and sillimanite. All these minerals except sillimanite occur in the rocks of the Bradford-Thetford area, and their distribution indicates a systematic increase of temperature toward the northwest.

Chlorite is the only one of these minerals present in the rocks of the Sawyer Mountain belt; it imparts much of the green color to the greenstone and green schists and is also present more or less abundantly in the black slates. Chlorite is found throughout the Meetinghouse slate also. A short distance west of the Meetinghouse slate belt, however, tiny grains of *biotite* appear in the quartzites and chloritic phyllites of the Gile Mountain formation. The biotite isograd, or line which indicates the southeastern limit of outcrops in which biotite was found, closely parallels the western border of the Meetinghouse slate, as shown on the geologic map (Pl. 1). Northwestward from this line, biotite porphyroblasts, at first tiny and obscure, become more prominent, until, half a mile to a mile west of the isograd, biotite has almost completely supplanted chlorite and individual biotite grains reach a length of a millimeter or more. Beyond this point the rocks have lost their greenish color and are various shades of gray. Most of the biotite in these rocks has the normal reddish-brown color, but some thin sections show that the earliest biotite to develop in the vicinity of the biotite isograd is a green variety. There is similar evidence that the growth of small porphyroblasts of chlorite preceded development of biotite in some rocks, but that they were quickly changed to biotite as the temperature increased.

Garnet first appears 1 to 2 miles west of the biotite isograd. Well-formed dodecahedral crystals of red or pink garnet a millimeter or two in diameter occur along with biotite porphyroblasts in the more micaceous beds, and less conspicuous grains of garnet were found in some of the quartzites. Dark-brown *staurolite,* does not appear until considerably farther west, where it is found as shapeless grains, and more rarely as prismatic crystals as much as an inch long, in the vicinity of Old Buffalo and in the area to the north of it. Traces of *kyanite* also are found in quartz-mica schist along the western quadrangle boundary, west of the staurolite isograd and south of Wormwood Hill. Rocks favorable for the growth of staurolite and kyanite, however, are apparently not abundant in this part of the formation. Although *sillimanite* was not found in the Bradford-Thetford area, it is reported from the Strafford quadrangle 6½ miles west of High Peak (Jacobs, 1944, p. 34).

Biotite, garnet, and staurolite were formed in the rocks of the Gile Mountain formation sometime *after* the later stage of deformation in the Bradford-Thetford area. This is shown, first, by the concentration of biotite porphyroblasts in slip cleavage or fracture cleavage planes; and second, by the fact that the larger porphyroblasts commonly lie across slip cleavage planes without being rolled or broken. On the other hand, flakes of sericite or fine-grained muscovite throughout the area are rotated, if not actually bent, by motion along the slip cleavage planes. Schistosity-forming chlorite behaves similarly to sericite in being rotated, although some chlorite occurs in undeformed porphyroblasts.

Thus there are two distinct stages of development of metamorphic minerals in the area, as well as two stages of deformation. The earlier stage seems to have progressed no farther than to produce chloritic schists, and muscovitic slates and phyllites, composed of minerals characteristic of relatively low temperatures. The metamorphism of this stage appears to be truly regional, accompanying the earlier folding and affecting all the rocks of central and eastern Vermont and western New Hampshire. During the waning of the later stage of deformation, higher temperatures were achieved in much of the Bradford-Thetford area and in the Strafford quadrangle to the west. The presence in or near the zone of higher temperature of granitic bodies such as those at Barre and Ryegate, Vt., and the Brocklebank granite in the Strafford quadrangle suggests that a connection, although probably indirect, exists between these intrusives and the later stage of thermal metamorphism in the region.

ECONOMIC ASPECTS OF THE GEOLOGY

Although no large mineral deposits have been found in the Bradford-Thetford area, some minerals and rocks of commercial value have been obtained there in the past.

A lead-zinc prospect, now caved and overgrown with trees, was found on the crest of a ridge half a mile northeast of the crossroads at Thetford village. The opening was a trench 15 feet wide, more than 8 feet deep and 80 or 100 feet long in quartzite and slate of the Gile Mountain formation. No exposure of the vein was seen; but abundant material on the dump shows galena, pale yellow sphalerite, vuggy quartz, and brownish carbonate gangue in brecciated quartzite.

An extensive copper prospect was formerly opened in the rocks of the Post Pond member of the Orfordville formation on the northwest slope of Blood Mountain in Norwich. A very large hole and many smaller ones were dug in search of copper ore during the period of active copper mining in Orange County according to W. S. White (personal communication).

Roofing slate was formerly obtained from a large quarry in the Meetinghouse slate at the base of the escarpment west of the Connecticut River half a mile southwest from Ely school. The slate in this quarry is tough, fissile, and has an unusually straight cleavage, bent at wide intervals by late-stage shearing movements. A few shaped and pierced slates can be found on the floor of the quarry.

Granite, used locally in foundations, houses, bridge abutments, hitching posts, etc., was taken largely from the Fairlee quartz monzonite. Most of the material used came presumably from talus blocks, as little quarrying has been done.

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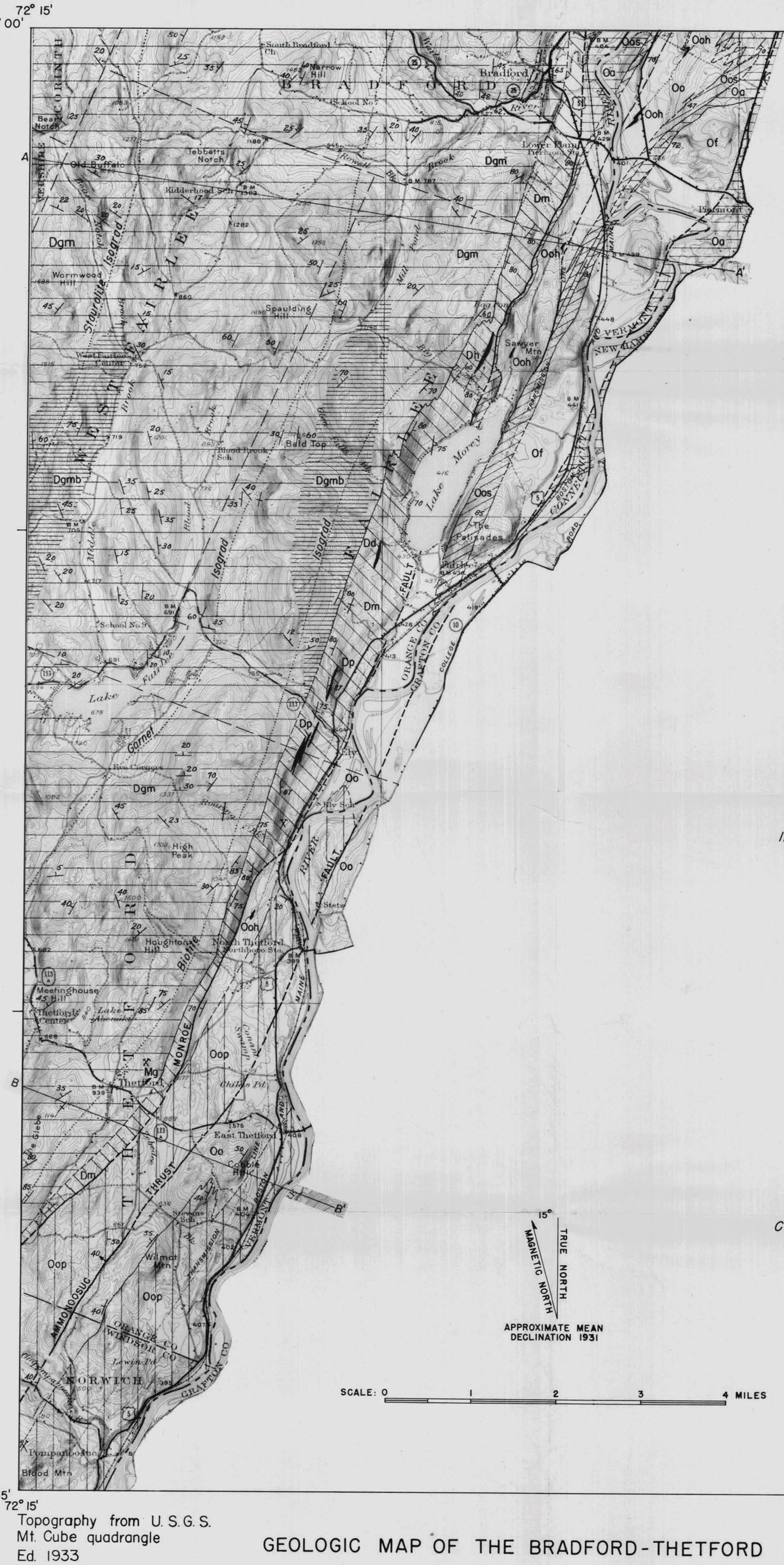


EXPLANATION

CARBONIFEROUS (?)

Mg — Olivine gabbro porphyry

DEVONIAN (?)

Dp — Granodiorite porphyry

Dd — Quartz diorite

Dh — Hornblende diorite

Dm — Meetinghouse slate
Lustrous dark gray slate, in part containing many thin white quartzite beds

Dgm, Dgmb — Gile Mountain formation
Interbedded feldspathic quartzite and phyllite or quartz-feldspar-mica schist, with interbeds of sandy limestone and dark gray porphyroblastic phyllite in the lower part (Dgm). Same invaded by basic dikes (Dgmb)

ORDOVICIAN

Of — Fairlee quartz monzonite

Oa — Albee formation
Interbedded light-gray slate and quartzite

Oos, Oo, Ooh, Oop — Orfordville formation
West of Ammonoosuc thrust: dark gray to black slate (Oo) with quartzite lenses representing the Hardy Hill quartzite member (Ooh); Sunday Mountain metavolcanic member (Oos) and Post Pond metavolcanic member (Oop) consist of greenstone, chloritic schist, felsite, and quartz-feldspar-sericite schist. East of Ammonoosuc thrust: feldspathic quartzite and quartz-mica schist (Oo); Post Pond metavolcanic member consists of amphibolite, hornblende gneiss and quartz-feldspar gneiss (Oop)

30 — Strike and dip of beds
Commonly overall attitude of folded beds

Strike of vertical beds

40 — Fault, showing dip
Dashed where approximately located

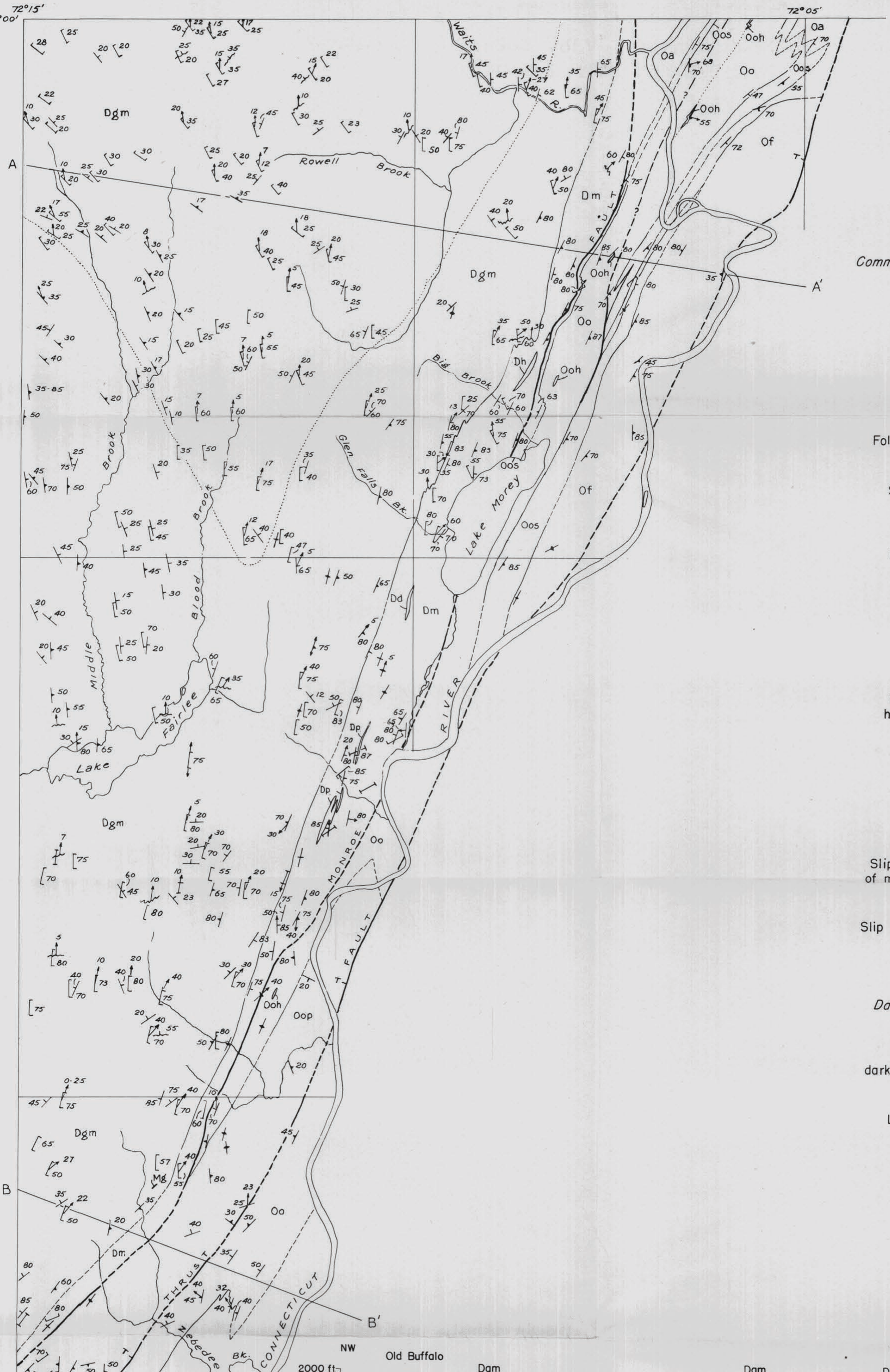
Prospect or quarry

Topography from U. S. G. S. Mt. Cube quadrangle Ed. 1933

Geology by Jarvis B. Hadley, 1948

GEOLOGIC MAP OF THE BRADFORD-THETFORD AREA
ORANGE COUNTY, VERMONT

PLATE 2



EXPLANATION

Strike and dip of beds
Commonly over-all attitude of folded beds

Strike of vertical beds

Strike and dip of beds
Showing direction and plunge of minor folds

Folded beds with plunge of minor folds

Strike and dip of schistosity, slaty cleavage or foliation

Strike of vertical schistosity, slaty cleavage or foliation

Strike and dip of schistosity with direction and plunge of minor folds in bedding

Strike and dip of schistosity with horizontal minor folds in bedding

Strike and dip of slip cleavage

Strike of vertical slip cleavage

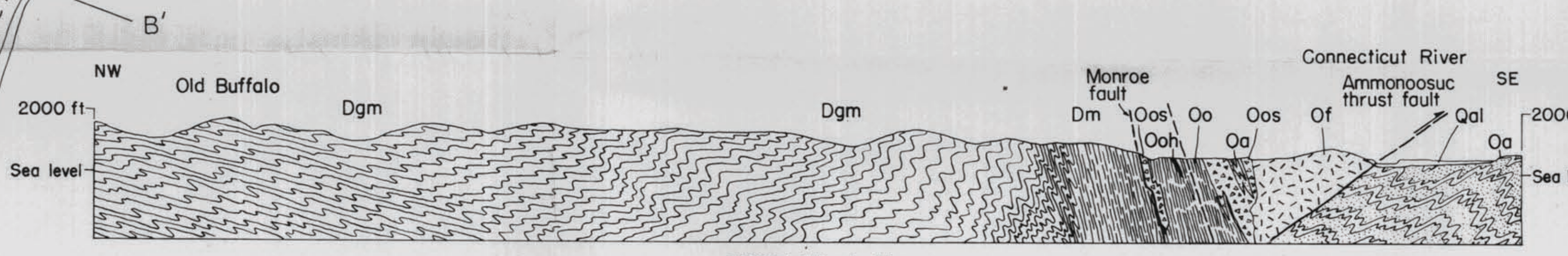
Slip cleavage with direction and plunge of minor folds in schistosity and bedding

Slip cleavage with horizontal minor folds in schistosity and bedding

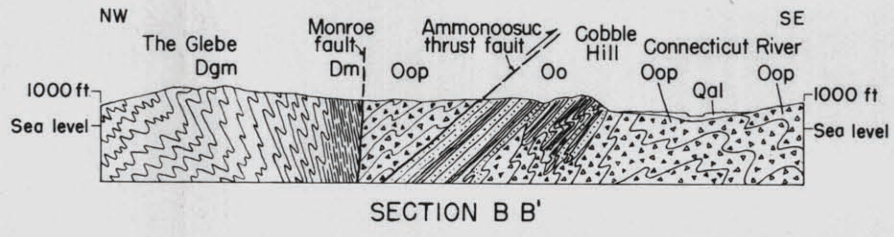
Fault, showing dip
Dashed where approximately located

Approximate southern limit of dark colored and calcareous beds in the Gile Mountain formation

Letter symbols as on geologic map



SECTION A-A'



SECTION B B'

Base from U.S.G.S.
Mt. Cube quadrangle

Geology by Jarvis B. Hadley, 1948

STRUCTURE MAP AND SECTIONS
BRADFORD - THETFORD AREA, ORANGE COUNTY, VERMONT

SCALE: 0 1 2 3 4 MILES