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Stratigraphy, Structural Geology, and Metamorphism of the Waterville-Vassalboro Area, Maine

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STRATIGRAPHY, STRUCTURAL GEOLOGY, AND METAMORPHISM OF THE WATERVILLE-VASSALBORO AREA, MAINE

ABSTRACT

The Mayflower Hill Formation, the Waterville Formation, and the Vassalboro Formation have been delineated in the Waterville-Vassalboro area. Both the Mayflower Hill and the Vassalboro Formations are dominantly heavy bedded, blue-gray wacke. The Waterville Formation consists of greenish gray, thinly laminated phyllite and limestone in the central part of the area, but to the west it contains heavy beds of wacke as well.

Sedimentary features at the formational contacts indicate that the stratigraphic order, from oldest to youngest, is Mayflower Hill Formation, Waterville Formation, and Vassalboro Formation. Fossils suggest that the Mayflower Hill Formation is upper Llandovery in age, and that the Waterville Formation is Wenlock or Ludlow in age.

Bodies of biotite granodiorite and binary quartz monzonite intrude the sedimentary units. These bodies are interpreted to be of Middle Devonian age.

Folds formed in three episodes of deformation. The earliest folds are the dominant structural element. They are represented by isoclinal folds with northeast axial traces. A second generation of folds, superposed on the isoclinal folds, are asymmetrical and have northeast-trending axial surfaces. A much younger deformation is represented by conjugate asymmetrical folds, conjugate flexures, and kink-bands.

Contact metamorphic aureoles are associated with the intrusive bodies in the northwest part of the area. To the south, however, the contact metamorphism is overprinted by a younger regional metamorphism of the Buchan type. Garnet, andalusite-staurolite, cordierite, and sillimanite isograds have been mapped in pelite. The regional metamorphism is interpreted to have a Permian age.

INTRODUCTION

Purpose

Geological studies were undertaken in the Waterville-Vassalboro area in an attempt to further the understanding of the stratigraphy and structural geology of south-central Maine. These studies have regional importance. Two fossil localities near Waterville and the stratigraphic relationships determined there form part of the basis for dating rocks in southeastern New Hampshire, central Massachusetts and central Connecticut. In addition the area affords an excellent opportunity to study the progressive metamorphism of pelite and associated calcareous rocks from the low chlorite zone into the sillimanite zone.

Location

The Waterville-Vassalboro area lies in south-central Maine between west longitude 69°35′ and 69°50′ and north latitude 44°20′ and 44°35′ (see Index Map, Fig. 1). It covers parts of the Augusta, Norridgewock, Waterville, and Vassalboro quadrangles of the Topographic Atlas of the United States Geological Survey.

Waterville, the largest city within the area, is situated in the north central part of the region. Augusta lies just south of the mapped area.

Topography and drainage

A surface of low relief averaging between 100 and 200 feet underlies much of the area. Rivers and streams that cut into this surface are in steep walled valleys. Rounded hills rise as much as 400 feet above the general level in the southern part of the area and as much as 700 feet in the north.

The Kennebec River is the main drainage of the area. The Sebasticook River is tributary to the Kennebec, joining it at Winslow. McGrath and Ellis Ponds, Great Pond, and Messalonskee Lake flow into the Kennebec via Messalonskee Stream; China Lake flows into the Sebasticook through Outlet Stream; and Webber Pond, Threemile Pond, and smaller ponds in the southeast part of the area drain into the Kennebec through Seven-mile Brook.

Acknowledgements

The geological study of the Waterville-Vassalboro area was done under the auspices of the Maine State Geological Survey, Department of Economic Development. The cooperation and assistance of this

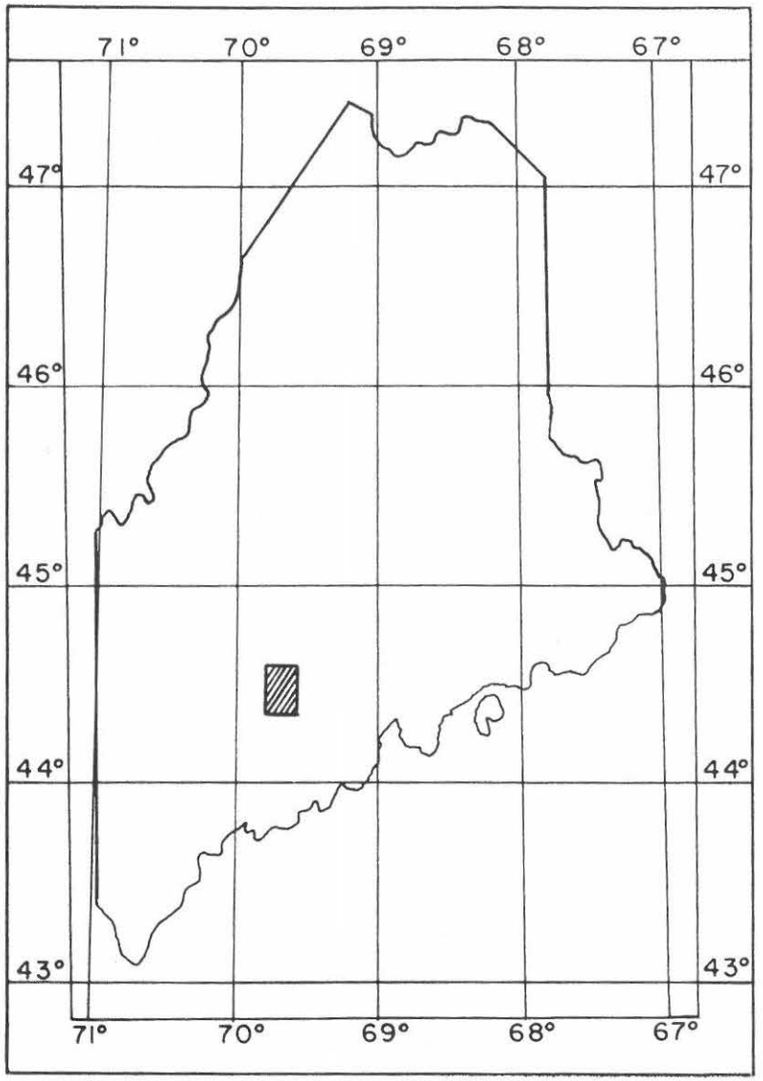


Figure 1. Location of the Waterville-Vassalboro area, Maine.

office, and particularly of Robert G. Doyle, State Geologist, are much appreciated.

In addition many geologists have provided stimulation and a more complete understanding of the regional geology. Among these are Daniel Barker, Charles V. Guidotti, Kost Pankiwskyj, Jeffrey Warner, and

Arthur Hussey. The manuscript was read and criticized by Marland P. Billings and Bradford A. Hall.

PREVIOUS WORK

Geological observations were made along the Kennebec River as early as 1839 (Jackson, 1839). Additional observations in this area were made by Hitchcock (1861, 1862). This work was rough reconnaissance.

The first significant work was that of Perkins and Smith (1925), who mapped and described the rocks within a rectangular area between Waterville and Penobscot Bay. Within the vicinity of Waterville they defined the Waterville Shale and the Vassalboro Sandstone. The Waterville Shale was assigned a Silurian age on the basis of graptolites from a quarry northwest of Waterville. The Vassalboro Sandstone was interpreted to be older than the Waterville Shale mainly because exposures of unaltered Vassalboro along the east margin of its outcrop "occur within a few rods of highly metamorphic rocks."

Raymond (1931) examined and redescribed specimens identified as *Phyllodocites* and *Nereites* from the Waterville Shale. The specimens apparently belonged to a mixed collection taken from the west shore of the Kennebec River at the old campus of Colby College and from a railroad cut near Benton.

Keith (1933) compiled a preliminary geologic map of Maine. His map shows the rocks in the vicinity of Waterville occurring in a large north-plunging syncline and resting on Precambrian to the east, south, and west. Thus, on this map, the contact between the Vassalboro Sandstone and rocks to the south and west is inferred to be a profound unconformity.

Fisher (1941) described the geology of the Lewiston quadrangle and the surrounding terrain as far north as Waterville. His work indicated that the rocks in the Lewiston quadrangle could be traced directly into those at Waterville, and that the differences in the rocks were due to increased grade of metamorphism to the south. He recognized units equivalent to the Vassalboro Sandstone and the Waterville Shale of Perkins and Smith. He followed their interpretation and made the rocks equivalent to the Waterville Shale younger than those equivalent to the Vassalboro Sandstone.

Barker (1961) studied the granite at Augusta and Hallowell and made numerous observations on the adjacent schist and granulite. His stratigraphy follows that of Perkins and Smith in that he interprets the Waterville Shale to be younger than the Vassalboro Sandstone, and both the Waterville and the Vassalboro to rest on older units toward the east.

STRATIGRAPHY OF THE LAYERED ROCKS

General statement

Fine-grained calcareous wacke, quartz wacke, thinly interbedded phyllite and quartzite, gray limestone, and minor units of black phyllite have been mapped in the Waterville-Vassalboro area. These rocks have been grouped into three formations: the Mayflower Hill Formation, the Waterville Formation, and the Vassalboro Formation. Their distribution is shown in Plate 1.

Mayflower Hill Formation

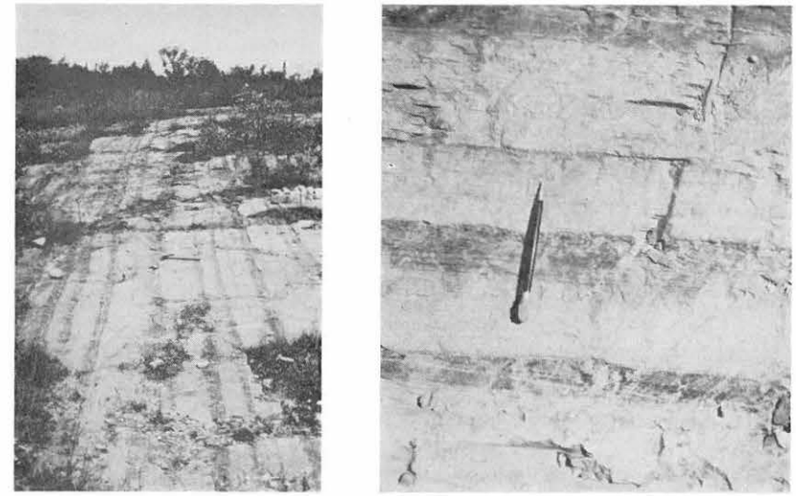
Name. The name, Mayflower Hill Formation (new name), is used to designate wacke and minor phyllite exposed in a narrow belt between Fairfield and Belgrade (Pl. 1). Good exposures may be studied at the quarry 1.1 miles 0° from Colby College, on the campus of Colby College, and 1.3 miles 97° from Oakland. The formation receives its name from Mayflower Hill, just south of Colby College.

Distribution. The distribution of the Mayflower Hill Formation is shown in Plate 1. It crops out in a band 7,000 feet to a few tens of feet wide that extends across the Waterville-Vassalboro area from the north edge of the map, two miles 335° from Fairfield, to the west margin of the map at Belgrade. A second band with a maximum width of 4,000 feet parallels the first. It extends southward from Fairfield to the vicinity of Cowan School.

Thickness. The Mayflower Hill Formation is bounded east and west by the Waterville Formation. Its contact with the Waterville Formation is gradational by interbedding over a distance of 50 feet. A thin black phyllite unit occurs within a few feet of this contact, and for convenience, it has been used to delineate the contact with the overlying Waterville Formation in Plate 1.

No estimate of thickness can be given, but it certainly must be in excess of 1,000 feet.

Lithology. Wacke and phyllite are the common lithic types of the Mayflower Hill Formation. These lithic types are vertically gradational within the same bed (Fig. 2B), the thickness of the wacke generally being eight to nine times that of the phyllite. In some places where thick beds of wacke are well exposed, they display delicate cross lamination. Black phyllite forms a single unit, 100 to 200 feet thick.



A. B.

Figure 2. Exposures of the Mayflower Hill Formation. A. Bedding characteristics of the Mayflower Hill Formation, 1.2 miles 98° from Oakland. B. Graded bedding in the Mayflower Hill Formation, 1.2 miles 98° from Oakland.

Although the Mayflower Hill Formation is exposed in the chlorite and garnet zones of metamorphism, its mineralogy is much the same over its entire outcrop.

The wacke commonly weathers white or very light gray. A close examination of the surface reveals small clasts of quartz, white feldspar, and minor slate. The clasts stand out in minute relief against the groundmass. On fresh surfaces the rock is bluish gray with a few plates of muscovite parallel to the surface of foliation. Most beds effervesce slightly with cold, dilute hydrochloric acid.

Under the microscope the wacke consists of clasts of quartz, feldspar, and minor slate in a matrix of quartz, biotite, calcite, and muscovite. Modes appear in Table 1. Clasts of quartz, 0.03mm to 0.3mm in longest dimension, are subangular. Both single and multi-

crystal clasts are common, and all show undulatory extinction. Feldspar ranges from 0.3mm to 0.5mm in size, and most of these clasts are subangular. Grains that are relatively free of inclusions and show polysynthetic twinning are sodic plagioclase, whereas those grains that are much sericiticized are aklali feldspar. Fragments of slate, 0.5mm to 0.6mm in size, consist of fine-grained quartz and micaceous minerals.

The matrix of the wacke contains abundant quartz, 0.01mm to 0.03mm in size. These grains are nearly equant, and most are strained. Biotite, in ragged plates 0.01mm to 0.04mm across, is distributed through the groundmass. Many of the plates have a crudely preferred orientation that approximately parrallels the schistosity. Biotite penetrates quartz of all sizes. Calcite forms irregularly shaped grains that mold around quartz and biotite. Grains of calcite range from 0.04mm to 0.2mm in size. Locally, biotite and quartz are included in the calcite. Muscovite forms grains that range from 0.01mm to 0.1mm in size. Their basal faces are roughly aligned and along with the biotite define the schistosity. Accessories include ilmenite, tourmaline, rutile, zircon, apatite, and chlorite.

Table 1
Modes of the Mayflower Hill Formation
(Based on visual estimates)

	1	2	3
Quartz	55%	77%	80%
Microcline Plagioclase	} 2	} 8	
Muscovite	2	6	1
Biotite	3	2	18
Chlorite		4	
Calcite	38	2	1
Accessories	<1	1	<1
Clasts	15	35	23
Matrix	85	65	77

1. Dark medium-gray (N4) massive, calcareous wacke. Drummond Avenue, two miles northeast of Waterville.
2. Light-gray (N6) massive, slightly calcareous quartz wacke. Holland Brook, 1.3 miles southwest of Fairfield.
3. Light-gray (N6) massive, slightly calcareous quartz wacke. East shore of Lake Messalonskee, 0.3 mile west of Cowan School.

Dark medium gray phyllite forms the upper part of many beds. Quartz is abundant as anhedral grains <0.02mm in size. The quartz grains are interwoven with fine-grained muscovite, the orientation of

which defines the schistosity. Biotite forms both as porphyroblasts and as small grains. These grains do not have as good a preferred orientation as the muscovite. Chlorite, ilmenite, and zircon are accessories.

Outcrops of black phyllite are commonly heavily coated with limonite and manganese minerals. The rock is well cleaved and is commonly crumpled by minor folds. Quartz and mucovite are the dominant minerals, although graphite and pyrrhotite are common.

Waterville Formation

Name. Perkins and Smith (1925, p. 220) used the name Waterville Shale to designate rocks exposed west of the Kennebec River in the vicinity of Waterville. This unit was somewhat vaguely defined and originally included the Mayflower Hill Formation of this report. As currently defined the Waterville Formation includes the pelite and interbedded limestone between the Mayflower Hill and Vassalboro Formations. It also includes interbedded quartz wacke, phyllite, and limestone west of the outcrop of Mayflower Hill Formation. For convenience, that part of the Waterville Formation exposed east of the Mayflower Hill Formation is called the eastern facies, and those rocks belonging to the Waterville Formation west of the Mayflower Hill Formation are called the western facies.

The eastern facies of the Waterville Formation is dominantly thinly laminated phyllite. A prominent member of limestone, possibly 300 feet thick, appears about midway between the top and bottom of the formation. A horizon of black phyllite can be mapped locally beneath the limestone unit (see Pl. 1).

The western facies of the Waterville Formation contains abundant quartz wacke and limestone. The limestone appears in several belts of outcrop, which may represent a single folded unit or several limestone units interbedded with the wacke in a normal sequence. Although outcrops are poorly exposed, the repetition of sequence suggests the first alternative. The distribution of the units is shown in Plate 1.

Although the rocks of the eastern and western facies of the Waterville Formation are in part lithologically different, they must be considered to be lateral equivalents. The intervening Mayflower Hill Formation, which separates the eastern and western facies of the Waterville Formation in the Waterville-Vassalboro area, is not

present south of Belgrade. South of this point the eastern facies may be traced directly into the western facies. Columnar sections comparing the eastern and western facies appear in Figure 3.

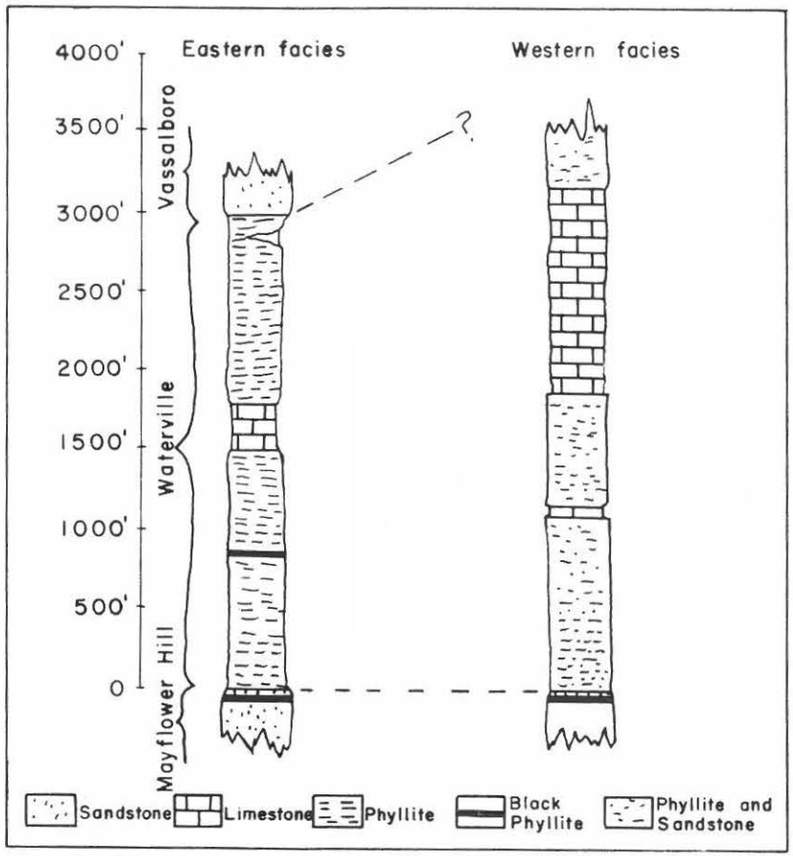


Figure 3. Columnar sections comparing the eastern and western facies of the Waterville Formation.

Distribution. The eastern facies of the Waterville Formation is exposed in a northeast-trending belt that extends from the vicinity of Fairfield to the southwest corner of the map (Pl. 1). The outcrop of the eastern facies is three to four miles wide.

Rocks of the western facies of the Waterville Formation underlie much of the northwestern third of the area (Pl. 1). Its eastern boundary extends from a point 1.4 miles 4° from Colby College

southwest to Belgrade parallel to the valley that contains Messalonskee Lake and Messalonskee Stream. Its contact with stratified rocks to the west is not exposed within the Waterville-Vassalboro area.

Thickness. The contact of the Waterville Formation with the Mayflower Hill Formation is gradational by interbedding over a distance of about 50 feet. Its contact with the Vassalboro Formation is drawn on the first massive beds of wacke. Locally a black phyllite, 0 to 100 feet thick, occurs at this contact.

The thickness of the Waterville Formation may be as great as 3000 feet.

Lithology. The rocks of the Waterville Formation are mainly greenish gray pelite, quartz wacke, gray limestone, minor black phyllite, and their metamorphic equivalents. Mineral assemblages characteristic of the low-pressure intermediate group of metamorphism defined by Miyashiro (1961, p. 283) are developed in these rocks. Modes appear in Table 2.

Greenish gray pelite characteristically consists of 1/16 inch to 1/8 inch beds of micaceous quartzite alternating with 1/2 inch to 1 inch beds of phyllite. A pronounced schistosity parallels the bedding in most places, although it truncates bedding in the noses of some isoclinal folds. At higher grades of metamorphism the schistosity is interrupted by porphyroblasts of garnet, andalusite, staurolite, and cordierite. Photographs of the pelite are illustrated in Figure 4.

In the chlorite and garnet zones of metamorphism the pelite is represented by purplish phyllite and greenish gray phyllite with or without garnet. The proportions of biotite and chlorite are variable depending on the bulk composition and the metamorphic grade. Garnet is never abundant. Purplish phyllite may be studied on Route 201 under the railroad bridge 0.3 mile south of Fairfield. Greenish gray phyllite may be examined 1.2 miles 314° from North Sidney, and greenish gray phyllite containing garnet is exposed on the east-west road 320° 1900 feet from Longfellow School.

Thin sections of pelites show quartz in rectangular or wedge-shaped grains, <0.02mm across, with mosaic articulation. Most of these grains have slightly undulatory extinction. Muscovite forms subhedral plates, <0.02mm to 0.05mm in size. It generally has good shape orientation that determines the schistosity. In all phyllites, including those without biotite, the basal x-ray spacings indicate normal musco-

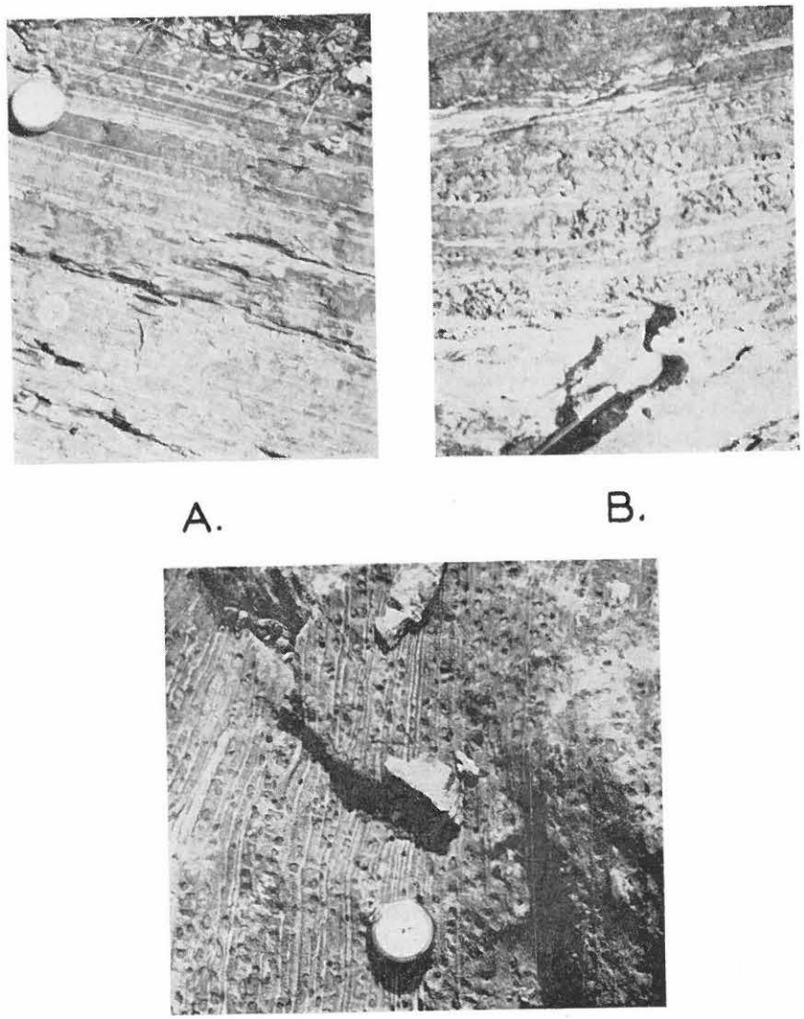


Figure 4. Thinly laminated phyllite of the Waterville Formation. A. Light greenish gray phyllite, 1.7 miles 226° from Benton. B. Light gray mica schist with porphyroblasts of staurolite and andalusite, 1.2 miles 30° from North Augusta. C. Light gray mica schist with porphyroblasts of cordierite, staurolite, and andalusite, West Sidney.

Table 2

Modes of the Waterville Formation (Based on visual estimates)

	1	2	3	4	5	6	7	8	9	10	11	12	13
Quartz	35%	40%	38%	35%	70%	75%	73%	80%	2%	1%	7%	1%	52%
Microcline						} 3	} 1	} 5					
Plagioclase					4								
Muscovite	49	33	21	20	5	17	19	3		1	1		30
Biotite		15	30	38	15	2		4	6	3	4	<1	
Chlorite	16	11	8	2	1	2	7	3	2	1			
Garnet			2	1								25	
Andalusite				3									
Sillimanite													
Staurolite				T									
Cordierite					5								
Actinolite											2	20	
Diopside												28	
Calcite								5	90	92	85	25	
Graphite													8
Pyrrhotite													10
Accessories		<1	<1	1	<1	<1	<1	<1	<1	<1	1	1	
Clasts						30	28	35					
Matrix						70	72	65					
Granoblastic						X	X	X	X	X	X	X	
Schistose	X	X	X	X	X								X

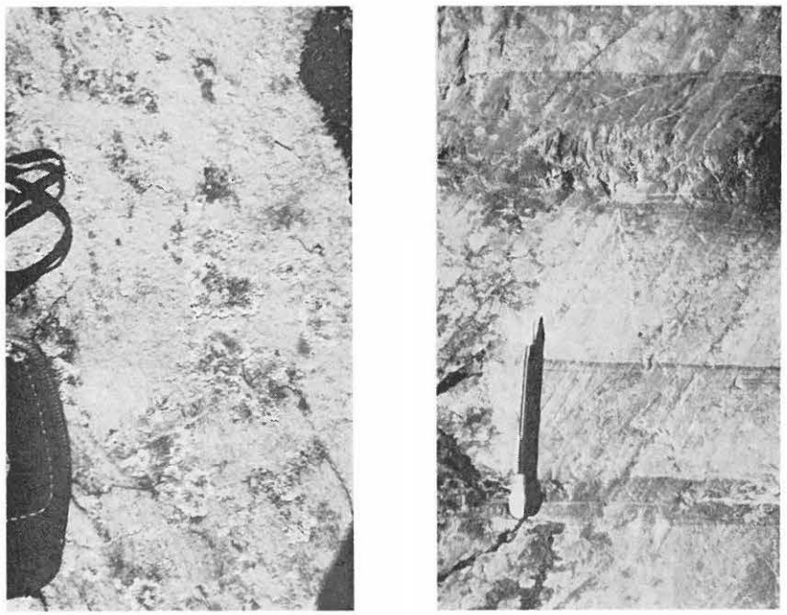
1. Greenish gray (5GY6/1) phyllite. 1.1 miles east of Winslow-Waterville bridge.
2. Greenish gray (5GY6/1) phyllite. Intersection of Drummond Road and Route 95, 1.3 miles northwest of North Sidney.
3. Light greenish gray (5GY7/1) phyllite with garnet. 0.3 mile northeast of Vassalboro.
4. Light grayish blue (5B7/1) mica schist with andalusite, staurolite, and garnet. 1.9 miles north of North Augusta.
5. Light gray (N6) mica schist with cordierite. West Sidney.
6. Medium gray (N5) massive, quartz wacke. Route 23, 2.5 miles south of Oakland.
7. Medium gray (N5) massive, quartz wacke. North end of Messalonskee Pond, 2 miles northeast of Oakland.
8. Light gray (N6) massive, slightly calcareous quartz wacke. In brook 1 mile west of Oakland.
9. Medium gray (N4) limestone, 0.2 miles northeast of BM 334, Belgrade.
10. Medium gray (N5) limestone. 1 mile northwest of North Sidney.
11. Medium gray (N5) marble. Route 95, 2.3 miles northeast of North Augusta.
12. Light gray (N3) lime-silicate granulite. 0.3 mile southeast of Stone School, North Augusta.
13. Medium dark gray (N4) mica phyllite with pyrrhotite. Hammond Brook, 2.9 miles southwest of North Sidney.

vite (not phengite). Chlorite is intimately intergrown with muscovite and is of such a grain size that in many specimens its presence can be unambiguously recognized only by x-ray methods. Biotite is porphyroblastic ranging in size from 0.02mm to 0.13mm. The plates are subhedral with somewhat ragged edges and contain minute inclusions of quartz. Many crystals do not have good preferred orientation. Garnet occurs as euhedral to subhedral porphyroblasts 0.05mm to 0.06mm across. Most grains contain inclusions of quartz and opaques. Hematite, magnetite, and ilmemite are the common opaques.

In higher grades of metamorphism the pelite is represented by light gray mica schist exhibiting somewhat coarser grain size than rocks of lower grade. Quartz, biotite, and muscovite are the dominant minerals. Garnet, andalusite, staurolite, and cordierite form in those rocks of appropriate composition and under requisite external conditions. Outcrops of quartz-muscovite-biotite-staurolite-andalusite-garnet schist may be observed along Bog and Middle Roads north of North Augusta, and cordierite-bearing schist may be seen in West Sidney.

In these rocks quartz forms a mosaic of grains 0.02mm to 0.03mm across. It occurs in both the groundmass of the schist and in quartz-rich beds and segregations. The quartz in the segregations reaches 1.3mm in size and exhibits consertal articulation. Most grains of quartz show undulatory extinction. Muscovite forms porphyroblasts as well as subhedral plates in the groundmass. The porphyroblasts are 0.3mm to 0.4mm across, whereas in the groundmass the muscovite is 0.05mm to 0.06mm in size. It has simple articulation. Much of the muscovite has preferred orientation and its parallelism defines the schistosity. Biotite tends to be porphyroblastic in some specimens, but in others it is about the same size as muscovite. Its size ranges from 0.06mm to 0.2mm. It forms subhedral plates with somewhat ragged edges, and commonly encloses quartz and zircon. Staurolite, in grains 3.4mm to 4.8mm across, forms euhedral to subhedral porphyroblasts. These crystals are crowded with inclusions of quartz, muscovite, garnet, and chlorite. A few grains show ghost-like spirals of inclusions suggesting rotation of the grain during its growth. Many staurolite crystals are twinned on [232]. Andalusite occurs as prismatic crystals 0.14mm long grouped into irregularly shaped glomeroblasts that reach a size of 2.7mm. These glomeroblasts include quartz and biotite. Garnet forms euhedral to subhedral porphyroblasts, 0.07mm to 1.3mm across. Most garnet crystals have opaque inclusions at their center with clear rims. Cordierite forms as subhedral hexagonal prisms that dissolve out to form pits on a weathered exposure (Fig.

4C). Under the microscope the porphyroblasts are 7 mm to 1 cm in length. Commonly cordierite is sieved by biotite, quartz, and some muscovite. Boundaries are symplectitic. Δ-values indicate that the cordierite is low cordierite (Miyashiro, 1957, p. 44). Chlorite occurs in nearly all specimens as plates as large as 0.2mm across. These plates cut across the schistosity indicating that their growth post dates that of the muscovite and biotite. Accessories include tourmaline, zircon, magnetite, and local pyrite.



A. B.

Figure 5. Quartz wacke in the Waterville Formation. A. Quartz wacke, 0.4 mile 92° from Oakland. B. Graded bedding in quartz wacke, spillway to Central Maine Power Station, 2.4 miles 51° from Oakland.

Quartz wacke occurs only in the western facies of the Waterville Formation. It is either gray and biotite-rich or green because of abundant chlorite. Commonly, small white grains of feldspar are prominent, particularly on weathered surfaces. The wacke occurs in beds 6 inches to over 8 feet thick (Fig. 5A). In some beds wacke grades up into dark gray phyllite (Fig. 5B). Other beds show no grading. At most exposures the wacke is cut by cleavage that truncates bedding.

Although the quartz wacke is exposed in the chlorite and garnet zones of metamorphism, the differences in mineralogy in the two zones are slight and a single description will suffice. Exposures of quartz wacke and phyllite may be examined 0.5 mile 153° from Oakland and on Route 27, 1.75 miles 0° from Sidney Church (Pl. 1).

Microscopically, the quartz wacke consists of clasts 0.03mm to 0.2mm in size set in a matrix whose grain size is generally less than 0.03mm. Clasts of quartz, feldspar, slate, and volcanic rock make up 20 to 30% of the rock. The quartz occurs as both single and multicrystalline fragments. Some of the feldspar clasts are filled with sericitic inclusions, whereas others are clear and polysynthethically twinned. The volcanic fragments contain feldspar of intermediate composition. All the clasts are subrounded to subangular and have their shortest dimension approximately perpendicular to the schistosity. The matrix of the quartz wacke consists of fine-grained quartz, and lesser amounts of biotite, muscovite, and chlorite. The micaceous minerals have preferred orientation that defines the schistosity. In some rocks the muscovite and biotite are slightly porphyroblastic. The porphyroblasts are not as well oriented as the grains of the same minerals in the groundmass. Calcite forms irregularly shaped grains in some specimens. Accessories include ilmenite, magnetite, pyrite, tourmaline, apatite, and zircon.

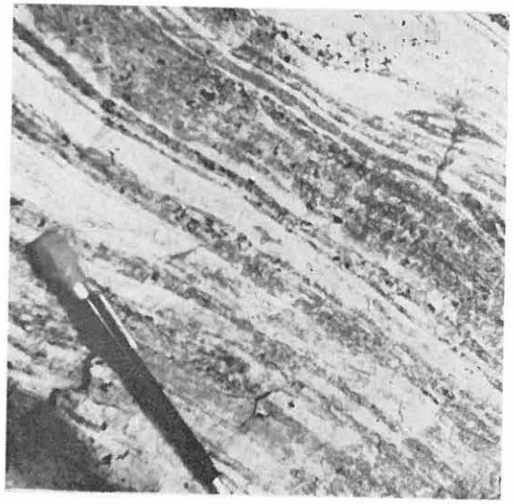
Gray limestone is present both in the eastern and western facies of the Waterville Formation. It characteristically is well bedded with 1 to 4 inch beds of limestone alternating with 1/4 to 2 inch beds of phyllite. At some localities thin beds of limestone are sufficiently sandy to display prominent cross-bedding on weathered surfaces (Fig. 6A). The limestone is cut by cleavage and numerous quartz-calcite veins. A characteristic exposure of the limestone is shown in Figure 6B.

Limestone is progressively metamorphosed from the chlorite zone through the sillimanite zone. Outcrops characteristic of the chlorite zone may be observed beneath the Waterville-Winslow bridge or the spillway of the Central Maine Power station 2.4 miles 51° from Oakland. Exposures of limestone in the garnet zone may be examined in the "Blue Rock Quarry" 1.6 miles 236° from North Sidney, and marble in the sillimanite zone may be studied in the turn-around 1.9 miles 195° from North Augusta.

In the chlorite and garnet zones of metamorphism the limestone locally contains such minerals as biotite, actinolite, and garnet.

A.

B.



C.

Figure 6. Limestone member of the Waterville Formation. A. Cross-bedding in sandy limestone, Sebasticook River, Benton Falls. B. Characteristic "ribbon" bedding of limestone, Kennebec River, Winslow bridge. C. Quartz-calcite-diopside marble interbedded with quartz-biotite-diopside schist, turn-around 1.9 miles 195° from North Augusta.

The garnet and actinolite are present in rocks of appropriate composition that have recrystallized under conditions of the higher part of the garnet zone.

On a microscopic scale calcite forms anhedral grains 0.02mm to 0.08mm in size, the coarser grain size occurring at higher metamorphic intensity. Grains have simple articulation and are not visibly twinned, although the calcite in cross-cutting veins is twinned. Quartz forms clasts 0.05mm to 0.08mm across. These grains have simple articulation and most show slight undulatory extinction. In general they are scattered through the calcite-rich layers, but locally quartz is weakly concentrated into beds. Biotite, in grains 0.06mm to 0.1mm across, is distributed throughout the rock. Biotite has fair shape orientation. Plates are subhedral and most contain minute opaque inclusions. Actinolite forms under more intense conditions of metamorphism in the garnet zone. It forms elliposidal porphyroblasts 0.9mm to 3.6mm in length which in hand specimen stand out in relief. In thin section these porphyroblasts include biotite and finely divided opaques. Garnet forms porphyroblasts 0.4mm to 0.9mm in size. Crystals are subhedral to euhedral and contain inclusions that are distributed either in diamond or square patterns. Accessories include graphite, muscovite, chlorite, apatite, ilmenite, zircon, and pyrite.

In the andalusite-staurolite, the cordierite, and the sillimanite zones the limestone is represented by marble and granulite locally containing quartz, biotite, actinolite, diopside, and/or garnet (Fig. 6C).

In general the marble and granulite at this metamorphic grade are coarser and lighter in color than those of the lower zones.

Calcite forms anhedral grains with simple articulation. Grains range in size from 0.06mm to 0.3mm. Inclusions of quartz and muscovite are present in some grains. Few show twinning. In the andalusite-staurolite zone actinolite forms bladed porphyroblasts 0.16mm to 1.7mm long. These crystals are euhedral to subhedral with somewhat symplectitic boundaries. Actinolitic hornblende forms in the sillimanite zone in rocks of requisite composition. It forms bladed crystals 0.05mm to 0.16mm long. These crystals have mutual contacts with diopside and garnet but were not observed in contact with calcite. Diopside forms stubby crystals 0.06mm to 0.2mm in size. They are subhedral and have simple articulation. Garnet occurs as porphyroblasts up to 3.2mm across. These crystals are euhedral to subhedral. Some are fractured and most include calcite, quartz, chlorite, and opaques. Biotite occurs as subhedral plates 0.08mm to 0.8mm across. It is scattered through

calcite-rich beds and is highly concentrated in the siliceous interbeds. Some grains include quartz, zircon, calcite, and opaques. Quartz, in grains 0.02mm to 0.03mm in size, forms anhedral grains with simple articulation. These grains are sparse, isolated constituents in the calcite rich beds but are the most abundant constituents in the siliceous interbeds. The larger grains of quartz show undulatory extinction. Accessories include sphene, muscovite, chlorite, plagioclase, graphite, zircon, magnetite, and pyrite.

Black phyllite is comparatively insensitive to metamorphic reconstitution within the metamorphic conditions realized in the Waterville-Vassalboro area. Consequently, a single description will suffice. Its most characteristic feature is the weathered condition of its exposures. Outcrops are coated with up to 1/2 inch of limonite and manganese minerals that color the outcrop orange and black. On fresh surfaces the rock is medium gray, and apparently unbedded. All exposures exhibit excellent schistosity that commonly is crumpled.

The microscope shows that the principal minerals are muscovite, quartz, graphite, and pyrrhotite. Muscovite forms subhedral plates that range from 0.02mm to 0.03mm in size. The crystals have good shape orientation that defines the schistosity. Quartz, in grains 0.24mm across occurs in small pods and lenses. It is anhedral and has mosaic articulation. Most of the quartz shows undulatory extinction. Graphite is intimately intergrown with muscovite. It occurs as either small plates many of which parallel the schistosity or as fine dust distributed through the rock. Pyrrhotite occurs in glomeroblasts up to 2.2mm in size. The crystals are anhedral and have somewhat embayed boundaries. Accessories include sphene, zircon, and biotite.

Vassalboro Formation

Name. Perkins and Smith (1925, p. 222) grouped the massively bedded, bluish graywacke cropping out between the Kennebec River and China Lake into the Vassalboro Sandstone. Both Fisher (1941, p. 124) and Barker (1961, p. 17) emended the name to Vassalboro Formation. Because the unit contains numerous argillaceous interbeds and because it is represented in different metamorphic grades by different textures and mineralogy, the name Vassalboro Formation is preferred.

Distribution. The Vassalboro Formation underlies somewhat less than the southeastern half of the Waterville-Vassalboro area (Pl. 1). Its contact with the Waterville Formation lies just east of the Sebasti-

cook River, crosses the Kennebec River near Vassalboro, and lies just east of North Augusta at the south margin of the map.

Thickness. Only the west contact of the Vassalboro Formation is exposed within the Waterville-Vassalboro area. This contact, against the Waterville Formation, is abrupt. Locally, a discontinuous black phyllite, 0 to 100 feet thick, separates massively bedded wacke of the Vassalboro Formation from the greenish-gray phyllite of the Waterville Formation, but where black phyllite is absent, the wacke and the greenish-gray phyllite are juxtaposed.

The thickness of the Vassalboro formation is unknown, as its eastern contact is not exposed within the area of study. However, its large area of outcrop suggests that it is at least several thousand feet thick.

Lithology. The Vassalboro Formation consists of a monotonous sequence of heavy bedded wacke with minor phyllitic interbeds. A thin black phyllite at the contact with the Waterville Formation is discontinuous along strike. Two additional black phyllite units occur within the body of the Vassalboro Formation. Their exposure, however, is insufficient to allow them to be mapped continuously, and their stratigraphic relationships are uncertain.

The rocks of the Vassalboro Formation have recrystallized in response to low-pressure intermediate metamorphism (see Miyashiro, 1961, p. 283). Exposures characteristic of low grade metamorphism may be observed on Route 137, 2.5 miles from Winslow. Outcrops characteristic of higher grade metamorphism may be seen in the quarry 1.6 miles 186° from Vassalboro and on Route 201, 1.5 miles 36° from Augusta.

Heavy bedded, light-grayish blue, slightly calcareous wacke is the dominant lithology. Thin beds of medium gray phyllite, although ubiquitous, are distinctly less abundant than the wacke. Black phyllite and quartzite are minor in amount. Modes appear in Table 3.

Beds of light-grayish blue wacke range from 3 inches to over 10 feet in thickness. Most beds are even textured and show few internal sedimentary features. Exceptions, noted locally, include scour-and-fill and crude grading. In general the beds display little of the rhythmic grading characteristic of the Mayflower Hill Formation. Schistosity is only crudely developed. Wacke that has recrystallized in higher grades of metamorphism contains ellipsoidal segregations of carbonate and lime-silicate minerals.

At the lower grades of metamorphism the wacke is represented by granulite consisting of such minerals as quartz, biotite, calcite, ankerite, chlorite, muscovite, plagioclase, astinolite, and garnet. A typical exposure is shown in Figure 7A.

In these rocks quartz forms both clasts and matrix. As clasts it is subrounded to subangular and is 0.1mm to 0.2mm in size, whereas in the matrix it is 0.02mm to 0.03mm in size. Articulation is simple. Most grains of quartz show undulatory extinction. Biotite, in grains as large as 0.05mm occurs as subhedral tabular crystals. The orientation of these plates is to a large extent controlled by the boundaries of the quartz grains, although some preferred orientation has been established over and beyond this control. Biotite has simple articulation, though many grains contain inclusions of opaques and tiny grains of quartz. Chlorite may also be present but never in the same abun-

Table 3
Modes of the Vassalboro Formation
(Based on visual estimates)

	1	2	3	4	5	6
Quartz	63%	60%	69%	32%	25%	30%
Microcline	} 5					
Plagioclase		5	3		3	
Muscovite	15			25	15	52
Biotite	1	20		35	43	
Chlorite	7			7		
Garnet						
Andalusite						
Sillimanite					10	
Actinolite		5	10			
Diopside			13			
Clinczoisite			3			
Calcite		1				
Ankerite	7					
Pyrrhotite						3
Graphite						10
Accessories	2	1	2	1	3	5

1. Light-gray (N6), fine-grained, calcareous wacke. 1.8 miles east of Hayden Corner.
2. Light-gray (N6) biotite-actinolite granulite. Quarry 1.7 miles south of Vassalboro.
3. Light-gray (N7) diopside-actinolite granulite. 0.3 mile west of Spectacle Pond.
4. Dark-gray (N4) mica phyllite. 0.3 mile northwest of Taber Hill.
5. Medium gray (N5) sillimanite-mica schist. 0.8 mile 25° from south Vassalboro.
6. Dark-gray (N4) phyllite. 0.3 mile east of Vassalboro.

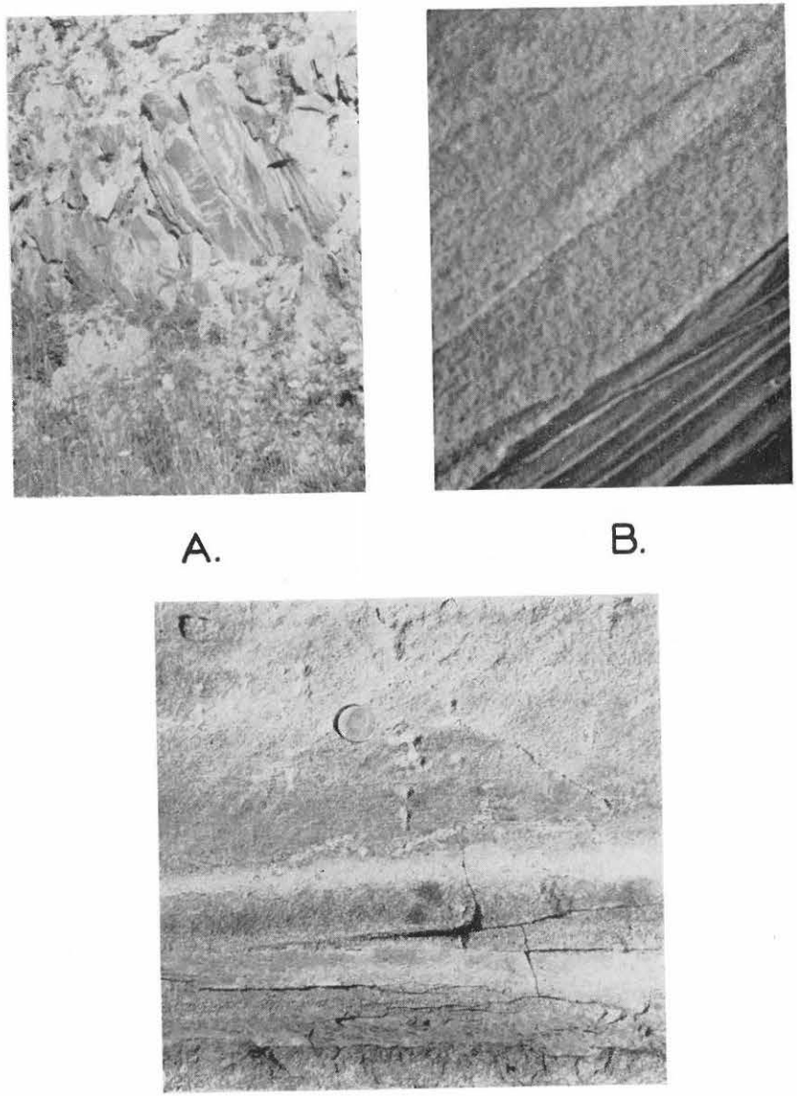


Figure 7. Vassalboro Formation. A. Characteristic exposure of Vassalboro wacke in low metamorphic grade, Route 137, 1.0 mile 92° from Hayden Corner. B. Quartz-plagioclase-actinolite-biotite granulite interbedded with mica schist, Route 201, 2.7 miles 50° from Ballard School. C. Quartz-plagioclase-diopside-actinolite-biotite granulite, Route 201, 0.9 mile 100° from Ballard School.

dance as biotite. It forms subhedral plates 0.03mm to 0.02mm across and generally has simple articulation. Calcite and/or ankerite occur as common constituents of this wacke. These grains have simple articulation, and their size ranges from 0.03mm to 0.08mm. The carbonate is disseminated as anhedral grains which locally coalesce to form glomeroblasts. Actinolite, found only in the garnet zone occurs as sunbursts and single crystals. Some of the larger crystals reach 0.08mm in length. The crystals are subhedral and have simple articulation. Garnet, although not common, occurs sporadically as subhedral grains and glomeroblasts. Its size ranges from 0.2mm to 0.4mm. The exterior boundaries of the garnet are simple, but the interiors are crowded with inclusions of quartz and biotite. Accessories include muscovite, apatite, sphene, tourmaline, zircon, plagioclase, ilmenite, magnetite, and pyrite.

At higher grades of metamorphism the wacke is represented by granulite consisting of various combinations of quartz, plagioclase, biotite, actinolite, diopside, clinozoisite, hornblende, and calcite. Biotite, actinolite, hornblende, diopside, and clinozoisite occur as porphyroblasts set in a matrix of quartz and disseminated calcite. Biotite and the prismatic minerals have only a rough preferred orientation. Characteristic photographs appear in Figure 7.

In thin section, quartz forms anhedral grains, 0.02mm to 0.03mm across, with simple articulation. Most grains show considerable undulatory extinction. Actinolite and hornblende occur as poikiloblasts and glomeroblasts from 0.3mm to 0.8mm long. They include quartz and calcite. Biotite is scattered through the rock and locally it is intergrown with the actinolite. It forms subhedral plates with somewhat ragged margins, and its size ranges from 0.1mm to 0.6mm across. Zircon and quartz are common inclusions. Locally it is interleaved with chlorite. Clinozoisite forms subhedral prisms, 0.1mm to 0.2mm long. Its articulation is simple. Calcite forms irregularly shaped grains, 0.05mm to 0.2mm in size. Accessories include sphene, apatite, zircon, chlorite, and plagioclase.

Two types of phyllite are interbedded with the wacke of the Vassalboro Formation. One is medium dark gray and biotite-rich; the other is light gray or light greenish gray and contains abundant muscovite with subordinate biotite. The medium dark gray pelite occurs in 1 inch to 3 inch beds with sharp contacts with the enclosing wacke. These beds are irregularly distributed in the wacke and always

make up a minor part of any stratigraphic section. The greenish gray phyllite is thin bedded and contains 1/8 inch to 2 inch quartz-rich layers alternating with mica-rich layers. In short stratigraphic intervals the proportions of phyllite to wacke vary considerably, but phyllite to wacke ratio rarely exceeds 3:7. Schistosity is well developed in both phyllites and commonly is essentially parallel to bedding.

At low grades of metamorphism the greenish gray phyllite consists of quartz, muscovite, chlorite, and biotite. Biotite is porphyroblastic and is set in a fine-grained matrix of quartz, muscovite, and chlorite. The biotite forms subhedral plates with ragged edges. Many include quartz, muscovite, and zircon. Their size ranges from 0.1mm to 0.3mm. Quartz, in grains <0.02mm in size, occurs as anhedral grains with mosaic articulation. Muscovite is interwoven with the quartz, forming subhedral plates 0.02mm to 0.03mm across. These crystals have good shape orientation which determines the schistosity. Chlorite, although not unambiguously identified optically, is indicated by x-ray methods. It is intimately interleaved with muscovite. Accessories include zircon and pyrrhotite.

The dark-medium gray phyllite also consists essentially of quartz, biotite, muscovite, and chlorite. Porphyroblasts of biotite have rectilinear arrangement. These porphyroblasts are set in a groundmass of quartz and muscovite. Chlorite is subordinate. Biotite, in grains 0.05mm to 0.2mm across, occurs as subhedral plates enclosing quartz and zircon. Quartz forms grains <0.02mm in size. These grains are anhedral and have mosaic boundaries. Muscovite is in plates <0.02mm in size also. It is interwoven with the quartz, but its orientation is sufficiently preferred to define the schistosity. Chlorite forms sparse porphyroblasts which reach a size of 0.1mm. These plates poikiloblastically enclose quartz and opaques. Accessories include magnetite, ilmenite, and zircon.

At high grades of metamorphism both the light-greenish gray phyllite and the dark-medium gray phyllite contain minerals such as quartz, biotite, muscovite, garnet, andalusite, and sillimanite.

In the equivalents of the light greenish gray phyllite biotite and muscovite have crudely parallel orientation that defines the schistosity. The micaceous minerals are interwoven with quartz and minor plagioclase. Porphyroblasts of garnet and glomeroblasts of andalusite interrupt the schistosity. Quartz occurs as anhedral grains with simple articulation. Its size ranges from 0.05mm to 0.2mm. Many grains show

undulatory extinction. Biotite, 0.1mm to 0.3mm across, forms subhedral crystals with simple boundaries. Some grains include quartz, muscovite, opaques, and zircon. Muscovite occurs as subhedral plates exhibiting simple articulation. Their size ranges from 0.4mm to 0.5mm across. Some grains include quartz. Garnet forms rounded porphyroblasts 0.3mm to 0.7mm in size. Most crystals are fairly clear of inclusions although some contain small amounts of quartz and biotite. Andalusite occurs as small needle-like grains that form clusters of irregular shape. These clusters enclose all other minerals. Sillimanite, when present, occurs as fibrolite. Accessories are tourmaline, magnetite, and plagioclase.

The equivalents of the medium dark gray phyllite contain biotite and muscovite in a decussate arrangement with quartz and minor plagioclase in the interstices. Fibrolite is commonly associated with the biotite. Biotite, in plates 0.05mm to 0.2mm across, is subhedral with ragged boundaries. Many crystals include quartz, sillimanite, and zircon. Muscovite forms subhedral plates with simple boundaries. Its size ranges from 0.2mm to 0.3mm. Some of the larger grains include quartz, biotite, sillimanite, and magnetite. Fibrolite occurs in masses composed of many small needles. It is generally associated with biotite. Andalusite, when present, occurs as small needle-shaped crystals that form clusters. The clusters, unlike sillimanite, are commonly associated with quartz. Quartz, in grains 0.02mm to 0.1mm in size, forms anhedral grains with mosaic articulation. Most of the quartz exhibits some degree of undulatory extinction. Plagioclase occurs as anhedral grains with simple articulation. Their size is 0.05mm to 0.2mm. Some grains enclose quartz. Polysynthetic twinning is common. Accessories are magnetite and zircon.

Dark gray phyllite containing abundant pyrrhotite and interbedded dark gray quartzite constitute a minor lithology in the Vassalboro Formation. The rock contains lenses of pyrrhotite and thin quartzose seams that parallel a well-developed schistosity. This schistosity is essentially parallel to bedding. On weathered surfaces the phyllite is black and rusty.

The dark gray phyllite consists of fine-grained muscovite with good parallel alignment. Graphite is disseminated throughout the rock. Little quartz is visible except in pods and lenses. Pyrrhotite is scattered through the phyllite and locally is concentrated into lens-shaped glomeroblasts. The muscovite is 0.02mm to 0.03mm across and is subhedral with simple articulation. It has good shape-orientation

that defines the schistosity. Quartz, in grains 0.2mm in size, forms anhedral crystals with mosaic articulation. Most grains exhibit undulatory extinction. Graphite is associated with muscovite. Pyrrhotite is a prominent accessory.

THE STRATIGRAPHIC COLUMN

The sequence adopted here has been established mainly on the basis of facing-directions within the Waterville-Vassalboro area. Features that indicate facing-direction are common, but they are significant only where located at contacts between rock units because of ubiquitous isoclinal folding. Thus, information bearing on the stratigraphic sequence is meager and to a degree uncertain. Pertinent observations suggest that the Mayflower Hill Formation, the Waterville Formation, and the Vassalboro Formation are younger in the order listed. This sequence is tentative, however, and as the regional geology of south-central Maine becomes more completely understood, revisions in this stratigraphy may be necessary.

A columnar section for the Waterville-Vassalboro area is presented as Table 4. Relationships suggesting this sequence are detailed below. Those observations pertaining to the stratigraphic positions of the Waterville and Mayflower Hill Formations are as follows:

(1) Wacke and limestone of the Waterville Formation is exposed in the spill-way of the Central Maine Power station located one mile 295° from Colby College (Pl. 1). The graywacke displays well developed graded bedding that indicates a "younging" toward the west. Somewhat less obvious graded bedding is preserved in the graywacke at the contact with the limestone. The relationships at this contact also indicate that the sequence becomes younger toward the northwest. Because the limestone is not repeated toward the east between the outcrops described above and the contact between the Waterville Formation and the Mayflower Hill Formation, the formational contact must be assumed to face west also, i.e., the Waterville Formation must be regarded as younger than the Mayflower Hill Formation.

(2) The contact between limestone and thinly laminated phyllite and quartzite of the Waterville Formation is exposed beneath the east end of the bridge between Fairfield and Benton Station (Pl. 1). The relationships are shown in Figure 8. Thirty

Table 4
Stratigraphic Column

Age	Formation	Lithology	Thickness
Devonian or Silurian	Vassalboro Formation	Massively bedded, bluish gray wacke with minor interbeds of gray phyllite	Probably several thousand feet
Silurian (probably Wenlock or Ludlow)	Waterville Formation	Eastern facies: thinly laminated greenish gray phyllite; interbedded gray limestone and gray phyllite in beds 1 to 3 inches thick	
		Western facies: heavy bedded quartz wacke some of which are graded; interbedded gray limestone and gray phyllite in beds 1 to 3 inches thick; greenish gray phyllite	3000± feet
Silurian (upper Llandovery)	Mayflower Hill Formation	Heavy bedded, bluish gray wacke and phyllite. Beds are prominently graded	Greater than 1000 feet

to forty feet west across strike from the contact, the thinly laminated phyllite and quartzite exhibit graded beds that face east indicating that the limestone is the younger unit. This exposure is the western-most outcrop of limestone east of the Mayflower Hill Formation (see Pl. 1), and therefore the limestone and associated phyllite of the Waterville Formation must overlie the Mayflower Hill Formation.

(3) Both the Mayflower Hill Formation and the Waterville Formation contain fossils. Berry (written communication, 1962) has described Monograptids from the Mayflower Hill Formation and *Inocaulis* from the Waterville Formation. Berry (written communication, 1963) writes as follows concerning the relative ages of the two forms.

"I can't give you a definitive answer to the question of relative age of the beds with *Inocaulis* and these with the *Monograptus priodon*-like and related forms. *Inocaulis* does range from Ordovician into Silurian. The forms most like those from Maine seem to occur in beds of about late Wenlock or perhaps early Ludlow age. This would appear to make the beds with robust *Inocaulis* a bit younger than the beds with the *Monograptus priodon*-like and related forms. My suggestion, and it's just that, is that the *Inocaulis*-bearing beds are a bit younger. This is a very hesitant suggestion . . . because we have such limited information about the ages of rocks bearing *Inocaulis*. . ."

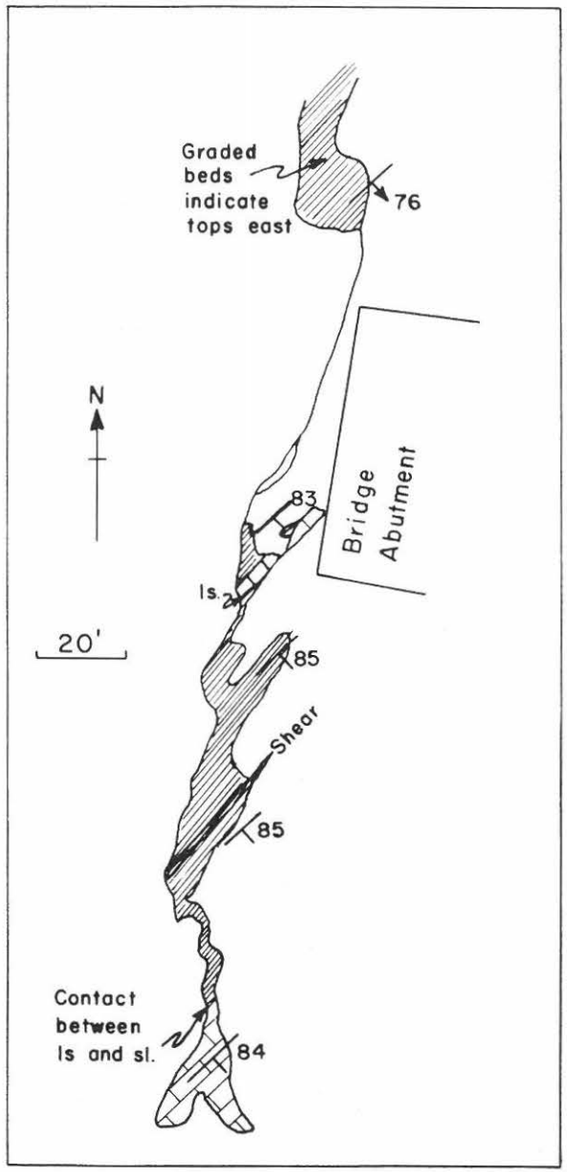


Figure 8. Stratigraphic relationships at Fairfield-Benton bridge.

A single observation is significant concerning the relative positions of the Waterville and the Vassalboro Formations.

(1) Outcrops of the Waterville formation occur within 10 feet of outcrops of the Vassalboro formation in the small brook 2250′ 167° from Longfellow School, North Sidney (Pl. 1). An exposure of graded bedding 20 to 30 feet from the contact indicates that the Vassalboro formation overlies the Waterville formation.

Age and correlation

General statement. Age determinations of the formations within the Waterville-Vassalboro area hinge on fossils contained in the rocks and on the sequence established from primary sedimentary structures. Correlations with rocks in outlying regions are based on similarity of age as deduced from contained fossils, similarity of lithology, and/or similarity of sequence.

Mayflower Hill Formation. The Mayflower Hill Formation has been dated on the basis of a few fragmentary graptolites. Perkins (1924) described two graptolite localities within this formation, one at the quarry 1.1 miles 0° from Colby College, and the second on "the road from Fairfield to Fairfield Center, about half way between the two places, . . .". He states that the fossils from the two localities "all seem to be *Monograptus*".

Ruedeman (in Perkins, 1924, p. 225-226) described a graptolite from a collection housed at Colby College.

"The specimen, partly preserved in pyrite and embedded in black slate, but without label, belongs to the group of *Monograptus priodon;* . . . The form differs, however, from *M. priodon* in its remarkably coarse structure, which distinguishes it also from all other congeners. It may therefore be here distinguished as *M. colbiensis* . . . ."

The location from which this specimen was collected was not given.

Ruedeman also compared fossils "from northwest of Waterville" (presumably from the Messalonskee quarry) with the above specimen. He concluded that, although the material was poorly preserved, a single species of *Monograptus* was present, and it probably was identical with *M. colbiensis.*

Ruedeman indicates a late Llandovery to lower Wenlock age for these fossils.

A new collection of graptolites was made by Robert G. Doyle from the quarry north of Colby College (written communication, 1960) and sent to William B. N. Berry. Berry (written communication, 1962) has found the following fossils in this collection:

Monograptus halli (Barrande)?
Monograptus cf. *M. priodon* (Bronn)
Monograptus sp. — with lobate thecal and ventral curvature
Monograptus sp. — with ventral curvature, thecal shape?
Monograptus sp. — with lobate thecae that apparently have spinose apertures
Petalograptus? sp.

He suggests a late Llandovery age for this assemblage.

The Mayflower Hill Formation is the same age as that of part of the Smyrna Mills Formation (Pavlides and Berry, 1966), the Hovey Hill Formation at Maple and Hovey Mountains (Pavlides, 1962, p. 23) in northeastern Maine, the unnamed limestone at Presque Isle (Boucot, et al, 1964, p. 28), and the Quoddy Shale at Eastport (Bastin and Williams, 1914, p. 3).

Based on similarity of lithic type and stratigraphic sequence the Mayflower Hill Formation is equivalent to the Kittery Formation in southeastern Maine (Hussey, 1962, p. 20-22), and the Allsbury Formation near Shin Pond in north-central Maine (Neuman, oral communication, 1959).

Waterville Formation. Meager observations of primary sedimentary features have been interpreted to indicate that the Waterville Formation overlies the Mayflower Hill Formation. On this basis, because the Mayflower Hill Formation contains Monograptids of Late Llandovery age, the Waterville Formation must be Late Llandovery or younger.

The above age is consistent with that of dendroid graptolites collected by William Forbes and the author from Benton Station (Pl. 1). This collection apparently consisted of a single genus of dendroid graptolite, *Inocaulis,* and some markings similar to those described by Raymond (1931). The fossils were sent to William B. N. Berry. He reported (written communication, 1962):

"The genus *Inocaulis* is known to occur in rocks of Ordovician and Silurian age but the majority of the species are from the Silurian. Also, large robust forms like the ones sent to me are known only from the Silurian. I have seen specimens similar to those you sent in

collections of undoubted Silurian age. Thus, on the basis of the general shape and size, I would suggest the phyllite bearing those forms is probably Silurian in age."

After a restudy of these specimens, Berry (written communication, 1964) stated:

"As you will see, I haven't changed my opinion much from what I wrote you in March except that I feel a bit more strongly that the Benton Station material indicates a slightly younger age for the rocks than those near Waterville. I have come to this somewhat stronger stand on the basis of evaluating the evolutionary development within the genus *Inocaulis* such as it is and trying to place the Benton Station material in the light of that development. On the basis of position in terms of evolutionary development within the genus, the Benton Station *Inocaulis* compares most favorably with the level of development attained by Wenlock and Ludlow age species of *Inocaulis.* Because no undoubted species of the genus have been recorded from Llandovery age beds, this conclusion is tenuous for I have no way of knowing what level of development was attained during the Llandovery by members of this Genus . . . . . but at the moment and on the basis of the evidence at hand, I believe the Benton Station beds to be . . . . about Wenlock or perhaps Ludlow in age."

On the basis of the stratigraphic position as indicated by meager sedimentary features and on the probable age of the contained fossils, the Waterville Formation is assigned a Wenlock or possibly Ludlow age.

The Waterville Formation is presumably the same age as the Dennys Shale (Bastin and Williams, 1914) near Eastport and the lower Perham Formation (Boucot et al, 1964) near Presque Isle. It is lithologically similar to, but not necessarily correlated with, the Island Falls Formation (Ekren, oral communication, 1959) near Patten, part of the Meduxnekeag Formation (Pavlides, 1965) at Houlton, the Noyes Mountain, Berry Ledge, and Moody Brook Formations (Guidotti, 1965) at Bryant Pond, the Scarboro, Spurwink, and Jewell Island Formations (Katz, 1918) near Portland, and possibly the Eliot Formation (Hussey, 1962) near Kittery.

Vassalboro Formation. The age of the Vassalboro Formation cannot be given unequivocally. Sedimentary features at its contact with the Waterville Formation suggest that it lies above the Waterville Formation. Thus, because the Waterville Formation has been assigned

to the Wenlock or possibly the Ludlow, the Vassalboro Formation must be Wenlock, or younger.

An upper limit for the age of the Vassalboro Formation is provided by intrusive bodies of granodiorite and quartz monzonite. On the basis of lithic similarity to bodies dated by radiometric methods (Faul et al, 1963), these bodies are assigned an Early Devonian age. Thus, the Vassalboro Formation must be Wenlock to earliest Devonian in age.

On the basis of its lithology and stratigraphic position, it is correlated with the Lobster Lake and the Hardwood Mountain Formations (Boucot, 1961) of the Moose River area, the Upper Perham Formation (Boucot et al, 1964) near Presque Isle, the Pembroke and Edmunds Formations (Bastin and Williams, 1914) at Eastport, the Ludden Brook Formation (Guidotti, 1965) of the Bryant Pond quadrangle, and the Berwick Formation (Hussey, 1962) of southern Maine.

DESCRIPTION OF THE ERUPTIVE ROCKS

General statement

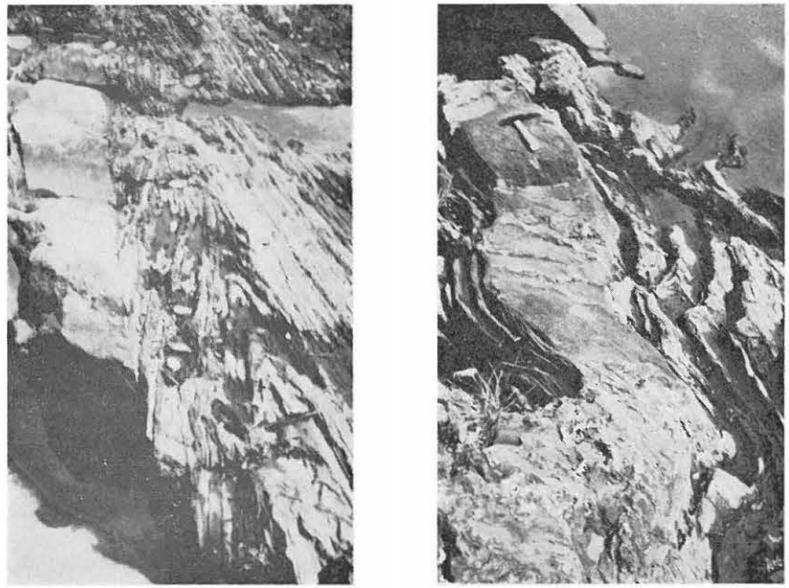
The eruptive rocks occur as dikes of plagioclase granulite, and as bodies of binary quartz monzonite, biotite granodiorite, and hornblende diorite.

Dikes of plagioclase granulite

Mode of occurrence. Dikes of plagioclase granulite are two to ten feet thick. Most are essentially parallel to the bedding in the limbs of nearly isoclinal folds (Fig. 9A), although at a few localities they cut across bedding at a large angle. All of the contacts, when examined closely, have local crosscutting relationships with the enclosing stratified rocks.

The dikes have been recrystallized to assemblages which are characteristic of the chlorite zone of metamorphism. In addition to the metamorphism these dikes are cut by a well developed cleavage, and at some localities are deformed by minor folds and by boudinage.

Distribution. Dikes of plagioclase granulite have been observed in an area bounded by Fairfield, Waterville, North Vassalboro, and the east margin of the map (Pl. 1). They intrude the Waterville and the Vassalboro Formations. Dikes are well exposed for study in the Sebasticook River at Benton Falls and in the Kennebec River under the Waterville-Winslow bridge (Pl.1).



A. B.

Figure 9. Relationships of dikes of plagioclase granulite to isoclinal and asymmetrical folds, Secasticook River, Benton Falls. A. Dike cutting isoclinal fold in limestone member of Waterville Formation. B. Asymmetrical folds with north trending axial surfaces deforming dike.

Lithology. Dikes of plagioclase granulite consist dominantly of highly altered, subhedral plagioclase. Grains of plagioclase range in size from 0.1mm to 0.4mm in greatest dimension. Many grains display polysynthetic twinning. Grains of calcite, 0.03mm to 0.2mm in size, are subhedral to anhedral. These grains commonly form ramifying aggregates around the plagioclase. Quartz is anhedral and slightly strained. It occurs in grains 0.03mm to 0.1mm in size. Muscovite forms subhedral plates varying in size from dust included in plagioclase to grains 0.2mm across. The larger grains form part of the matrix in which the feldspar is embedded. The muscovite in the matrix has good shape orientation. Magnetite is the only accessory. A mode is presented in Table 5.

The protolith of the plagioclase granulite, based on its composition, is perhaps a leucocratic granodiorite. The comparison, however, is only approximate because of metasomatic changes that have occurred in the dike-rock during metamorphism.

Age. The dikes intrude rocks presumed to be of Silurian age, and they cut isoclinal folds and some open folds in the surrounding rocks. On the other hand, the dikes are recrystallized to a mineral assemblage that reflects the regional metamorphism. They are also deformed by the youngest folds of the area (Fig. 9B).

Regional considerations, combined with these local observations, suggest the possibility that the dikes were emplaced in Late Silurian or in Devonian time.

Hornblende diorite

Mode of occurrence. The hornblende diorite forms inclusions and remnants of a preexisting rock in biotite granodiorite.

Distribution. Two areas of outcrops of hornblende diorite, 1/2 to 3/4 mile in size, occur within the biotite granodiorite exposed at the south margin of the map, south of Threemile Pond (Pl. 1).

Lithology. The hornblende diorite has not been studied in any detail. It is an equigranular, hypidiomorphic diorite that consists of hornblende and oligoclase-andesine in about equal amounts. Biotite is present in some specimens.

Age. The hornblende diorite occurs as inclusions in biotite granodiorite, and consequently it is older than the granodiorite. Its age relationship to folding has not been determined.

Biotite granodiorite

Mode of occurrence. The biotite granodiorite forms an oval stock elongated parallel to the regional strike of the country rocks, but on a local scale its contacts cut across the stratification in the adjacent rocks, and near its contacts the biotite granodiorite commonly contains numerous inclusions. Smaller satellitic bodies include a small stock and numerous dikes.

Distribution. The boundary of the biotite granodiorite passes through West Windsor, west of South China, north and west of South Vassalboro, and Anderson Pond (Pl. 1). A small outlying stock crops out at the northern margin of the main body of granodiorite. Numerous dikes have been located, and where their size warrants it, they have been placed on Plate 1.

Lithology. The biotite granodiorite is inequigranular-seriate. It contains plagioclase, quartz, microcline, biotite, and locally garnet or hornblende. The biotite grandiorite has a perceptible foliation

Table 5
Modes of Eruptive Rocks
(Based on visual estimates)

	1	2	3
Quartz	6%	33%	30%
Microcline		20	35
Plagioclase	76	40 (An_{18})	30 (An_{12})
Muscovite	8		2
Biotite		4	2
Chlorite	6		<1
Garnet		<1	<1
Hornblende			
Calcite	4		
Accessories	<1	3	<1

1. Very light-gray (N7) plagioclase granulite. East bank of Kennebec River. 0.2 mile south of Waterville-Winslow Bridge.
2. Light-gray, coarse-grained, inequigranular-seriate granodiorite. 0.35 mile southeast of Threemile Pond.
3. Light-gray, coarse-grained, equigranular binary quartz monzonite. 0.75 mile northwest of Ballard School.

due to the preferred arrangement of the biotite. Plagioclase forms subhedral to euhedral grains 0.6mm to 1.6mm in size. Polysynthetic twinning is common, and most grains are slightly altered to sericite. Myrmekitic intergrowths are present where grains of plagioclase and alkali feldspar are adjacent. Quartz occurs as irregular grains 0.2mm to 0.5mm in size. It commonly exhibits undulatory extinction and mortarboard arrangement. Microcline, in grains 0.6mm to 1.6mm in size, forms insets. It shows grid twinning and fine perthitic intergrowths. Microcline is either embayed by or includes plagioclase and biotite. Biotite occurs as subhedral plates 0.5mm to 1.5mm across. These crystals have irregular edges, and locally they have altered to chlorite. Some specimens contain garnet or hornblende. Accessories include apatite, zircon, clinozoisite, and magnetite. A mode is present in Table 5.

Age. The biotite granodiorite transects the isoclinally folded Vassalboro Formation and hence is younger than the isoclinal folding. It is lithologically similar to the Hartland "granite" near Skowhegan. Faul et al (1963, p. 9) report a Middle Devonian Pb/alpha age for the Hartland "granite". Because of the lithic similarity of the two bodies, they are believed to have been intruded at the same time.

Binary quartz Monzonite

Mode of occurrence. The binary quartz monzonite occurs as lenticular stocks that in a general way are elongated parallel to the regional strike of the host rock. When examined in detail, however, the contacts of the binary quartz monzonite with the host rock are cross-cutting. Inclusions of host rock, numerous pegmatites and satellitic dikes complicate the contact relations.

Distribution. Binary quartz monzonite forms a narrow triangular outcrop south of North Augusta (Pl. 1). It also forms a tear-drop shaped body that lies roughly between Tolman Pond, the hill west of Spectacle Pond, Churchill School, and Hewins School. Two small lens-shaped bodies lie just east of Augusta. A large body of binary quartz monzonite underlies Bickford, Howland, and Mutton Hills in the northwest corner of the Waterville-Vassalboro area. The boundary of this body is difficult to delineate because of poor exposure.

Lithology. The binary quartz monzonite near Augusta has been described by Barker (1961, p. 52-95) and that near Tolman Pond, in part, has been studied by Goodspeed (1962, p. 33-51). A mode appears in Table 5. Plagioclase, microcline, and quartz form an interlocking, inequigranular mosaic. Muscovite and biotite are scattered through the rock without good preferred orientation. Microline, in grains 0.5mm to 0.9mm in size, forms equant grains with somewhat irregular margins. Most of these grains are free of inclusions and exhibit grid twinning. The difference between the x-ray reflections $2\theta(\bar{1}31)$-$2\theta(1\bar{3}1)$ indicates a composition of Or_{84}. Plagioclase occurs as grains 0.9mm to 1.4mm in size. These crystals are subhedral and prismatic. Their composition is An_{18} as determined by immersion methods. Albite and carlsbad twinning are common; pericline twinning is less so. Quartz forms anhedral grains, 0.5mm to 0.9mm in size. Much of the quartz has a mortarboard arrangement. All grains are strained. Biotite is sporadically distributed through the quartz monzonite. It occurs as subhedral plates, 0.09mm to 0.9mm across. Muscovite, in flakes 0.3mm to 0.8mm across, is subhedral and possesses a limited preferred orientation. Garnet forms subhedral grains, 0.05mm to 0.5mm in diameter. These grains are free of inclusions and have simple articulation. Accessories are zircon, apatite, chlorite, and magnetite.

Age. The binary quartz monzonite intrudes rocks of Silurian and possibly earliest Devonian age, and cuts across the regional trends of isoclinal folds. Hurley et al (1958) have reported a K-A age of 260 my (Permian) for the binary quartz monzonite near

Augusta. Faul et al (1963) have given a Rb-Sr age of 384-390 my for a binary "granite" at South Orland. The two bodies are lithologically similar and were probably intruded at approximately the same time. The Permian date is interpreted to be metamorphic. Thus, the intrusion of the binary quartz monzonite is assigned a Lower Devonian age.

STRUCTURAL GEOLOGY

Major Structural Features

General statement. The major structural features are delineated on the basis of the distribution of lithic units and the stratigraphic sequence established during areal mapping. Field observations of sedimentary features at the contacts of the Mayflower Hill and the Waterville Formations indicate that the Mayflower Hill Formation forms the core of a large anticline. This anticline must be regarded as one of the major structural features of south-central Maine. On a local scale, too, the distribution of lithic units indicates that the sequence is considerably folded, and in single outcrops beds are commonly folded.

Major folds. The distribution of lithic units outlines numerous folds in Plate 1. Isoclinal folds with wavelengths of the order of 0.4 to 1.0 mile corrugate the stratigraphic succession. Higher order harmonics produce large folds, such as the anticline delineated by the Mayflower Hill Formation. Judging from regional reconnaissance, the large folds have wavelengths of the order of 15 to 18 miles.

The axial traces of the folds within the Waterville-Vassalboro area are shown in Figure 10. The axial traces trend approximately N.40°E. The fold patterns are symmetrical and elongated indicating upright folds with gentle plunges. Many folds are doubly plunging within the limits of the map-area. The patterns of the folds are similar regardless of whether they occur in pelite, limestone, or massive wacke.

The flexure in the limbs of the eastern most anticline (1.5 miles 145° from Winslow) outlined by the limestone member of the Waterville Formation (Fig. 10) is interpreted as a late fold. The fact that it folds both limbs of the anticline supports this view

Minor Structural Features

General Statement. Minor structural features are abundantly displayed in the Waterville-Vassalboro area. Bedding and schistosity

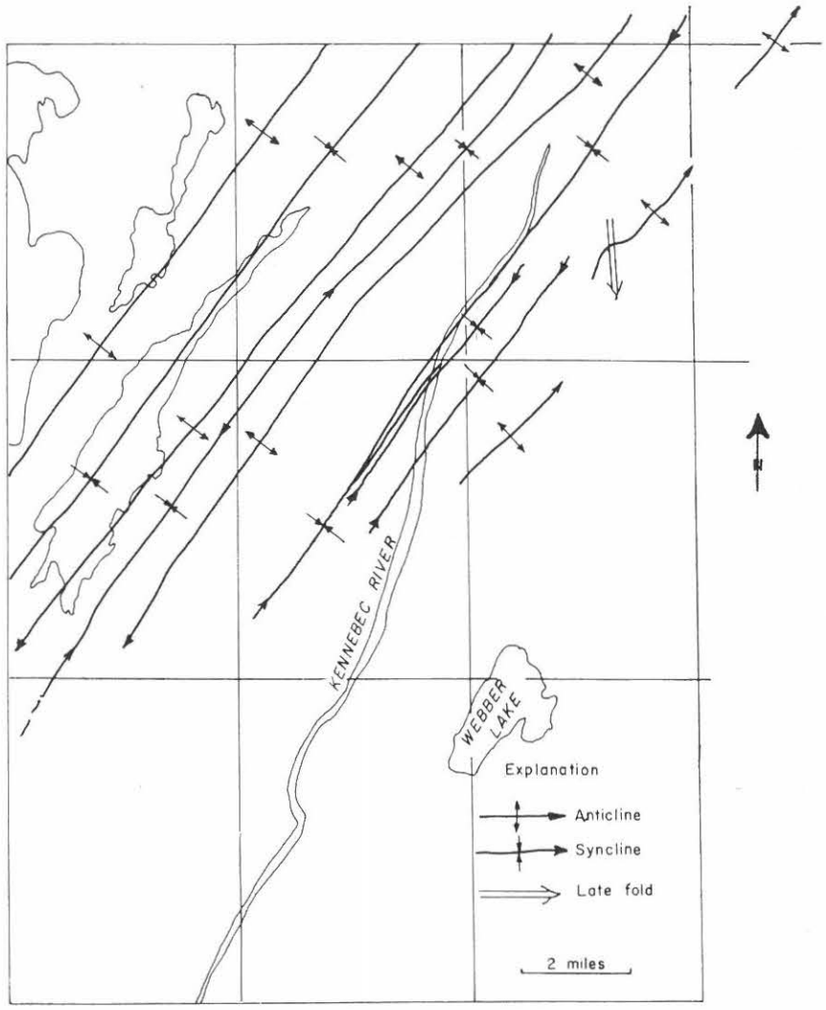


Figure 10. Axial traces of folds in the Waterville-Vassalboro area.

are exposed in nearly all outcrops, and cleavage, minor folds, and boudinage, although less commonly observed, are locally well developed.

Bedding. Bedding is preserved in all lithic units. In the Vassalboro, the Mayflower Hill, and the Waterville Formations heavy beds of wacke are separated by thin beds of phyllite. Where observed,

wacke beds are rarely in contact without an intervening bed of phyllite. The Waterville Formation also contains alternations of phyllite and thin beds of quartzite and within limestone units alternations of limestone and phyllite or quartzite.

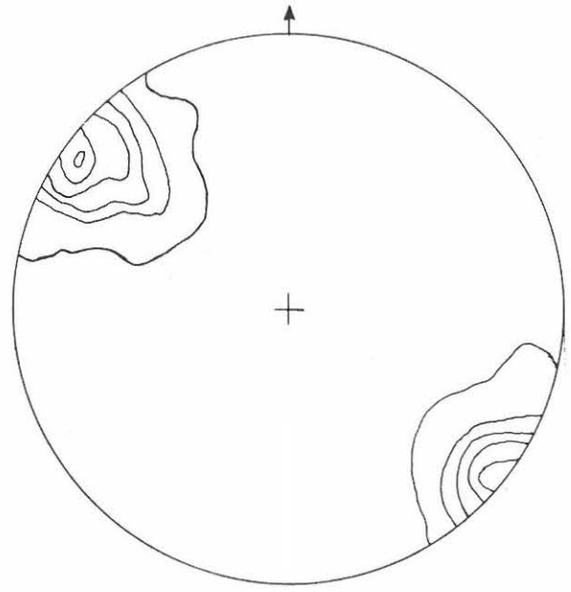


Figure 11. Equal area projection of poles of bedding; contours 1, 5, 10, 15, 20, and 25% per 1% area; 720 poles.

Attitudes of bedding are indicated by appropriate symbols on Plate 1. In addition an equal-area projection shows these data (Fig. 11) for the entire area. The well defined maximum indicates the general uniformity of the data. The average strike is approximately N.45°E. and dips are within a few degrees of vertical.

Cleavage-bands. Cleavage-bands are developed throughout the area, and particularly in phyllite and limestone. The cleavage-bands are shears along which the foliation in the rock is dragged. In the Waterville-Vassalboro area they deform both bedding and schistosity.

Cleavage-bands have two orientations. One set strikes N.5°E. to N.10°W., and the other set N.87°E. to N.83°W. Dips are steep. The north-trending set drags the foliation into right-handed patterns, whereas the east-trending set drags the foliation into left-handed patterns. Typical cleavage-bands are illustrated in Figure 12. Both shears are present at many localities, but at others only a single shear is present.

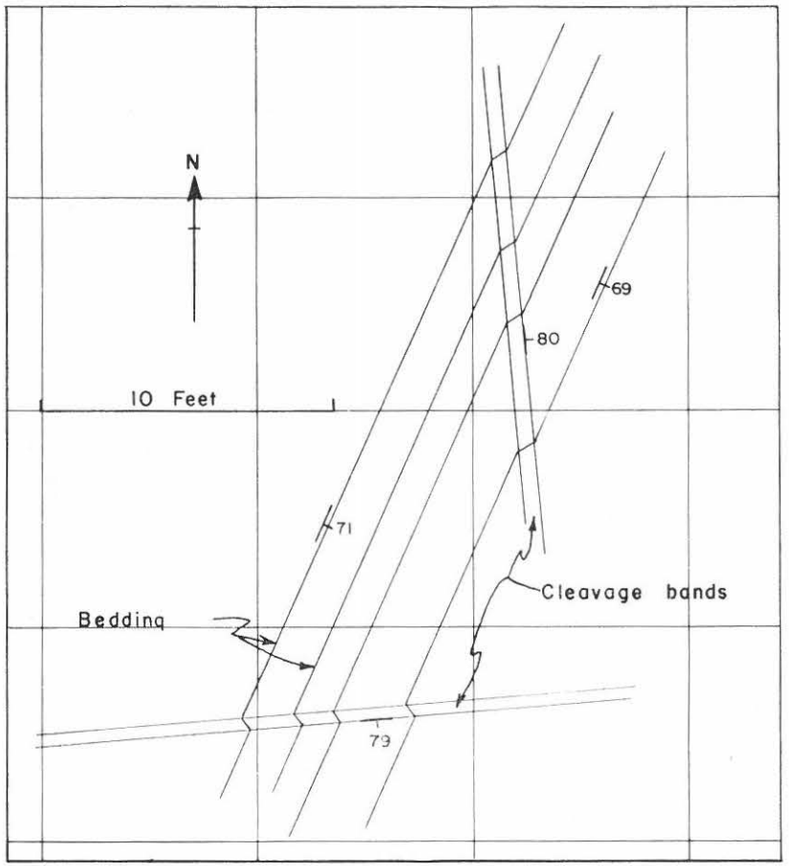
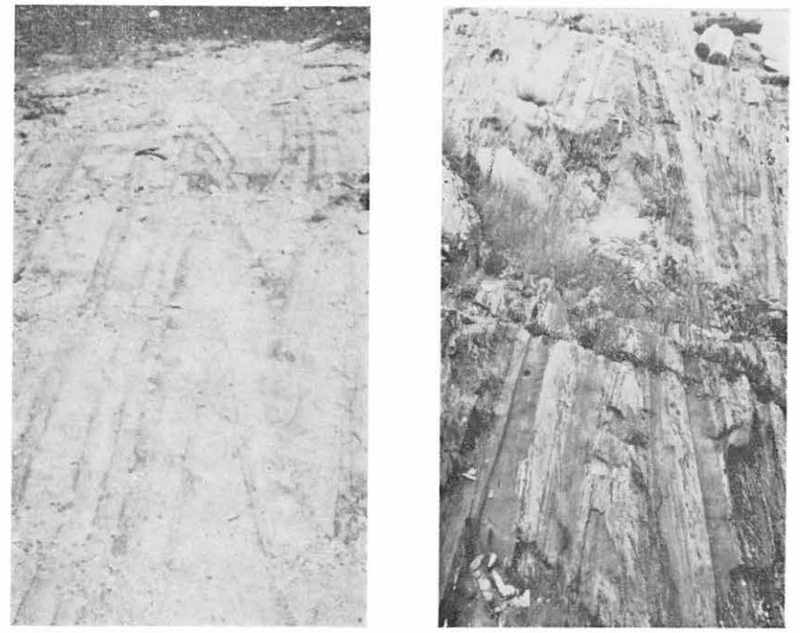


Figure 12. Cleavage bands in well-bedded limestone, Benton Falls.

Minor folds. Three contrasting styles of minor folds are present in the Waterville-Vassalboro area; isoclinal folds, monoclinal flexures, and asymmetric folds. Attitudes of these folds are indicated by conventional symbols on Plate 1.

Isoclinal folds are observed in all metasedimentary units. Their style is shown in Figure 13A and B. These folds are essentially symmetrical with wavelengths from 10 feet to 200 feet. They deform bedding but not schistosity. Beds are greatly thickened in crests and troughs, and schistosity is parallel to their axial surfaces and cuts across bedding at a large angle in their noses. Attitudes of axial surfaces of these folds are plotted in the projection of Figure 14A and



A. B.

Figure 13. Isoclinal folds. A. Isoclinal folds in Mayflower Hill Formation (note graded beds), 1.2 miles 98° from Oakland. B. Isoclinal folds in limestone member of Waterville Formation, Kennebec River, 0.1 mile south of the Waterville-Winslow bridge.

their plunges in Figure 14B. The clustering of the poles of axial surfaces indicates a certain degree of uniformity of attitude over the entire area. Axial surfaces strike N.35°E. to N.45°E. and dip steeply. Plunges are gentle, of the order of 5° to 20°, either to the northeast or southwest.

Monoclinal flexures occur sporadically. These flexures deform both bedding and schistosity. They have both right-handed and left-handed rotational senses. The right-handed flexures have axial surfaces that strike approximately north and dip steeply. The left-handed flexures have axial surfaces that strike nearly east and dip steeply. Plunges are steep regardless of rotational sense. These relationships are shown in Figure 15A and B.

Asymmetric folds are the most commonly observed folds in the Waterville-Vassalboro area. Their styles are shown in Figure 16A

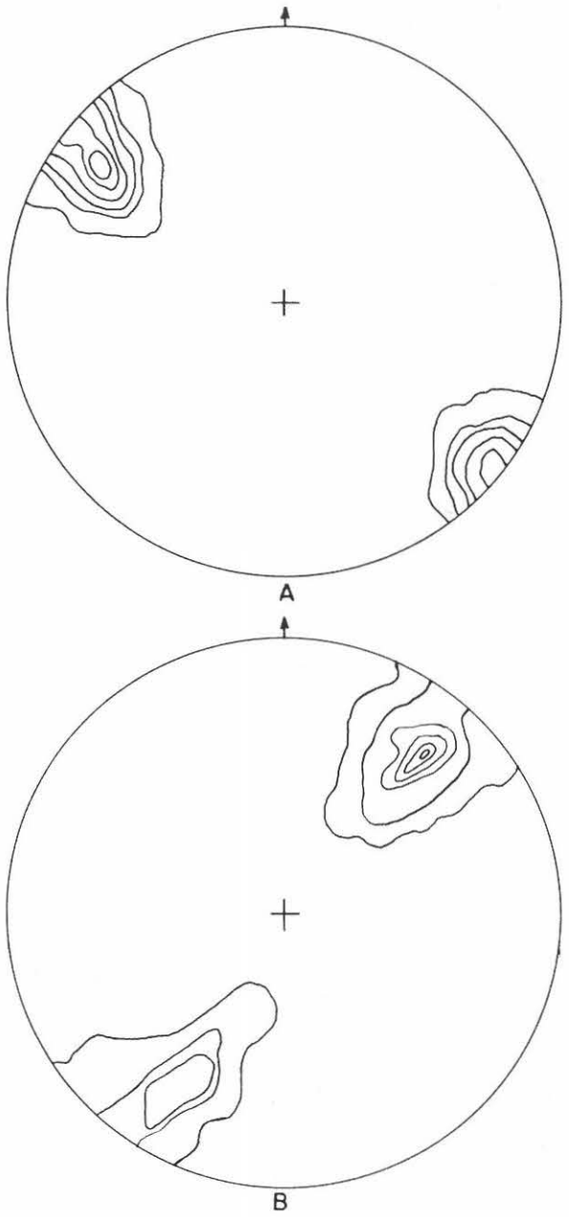


Figure 14. Equal area projection of isoclinal folds. A. Poles of axial surfaces; contours 2, 6, 10, 14, 18, and 22% per 1% area; 43 poles. B. Poles of axes; contours 2, 6, 10, 14, 18, and 22% per 1% area; 43 points.

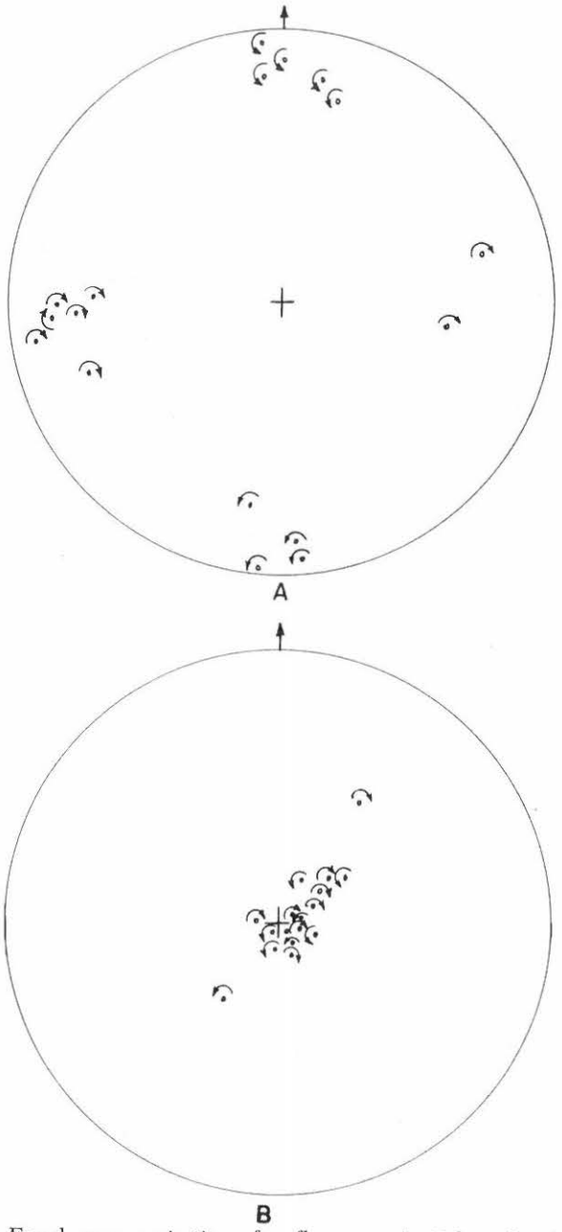
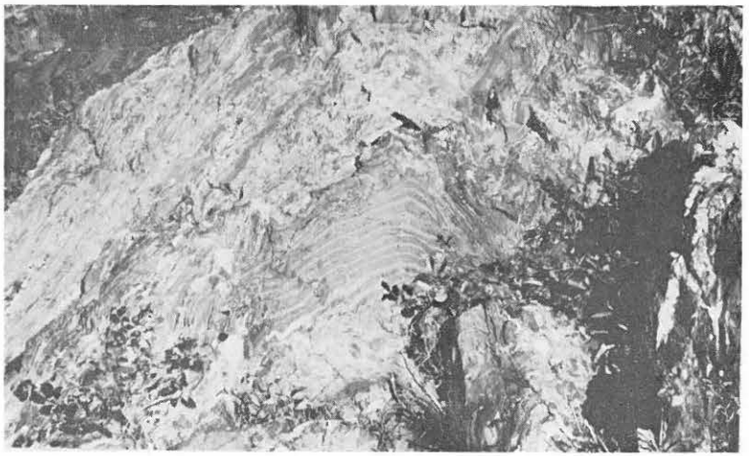
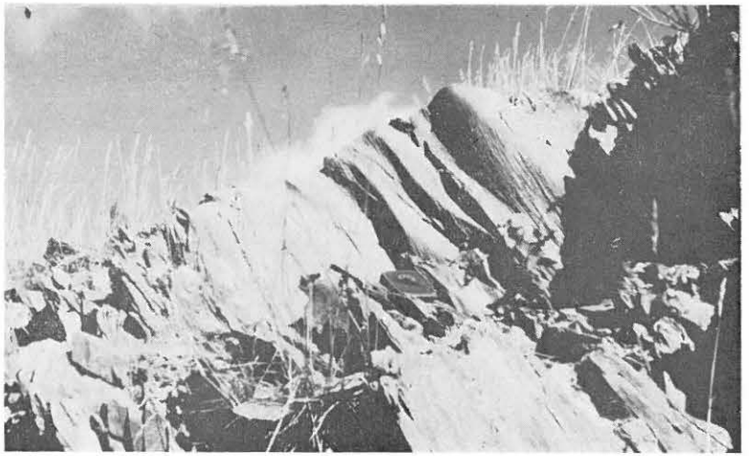


Figure 15. Equal area projections for flexures. A. Poles of axial surfaces; rotational sense of folds is indicated; 17 poles. B. Poles of axes; rotational sense is indicated; 17 poles.



A.



B.

Figure 16. Asymmetrical folds. A. Asymmetrical folds with north-trending axial surfaces in phyllite of the Waterville Formation, Kennebec River, 0.2 mile south of Waterville-Winslow bridge. B. Asymmetrical folds with north-trending axial surfaces in the Vassalboro Formation, Route 137, 1.8 miles 92° from Hayden Corner.

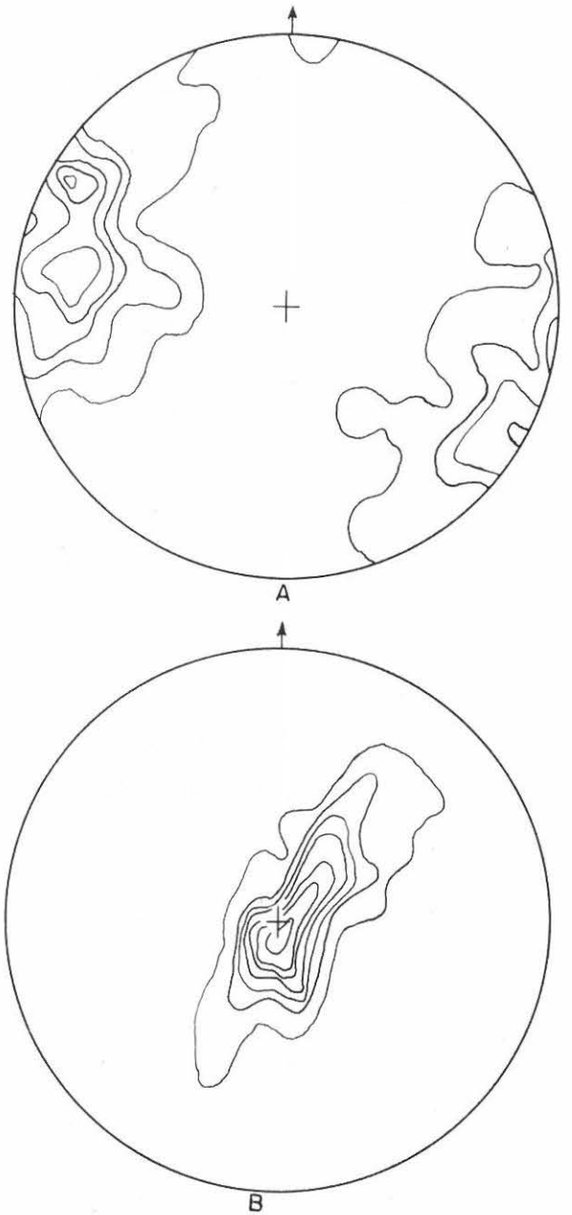


Figure 17. Equal area projections for asymmetrical folds. A. Poles of axial surfaces; contours 2, 4, 6, 8, 10, and 12% per 1% area; 137 poles. B. Poles of axes; contours 2, 4, 6, 8, 10, 12, and 14% per 1% area; 137 poles.

and B. These folds deform bedding, and in addition they locally fold schistosity and cleavage. Both right-handed and left-handed folds occur, but the right-handed type is more abundant. The axial surfaces of these folds have strikes that range from N.58°E. to N.12°W. and dips are generally steep. Their plunges are moderate to steep. These data are shown on the equal area projection of Figure 17A and B.

Schistosity. Schistosity is well developed in phyllitic beds of all units, and, although developed to a lesser extent in the wackes and limestone beds, it is still perceptible. In the phyllites the schistosity is obviously due to the parallelism of fine-grained muscovite and chlorite. In the wackes the schistosity results partly from the preferred orientation of ellipsoidal grains of quartz. In addition, fine-grained muscovite, chlorite, and biotite wrap around the quartz, and the resulting orientations enhance the schistosity. In limestone and marble the schistosity is due to the preferred orientation of muscovite and biotite.

Attitudes of schistosity are indicated on Plate 1 with conventional symbols. The schistosity is sensibly parallel to bedding in most outcrops, and, thus, like bedding has a uniform orientation throughout the area.

Although schistosity closely parallels bedding in the Waterville-Vassalboro area, it cannot be considered to be mimetic after bedding. Schistosity cuts across bedding in the noses of some isoclinal folds. These folds are distributed throughout the area, and therefore these relationships must be true for the entire area. Consequently, the schistosity must be regarded as a secondary structural feature related to the development of the isoclinal folds. The parallelism of schistosity and bedding is coincidental.

Cleavage. Although cleavage occurs throughout the Waterville-Vassalboro area, it is less well developed than schistosity. Attitudes of cleavage are shown on Plate 1 with appropriate symbols. In addition these data are shown in Figure 18 in an equal area projection for the entire area. The maximum indicates that many cleavage surfaces strike N.24°E. and dip steeply. However, the poles lie in a partial girdle so that the strikes range from N.35°E. to N.18°W.

The cleavage is observed as close-spaced fractures. In phyllite and limestone it is a slip cleavage, whereas in heavy bedded wacke it approaches a fracture cleavage.

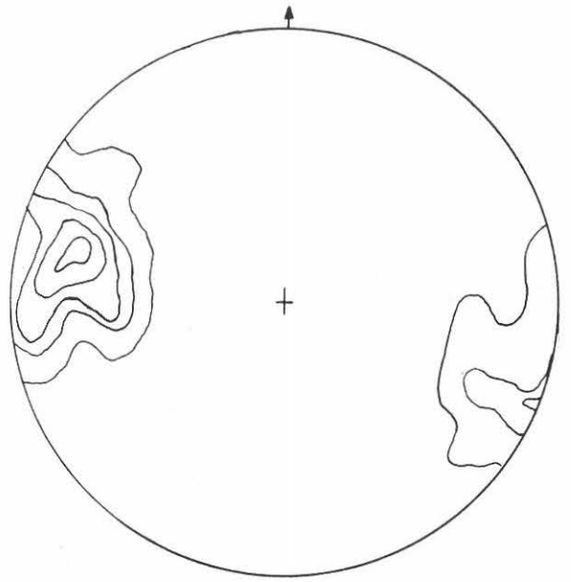


Figure 18. Equal area projection of poles of cleavage; contours 2, 4, 6, 8, and 10% per 1% area; 188 poles.

Boudinage. Although boudinage is common in the Waterville-Vassalboro area, it was not intensively studied in this investigation. In some boudinage the brittle layer is necked at the boudin line, whereas in others the brittle layer is sheared off in such a way as to suggest that the boudin line follows the intersection of a shear plane with the bedding. No information was collected to indicate whether or not the boudinage were developed in several episodes of deformation.

Structural Synthesis

General statement. In this section the writer attempts to unify the diverse structural observations. Relationships between structural features at certain exposures clearly show that the deformational history is complex. Three stages of deformation are recognized, and, in general, features that formed during the same stage of deformation have characteristic ranges of orientation over the entire area.

The areal distribution of lithic units (Pl. 1) and direct observations of minor structural features indicate that folding is the principal mode of deformation and schistosity and cleavage are consequences

of folding. Of the folds associated with each of the three stages of deformation, those belonging to the earliest phase are much the largest and the folds formed in succeeding episodes of deformation are small and do not appreciably control the areal distribution of rock units.

The characteristic ranges of orientation of structural features formed in a given episode of deformation implies that elements of each episode developed in response to a unique regional stress field. Some inferences regarding the regional stress field for each episode can be made.

Relative ages of structural elements. Cleavage-bands cut isoclinal folds. They have not been observed to cut asymmetrical folds. On the other hand, the cleavage-bands are not folded or deformed, and their observed orientations are similar throughout the Waterville-Vassalboro area. The cleavage bands are interpreted to have formed late in the tectonic history when the rocks deformed brittlely and isotropically.

Monoclinal flexures deform isoclinal folds but their relationships with the asymmetrical folds have not been established by direct observation. Indirect argument suggests that the monoclinal flexures were formed either contemporaneously with or just prior to the cleavage-bands. The axial surfaces of these flexures have the same orientations as do the cleavage-bands. Furthermore, the rotational senses of the monoclinal flexures are identical to those of the cleavage-bands, i.e., those having axial surfaces that strike north are right-handed and those having axial surfaces that strike east are left-handed (Fig. 15). This identity of orientation and rotational sense between the cleavage-bands and monoclinal flexures suggests that they were formed in the same stress field and at approximately the same time.

The orientations of asymmetrical folds are diverse but not random (Fig. 17). For convenience it is well to separate these folds into two groups on the basis of their rotational senses and the trends of their axial surfaces. The following designations are used: right-handed asymmetrical folds with north-trending axial surfaces, right-handed asymmetrical folds with northeast-trending axial surfaces, left-handed asymmetrical folds with northeast-trending axial surfaces, and left-handed asymmetrical folds with east-trending axial surfaces.

The right-handed asymmetrical folds with north-trending axial surfaces are younger than the isoclinal folds. Figure 19 contains a sketch-map of an isoclinal fold with identically oriented right-handed asymmetrical folds in both limbs. Such relationships can occur only if the right-handed asymmetrical folds developed later than the isoclinal folds. Furthermore, the right-handed asymmetrical folds with north-

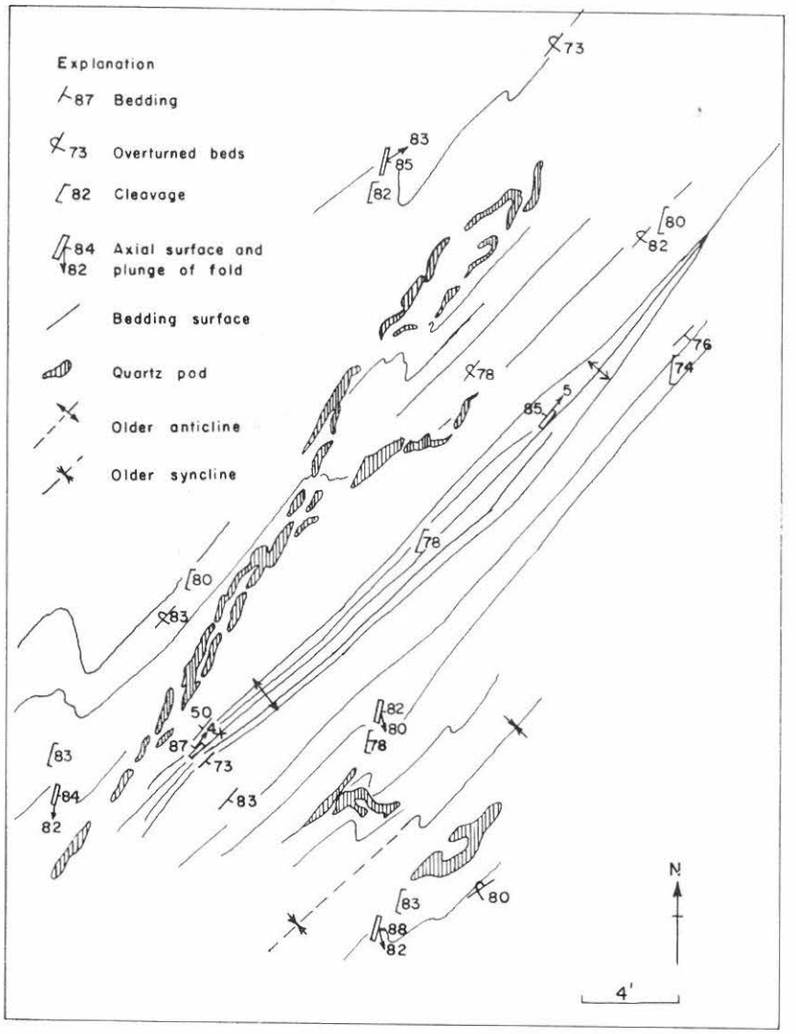


Figure 19. Folded folds at Winslow.

trending axial surfaces were formed in an episode of deformation distinct from that in which the isoclinal folds were formed. Figure 9A shows a dike of plagioclase granulite cutting across a limb of an isoclinal fold. At the same locality (Fig. 9B) a dike of plagioclase granulite is folded by right-handed asymmetrical folds with north-trending axial surfaces.

The right-handed asymmetrical folds with north-trending axial surfaces are also younger than left-handed asymmetrical folds with northeast-trending axial surfaces. Thus, in Figure 20, a small right-handed asymmetrical fold with north-trending axial surfaces deforms cleavage in a left-handed asymmetrical fold with northeast-trending axial surfaces.

No age relationships were observed between the right-handed asymmetrical folds with north-trending axial surfaces and the right-handed asymmetrical folds with northeast-trending axial surfaces.

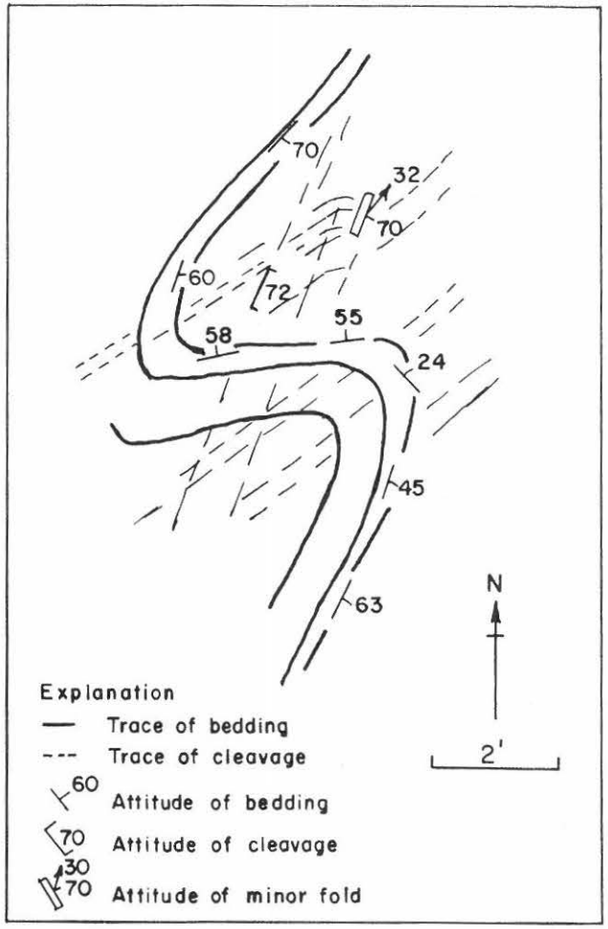


Figure 20. Folded cleavage, Benton Falls.

However, the orientations of the right-handed asymmetrical folds with northeast-trending axial surfaces are similar to those of the left-handed asymmetrical folds with northeast-trending axial surfaces, and on this basis these two northeast fold sets are thought to be of the same age. This correlation suggests that the right-handed asymmetrical folds with north-trending axial surfaces are younger than the right-handed asymmetrical folds with northeast-trending axial surfaces.

Both the left-handed asymmetrical folds with northeast-trending axial surfaces and those with east-trending axial surfaces deform schistosity, which elsewhere is shown to be parallel to the axial surfaces of isoclinal folds. Consequently, both sets are younger than the isoclinal folds.

Left-handed asymmetrical folds with northeast-trending axial surfaces are deformed by right-handed asymmetrical folds with north-trending axial surfaces (Fig. 20). Therefore, these folds must be older than the right-handed asymmetrical folds with north-trending axial surfaces.

No relationships have been observed between left-handed asymmetrical folds with east-trending axial surfaces and the right-handed asymmetrical folds with north-trending axial surfaces. However, they are believed to be contemporaneous because both these left-handed and right-handed asymmetrical folds have orientations that are similar to those of conjugate monoclinal flexures. Thus, these sets of asymmetrical folds are interpreted to be conjugate also.

Isoclinal folds are deformed by all other structural elements observed in the Waterville-Vassalboro area. Moreover, these isoclinal folds must represent the initial deformation in the area, because primary sedimentary features, where observed, are consistent with isoclinal anticlines and synclines. Figure 13A shows graded bedding consistent with an isoclinal anticline and an isoclinal syncline. Such relationships would not necessarily exist in later folds.

Much of the variation in strike of cleavage (Fig. 18) is attributed to the existence of cleavages developed in more than a single episode of deformation. Presumably each set of cleavage initially had a characteristic orientation, but the special orientation of the earlier cleavage has been somewhat modified by later folding. In addition

some variation in strike may be due to the control exerted by beds of differing competency. Cleavage makes a smaller angle to bedding in pelite than in wacke. Little regional variation in orientation could be ascertained.

These structural observations and conclusions are consistent with three episodes of deformation. The earliest deformation is represented by the isoclinal folds. The latest deformation is represented by cleavage-bands, monoclinal flexures, and the conjugate asymmetrical folds (the right-handed asymmetrical folds with north-trending axial surfaces and the left-handed asymmetrical folds with east-trending axial surfaces). Moreover, the latest deformation occurred after a time lapse sufficient for the emplacement of dikes and, therefore, must be considered a distinct episode. An intermediate deformation is suggested by the left-handed and right-handed asymmetrical folds with northeast-trending axial surfaces. These folds may represent either a distinct episode of deformation or merely an extension of the earliest deformation.

Inferences concerning the regional stress field. The characteristic orientations of structural features belonging to a single episode of deformation suggests that the regional stress field during the deformation was approximately uniform. Moreover, the orientations of structural features identified with each episode of deformation suggests that the regional stress field differed from episode to episode. Some inferences concerning the orientations of the regional stress field for each episode of deformation can be made from the orientations of structural features.

Because the isoclinal folds are much larger features than folds produced by subsequent deformations, their orientations have not been much altered by subsequent deformations. Experimental work (Biot, 1961; Ramberg, 1963) on the formation of similar folds in a single episode of deformation suggests that the maximum compressive stress lies in a plane normal to the axes of the folds. Thus the principal compressive stress at the time of the initial folding is inferred to lie in a plane that strikes N.51°W. and dips 80°S.W. Because the folds are symmetrical, the maximum compressive stress must have been nearly horizontal within this plane.

The asymmetrical folds with northeast-trending axial surfaces are identified with a second deformation. Folds of the second deformation were formed with the maximum compressive stress orientation in a direction 8° N.58°W.

The folds of the third episode of deformation have been interpreted as conjugate folds, and the stress relationships involved in conjugate folds have been studied by Ramsay (1960). The principal stress direction is the bisector of the angle between the axial surfaces of the conjugate pairs. This direction is 5°-10° N.43°E. Presumably the asymmetrical folds with north- and east-trending axial surfaces, the monoclinal flexures, and the cleavage-bands represent a series of structural features formed in the same stress field as the rocks became increasingly brittle.

METAMORPHISM

General statement

The rocks of the Waterville-Vassalboro area are conveniently grouped according to their compositions into pelitic rocks, calcareous quartz-rich rocks, and argillaceous limestones and marbles. The dominant lithic type of the Waterville Formation and minor interbeds in the Vassalboro Formation is pelite, most of the lithic types of the Vassalboro, the Mayflower Hill, and the western facies of the Waterville Formations are calcareous quartz-rich rocks, and the limestone members of the Waterville Formation belong to the argillaceous limestone group. All the rocks have been progressively recrystallized from the north increasing to the south; so that toward the south there were minerals formed which are not present in rocks of similar composition to the north. This recrystallization is the result of progressive changes in external conditions realized during metamorphism.

The first appearance of certain metamorphic minerals in rocks of a given compositional group can be mapped as isograds. Those for the pelitic rocks appear on Plate 1. The development of an index mineral for an isograd, however, is compositionally sensitive and not all rocks on the high intensity side of the isograd crystallize the index mineral. Moreover, the isograds based on pelitic rocks cannot be used in rocks of other compositional groups.

Pelitic rocks

The pelitic rocks are represented by a variety of mineral associations which depend on external conditions and the composition of the protolith. In a general way the increase in grade of metamorphism in these rocks can be indicated by isograds drawn on the first appearance of garnet, staurolite-andalusite, cordierite, and sillimanite (Pl. 1).

In the chlorite and biotite zones of metamorphism, which occur north of the garnet isograd, three assemblages have been observed:

quartz-muscovite-chlorite-hematite
quartz-muscovite-chlorite
quartz-muscovite-chlorite-biotite.

The biotite of the last assemblage is porphyroblastic, and rocks containing it have recrystallized under slightly higher metamorphic conditions than rocks of equivalent composition that develop the first two assemblages.

The garnet zone is characterized by nearly colorless to red euhedral garnets in rocks of appropriate composition. The following assemblages have been observed:

quartz-muscovite-biotite-chlorite-garnet
quartz-muscovite-biotite-chlorite
quartz-muscovite-chlorite.

The first appearance of andalusite or staurolite in rocks of appropriate composition delineates the staurolite-andalusite zone. The assemblages are not all compatible under arbitrary external conditions. As judged from the field occurrence, the associations containing chlorite represent lower metamorphic conditions. The two groups of assemblages are indicated below as A and B.

A

quartz-muscovite-biotite-chlorite-staurolite-garnet
quartz-muscovite-andalusite-chlorite
quartz-muscovite-biotite-chlorite
quartz-muscovite-biotite

B

quartz-muscovite-biotite-staurolite-andalusite-garnet
quartz-muscovite-biotite-staurolite-garnet
quartz-muscovite-biotite-andalusite-garnet
quartz-muscovite-biotite-garnet
quartz-muscovite-biotite

Under more intensive metamorphic conditions cordierite develops in association with andalusite and staurolite, and it serves to define the cordierite isograd. Assemblages that are associated with cordierite-bearing rocks or include cordierite are as follows:

A

quartz-muscovite-biotite-staurolite-cordierite-garnet
quartz-muscovite-biotite-cordierite-garnet
quartz-muscovite-biotite-staurolite-garnet
quartz-muscovite-biotite-cordierite
quartz-muscovite-biotite-staurolite,

B

quartz-muscovite-biotite-andalusite-staurolite-cordierite-garnet,

C

quartz-muscovite-biotite-andalusite-cordierite-garnet
quartz-muscovite-biotite-andalusite-staurolite-garnet
quartz-muscovite-biotite-andalusite-garnet
quartz-muscovite-biotite-cordierite-garnet
quartz-muscovite-biotite-staurolite-garnet
quartz-muscovite-biotite-cordierite
quartz-muscovite-biotite-staurolite.

These assemblages are not stable under the same set of external conditions. Group A represents a lower metamorphic intensity than group B and C, and group B represents a lower grade than does group C.

Sillimanite does not have a wide occurrence. It has been observed in thin sections of rocks collected from the south margin of the area. It occurs as fibrolite and has a particularly close association with biotite. The characteristic mineral associations are:

quartz-muscovite-biotite-sillimanite-garnet
quartz-muscovite-biotite-sillimanite.

Calcareous quartz-rich rocks

The following mineral assemblages are representative of low metamorphic grade in the calcareous quartz-rich rocks:

quartz-biotite-calcite-chlorite-muscovite
quartz-biotite-calcite-muscovite
quartz-biotite-chlorite-calcite
quartz-calcite-chlorite.

Much of the calcite is ferroan calcite, and on weathered surfaces produces limonite-filled pits.

With an increase in grade of metamorphism actinolite and clinozoisite develop. The observed mineral assemblages include:

quartz-biotite-calcite-actinolite-clinozoisite-plagioclase
quartz-biotite-actinolite-clinozoisite-plagioclase
quartz-biotite-calcite-actinolite-plagioclase
quartz-biotite-plagioclase-calcite
quartz-biotite-plagioclase.

At the highest grade observed in the Waterville-Vassalboro area, diopside is stabilized. Mineral assemblages characteristic of this grade are as follows:

quartz-plagioclase-biotite-actinolite-diopside-clinozoisite
quartz-plagioclase-biotite-hornblende-calcite-clinozoisite
quartz-plagioclase-biotite-calcite-actinolite-diopside
quartz-biotite-actinolite-clinozoisite
quartz-plagioclase-biotite.

Limestone and marble

The most apparent effect of metamorphism of the limestone and marble is the coarsening of grain size with increase in metamorphic grade. Reconstitution also takes place, but it becomes striking only at the highest grade of metamorphism (compare Fig. 6B and Fig. 6C).

At low grade calcite, biotite, muscovite, chlorite, and quartz are associated. With increase in metamorphism actinolite makes its appearance. The actinolite is porphyroblastic, commonly crowded with inclusions of biotite so that they stand out as black grains on the weathered surface. At the highest grade of metamorphism diopside occurs as well as actinolite and grossularite.

Conditions of metamorphism

Mineral associations that form in metamorphic rocks are a consequence of the relative amounts of the determining components[1], temperature, pressure, and chemical potentials of mobile components[2].

[1]Determining components are those whose mutual relationships determine the variety of mineralogical composition of a paragenetic group (Korshinskii 1959, p. 71).

[2]Mobile components are those whose chemical potentials are determined for a given mineral facies by the external conditions (Korshinskii 1959, p. 71).

The number of variations in the compositions of coexisting minerals at constant external conditions is equal to the determining components less the number of coexisting minerals. The external parameters, which include temperature, pressure, and chemical potentials of mobile components, are equal in number to the mobile components plus two.

In the pelitic rocks the determining components are considered to be SiO_2, Al_2O_3, FeO, MgO, MnO, and K_2O—six in number. Assemblages of six minerals have no internal variability in the compositions of coexisting minerals at arbitrary external conditions. Thus, the ratios of exchangeable ions in coexisting quartz-muscovite-biotite-staurolite-garnet-chlorite, for example, would be constant for a given set of external conditions. Assemblages of five minerals have a single degree of compositional variability between coexisting minerals at arbitrary external conditions; assemblages of four minerals have two degrees of compositional variability at arbitrary external conditions; and assemblages of three minerals have three degrees of compositional variability at constant external conditions.

The single assemblage of seven minerals was found at only one locality. It is thought to represent a transition between two states. In such transitions the number of minerals is one more than the number of determining components (excluding accessory minerals). For this assemblage there is no compositional variability between coexisting minerals, and the external conditions are not arbitrary. There exists a single relationship between them, i.e., the independent external variables are equal in number to the mobile components plus one.

In the calcareous quartz-rich rocks and the limestones and marbles the mineral associations can be represented by seven determining components (SiO_2, Al_2O_3, FeO, MgO, CaO, K_2O, and Na_2O). No assemblages of seven minerals were observed in these rocks from the Waterville-Vassalboro area. Assemblages of six minerals have a single degree of compositional variability at arbitrary external conditions; assemblages of five minerals have two degrees of chemical variability at fixed external conditions; assemblages of four minerals have three degrees of chemical variability at fixed external conditions; and assemblages of three minerals have four degrees of chemical variability at constant external conditions.

Water and carbon dioxide are considered to be mobile components and, therefore, their molecular amounts are dependent on the external

conditions. Arguments favoring this assignment are two-fold. (1) In rocks of appropriate composition, both water and carbon dioxide are fixed in minerals of high grade assemblages to lesser extent than in minerals of low grade equivalents. These relationships suggest that both water and carbon dioxide were driven off during the metamorphic process. (2) If water and carbon dioxide were not mobile but their amounts determined by the composition of the original sediment, the type and number of carbonates or hydrated minerals should vary stratigraphically in beds containing similar determining components but different quantities of water and carbon dioxide. Such relationships do not appear to exist in the Waterville-Vassalboro area.

No absolute values for temperature and pressure during metamorphism have been established. However, the existence of andalusite and cordierite in regionally metamorphosed rocks suggests moderate temperatures and relatively low pressures. Bell (1963, p. 1056) has established the triple point for the Al_2SiO_5 system at 300°C and

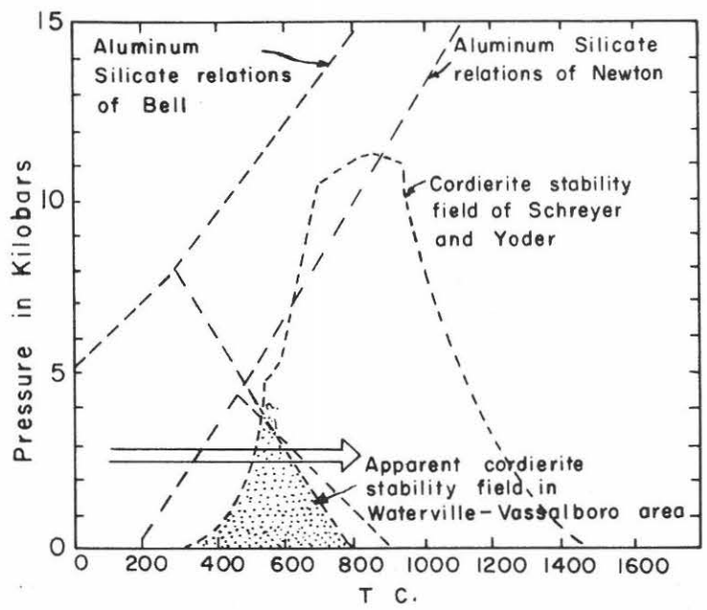


Figure 21. Schematic diagram showing stability relations for kyanite-andalusite-sillimanite and cordierite after the data of Schreyer and Yoder (1964), Bell (1963), and Newton (1966). The stability field for cordierite from Schreyer and Yoder is for $P_{H_2O}=P_{TOTAL}$. The reduced stability field for cordierite in the Waterville-Vassalboro area may be due to $P_{H_2O}<P_{TOTAL}$, Fe-content of natural cordierite, or both. Arrow indicates path of metamorphism in Waterville-Vassalboro area.

8± 6Kb. Newton (1966, p. 1223) suggests a triple point at 450°C and 3.5Kb. The stability field of cordierite in rocks for which $P_{H_2O}=P_{TOTAL}$ for pressure up to 10Kb has been explored experimentally by Schreyer and Yoder (1964, p. 297-299). These relationships are shown in Figure 21, in which the path of metamorphism is shown by the arrow. The metamorphism must have occurred at temperatures up to 600 or 700°C and at fluid pressure below 4Kb. These conditions are those of the low-pressure-intermediate metamorphic group of Miyashiro (1961, p. 283).

Chlorite in the higher grade zones of metamorphism in the pelitic rocks exhibits anomalous relationships. It occurs as porphyroblasts that truncate the schistosity at a large angle. These relationships suggest that the porphyroblastic chlorite formed late in the sequence of mineral formation. Two interpretations are possible: (1) the porphyroblastic chlorite is a retrograde product formed after the climax of metamorphism, or (2) the porphyroblastic chlorite is in equilibrium with coexisting mafic aluminous silicates and merely represents a recrystallization of chlorite that was formerly finely disseminated in the rock.

GEOLOGIC HISTORY

The fossils contained in the Mayflower Hill and the Waterville Formations indicate that these rocks were deposited in Silurian time. The Vassalboro Formation may have been deposited in Late Silurian or earliest Devonian time. The character of sedimentary rocks suggests that they were deposited below wave base in a tectonically active basin. No major stratigraphic breaks are recognized within this sequence.

After deposition and lithogenesis, the rocks now exposed in the Waterville region were folded into isoclinal folds. This folding was post Silurian and pre-Middle Devonian. Intrusives dated as Lower Devonian cut the isoclinal folds. Probably only slight recrystallization attended this early deformation.

Asymmetrical folds with northeast-trending axial surfaces postdate the isoclinal folds. They may have been formed at the close of the isoclinal folding, or they may have been formed in a separate episode of folding.

Dikes of granodiorite composition cut both the isoclinal folds and asymmetrical folds with northeast-trending axial surfaces. They are

metamorphosed to plagioclase granulite and their recrystallization conforms to the pattern of regional metamorphism. Consequently, the dikes predate the regional metamorphism.

The granodiorite in the vicinity of Threemile Pond is lithologically like the Hartland "granite". Faul et al (1963) have dated the Hartland "granite" as 450 my by the Pb/alpha method and 356 my by K-A method. Thus, the granodiorite of the Waterville-Vassalboro area is interpreted to have been emplaced in Lower Devonian time.

The quartz monzonite cuts the granodiorite. Faul et al (1963) report a Rb-Sr age of 384-390 my on muscovite from a binary "granite" at South Orland. Because of the lithic similarity of the "granite" at South Orland to the quartz monzonite in the Waterville-Vassalboro area, the ages of both are interpreted to be Lower Devonian.

The conjugate folds deform the dikes of plagioclase granulite. They also deform quartz veins and aplites associated with the biotite granodiorite. On this basis the conjugate folds are interpreted to be younger than the Lower Devonian.

Contact metamorphic aureoles are associated with the quartz monzonite body in the northwest part of the Waterville-Vassalboro area and with similar intrusives to the north. Toward the south the contact metamorphism is overprinted by regional metamorphism. Because the contact metamorphism must have an age similar to that of the intrusive body, the regional metamorphism must be younger than the Lower Devonian. The reduction in K-A ages on plutons from north-central Maine toward the south coincides with the general increase in regional metamorphism, and the wide spread occurrence of the 260 my K-A age in high grade metamorphic terrains suggests that the regional metamorphism is of that age, i.e., Permian.

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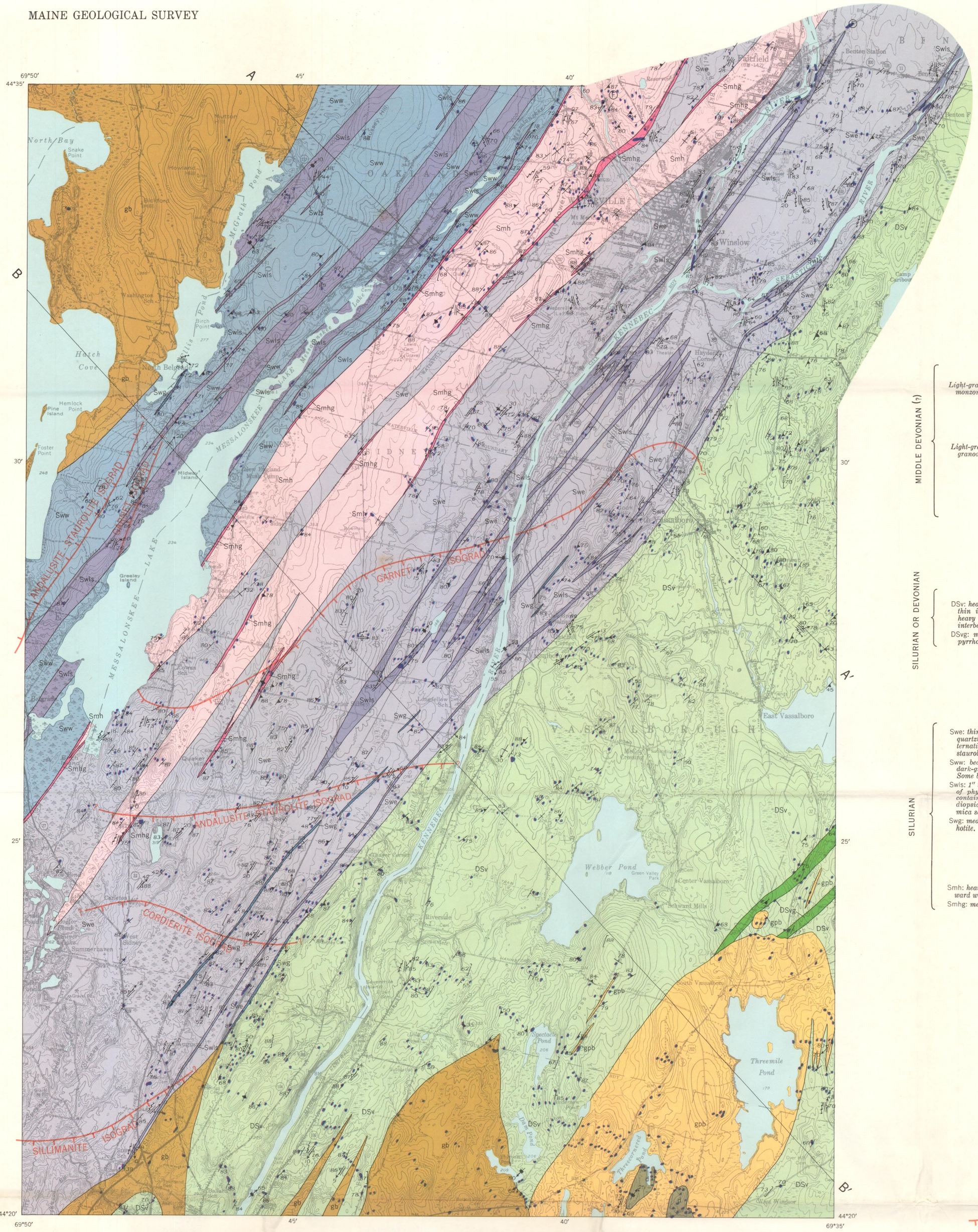


GEOLOGICAL MAP AND STRUCTURE SECTIONS OF THE WATERVILLE-VASSALBORO AREA, MAINE

SCALE 1:62500

1 ½ 0 1 2 3 4 MILES

3000 0 3000 6000 9000 12000 15000 18000 21000 FEET

EXPLANATION

Outcrops are printed in purple

ERUPTIVE ROCKS

MIDDLE DEVONIAN (?)

gb — Binary quartz monzonite
Light-gray, medium-grained, equigranular biotite muscovite quartz monzonite.

gpb — Biotite granodiorite
Light-gray, medium-to coarse grained, inequigranular-seriate biotite granodiorite.

d — Diorite
Medium gray, equigranular hornblende diorite.

STRATIFIED ROCKS

SILURIAN OR DEVONIAN

DSv, DSvg — Vassalboro Formation

DSv: *heavy bedded, light bluish gray, slightly calcareous wacke with thin interbeds of medium gray phyllite. Where metamorphosed, heavy bedded light gray QtzBiotActDiopPlag granulite with thin interbeds of gray QtzBiotMusc schist.*

DSvg: *medium dark gray phyllite, locally containing abundant pyrrhotite.*

SILURIAN

Sww, Swe, Swg, Swls — Waterville Formation

Swe: *thin beds of alternating greenish gray pelite and micaceous quartzite of eastern facies. Where metamorphosed, thin beds of alternating light-gray mica schist with porphyroblasts of garnet, staurolite, andalusite, and cordierite and micaceous quartzite.*

Sww: *beds with variable thickness of light-gray quartz wacke and dark-gray to greenish gray pelite belonging to the western facies. Some beds are graded.*

Swls: *1″ to 3″ beds of gray limestone interbedded with 1/2″ to 1″ beds of phyllite. Where metamorphosed, thin beds of calcite marble containing biotite and actinolite or calcite granulite containing diopside, hornblende, garnet, and biotite alternating with light-gray mica schist.*

Swg: *medium dark-gray phyllite, locally containing abundant pyrrhotite.*

Smh, Smhg — Mayflower Hill Formation

Smh: *heavy-bedded, light-gray, slightly calcareous wacke grading upward within a bed into medium gray phyllite.*

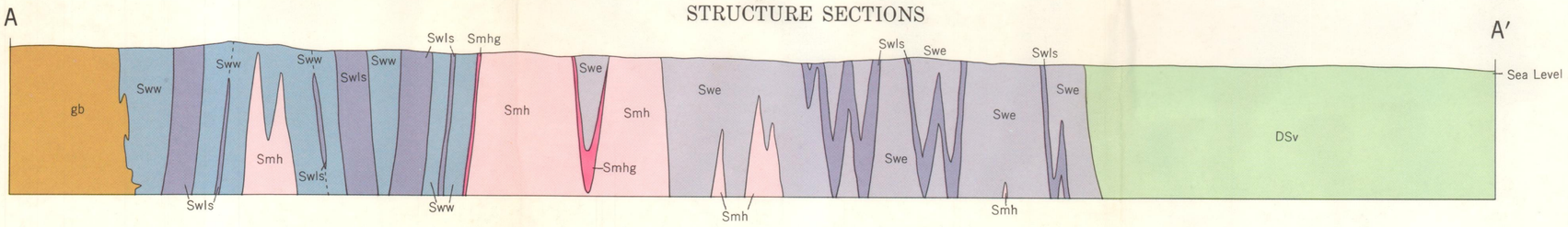
Smhg: *medium-gray phyllite containing abundant pyrrhotite.*

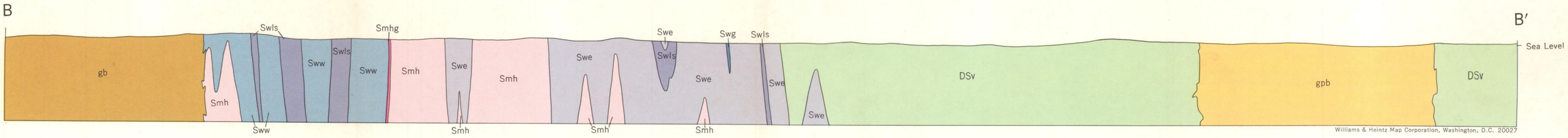
STRUCTURE SYMBOLS

- Formation contact
- Dip and strike of bedding where geopetal criteria indicate tops.
- Strike of vertical bedding where geopetal criteria indicate tops.
- Dip and strike of overturned beds.
- Dip and strike of bedding.
- Strike of bedding where vertical.
- Dip and strike of schistosity.
- Strike of vertical schistosity.
- Dip and strike of cleavage.
- Strike of cleavage where vertical.
- Dip and strike of axial surface of minor fold with trend and plunge of axis. Rotational sense where observed is shown beside symbol.
- Strike and plunge of minor fold where axial surface is vertical.
- Trend and plunge of intersection of cleavage and bedding
- Trend and plunge of boudin line.
- Isograd
- Fossil locality

Geology surveyed during the summers of 1958, 1959, 1960, and part of 1961 by P. H. Osberg

STRUCTURE SECTIONS





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