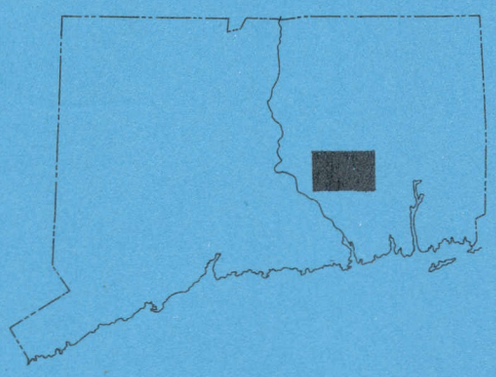
The Bedrock Geology of the Moodus and Colchester Quadrangles

WITH MAPS

Open Plate 1
Open Plate 2

LAWRENCE LUNDGREN, JR., LAWRENCE ASHMEAD, AND GEORGE L. SNYDER



STATE GEOLOGICAL AND NATURAL HISTORY SURVEY OF CONNECTICUT

A DIVISION OF THE DEPARTMENT OF AGRICULTURE AND NATURAL RESOURCES

1971

QUADRANGLE REPORT NO. 27

STATE GEOLOGICAL AND NATURAL HISTORY SURVEY
OF CONNECTICUT

PREPARED IN COOPERATION WITH THE
U. S. GEOLOGICAL SURVEY

The Bedrock Geology of the Moodus and Colchester Quadrangles

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The Bedrock Geology of the Moodus and Colchester Quadrangles[1]

by

Lawrence Lundgren[2], Lawrence Ashmead[2], and George L. Snyder[3]

INTRODUCTION

The Moodus and Colchester quadrangles lie in the middle of the Eastern Highlands of Connecticut. All the adjoining quadrangles have been mapped geologically at a scale of 1:24,000 and, except for the Middle Haddam quadrangle, geologic maps of these, with or without text, have been published (fig. 1). The maps accompanying this report (pls. 1 and 2, in pocket) complete the central part of a picture whose major elements have already been established.

The bedrock geology of the area comprising the Moodus and Colchester quadrangles is quite simple in its broad aspect. Two major stratigraphic units, the Hebron Formation and the Brimfield Schist, form a basinlike structure with its center near Thousand Acre Pond (fig. 2, M IX, C VII). The central part of this basin is occupied by gently dipping mica schists of the Brimfield Schist. The rim of the basin consists of Hebron Formation, which physically underlies the Brimfield Schist throughout most of the area. Thus the rocks generally dip gently but, nonetheless, they are high-grade metamorphic rocks, as can be seen readily by driving along those segments of Connecticut Route 2 constructed since 1960. Other rock units appear only in the extreme corners of the area and in the southwestern part of the Colchester quadrangle (fig. 2, C VII, VIII). The structural features and rock units in the southeastern, northeastern, and northwestern corners of the area have been described in reports on contiguous quadrangles (fig. 1) and these must be consulted for more complete information.

The text of this report was written by Lundgren and reviewed by Ashmead and Snyder. The maps are a composite of work done by all three. Lundgren mapped three-fourths of the Colchester quadrangle in 1965 and 1966; the remaining fourth, the northeastern quarter, was mapped by Snyder in conjunction with a gravimetric survey of the gabbro body at Lebanon (Kane and Snyder, 1964). Ashmead made a detailed outcrop map of the Moodus quadrangle in 1958 and 1959; the present map (pl. 1) was compiled by Lundgren by combining Ashmead's map with mapping done during 1966 and 1967. The diabase dikes shown in the Moodus quadrangle were mapped on the basis of outcrops, float, and a limited ground-magnetometer survey.

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[1] Publication approved by Director, U.S. Geological Survey.

[2] Connecticut Geological and Natural History Survey.

[3] U.S. Geological Survey.

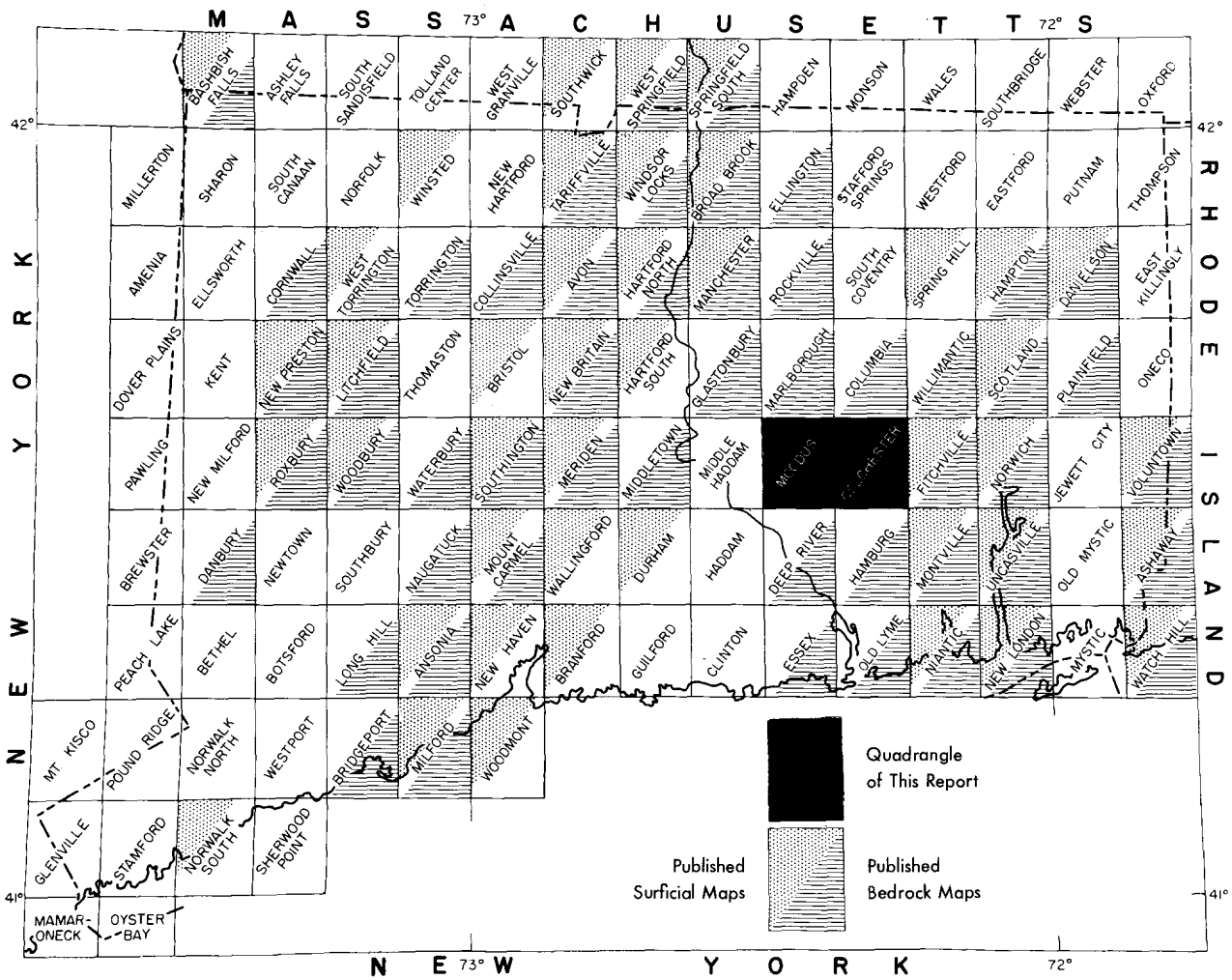


Fig. 1. Index map of Connecticut showing the location of the Moodus and Colchester quadrangles and of other published quadrangle maps.

Thomas McGuire helped to make this magnetometer survey and James Kaufman prepared many of the thin sections studied for this report. The Connecticut Geological and Natural History Survey supported field work by Lundgren and Ashmead, and Snyder's work was supported by the U.S. Geological Survey.

ROCK UNITS

General Remarks

The rocks in the two quadrangles lie within the sillimanite zone of metamorphism, as indicated by the presence of sillimanite in biotite-muscovite schists of the Brimfield Schist throughout both quadrangles. Other rock units display assemblages compatible with this high grade of metamorphism (table 1). Most of the rock units exposed within the quadrangles have been described in some detail by Lundgren (1963, 1966b) and numerous modal analyses are found in his reports. Therefore, the characteristics of each unit, as seen in one or two natural or artificial exposures and in hand specimens, are emphasized here to illustrate the characteristics used to distinguish these units in eastern Connecticut, thus presenting a guide to some of the major rock units. Information obtained from the examination of about 150 thin sections supplements these descriptions of larger scale features.

Locations of outcrops and samples are indicated by citing the ninth of the quadrangle in which the outcrop is located or from which the sample came (for example, M I *or* C II, fig. 2). In addition, any or all of the following are cited where appropriate: a geographic name, a Connecticut State Highway number, and Connecticut Grid System coordinates, which are marked on the edges of topographic map sheets and on plates 1 and 2. For example, coordinates given as 28.83 N, 67.77 E indicate a location 288,300 ft N and 677,700 ft E of a reference point located south and west of the Connecticut border.

In the thin sections described and studied, potassium feldspar and plagioclase were stained for easy identification. Colors of minerals in thin sections of standard thickness (magnification 50X, plane-polarized light) and colors of hand specimens of rocks or minerals are described throughout the report by citing the most nearly similar color on the Rock Color Chart distributed by the Geological Society of America. The meta-sedimentary and meta-volcanic units are described in order, beginning with the oldest. Units that are definitely, or probably, intrusive igneous rocks are described separately, whether they are younger or older than the regional metamorphism.

Ivoryton Group of Lundgren (1966b)

NOMENCLATURE

The name Ivoryton Group was introduced by Lundgren (1966b, p. 14) to designate a sequence consisting largely of plagioclase gneisses that lies stratigraphically below a sequence of micaceous rocks, including the Brimfield and Hebron Formations. The Ivoryton consists of New London Gneiss at the base, Monson Gneiss in the middle, and Middletown

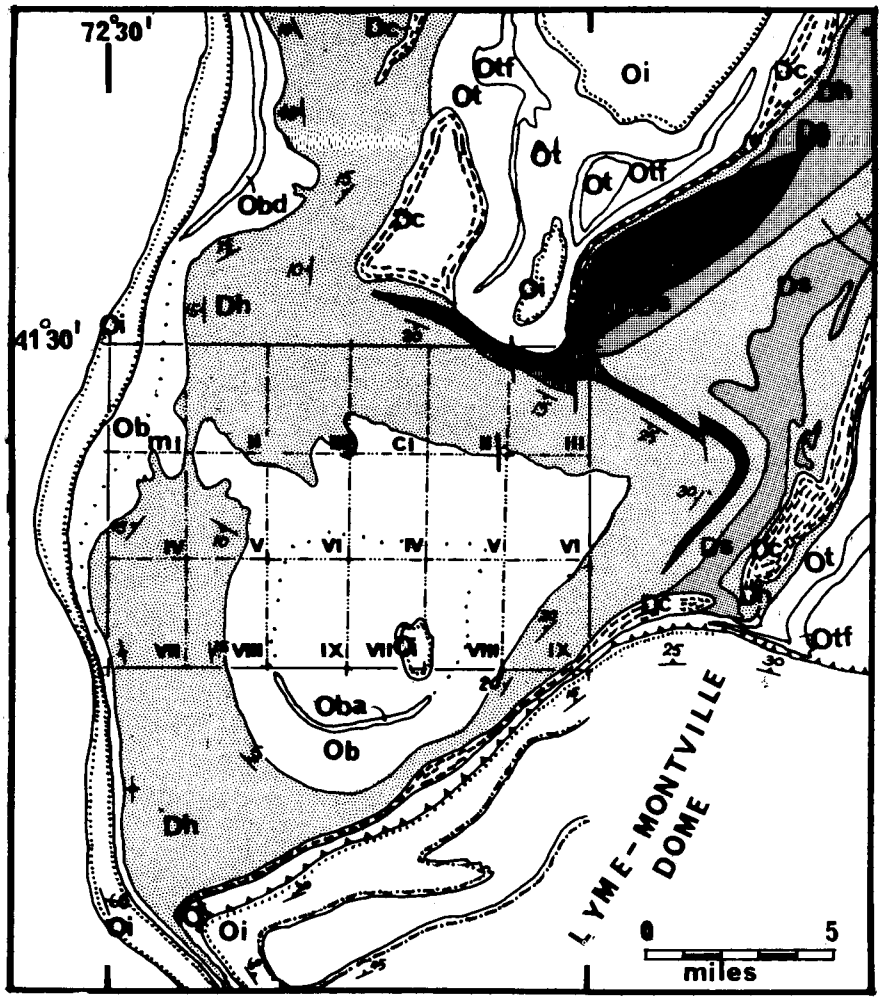
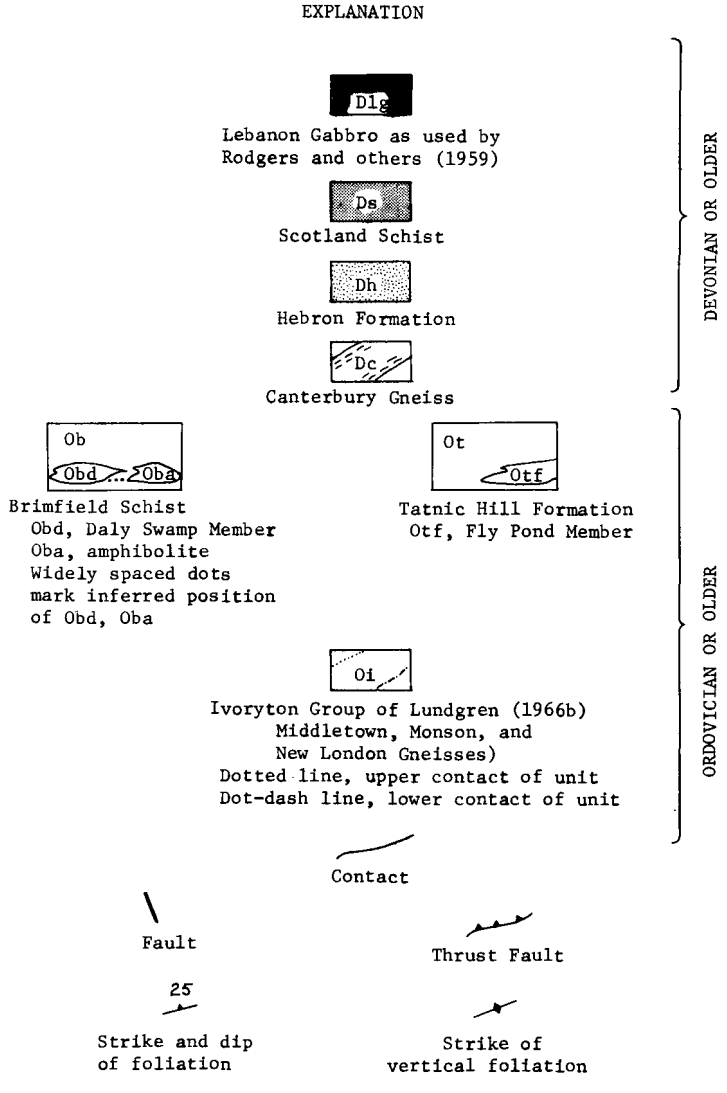


Fig. 2. Division of the Moodus (M I-IX) and Colchester (C I-IX) quadrangles into ninths, and geologic map of the area surrounding these quadrangles.

Gneiss at the top. However, no single section is known to expose all three units in continuous sequence. The Monson Gneiss of this report is continuous with the Monson in the type area of Ivoryton Group. The Middletown Gneiss of this report is not in contact with Monson Gneiss, and its designation as Middletown can be questioned if the structural and stratigraphic arguments presented in Lundgren (1963, 1966b) are not accepted.

MONSON GNEISS

The Monson Gneiss is a light-gray, medium-grained, plagioclase-quartz gneiss in which biotite and hornblende together constitute 10 to 20 percent in modal analyses of most samples. Layers of black amphibolite are present in the gray gneisses. The Monson Gneiss cuts across the



Explanation for geology in fig. 2, page 4.

northwestern corner of the Moodus quadrangle, where it is exposed in long, rounded outcrops in which layering is relatively inconspicuous. The best place to see the Monson Gneiss in this area, however, is in the highway cuts on Connecticut Route 2 in the Marlborough quadrangle (Marlborough VII, Snyder, 1970) just north of the Moodus quadrangle.

MIDDLETOWN GNEISS

The Middletown Gneiss normally overlies the Monson Gneiss of the Ivoryton Group and underlies the Brimfield Schist; however, no definite Middletown Gneiss is exposed along the contact between Brimfield and Monson in Moodus (fig. 2, I). Although some garnet-bearing gneisses

Table 1.--Mineral assemblages in major stratigraphic units

	Hebron Formation			Brimfield Schist			Middletown Gneiss				
	schist	calc-silicate		schist	amphibolite		cummingtonite gneiss	coticule A	coticule B	amphibolite A	amphibolite B
quartz	●	●		●			●	●	●		
plagioclase		●		●	●		●		●	●	●
K-feldspar											
biotite	●	●		●							
muscovite	●			●							
hornblende		●			●					●	●
diopside		●									●
cummingtonite							●	●	●		
garnet				●				●	●		
epidote					●						●
sillimanite				●							
calcite		●									
sphene		●			●						●
Fe-sulfide	●			●							
Fe-oxide		●			●		●	●	●		●
graphite	●			●							

are present, these were assigned to the Brimfield here. Middletown rocks are exposed along this contact farther south in the Deep River Quadrangle (Lundgren, 1963). Middletown Gneiss, or rock that is strikingly similar to the Middletown, is present southwest of Lake Hayward, also called Gardner Lake, (C VII-VIII), where it caps several prominent hills, including Long Hill.

The Middletown Gneiss in the Deep River and other quadrangles is a varied stratigraphic unit consisting of a variety of amphibole-bearing rock units that were volcanic rocks before metamorphism. The Middletown commonly includes layered spessartite-quartz-amphibole rock formed from bedded chert associated with the volcanic rocks. The amphibole-bearing units are notable for the close association of gray quartz-plagioclase gneisses containing one of the non-calciferous Mg-Fe amphiboles *cummingtonite* or *anthophyllite* with black amphibolites containing ordinary Ca-Mg-Fe amphibole (hornblende), and with the layered, red, garnet-quartz rock, commonly called *coticule* by New England geologists. All these rock types are well exposed in cliffs in the extreme southeastern part of C VII and on or near the road in the adjoining Hamburg quadrangle (Lundgren, 1966b). There is no completely satisfactory evidence that these are Middletown Gneiss in the same stratigraphic position as the type Middletown. Mapping them as Middletown requires a structural interpretation that is not the only

plausible interpretation, at least on a regional scale. However, the three-unit sequence, Middletown-Brimfield-Hebron, seen here makes the assignment more plausible than any other that has been suggested. (See discussion of structural geology.)

The quartz-plagioclase gneisses are light-colored gray or rust-stained rocks, many of which contain prismatic crystals of light- to dark-brown anthophyllite or cummingtonite. Biotite and magnetite are also generally found with the amphiboles. The amphibolites interbedded with the quartz-plagioclase gneisses are hornblende-plagioclase rocks displaying a variety of textures and outcrop-scale structures. Some are sharply layered, evenly laminated black and white rocks in which hornblende-rich layers alternate with rust-stained light-colored layers. Other types of amphibolite are nearly massive, black, hornblende-plagioclase rock, biotitic hornblende-plagioclase rocks that generally are highly friable, and black hornblende-plagioclase rock containing green streaks rich in epidote. The amphibolites exposed at the northern end of the mass of Omia are interbedded with thin layers of a red rock (coticule) consisting essentially of spessartitic garnet and quartz plus moderate amounts of cummingtonite, or cummingtonite and hornblende. A less distinctive type of rock, a light-gray, even-grained quartz-plagioclase-biotite rock, is a substantial part of the Middletown Gneiss as mapped here. This rock is so indistinctly foliated in many of the broad outcrops on Long Hill that it is virtually a *granofels*. However, this unit changes along strike to become banded light-gray gneiss exposed on the north side of the road just south of the Colchester quadrangle.

Brimfield Schist

GENERAL REMARKS

The Brimfield Schist is essentially a coarse-grained biotite-muscovite-schist unit, which blankets more than 50 percent of the area. Another schist unit that we regard as stratigraphically equivalent to the Brimfield, is present in C IX (fig. 2). It was described by Snyder (1964a, p. 4-5) as the Putnam Gneiss but is now called the Tatnic Hill Formation (Lundgren, 1966b, p. 10-11). These schists are rather poorly exposed over most of the area. Where exposures are poorest, the schist is seen only adjacent to resistant pegmatite masses.

In the areas north and south of the Moodus and Colchester quadrangles the Brimfield contains readily mappable nonschist units that effectively divide the Brimfield into upper and lower parts. To the south, the nonschist unit (fig. 2) is an amphibolite (Lundgren, 1963, 1966b); to the north it is an interlayered biotite schist and calc-silicate schist, the Daly Swamp Member (Snyder, 1970; fig. 2, this report). Because neither of these units is exposed in the Moodus-Colchester area, the Brimfield here has not been formally divided into upper and lower units. However, the probable position of the horizon representing the Daly Swamp Member or the amphibolite unit is shown by a dotted line in figure 2, to indicate that either of these may be encountered beneath the surface.

The principal types of rock present in outcrops are described below. The relative abundances of each type of rock in the "upper" and "lower" parts of the Brimfield Schist are indicated.

BIOTITE-MUSCOVITE SCHISTS

The dominant rocks in the Brimfield Schist are rust-stained muscovitic schists. The bulk of the muscovitic schist seen in natural outcrops is coarse-grained, silvery-gray, biotite-muscovite schist with quartz and plagioclase in discontinuous lenses and folia and in augenlike aggregates. In large exposures it has a migmatitic or gneissic aspect. Generally it is spotted with small (1-2 mm) red garnets and contains traces of iron oxide (magnetite-ilmenite), graphite, and iron sulfide (pyrite or pyrrhotite). Muscovite is in scattered single flakes, in laminae consisting of randomly oriented small crystals, and in conspicuous porphyroblasts 5-10 mm across. Fine sillimanite needles are present and, locally, coarse-grained aggregates of sillimanite and quartz that appear in outcrop as silky white lenses.

Exposures made during the construction of Route 2 suggest that the schists seen in natural outcrops represent the most feldspathic, least micaceous, and least sulfidic variants of schist. Artificial exposures display highly micaceous schist that deteriorates rapidly on exposure to the atmosphere by the conversion of sulfide (pyrrhotite) to yellow- and reddish-brown iron oxides and white sulfates that quickly encrust the exposures. It appears that these rapidly deteriorating schists contain more muscovite and graphite than the schists seen in most large natural exposures.

GARNETIFEROUS QUARTZ-BIOTITE GNEISS

The lower part of the Brimfield Schist includes numerous layers of nonmuscovitic schist and gneiss. These rocks are particularly well exposed at Mill Hill (C IV) and Prospect Hill (M VI, C IV), and in roadcuts west of Colchester at the junction of Route 2 and Route 16. The cuts display evenly bedded, generally equigranular, millimeter-grained, light- to dark-gray quartz-biotite-plagioclase-garnet gneiss with scattered sulfide. This type of rock is characterized by small (1-3 mm) red garnets scattered through most layers but concentrated locally on bedding or foliation surfaces.

SILLIMANITIC ROCKS

Sillimanite is present but is rather inconspicuous in many samples of ordinary biotite-muscovite schist. However, there are several areas in which sillimanite is a conspicuous mineral. Most of the rocks in which it is particularly conspicuous are in the lower part of the Brimfield but scattered outcrops of sillimanitic rock have been seen within the belt of upper Brimfield.

In the vicinity of Prospect Hill (M VI, C IV) there are particularly good exposures of granular quartz-biotite-plagioclase gneisses that are studded with white lenses and cigar-shaped masses (1 to 2 in. long) generally consisting of sillimanite, muscovite, and quartz. Some of these

lenses do not contain sillimanite but they do contain muscovite and their resemblance to the sillimanite lenses suggests that this mineral was converted to muscovite. From Prospect Hill southward a belt of sillimanitic rocks can be traced in outcrops lying west of Pine Brook, Babcock Pond, and Babcock Swamp (M VI, IX). These rocks include that described above as well as a very coarse-grained biotite-muscovite schist that contains large masses of silky, lustrous white aggregates of sillimanite needles intergrown with quartz. The sillimanite masses stand out on the readily weathered schist matrix.

AMPHIBOLITE

Black hornblende-plagioclase amphibolite units are present in layers in biotite-muscovite schist located near both the upper and lower contacts of the Brimfield Schist. Curiously, in the Moodus-Colchester area, none has been seen near the middle of the Brimfield, even though a major amphibolite is present in the middle Brimfield in the Deep River and Hamburg quadrangles.

The amphibolites close to the upper (Hebron) contact are best exposed on the northern side of Deep River Reservoir (C VI). These are medium-grained layered hornblende-plagioclase rocks. The hornblende is black in hand specimen, dusky yellow green (Z=5GY 5/2) in thin section; the plagioclase is clear, moderately well twinned andesine. Some folia consist of complexly intergrown granules of a pale green amphibole, scapolite, and epidote.

Amphibolites close to the lower (Middletown or Monson) contact are best exposed southwest of Lake Hayward but can be seen throughout the lower Brimfield along the contact with the Monson Gneiss (M I). The Lake Hayward exposures display interlayered, highly friable biotite-bearing amphibolites and a moderately friable amphibolite, containing no biotite, that seems to be the most distinctive amphibolite type in the Brimfield Schist. It consists of hornblende, plagioclase, and sphene. Typically, the hornblende forms large, round grains set in a granular plagioclase matrix, giving the rock a spotted appearance. This friable, spotted amphibolite, which is invariably associated here with muscovitic schists, differs from the amphibolites in the units mapped as Monson and Middletown.

Hebron Formation

The Hebron Formation is well exposed in a variety of structural situations (see section on structural geology) and is the unit that contains the most complete record of the metamorphic, igneous, and structural evolution of the rock complex in this area. Most Hebron is well bedded, consisting of layers of quartz-biotite schist and calc-silicate granofels. Layers of muscovite-biotite schist are distributed only locally and are nowhere abundant. The clearest and most easily accessible exposures of Hebron rocks are artificial ones along Connecticut Route 2 (M II-III, fig. 2).

The quartz-biotite-schist layers exposed at the intersection of Route 2

and Route 149 are brownish-gray, equigranular, fine-grained (0.5 mm) quartz-plagioclase-biotite rocks in which biotite (Z=moderate brown) is 20 to 30 percent by volume. The calc-silicate granofels is light-gray to light-greenish-gray, equigranular, fine- to medium-grained rock consisting of quartz and andesine and one or more of the following minerals: hornblende, diopside, scapolite, sphene, calcite, and biotite. Microcline, muscovite, and garnet are very rare. Most individual calc-silicate layers or quartz-biotite layers are inches thick; the two rocks are interbedded with one another through sections tens of feet thick in some outcrops but in others one rock dominates to the virtual exclusion of the other. Other types of rock intercalated with these two types include granitic rocks, inequigranular, coarse-grained, rather schistose variants of the quartz-biotite schist, and muscovite schist.

The muscovite schists form layers a few feet thick at most, within calc-silicate gneiss; however, the schists are so nonresistant that surface outcrops may not give a fair indication of their abundance. Most schist layers large enough to map are within the Colchester quadrangle. These schists are mineralogically and texturally very different from the dominant rock types of the Hebron. They are coarse-grained (1-3 mm), rust-stained rocks (variegated, ranging from strong yellowish brown, 10YR 5/8, to weak yellow, 5Y 8/4), which are silvery gray when fresh. The mineralogy is simple: muscovite, biotite (Z=moderate reddish brown) and quartz. Muscovite is the more abundant mica. The only other minerals are the opaque accessories graphite, pyrrhotite, and possibly pyrite. The muscovite schists are notable for a relative abundance of muscovite and a general absence of plagioclase and garnet, mineralogic attributes which distinguish them from schists mapped as Brimfield but possibly not from all those mapped as Scotland Schist (Snyder, 1964a). The muscovite-schist masses are treated here as integral parts of the Hebron, representing metamorphosed shale lenses, although some might be tectonic inclusions of the Scotland Schist in the core of an isoclinal fold.

Intrusive rocks

CANTERBURY GNEISS

The Canterbury Gneiss comprises relatively coarse-grained (1-3 mm) biotitic quartz-plagioclase-microcline gneisses that separate the Hebron Formation from the Tatnic Hill Formation or that lie within the Hebron close to the Hebron-Tatnic Hill contact. The Canterbury is most probably a metamorphosed intrusive and thus is placed with the intrusive rocks rather than with the metavolcanic units as was earlier done by Lundgren (1966b). The Canterbury is exposed only in C III and C IX; it is not found along the western edge of the Hebron. The belt of exposure in C IX is part of a belt already described in some detail (Snyder, 1964a, p. 110-111; Lundgren, 1966b). The belt in C III is the end of a belt well exposed in the Willimantic quadrangle (Snyder, 1964b). Within the Colchester quadrangle the best exposure of Canterbury is in a quarry (C IX), active in 1969. This rock is a medium- to light-gray, rather well foliated rock whose foliation is produced by the parallel orientation of biotite flakes, thin (0.3 mm) laminae of quartz, and laminae

of aggregates of plagioclase and microcline grains. Locally, this type of rock has conspicuous large crystals of microcline and plagioclase (Lundgren, 1966b, p. 6).

LEBANON GABBRO AS USED BY RODGERS AND OTHERS (1959)

The Lebanon Gabbro as used by Rodgers and others (1959) is a metamorphosed gabbro within the Hebron Formation along or near the contact between the Hebron and the Canterbury Gneiss in C II-III and in C IX. The form of the gabbro mass in C II-III has been determined by Kane and Snyder (1964). The small mass of gabbro in C IX is isolated within the Hebron Formation but clearly is similar to parts of the main mass of Lebanon described by Snyder (1964a, p. 1-13 and 1964b) and, in fact, must be the edge of the folded sheet of gabbro shown by Snyder in the Fitchville quadrangle (Snyder, 1964a); see also fig. 2, this report.

The gabbro in C II-III is principally a coarse-grained, black and white rock consisting of sharply and complexly twinned andesine, dusky green (Z=5G 3/2) hornblende filled with small inclusions of quartz, moderate reddish-brown (Z=5YR 3/4) biotite, and minor magnetite-ilmenite, sphene, and apatite. Hornblende is more abundant than biotite. This is equivalent to the Lg3 unit of Snyder (1964b).

The least deformed gabbro in C IX is also coarse-grained, black and white rock consisting principally of plagioclase, hornblende, and biotite. Apparently this rock is most nearly comparable to the Lg3 phase of the Lebanon Gabbro but differs from it in the following ways: The hornblende in the samples from C IX is pale yellow green; in the Lg3 unit it is dark green. The Colchester C-IX hornblende is filled with closely spaced opaque or reddish-brown inclusions; the Lg3 hornblende contains only quartz inclusions. Sphene is absent and biotite is only a minor constituent in the Colchester C-IX samples; sphene and biotite are important constituents in the Lg3 samples.

The more highly deformed (cataclastic) gabbro in C IX lies close to the Honey Hill fault. It is similar to the gabbro from C IX described above but is cut by apparent shear surfaces and the plagioclase twin lamellae are bent and offset along shear surfaces. Between crossed polars the plagioclase has a distinctive patchy or nonuniform extinction pattern.

PEGMATITES AND MINOR GRANITIC ROCKS

Pegmatite and other small masses of finer grained granitic rock form lenses, layers, and dikes in the layered units. These rocks all consist essentially of quartz, potassium feldspar, and plagioclase with less than 10 percent mafic minerals. Their texture varies from equigranular to strongly foliated; their chemical composition ranges from granite (in the narrow sense of the word) to granodiorite.

Most of the pegmatite has at least a weakly developed foliation, and in the Honey Hill fault zone is strongly foliated. Most pegmatites within the rather muscovitic Brimfield Schist contain conspicuous muscovite; most pegmatites in other units, particularly the Hebron and

Middletown, contain little or no muscovite but do contain conspicuous biotite.

The muscovitic pegmatites in the Brimfield have been described briefly in the Deep River and Hamburg quadrangle reports (Lundgren, 1963, 1966b) and need not be discussed further. Pegmatites in the Monson, Canterbury, and Middletown are relatively minor.

In the Hebron Formation the granitic rocks include pegmatite, both foliated and nonfoliated, foliated biotite granite, and foliated garnet-tourmaline granite. Most pegmatite (for example, that in M III) is exposed on hilltops, where long (20-ft) whaleback outcrops lie above calc-silicate granofels, commonly deeply weathered. The most conspicuous example of such a pegmatite is at Cave Hill (M II), where caves are developed in the calcareous calc-silicate granofels underlying a resistant pegmatite sheet. These pegmatites are white, uniform, coarse-grained granites, made up chiefly of quartz, potassium feldspar, and plagioclase. They contain scattered potassium-feldspar crystals, as large as 1 ft across, that stand out on the surface. However, most of the potassium feldspar is present in smaller grains. Biotite flakes ½ in. to 1 in. across are conspicuous but form only a small percentage of the rock. Red garnets are conspicuous also, whereas muscovite is inconspicuous. The one pegmatite in the area that has been quarried (Slater's Quarry, M VII) is of this type.

The Slater's Quarry pegmatites (pl. 2, 25.48 N, 67.54 E) comprise both dikes which cut across the bedding in the Hebron calc-silicate gneiss, and locally discordant sills. The pegmatites are white quartz-plagioclase-microperthite-biotite rocks. Some contain inch-thick books of muscovite, long (6-8 in.) slender, hexagonal prisms of yellow-green beryl, and, especially near contacts, abundant black tourmaline crystals. Others lack these exotic minerals that are of interest to collectors. Pegmatite in the Deep River quadrangle (Lundgren, 1963, p. 22) is mineralogically and texturally similar to the Slater pegmatites.

The foliated biotite granites in the Hebron form layers that are as much as 5 ft thick and traceable for hundreds of feet along strike. Cross-cutting dikes of similar or identical granite are common, generally crossing the bedding at an angle of 30° to 40°. All these biotite granites are light-gray, fine- to medium-grained rocks consisting of quartz, plagioclase, and microcline in about equal amounts, as well as some dark-brown biotite, which generally is uniformly oriented parallel to the contacts. They contain only traces of such nonopaque accessory minerals as apatite and zircon. The garnet-tourmaline granites are the most distinctive granitic rocks in the area. They are apparently restricted to the Hebron Formation and appear both in cross-cutting dikes and as extensive layers in Hebron calc-silicate gneiss (pls. 1, 2). The layers range in thickness from a fraction of an inch to 2 ft. These white layers, spotted with black tourmaline, red garnet, and rare yellow-green apatite, are striking in appearance. Most have a distinctive texture created by the contrast between large (2 to 5 cm) augen of feldspar with quartz "tails" and the fine-grained quartz-feldspar matrix. In this matrix, parallel quartz laminae bend around the feldspar augen and form

a clear foliation. The rocks are mineralogically simple aggregates of quartz, microcline, and albite with conspicuous garnet (sheathed in chlorite), strongly pleochroic varicolored (brown and green) tourmaline, needles of apatite, and traces of muscovite. Nonfoliated garnet-tourmaline pegmatite dikes cut the foliated planar sheets. The two types are probably variants of a single granite.

DIABASE

Two major lines marked by diabase dikes cross the western part of the Moodus quadrangle. They appear to consist of abutting segments successively oriented N 25° W and N 50°-60° E. All these dikes are steeply dipping. Careful magnetometric mapping, comparable to Snyder's (1970) work in the Marlborough quadrangle, might bring out further details of this pattern and refine the placement of contacts. The work done for this report seems to indicate that the dikes are nearly continuous for miles along strike and that they fill en echelon fractures having two distinct orientations.

The diabase samples display an ophitic intergrowth of ½-mm crystals of clinopyroxene and plagioclase (labradorite) with conspicuous patches of microscopically intergrown quartz and potassium feldspar in interstices among the main minerals. Scattered flakes of biotite, granules of magnetite-ilmenite, and needles of apatite are the other principal minerals present.

STRUCTURAL GEOLOGY

General pattern

The apparent structural pattern of the bedrock units is the pattern discernible from a study of the present attitudes of the bedding and from mapping the distribution of rock units without regard to their relative ages. It is the pattern that an engineering or ground-water geologist, planning shallow excavations, tunnels, or wells in this region, might find most important. This apparent structural pattern is a rather simple one; however, the true structural relations are not at all simple.

The apparent structural pattern is evident from the map pattern of the Hebron Formation and the contact between the Hebron and the Brimfield (fig. 2). The Hebron forms an almost complete ring around the central area of Brimfield Schist. Bedding in the Hebron Formation and foliation and bedding in the Brimfield (see amphibolite in fig. 2) dip toward this central region. This simple, if imperfect, basin structure is known as the Colchester basin. Examination of the foliation symbols and the Brimfield-Hebron contact (see pls. 1, 2) will show that there are many places where the foliation makes an angle with the contact as drawn. Clearly, the units are folded on a small scale, and clearer exposures would show either that the contact itself is folded on a small scale or that folds in units on either side of the contact are disharmonic or do not affect the contact itself. The basin clearly is a late structure, developed later than many other folds described below but prior to high-angle faults in C II-III and elsewhere. Only along

the western edge of the basin is the basinlike form broken. Here the Brimfield can be traced in outcrop westward across Bull Hill and Dickinson Creek and westward out of the basin, to connect with steeply dipping Brimfield along the eastern edge of the belt of Monson Gneiss. This physical continuity between Brimfield in the basin and Brimfield along the eastern side of the Monson Gneiss is an important fact that must be taken into consideration in attempting to work out the true structure.

The true structural relationships are those that can be understood only from a study of the regional distribution of units and from a consideration of their relative ages. As the relative ages of some of the units are not established with certainty, several different interpretations of the structure are possible. In the Moodus-Colchester area the major structural problem is the explanation of the physical position of Middletown above Brimfield and Brimfield above Hebron. We have concluded that these units are structurally inverted and that this inversion is the result of large-scale recumbent folding. An alternative interpretation, suggested by the work of Pease and Peper (1968) in northern Connecticut, is that individual units (for example, Middletown) are not inverted but, rather that the sequence of units has been shuffled by thrust faulting. Only the recumbent-fold hypothesis is described explicitly in the present report but the alternatives suggested by Pease and Peper are noted in the appropriate places.

Recumbent Fold

The basined sheet of Hebron is structurally overlain and underlain by schist units (Brimfield and Tatnic Hill Formations). The Hebron has been interpreted as a remnant of the core of a recumbent isoclinal fold that has been folded. The stratigraphic evidence for this recumbent fold has been noted in several papers (Lundgren, 1963, 1966b; Dixon and Lundgren, 1968), and the recumbent-fold hypothesis has been used as one possible model to be examined as work progresses in eastern Connecticut. Since some of the arguments for the recumbent-fold hypothesis originated from work in the Moodus-Colchester area, they are reviewed here.

The stratigraphic evidence comprises the relationships between the Hebron and the Brimfield in M I-II and IV-V and the position of the Middletown in C VII. The Brimfield is believed to be older than the Hebron, and it does lie beneath the Hebron in the Deep River and Essex quadrangles. Thus the supposed normal sequence is Monson-Middletown-Brimfield-Hebron. However, in Moodus I-II and IV-V the Brimfield extends east *over* the Hebron and structurally overlies it throughout most of the area of Brimfield outcrop. In the regional context, this requires that the Brimfield and the Hebron in contact with it are inverted. If so, then much of the Hebron must be upside down as well, forming the upper (inverted) limb of a recumbent fold. In addition, the Middletown in C VIII lies structurally above the Brimfield. If one accepts this as Middletown (see Lundgren, 1966b), then the Brimfield and Middletown are inverted.

The alternative of Pease and Peper (1968) deserves serious analysis as work is completed in the area north of the Marlborough and Willimantic quadrangles. They postulate that the Brimfield was thrust over the Hebron but was not inverted. Similarly, they suggest that the Middletown was thrust over the Brimfield but was not inverted. This suggestion is based on their observation that the Brimfield in northern Connecticut appears to be right side up although much faulted by a series of imbricate thrusts. We recognize that thrust faults may be hidden within the Brimfield in the Moodus quadrangle but we believe that any hidden thrust faults may have modified but not destroyed the large-scale pattern resulting from recumbent folding and probably were associated with the folding.

Structural features in the Hebron

The interpretation of the broad structures of the Hebron as a recumbent fold is represented rather schematically by Lundgren (1963, fig. 5; see also Snyder, 1970). This structure continues north into the Moodus quadrangle. Within the area shown in figure 2, the Hebron may be viewed as a basined triangular sheet. Part of each edge of this triangular sheet is exposed in the Moodus-Colchester area. The excellent exposures along each edge of the triangular sheet of Hebron Formation provide samples of relationships in different parts of the folded recumbent fold and in other major structures. The purpose here is merely to illustrate some of the features in different parts of the Hebron, with only brief comment on their possible significance. Along the northern edge of the sheet (M II-III, C I-III), exposure is best in the Moodus quadrangle, where it is enhanced by the numerous cuts along or close to Connecticut Route 2. Most clear exposures probably lie in the upper (inverted) limb or close to the axial surface of the postulated recumbent fold. Additional exposures at this same structural level are found along Route 16 (M VII). In both areas many exposures are located very near the contact with the inverted Brimfield Schist.

Exposures on the northern side of Route 2, east of Blackledge River, provide supplementary evidence that many units in the Hebron Formation are recumbently folded but do not prove that the entire Hebron is recumbently folded. The bulk of the rock here is light-gray, quartz-rich, quartz-biotite-oligoclase schist or gneiss in which a few layers of garnetiferous calc-silicate granofels are present. Generally, this sedimentary facies of the Hebron does not display folds very clearly but, in these exposures, large, weathered joint faces show recumbent isoclinal folds having amplitudes ranging from a few inches to tens of feet (fig. 3). Only the smaller folds are markedly asymmetric; the others are symmetrical and nearly isoclinal. No other outcrops or cuts display a comparable abundance of isoclinal folds, although many display some. It is evident from this exposure that the folds are only visible where surfaces are well weathered and cleanly exposed; where fresh faces have been produced by blasting, folds of this type are far more difficult to recognize. These folds are believed to be associated with major recumbent folding preceding the development of the Colchester basin but they could be much older features, even sedimentary ones.

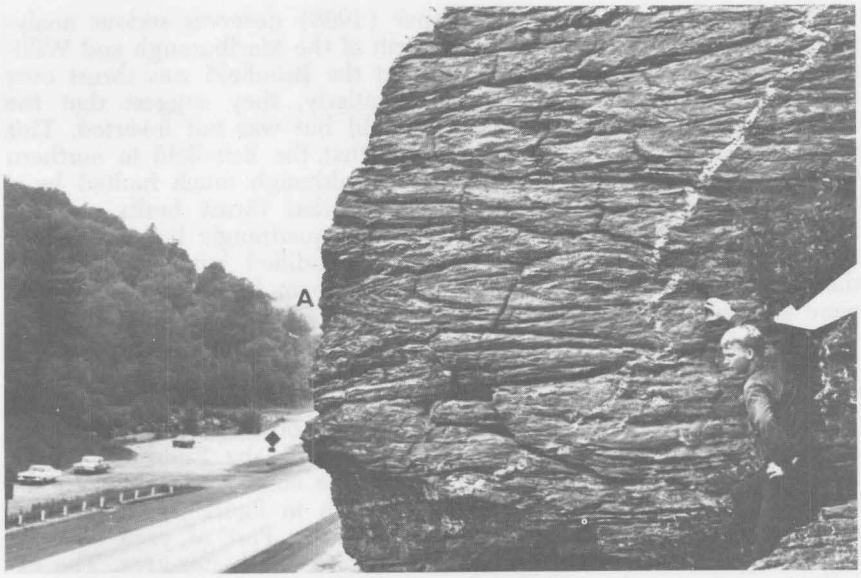


Fig. 3. Recumbent folds in Hebron quartz-biotite schists. The letter *A* is drawn at the nose of one fold. The face of the outcrop strikes 120° and dips 70° SW (toward the observer). Eastern side of Connecticut Route 2; 27.92 N, 69.08 E; M II.

Another element of the structure of the Hebron is provided by the Route-2 cuts, which extend for a mile west of the intersection with Route 149. These roadcuts show that bedding and granite layers in the Hebron were folded into a series of generally low-amplitude, rather open folds (figs. 4, 5), which folded all pre-existing folds, among them the isoclinal ones. These same cuts also illustrate extensive folding of the bedding and the granite layers into asymmetric folds of smaller amplitude with curved hinge lines (figs. 6, 7). Such folds, commonly called "drag folds" or "parasitic folds," document movement parallel to the layers. Detailed analyses of the type described by Hansen (1967) could prove fruitful in working out the structure but are beyond the scope of this report.

These road cuts on Route 2 also provide a record of the relationship between the time of emplacement of several types of granitic rock and the development of several types of structures. Here the thin layers of white-tourmaline-garnet granite are folded in both the small asymmetric folds (fig. 7) and the larger broad folds (fig. 4) and clearly were in place prior to any of the major structural events.

These layers are themselves cut by foliated biotite granite. Some of these dikes of biotite granite are located along faults marked by minor folds concentrated close to the dike contact. The remnants of an excellent exposure of this relationship may be seen, partly covered by asphalt coating, at the eastbound exit from Route 2 onto Route 149. Some of these dikes have themselves been displaced along the layering in the

Fig. 4. Open folds in Hebron calc-silicate gneiss and associated garnet-tourmaline granite. Southwestern side of Connecticut Route 2; 27.67 N, 69.18 E; M III.

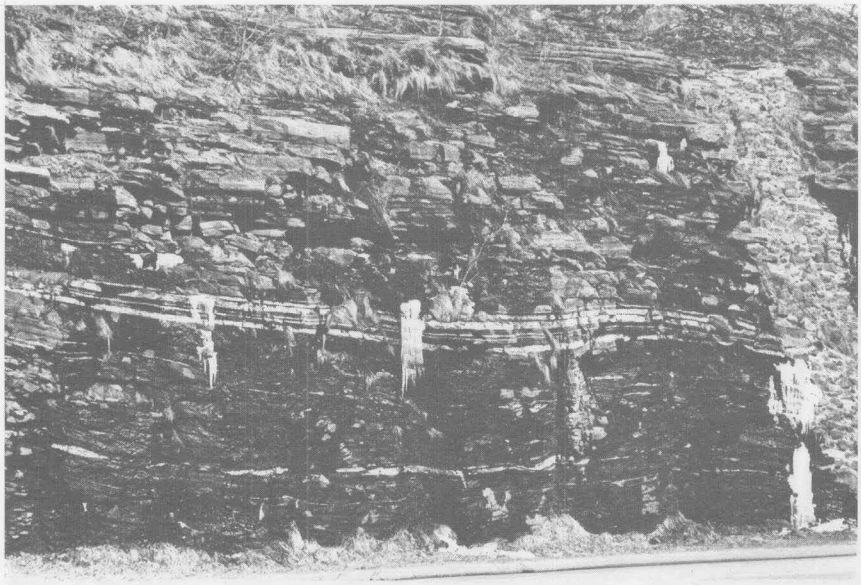


Fig. 5. Thin layers of garnet-tourmaline granite in Hebron calc-silicate gneiss. Northeastern side of Connecticut Route 2; 27.67 N, 69.18 E; M III.

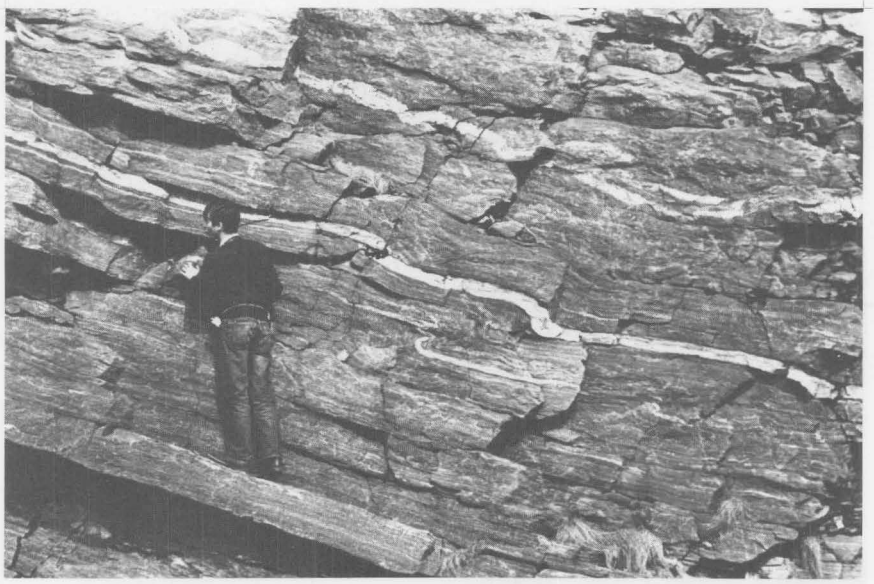


Fig. 6. Moderate-scale asymmetric folds in garnet-tourmaline granite within well bedded calc-silicate gneiss. Northeastern side of Connecticut Route 2; 27.67 N, 69.18 E; M III.

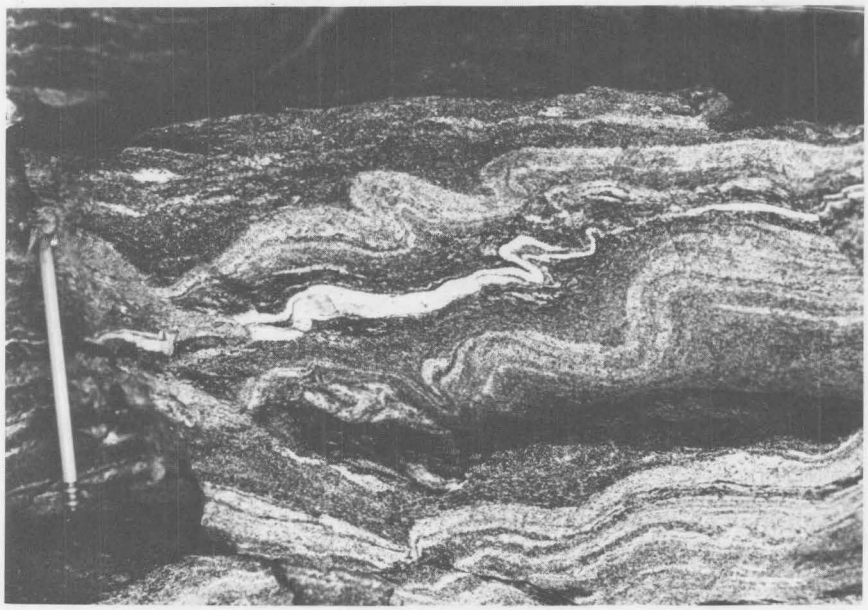
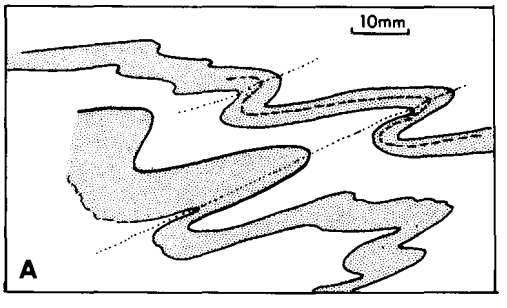


Fig. 7. Small-scale asymmetric folds in calc-silicate gneiss. Southwestern side of Connecticut Route 2; 27.67 N, 69.18 E; M III.

Hebron. In all these cuts, pegmatite appears both in dikes and in lenses, a large percentage of the lenses representing boudins or pinch-and-swell features formed from initially continuous layers.

The Hebron exposed along the southeastern edge of the sheet (C IX) displays structural features which are the products of cataclastic deformation within the Honey Hill blastomylonite zone of crushed and partially recrystallized rocks developed along low-angle faults. The types of features seen are listed below; detailed comment will be published separately (see Lundgren, 1969).



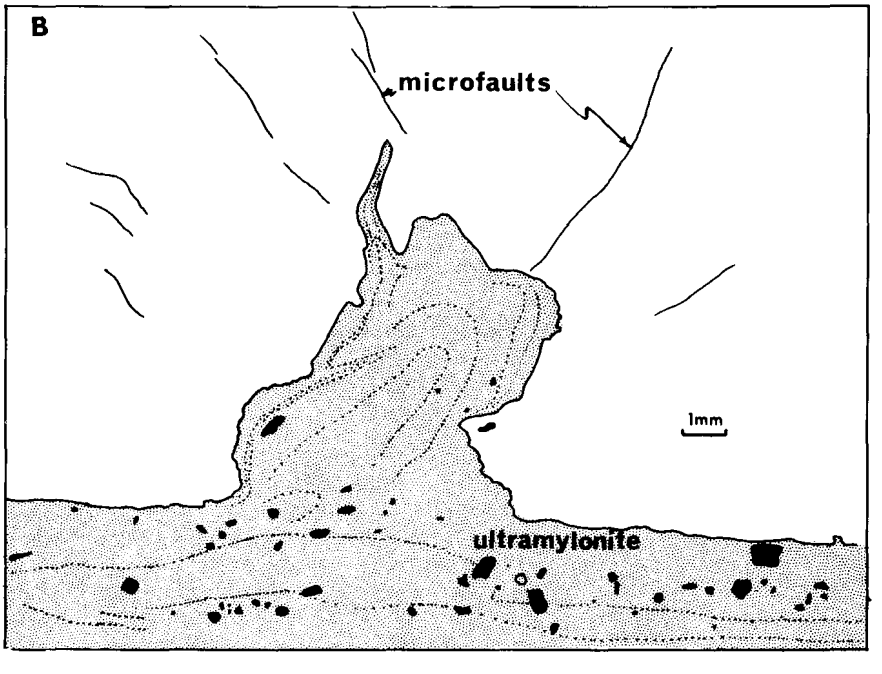


Fig. 8. Small-scale structures in cataclastic Hebron Formation. *A*. Asymmetric folds; stippled layers are calc-silicate granofels in blastomylonitic quartz-biotite-schist (C IX; 24.6 N, 73.14 E). *B*. Ultramylonite dike (patterned) in Hebron calc-silicate blastomylonite; black spots are quartz grains in aphanitic ultramylonite (C IX; 24.46 N, 73.12 E).

The features seen in outcrop include abundant small asymmetric folds in calc-silicate-granofels layers lying within crushed biotitic schist (fig. 8); small shears or slip surfaces on which the asymmetric folds are disrupted; layers of ultrafine-grained, nearly aphanitic rock (ultramylonite) and small dikelets of ultramylonite (fig. 8) that cut the layering of adjacent rock; and small folds and conjugate folds. The features seen in thin section indicate that one or more minerals in these rocks are crushed or granulated. The rocks containing partially crushed minerals are called blastomylonites. Most of the blastomylonites consist of relatively large grains of one of the original minerals, generally plagioclase, set in a finer grained matrix of the other minerals, generally quartz and biotite.

The Hebron along the western edge of the sheet (M IV and VII) dips W under the Brimfield and is nearly vertical in the extreme southwestern corner. Nearly vertical E-W joints provide good cross-section exposures through the Hebron in this zone. Rarely, such an exposure displays small recumbent isoclinal folds that have been folded but most do not display such recumbent folds. This western edge represents a zone in which the Hebron is rather sharply folded about an axis that probably trends between N and NE.

To summarize, the northern edge provides a sample of structures supposed to have formed during recumbent folding, during episodes of movement parallel to the layering, and during a stage of broad folding following the earlier recumbent folding. It also provides a good record of boudinage development and of late high-angle faulting. The southeastern edge illustrates the effects of shearing and granulation in a zone of low-angle movement above the Honey Hill fault. The western edge illustrates a zone in which the Hebron and adjacent Brimfield were folded about a N-trending hinge.

Faults and joints

The bedrock units are broken by faults of at least two distinct types: high-angle faults oriented N-S and NNW-SSE and low-angle faults (for instance, the Honey Hill fault, see Dixon and Lundgren, 1968) lying within the blastomylonite zone in C IX.

The high-angle faults are presumably very steep—probably vertical. They are most surely recognized from the offset of the Lebanon Gabbro (Kane and Snyder, 1964) in C III; each of these definite faults is marked by a linear topographic low. Other faults with similar orientations possibly underlie the numerous N-S and NNW-SSE linear valleys evident from the topographic map. Many of these valleys show outcrops with well developed joint faces parallel to the valley. Lines drawn along all such linear valleys that cross stratigraphic contacts produce a map that shows the probable positions of hundreds of faults with small displacements. However, the only faults actually shown on plate 2 have been drawn on the basis of apparent offsets in the Hebron-Brimfield contact.

The low-angle faults are inferred from the distribution of blastomylonitic rocks in C IX. Within the Colchester quadrangle these faults do not cut across stratigraphic units, indicating that displacements were essentially parallel to the stratigraphic contacts. These faults and the zones of blastomylonite must cut across these contacts at some point north or northwest of their present outcrop beneath the surface, because they do not follow the contacts at the surface in the Fitchville quadrangle. However, no subsurface information is available at present to document this inference. In areas of suspected thrust faulting, such as western Moodus, one would expect to find the rock types displayed by the known low-angle faults. There, however, no such rocks have as yet been found.

The blastomylonites are particularly well jointed rocks; their joints are more closely spaced and more uniformly distributed than those noted above. It appears that the blastomylonite zone is also a zone of thoroughly jointed rock that continues beneath the surface as a zone of rather weak and probably porous, even permeable, rock, different from anything else in the region.

The major joints appear to be steep or vertical, oriented either N-S or E-W. Rocks along some of the major linear valleys commonly show a conspicuously well developed set of N-S joints and the bedrock beneath any N-S topographic low is probably well jointed and probably faulted as well. The E-W joints are less prominent; they are not evident in the topography of the area. Many of these joints are fault surfaces; fresh exposures commonly are slickensided. Natural outcrops, however, rarely reveal these slickensides.

ECONOMIC AND ENGINEERING GEOLOGY

No significant use has been made of any of the rocks of the Moodus and Colchester quadrangles, although pegmatite was once quarried in the Moodus quadrangle and Canterbury Gneiss is now quarried on a small scale in the Colchester quadrangle (C IX). The most promising area for pegmatites is the southwestern part of the Moodus quadrangle within the area underlain by the Hebron Formation.

The distribution of the Brimfield Schist is of some importance, mostly negative, in the exploitation of ground-water resources, as its sulfide content is generally detrimental to water quality. In addition, rocks of the Brimfield are generally chemically and physically unstable upon exposure; any excavation in, or tunnel through, the Brimfield must be designed with this instability in mind.

The correlation between linear valleys and known faults or belts of closely spaced joints indicates that all such valleys must be viewed as belts of low-strength rock from the engineering point of view and as belts of high-permeability rock from the hydrologic point of view.

The cataclastic rocks of the Honey Hill fault zone have a tendency to fracture readily along closely spaced joints, and the subsurface position of this zone should be of some concern to anyone planning subsurface work in the Colchester quadrangle.

Finally, the known seismic history of the area, as chronicled by Foye (1949, p. 38-42), is of some engineering interest, as the Moodus area seems to have been the epicentral area for a number of significant earthquakes in the 18th and 19th centuries. This seismic history was taken into account in the design of the nuclear-power plant at Haddam Neck, just southwest of Moodus.

GEOLOGIC HISTORY

The geologic evolution of the bedrock units in the Moodus-Colchester area began in the Ordovician Period with the deposition of andesitic and basaltic volcanic rocks, now the Monson and Middletown Gneisses. This volcanic sequence was blanketed by the sulfidic shales and siltstones of the Brimfield Schist and Tatnic Hill Formation. The Brimfield shales were themselves covered by a sequence of well-bedded siltstones and calcarous siltstones constituting the Hebron Formation. The Hebron Formation may be as young as Silurian; no definite correlation with Silurian units in Maine has yet been made, although such a correlation is widely believed to be most probable. The antecedent of the Canterbury Gneiss probably was an intrusive sill emplaced in the sedimentary sequence. A sill-like body of gabbro, the Lebanon Gabbro, was intruded into the sedimentary complex at some time after the deposition of the Hebron and prior to at least the later stages of folding and the peak of metamorphism.

The whole complex was metamorphosed during a period of heating, probably a prolonged one, beginning in the Middle Devonian and producing the present complex of high-grade metamorphic rocks. In this metamorphism, sulfidic shale was progressively converted to sillimanitic, sulfidic schist; calcareous siltstone to calc-silicate granofels; gabbro to hornblende-plagioclase rock; basaltic volcanic rocks to amphibolite; and andesitic volcanic rocks to plagioclase gneiss, some containing anthophyllite and cummingtonite. This metamorphism was effected when the rocks were all deeply buried in the crust, probably at depths of 15 km to 20 km, where the temperature was 550°-650° C (Lundgren, 1966a).

During this time they were progressively deformed by a series of fold-deformations whose mutual relationships have not been clearly established. The first folding probably produced folds with NE-trending axial surfaces. These were overturned to produce recumbent folds, with the Hebron or Scotland forming the core of the major recumbent syncline. These major recumbent folds were themselves folded along their present western margins, so that the units which are gently dipping in eastern Moodus are steeply dipping along the western edge of the Moodus quadrangle. The relatively gently dipping units of the eastern two thirds of the area were further deformed by the development of domes to the north (Willimantic dome, Snyder, 1964b) and to the southeast (Lyme dome, Lundgren, 1967) and the complementary basin (Colchester basin). Within this structural evolution was an additional element, the translation or thrusting of the upper units (Hebron and Brimfield) over the lower units along the Honey Hill fault. Similar thrusts may be hidden within the Brimfield and near the structurally

higher contact of the Hebron. During the Honey Hill fault thrusting, the Hebron Formation, Lebanon Gabbro, Canterbury Gneiss, and Tatnic Hill Formation were extensively crushed, so that the Honey Hill fault is today marked by a thick zone of blastomylonitic rocks (Lundgren, 1969). Finally the whole complex was broken by high-angle faults and cut by dikes of basalt diabase during the Late Triassic or even the Jurassic. After all these events, the rocks were shaken yet again by the major earthquakes centered in the Moodus-East Haddam area, earthquakes felt as recently as the 18th century (Foye, 1949).

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ERRATUM

Quadrangle Report No. 27, Plate 2
Connecticut Geological and Natural History Survey

Color correction on the Colchester bedrock map:

In the northeast corner of the map a small area of unit Dlg_3 was printed in light blue instead of light purple.