The Bedrock Geology of the Haddam Quadrangle

WITH MAP

Open Map

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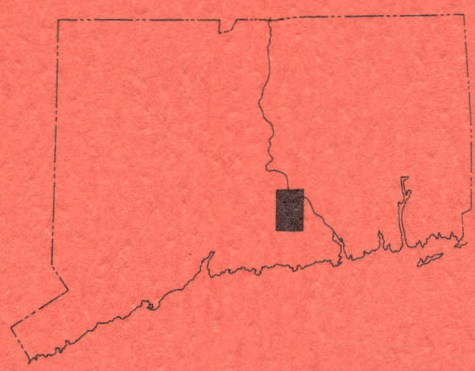
LAWRENCE LUNDGREN, JR.



STATE GEOLOGICAL AND NATURAL HISTORY SURVEY
OF CONNECTICUT

DEPARTMENT OF ENVIRONMENTAL PROTECTION

1979

QUADRANGLE REPORT NO. 37

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LAWRENCE LUNDGREN, JR.
University of Rochester

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For information on ordering this quadrangle report and other publications of the Connecticut Geological and Natural History Survey, consult the List of Publications available from the Survey, Dept. of Environmental Protection, State Office Building, Hartford, Connecticut 06115.

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Lawrence Lundgren, Jr.

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The Bedrock Geology of the Haddam Quadrangle

by

Lawrence Lundgren, Jr.

ABSTRACT

Bedrock in the Haddam quadrangle consists, from oldest to youngest, of metavolcanic and plutonic gneisses (Monson Gneiss and Middletown Formation) overlain by kyanite/sillimanite-grade mica schists, calc-silicate granofels, and metacherts or "coticule" of the Collins Hill Formation and its local equivalents. All are Ordovician, except possibly the Monson Gneiss, which may include older rocks. Pegmatites as young as 250 m.y. B.P. are intrusive into the metamorphic rocks. Diabase dikes of either Late Triassic or Early Jurassic age cut all units.

Major structural features are those seen all along the Bronson Hill anticline—gneiss domes, anticlines, and recumbent folds; the Killingworth dome, which dominates the structure, is the southernmost of the large domes along the Bronson Hill anticline. All these structures and the diabase dike are broken by prominent high-angle faults trending NE and NW. Several of the smaller faults are well exposed.

Pegmatite, diabase, and Monson Gneiss have been quarried in the past but none are quarried at present. High-angle faults, highly erodible mica schists, and the diabase dikes are the chief features of importance to geotechnical engineering in the quadrangle.

INTRODUCTION

The Haddam quadrangle (fig. 1) is the final 7½-minute quadrangle lying on the Bronson Hill anticlinorium in Connecticut to be mapped at a scale of 1/24000 and fills in an important part of the regional picture. The regional map (fig. 2) shows that the Haddam quadrangle is underlain largely by Monson Gneiss, which forms the cores of the Killingworth dome and the Monson anticline. It is apparent from figure 2 that the stratigraphic units surrounding the core of this dome are displayed also in all the contiguous quadrangles. Therefore, some familiarity with reports on these quadrangles (fig. 2, index map) is helpful in understanding some of the problems of the Haddam quadrangle. The map and correlation charts for the Middle Haddam quadrangle (Eaton and Rosenfeld, 1972) are particularly important.

Plate 1 (in pocket) shows bedrock exposures (outcrops and artificial cuts), as well as the types of bedrock believed to underlie areas where there are no outcrops. The text of this report is arranged to emphasize features of particular interest, comparing what is seen in the Haddam

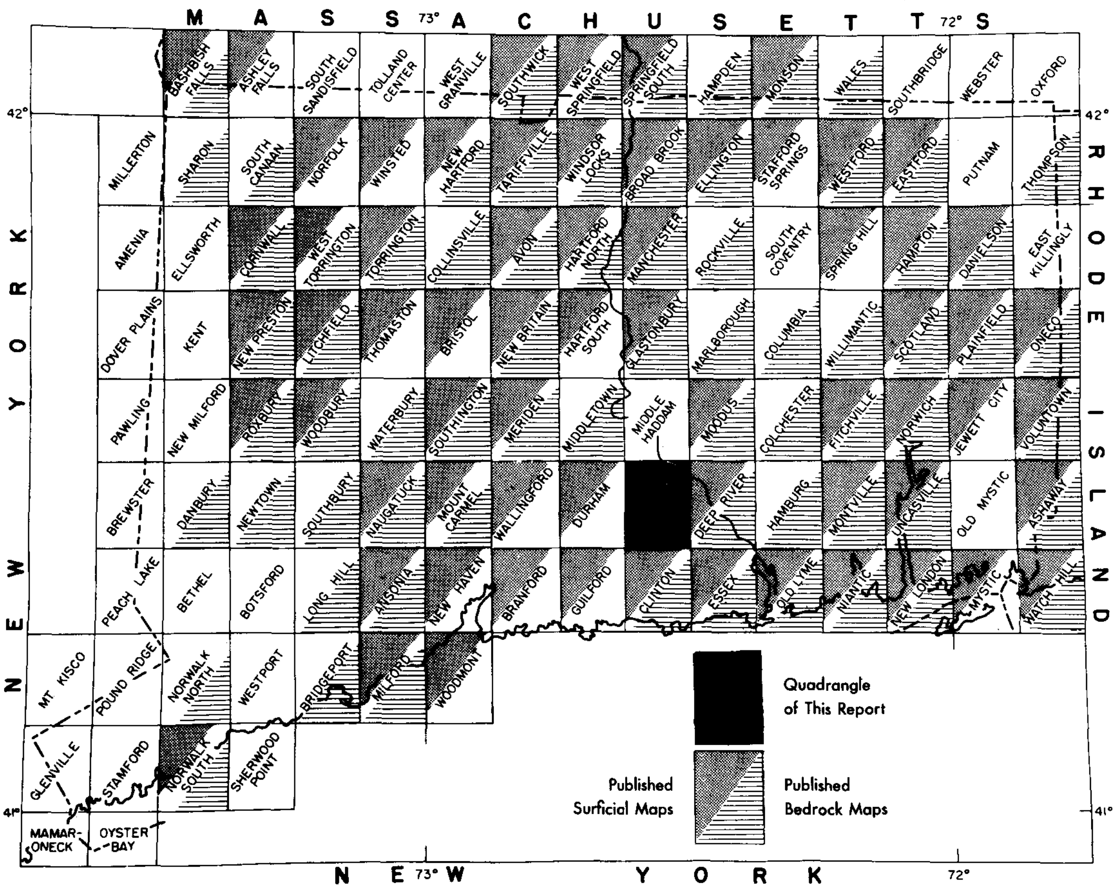


Fig. 1. Index map of Connecticut, showing the location of the Haddam quadrangle and of other published quadrangle maps.

quadrangle with what has been mapped in the contiguous quadrangles.

The quadrangle was mapped chiefly in July 1971, with some additional mapping in 1972, 1974, and 1975. The map was compiled in 1974 and 1975.

STRATIGRAPHIC UNITS

Major units and mapping conventions

The Haddam quadrangle is underlain by highly metamorphosed and folded sedimentary and volcanic rocks of Ordovician age or older. They are described in order of decreasing age. The Monson Gneiss, exposed in domes and antiforms, is the oldest unit exposed; it forms the base of most stratigraphic sections accompanying quadrangle geologic maps in the area included in figure 2 and for some distance northward to the Connecticut-Massachusetts border. Most published sections show the Monson as overlain by metavolcanic orthoamphibole-bearing units (Middletown Formation), which are overlain in turn by metasedimentary units (dominantly biotite-muscovite schist) that carry a variety of local stratigraphic names. East of the Monson anticline calcareous pelitic and psammitic gneisses of the Hebron Gneiss overlie the biotite-muscovite-schist units. This interpretation of the stratigraphic sequence works well in most of the quadrangles mapped to date. Geologic maps of those quadrangles that straddle the Monson anticline and the antiforms west of it illustrate the significant differences between stratigraphic sections on opposite sides of the Monson anticline and on opposite sides of such antiforms as the Killingworth dome. These differences are most obvious in the units above the Middletown Formation but are apparent in the Middletown as well. These differences are the chief concern of this report.

Eaton and Rosenfeld (1972) compiled a chart pointing out some of the differences between stratigraphic sections above the Monson at different localities along an E-W line crossing the Killingworth dome and Monson anticline. Their chart is the basis for figure 3, to which my interpretations in the Haddam quadrangle have been added. They consistently show the Middletown to lie *beneath* various muscovitic-schist units and do not report any muscovitic units in their Middletown Formation. Their interpretation or mapping convention causes some difficulty in drawing a map of the Haddam quadrangle, and I have made some modifications in an attempt to resolve this difficulty.

The convention followed here is to use the Eaton and Rosenfeld (1972) stratigraphic nomenclature but to designate as Collins Hill Formation only the biotite-muscovite schist and associated rocks that are *not* intercalated with orthoamphibole units[1]. Muscovitic schists inter-

[1]Orthoamphibole units are those units that contain the orthorhombic amphiboles, anthophyllite and gedrite. Both are non-calciferous amphiboles; gedrite is distinguished from anthophyllite by a higher Al content, being markedly pleochroic, and having higher refractive indices and a different crystal structure from anthophyllite.

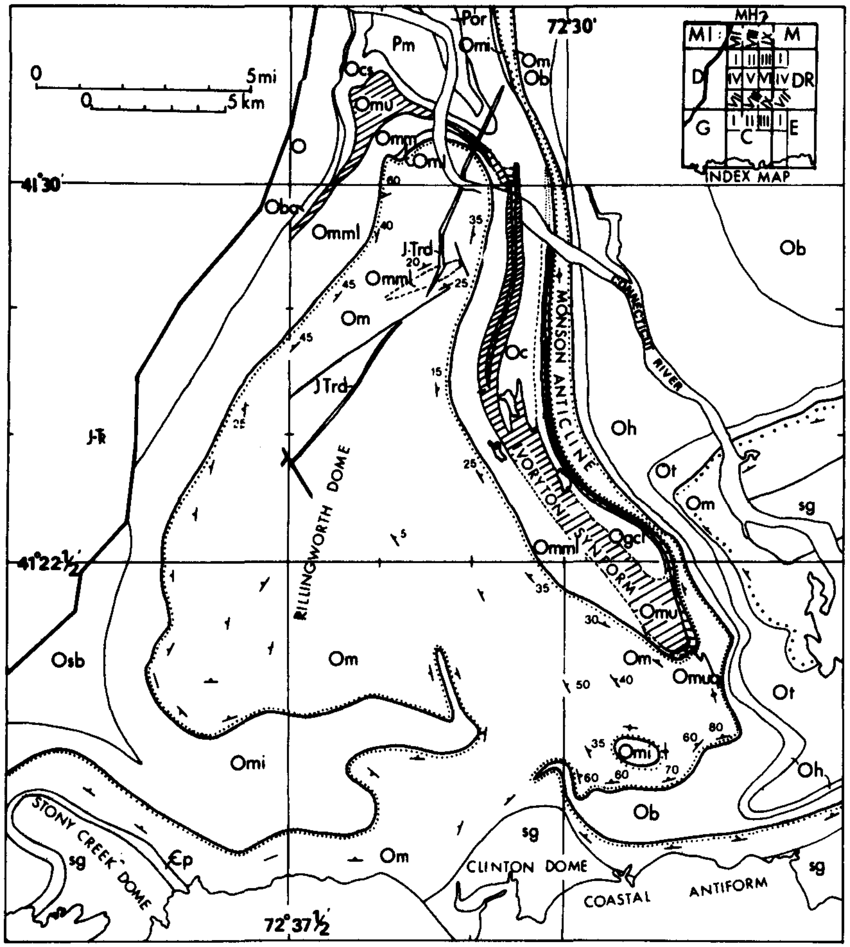
calated with orthoamphibole units are mapped as Middletown Formation.

The muscovitic units in the Middletown are mapped separately, so that anyone wishing to follow the Eaton and Rosenfeld interpretation may do so easily. It should be noted that in all previous publications I have shown these muscovitic units as Collins Hill Formation (see Lundgren, 1963).

Monson Gneiss

NOMENCLATURE

The Monson Gneiss is a complex of gray plagioclase gneisses that forms the cores of the Monson anticline and the Killingworth dome



(fig. 2). The gneiss in the Monson anticline is continuous with the type Monson Gneiss in Monson, Massachusetts, (Emerson, 1898, 1917) and has been traced southward to Ivoryton (fig. 2), where it merges with gneiss in the Killingworth dome, also designated as Monson Gneiss in this report. Eaton and Rosenfeld (1972) used the name Haddam gneiss for the gneiss in the dome, following Mikami and Digman (1957). I prefer to map all the physically continuous plagioclase gneiss as Monson, although recognizing variations in this gneiss. Gneiss in each of the major structural units is described separately below. The Monson Gneiss has been described in a series of reports (Lundgren, 1963, 1964; Lundgren and Thurrell, 1973), so attention is directed here to field localities in the Haddam quadrangle where the Monson may be readily examined.

MONSON ANTICLINE

Monson Gneiss in the Monson anticline is rather well exposed because it has been extensively quarried, especially at Haddam Neck (H III; see fig. 2 for explanation of location designations), Great Hill (H III), and Long Hill (H VI). The most easily accessible and largest quarries are on Great Hill (H III). In addition to these quarry exposures, extensive new exposures have been made in the Monson on Route 9 in H VI, and just east of H VI in the Deep River quadrangle (DR IV) where the Route 9 Interchange with the East Haddam Connector displays the Monson very well.

Fig. 2. Geologic map of the Lower Connecticut River area.

Quadrangle maps used as sources are Clinton (Lundgren and Thurrell, 1973), Deep River (Lundgren, 1963), Essex, (Lundgren, 1964), Moodus (Lundgren and others, 1971), Middle Haddam (Eaton and Rosenfeld, 1972).

For meanings of letter symbols for rock units, see Explanation to plate 1 (in pocket). Additional symbols are as follows: *Ob* = Brimfield Formation, *Ot* = Tatnic Hill Formation, *sg* = Sterling Granite Gneiss, *Omi* = undifferentiated Middletown Formation, *Oh* = Hebron Formation, *Cp* = Plainfield Formation, *Pm* and *Por* = phases of the Maromas Gneiss. The contact line bordered with dots represents the upper surface of the Monson Gneiss.

The index map in the upper right-hand corner shows the locations of quadrangles adjacent to the Haddam quadrangle. The Haddam quadrangle, in the center, is divided into ninths; each ninth is labeled with a roman numeral that is used in the text to aid in locating specific features. For example, H III refers to features in the ninth of the Haddam quadrangle marked III. Contiguous parts of adjacent quadrangles are similarly divided. The quadrangles included are: C = Clinton, D = Durham, DR = Deep River, E = Essex, G = Guilford, (Haddam in center, not labeled), M = Moodus, MH = Middle Haddam, and MI = Middletown.

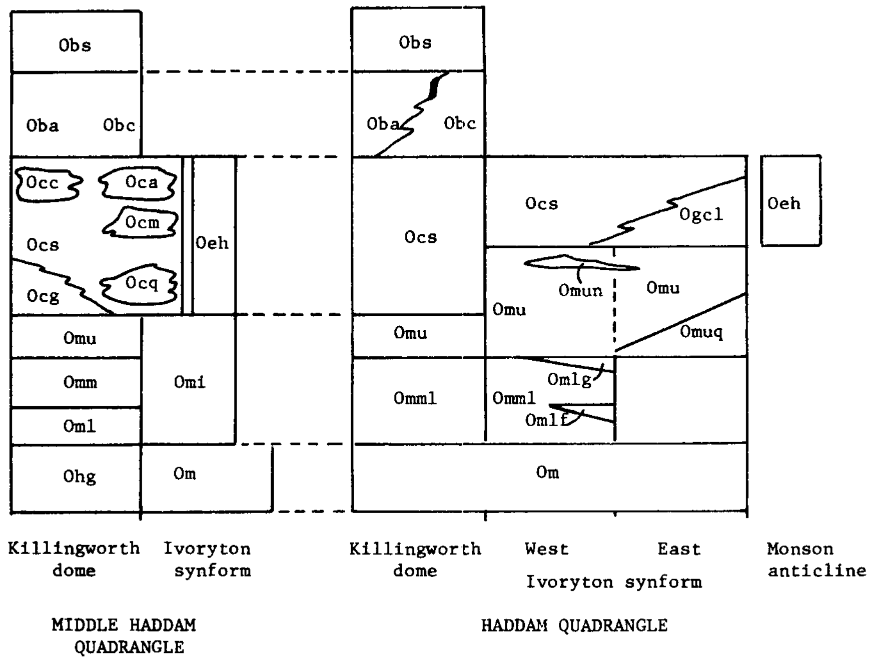


Fig. 3. Schematic sections of stratigraphic sequence from the Monson Gneiss to the top of the unit labeled *Obs*. Eaton and Rosenfeld's (1972) sections for the Middle Haddam quadrangle are modified slightly. Sections are shown as they appear above the Monson Gneiss in the Killingworth dome and the Monson anticline. The western side of the Ivoryton synform lies above the Killingworth dome; the eastern side of the Ivoryton synform lies above the Monson anticline. Dashed horizontal lines indicate matching units or contacts.

Eaton and Rosenfeld's symbols used are: *Om* (Monson Gneiss), *Ohg,* (Haddam Gneiss approximately equivalent to Monson Gneiss), *Omi* (undifferentiated Middletown Formation), *Oml, Omm, Omu* (lower, middle, and upper parts of Middletown Formation), *Ocs* (undifferentiated Collins Hill Formation) containing within it *Ocg* (sillimanite-quartz nodule gneiss), *Ocq* (quartzite), *Ocm* (diopsidic calc-silicate rock and hornblende-plagioclase rock), *Oca* (amphibolite), *Occ* (coticule = garnet-quartz granofels), *Oeh* (schist of East Hampton), *Oba* and *Obc* (metavolcanic rocks of Bible Rock Brook), *Obs* (calc-silicate rocks and schists of Bodkin Rock).

In addition, the following Haddam quadrangle symbols are used: *Omml* (lower and middle Middletown Formation), *Omlf* (microcline-bearing gneiss), *Omlg* (epidote-bearing plagioclase gneiss), *Omuq* (quartzite and schist of Middletown Formation), *Omus* (schist of Middletown Formation), *Omun* (sillimanite-quartz nodule gneiss).

The bulk of the rock in the Monson anticline is light to medium-gray medium-grained quartz-plagioclase rock containing both biotite and hornblende (see modal analysis, Lundgren, 1963, table 4). Pink granitic folia are common in rock that itself does not contain microcline. Layering, on a scale of inches to feet, reflects variations in the content of the mafic minerals. This layering is emphasized in the gneiss, close to the contact with overlying units, by layers of black amphibolite, inches to feet thick, and by layers of muscovite schist. The main rock type is well displayed at Great Hill, where the main quarry is placed in the most uniform, virtually nonlayered rock. This nonlayered rock contains folia of white pegmatite 2-3 cm thick, which accentuate the foliation created by parallel mica flakes. Many of the smaller quarries are located in the better layered varieties of Monson. Excellent exposures of these layered varieties are those on Route 9 (H VI) and in the Route 9/East Haddam Connector Interchange (DR IV).

KILLINGWORTH DOME

Monson (or Haddam) Gneiss in the Killingworth dome has been described by Mikami and Digman (1957), Lundgren (1964), and Lundgren and Thurrell (1973). It can be seen in a series of roadcuts on Route 9, described in detail in the section on structural geology. Most of the rock in the dome is light-gray, biotitic quartz-plagioclase gneiss; hornblendic gneiss is present but not as common, and gneiss in the dome is generally less mafic than that in the Monson anticline. It commonly contains folia and veins of pink pegmatite. The folia are of at least two ages. The oldest are parallel to an initial layering and have been folded with that layering; some of the younger folia are parallel to a weak younger foliation that cuts across the older. Amphibolite layers in the gray gneiss probably constitute less than 10 percent of the total volume of Monson Gneiss in the dome. Coarse-grained biotite-muscovite schist is rarely seen; it resembles the "East Hampton schist" and is so labeled on the map.

The gneiss in the dome commonly is less well foliated than that along the Monson anticline, and there are many areas on the map where few foliation symbols are shown. The apparent absence of foliation in much of this rock is, in part, a consequence of the disruption of one foliation by a younger foliation parallel to the axial planes of the youngest folds. Much of this rather massive-looking rock has two foliations, and both of them could possibly be measured and indicated at certain places on the map. In many places, both foliations are too weakly developed to be measured satisfactorily; such rock is represented on the map by outcrop symbols without foliation symbols. Where foliation symbols are shown, the gneiss has some semblance of a layering believed to be the older foliation, and this is the foliation that is shown.

Middletown Formation

CHARACTERISTIC ROCK TYPES

The Middletown Formation was first named Middletown Gneiss by

Gregory (Rice and Gregory, 1906) for exposures in the area just north of the Haddam quadrangle. The Middletown Formation as mapped in the Haddam quadrangle and in contiguous quadrangles (fig. 2) is distinguished throughout by rocks containing orthoamphibole (anthopyllite and gedrite), cummingtonite, or both orthoamphibole and cummingtonite (noncalciferous amphiboles). The orthoamphibole rocks are easily recognized in the field because the gedrite generally is present in aggregates of rather large prismatic crystals, much larger than crystals of calciferous amphibole (hornblende, tremolite), and the anthopyllite is present as distinctive light-brown prisms. These orthoamphibole rocks are characteristic of the Middletown; they are commonly associated with rather coarse-grained, massive aggregates of large red garnets and large black gedrite crystals. Most of the other rock types present in the Middletown—amphibolite, muscovite schist, coticule (bedded garnet-quartz rock), sillimanite-quartz-nodule rock—are also seen in either the Monson Gneiss below or the Collins Hill formation above and cannot be regarded as diagnostic of the Middletown Formation. The orthoamphibole rocks are the basis for distinguishing Middletown Formation; therefore, a special symbol (an inverted V) is used on the map to indicate outcrops in which orthoamphibole is conspicuous. However, many other outcrops containing these amphiboles are not specifically indicated on the map because they were not marked as such during field work.

The Middletown Formation is extraordinarily variable; any single outcrop may display four or five different rock types. It is therefore rather difficult to map separate rock units at the scale of the map or, indeed, at any scale. Nevertheless an attempt has been made to separate a few different units.

The two major areas of Middletown Formation, one on the northwestern flank of the Killingworth dome and the other in the Ivoryton synform, between the Killingworth dome and Monson anticline, are connected around the northern end of the dome (see fig. 2). However, because some of the rocks mapped as Middletown in the Ivoryton synform differ from any mapped on the northwestern flank of the Killingwork dome, rocks in the two areas are described separately. The isolated mass of Middletown Formation within the Killingworth dome (H II) is similar to the rocks mapped as lower Middletown in both areas.

ROCK UNITS ON THE NORTHWESTERN FLANK OF THE KILLINGWORTH DOME

Eaton and Rosenfeld (1972) divided the Middletown on the northern end of the Killingworth dome into three sub-units (in their notation, lower-Oml, middle-Omm, upper-Omu) apparently on the basis of the relative abundances of amphibolite, orthoamphibole gneiss, and ordinary quartz-plagioclase-biotite gneiss. Two of these units can be recognized in the northwestern part of the Haddam quadrangle. The upper unit, designated in this report as *Omua*, is largely epidote-bearing amphibolite within H I (fig. 2). The other unit, in which I combine Eaton and Rosenfeld's middle and lower units, is designated as *Omml*; it consists mainly of feldspathic gneisses and amphibolite.

The unit shown as *Omml* consists of three major rock types: quartz-plagioclase-biotite gneiss, quartz-plagioclase-orthoamphibole gneiss, and amphibolite, listed in order of decreasing abundance. The characteristic association is well displayed on the telephone line that crosses Wiese Albert Road (southwestern corner of H I). Note that *no* muscovite or sillimanite-bearing rocks were observed within *Omml.*

The quartz-plagioclase-biotite gneiss is dominant. It is very like the Monson Gneiss; however, much of it is finer grained and more rust stained than the bulk of the Monson, and it does not contain pink-granite folia. Except for the presence of interbedded gneisses containing orthoamphibole, it would not be possible to separate this gneiss from the Monson. The orthoamphibole gneisses typically are rust stained and the orthoamphibole is generally conspicuous as large, easily recognizable prisms of gedrite or anthophyllite. Much of the orthoamphibole gneiss contains conspicuous red garnet. It also characteristically contains large irregular masses of black tourmaline. The third rock type, amphibolite, is present throughout but is more abundant in association with orthoamphibole gneisses. The amphibolites are black hornblende-plagioclase rocks in layers having sharp contacts with the adjacent gneisses. Pods of epidote-rich rock are present in some of the amphibolite. Coticule (bedded garnet-quartz rock) is also present in beds less than a few centimeters thick.

The unit shown as *Omua* is a distinctive amphibolite that is seen most readily in the area around Millers Pond State Park in the Durham quadrangle (D III) just west of H I. This amphibolite is characterized by layers and pods of green epidote-rich rock and by masses and layers of green and white quartz-epidote rock that stand out against the black hornblende-plagioclase matrix of the amphibolite.

ROCK UNITS IN THE IVORYTON SYNFORM

Lower Middletown–Omml + Omlf + Omlg. The extensive area on the eastern flank of the Killingworth dome underlain by lower (?) Middletown displays the same rock types as lower (?) Middletown already described on the northwestern flank of the dome and appears to be continuous with it. Two additional units (Omlf and Omlg) have been mapped within the lower Middletown here.

The dominant rock types are rust-stained orthoamphibole gneiss and a variety of amphibolites. Coticule (bedded garnet-quartz rock) and sharply layered, gray, plagioclase-quartz-biotite gneiss are interleaved with the other rock types. The relative abundance of orthoamphibole gneiss varies widely from outcrop to outcrop. Amphibolite is the dominant rock in many parts of the area shown as *Omml* but it is too intimately interleaved with other rocks to permit mapping it separately. Schematic sections are shown in figure 4.

Two feldspathic units have been distinguished within the area of *Omml.* One of these (Omlf) is a weakly foliated unit consisting of quartz, microcline, plagioclase, biotite, and magnetite. The magnetite commonly is conspicuous in large (0.5-1.0 cm) grains. Thin black amphibolite layers are present locally. *Omlf* is readily distinguished over much of its extent because it is the only microcline-bearing rock in the Middletown and forms conspicuous rounded ledges. Its northern and southern terminations were not located exactly. The other feldspathic unit mapped separately is a light-gray, sharply layered gneiss (Omlg), consisting of gray layers (plagioclase, quartz, biotite), black layers (hornblende-plagioclase amphibolite), and lenses of pale-green epidote. A clear section may be seen on Route 9 (eastern side of southbound lane north of Beaver Meadow Road), where this gneiss is in contact with representative orthoamphibole gneisses of the lower and upper Middletown. This gneiss (Omlg) is traceable for several miles south of Route 9 to Pataconk Reservoir. It has not been distinguished with certainty from the rather featureless gray quartz-feldspar-biotite rocks south of the reservoir.

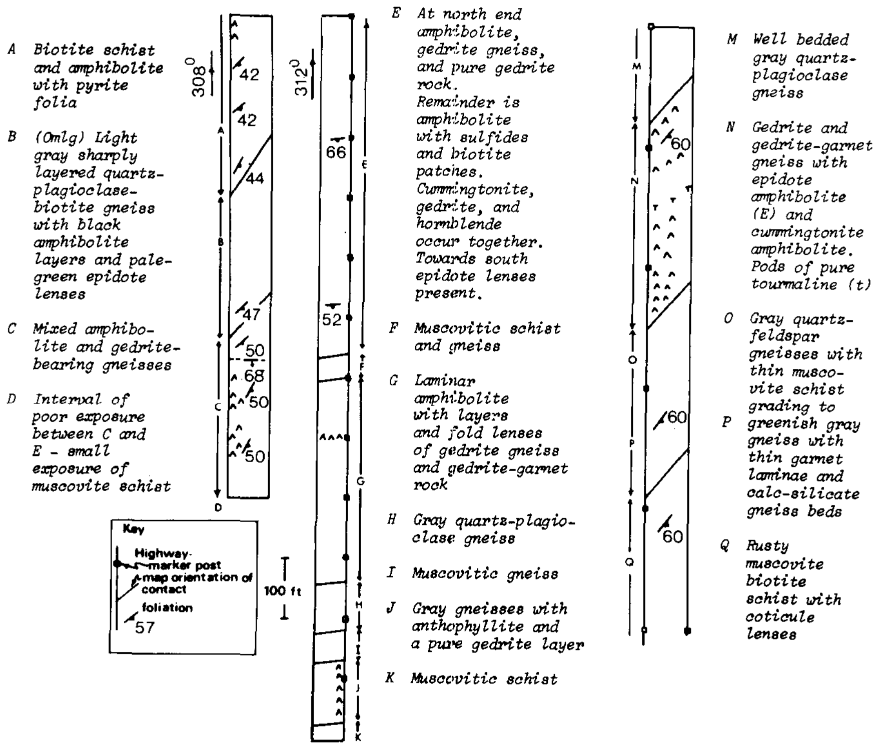


Fig. 4. Sections across the Middletown Formation, as viewed from above, along Route 9. Locations of sections A-D and E-K are shown on figure 5. The symbol ∧ indicates orthoamphibole gneiss or amphibolite. Location of section M-Q is on the eastern side of the northbound lane of Route 9, where it crosses the southern end of Turkey Hill. The northern end of the section is located at Connecticut coordinate 218,200 ft N; 665,500 ft E, approximately at the point where the State Forest boundary crosses Route 9.

Upper Middletown–Omu + Omuq+ Omun. This unit, mapped by Eaton and Rosenfeld as *Omu* and *Omu*(?), can be traced southward from the Middle Haddam quadrangle into the Haddam quadrangle, where it occupies a belt on the western side of the Ivoryton synform. All rock in this belt lying between lower Middletown and Collins Hill Formation is shown as upper Middletown Formation. Similar rocks are also present on the eastern side of the Ivoryton synform, where they generally are separated from the Monson Gneiss by a muscovitic quartzite and associated schist. As explained below, this muscovitic quartzite and schist are included in the upper Middletown. The manner in which the upper Middletown on one side of the Ivoryton synform merges with that on the other side is so unclear at present that I have described the two belts separately.

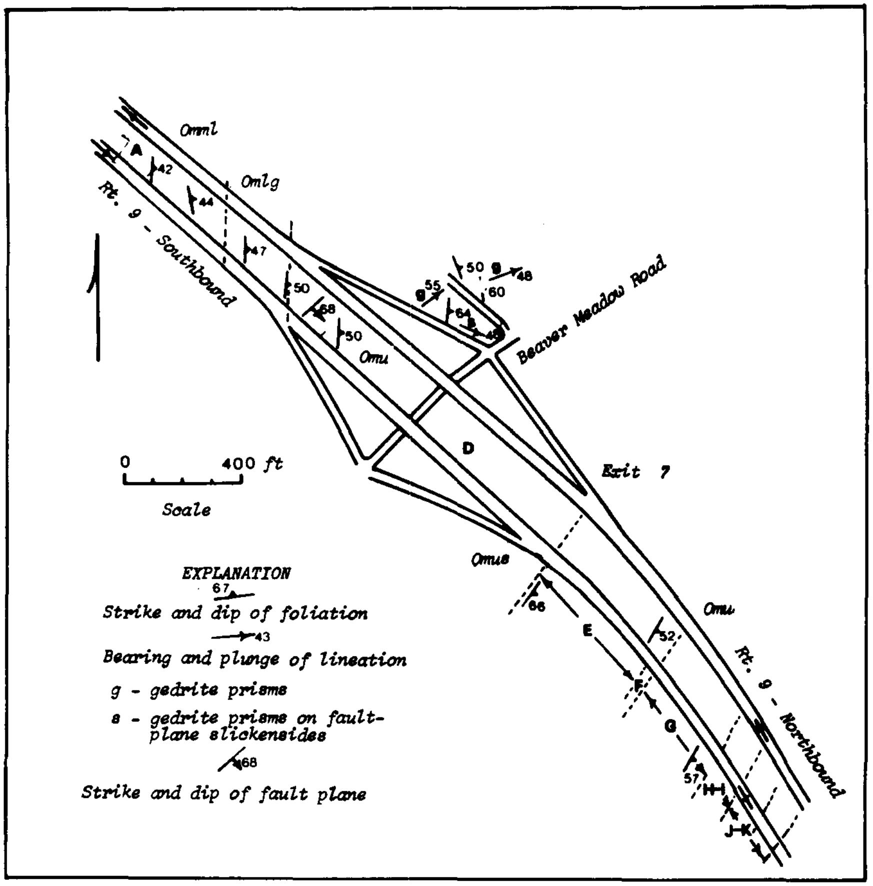


Fig. 5. Locations of sections A-D and E-K of figure 4.

For two reasons, the upper Middletown on the western side of the Ivoryton synform is used here as the reference section. On the western side of the synform it is separated from the Monson by lower (and middle ?) Middletown and the upper/lower distinction is clear. In addition, the upper Middletown is very well exposed in both artificial and natural exposures on this side of the synform.

The upper Middletown is characterized by the association of a variety of rather exotic rocks: coarse gedrite rock, coarse garnet rock, sillimanite-quartz-nodule rock, and staurolite- and cordierite-bearing rocks. However, the dominant rocks, with which these exotic rocks are associated, are layered amphibole-bearing rocks, including amphibolite, epidote amphibolite, orthoamphibole amphibolite, cummingtonite amphibolite, and orthoamphibole gneisses. Sections across upper Middletown at intervals as close as half a kilometer along strike are very different from one another. Thus no sub-units have been mapped.

The most easily accessible section of upper Middletown is on Route 9 north and south of the Beaver Meadow Interchange (H VI, fig. 2). This section is illustrated in figure 4. On Route 9 south of Beaver Meadow Road the dominant rock types are amphibolites. The section displays ordinary black hornblende-plagioclase amphibolite, black amphibolite with yellow-green lenses of epidote and gray lenses of plagioclase-epidote aggregate, cummingtonite amphibolite, and cummingtonite-gedrite-hornblende amphibolite. These amphibolites are interbedded with one another and grade into each other. They are interbedded with layers and lenses of other rocks; in this section alone one can see gedrite-garnet gneiss, gedrite rock, and muscovite schist. North of Beaver Meadow Road toward the contact with lower Middletown the section is less varied, consisting essentially of ordinary amphibolite and gray anthophyllite/gedrite gneiss. It contains one distinctive unit, a gneiss in which gedrite occurs both in well aligned prisms and in conspicuous rosettes of prisms. This unit also contains cordierite. It is well displayed in the cut on Hubbard Road at Beaver Meadow Road, the entrance to the northbound lane of Route 9, and in the exit from the southbound lane of Route 9 at Beaver Meadow Road (see fig. 5).

Most of the mineralogically exotic rocks of the upper Middletown are *not* well displayed in the Route 9 cuts. They may be seen best at any set of natural outcrops where sillimanite-quartz nodule rocks (Omun) are indicated on the map. Some of the exotic rocks contain large gedrite prisms, large garnet crystals, or both. These gedrite rocks, garnet rocks, and gedrite-garnet rocks form distinct layers and lenses within the amphibolites. They are very coarse grained; the maximum crystal dimension commonly is between 5 cm and 10 cm. The coarsest garnet rocks ("garnet-ball rocks") are aggregates of red garnets the size of tennis balls. The coarsest gedrite rocks are lustrous black rocks consisting of large prisms of gedrite. Some of these gedrite rocks are dikelike and are clearly structurally discordant, cutting sharply across fold structures and layering. Gedrite rocks also form planar layers parallel to layering in adjacent units and rather large (meters long), apparently irregular bodies in amphibolite. Some of these irregular bodies could be large boudins. These various structural types may be seen in the Route 9 cuts (fig. 4).

The area south of Turkey Hill Reservoir is strewn with large blocks of this rock type, which can also be seen in outcrop both northeast and south of the reservoir.

The gedrite-garnet rocks are interbedded with gray but rust-stained orthoamphibole gneisses and with gneisses spotted with, or even consisting largely of, sillimanite-quartz nodules. These are indicated on plate 1 by symbol and by letter designation. At least one of these nodular gneisses contains kyanite and cordierite in addition to sillimanite. Staurolite-bearing rocks have also been recognized at several outcrops of nodular gneiss.

A belt of muscovitic rocks associated with the rocks described above is also shown as Middletown Formation (Omus). These muscovitic rocks were included within the Collins Hill Formation by Eaton and Rosenfeld (1972), and they certainly resemble some biotite muscovite schists included in the Collins Hill Formation as I have mapped it. However, lacking any independent structural evidence that the muscovitic rocks lie in an isoclinal fold within upper Middletown, I have included them in the Middletown.

Units lying directly above the Monson Gneiss on the eastern side of the Ivoryton synform have been included here in the upper Middletown because of their resemblance to some of the units described from the western side of the synform and because of their apparent along-strike continuity with some of the upper Middletown on the western side of the synform.

The rocks mapped as *Omu* on the eastern side of the Ivoryton synform lie between the Monson Gneiss and the Collins Hill Formation in H III, VI, and IX. They apparently merge in the northwestern Essex quadrangle with rocks mapped as *Omu* on the western side of the synform. Where *Omu* lies between Collins Hill Formation and Monson Gneiss, as in H III and H VI, for example, two units can be distinguished.

The lower of these units (Omuq) is a thin but remarkably continuous and easily identifiable belt of muscovitic quartzite and muscovite-biotite schist directly in contact with Monson Gneiss. This is a reliable stratigraphic-marker unit that can be traced southward to meet what was mapped earlier as the Pine Ledge belt of Brimfield (Lundgren, 1963, 1964). It may be traceable north of the Connecticut River as well, but in the absence of orthoamphibole units separating it from the Collins Hill Formation it would certainly be mapped as Collins Hill Formation.

The distinctive feature of *Omuq* is coarse-grained white muscovitic quartzite that is in contact with the Monson Gneiss over a distance of thousands of feet. This quartzite is present in the Deep River and Essex quadrangles as well, and an unidentified quarry worker familiar with this quartzite at Great Hill (H VI) asserts that it was once visible at the Gillette Quarry (H III). The quartzite is associated with rust-stained biotite-muscovite schist, which is poorly exposed but which may be seen in the Route 9 roadcut that crosses *Omuq* in H VI. The roadcut shows that the schist contains sulfides (pyrite and pyrrhotite) which weather rapidly to sulfates and oxides. The schist contains beds of coticule and calc-silicate granofels.

The unit (Omu) that lies between *Omuq* and the Collins Hill Formation is a thin (0-300 ft) but readily mappable composite unit made up largely of gedrite and gedrite-garnet gneisses, amphibolite and epidote amphibolite, and pods of tourmaline rock. A good section across this unit is displayed on Route 9 (northbound lane) eastern side, south of Cedar Lake Road (H VI, fig. 2).

This unit also can be followed southward from Great Hill (H III) to the Deep River and Essex quadrangles, where it has been described in some detail as the Cedar Lake belt of Middletown (Lundgren, 1963, p. 11-14, 33-34; 1964, p. 12-15). These descriptions illustrate that this unit also contains coticule and sillimanite-quartz nodule rocks, as well as orthoamphibole units and amphibolite. Originally this unit was separated from gneisses mapped in the Deep River and Essex quadrangles as m_{CL}, because the gneisses mapped as m_{CL} contain only rather scattered orthoamphibole. It now appears that m_{CL} should be considered mostly Middletown Formation and, according to the interpretation here, mostly upper Middletown. Thus, on the present map, m_{CL} of the earlier maps is shown partly as *Omu* and partly as "Gneiss at Cedar Lake" (Ogcl).

Collins Hill Formation

GENERAL CHARACTER

The Collins Hill Formation, which lies in the core of the Ivoryton synform, was named by Eaton and Rosenfeld (Rodgers and others, 1959; Eaton and Rosenfeld, 1972). The listing of the various rock types in the Collins Hill Formation presented by Eaton and Rosenfeld (1972) is shown in condensed fashion here as part of figure 3. Most of these rock types are well represented in the Collins Hill Formation in the Haddam quadrangle. The dominant rock types appear to be muscovitic, ranging from muscovite-biotite schist to muscovitic quartz-feldspar gneisses and calcite-bearing calc-silicate gneisses. Pyrite and pyrrhotite are present in these rocks, and any artificial exposure made in them rapidly becomes rust stained, and coated for a time with sulfate encrustations. None of the dominant rocks are well exposed and natural exposures tend to display the less common types, such as quartz-feldspar gneiss, amphibolite, and quartzite, all of which are more resistant to weathering. One should assume, until subsurface information proves the contrary, that the area on plate I mapped as *Ocs* is underlain largely by the schist and calc-silicate gneiss.

The undifferentiated Collins Hill Formation (Ocs) that was mapped in the southeastern Middle Haddam quadrangle by Eaton and Rosenfeld (1972) splits into three separate belts within the Haddam quadrangle, each separated from others by orthoamphibole rocks. Only the central or main belt is mapped here as *Ocs;* the others are included in the upper Middletown Formation and are treated as layers intercalated with the orthoamphibole units.

MAIN BELT (Ocs)

The main belt of Collins Hill Formation (Ocs) is not particularly well exposed, but roadcuts on Route 9 display virtually all the rock types known to be present in the Collins Hill Formation. Most of the detailed information from these roadcuts is presented somewhat schematically in figure 6, which summarizes observations made in traverses along the eastern sides of the northbound and southbound lanes of the highway. The sections illustrate that muscovite-bearing rock (schist, gneiss, and quartzite) is dominant. Much of this muscovite-bearing rock is silvery white when first exposed, but it rapidly becomes rust stained and sulfate coated on exposure. Much of the muscovite-bearing rock is highly friable as well, and quickly crumbles on exposure. The sections also illustrate that gray biotite-bearing feldspathic gneiss, commonly containing calcite, is the second most common rock type; pin-striped hornblende-calcite gneiss is the third most common. An attempt to trace these units southward or northward from the highway rapidly shows that only the gray gneiss is even moderately well exposed naturally. Thus, this area illustrates what is assumed to be true for most of the area underlain by *Ocs;* natural exposures present a selective and misleading sample of the true nature of the formation.

The main belt of *Ocs* is bordered on the east by a unit shown as *Ogcl* ("Gneiss at Cedar Lake"). Within this unit (Ogcl) the common muscovite-biotite schist of the Collins Hill Formation is interbedded with fine-grained, light-gray biotitic and/or hornblendic plagioclase-quartz gneiss. Thin black amphibolite layers are present in the gneiss. A good exposure of these rocks can be seen beneath the bridge that carries Route 9 over Cedar Lake Road (H VI). Here about one-third of the section is schist and about two-thirds are gray gneiss and amphibolite. As this belt is traced northward, the muscovite schists are more abundant than the gneiss; as it is traced southward the muscovite schists disappear, and in the area north of Cedar Lake the unit consists entirely of well layered gray gneiss with amphibolite layers. This gray gneiss containing no muscovite schists was mapped earlier as the Cedar Lake belt of Haddam Gneiss (Lundgren, 1963); it is now treated as a unit that is part of the Collins Hill Formation and designated as "Gneiss at Cedar Lake." It presents the most severe mapping problems of any unit in the quadrangle, and very detailed remapping in Deep River and Essex quadrangles, as well as in the Haddam quadrangle, might help to clarify the relationship of the "Gneiss at Cedar Lake" to the adjacent stratigraphic units.

"Metavolcanic rocks of Bible Rock Brook"

The sequence above the Middletown Formation in the northwestern part of the Haddam quadrangle includes two distinctive stratigraphic units that Eaton and Rosenfeld (1972) have designated as "metavolcanic rocks of Bible Rock Brook" from exposures in the southwestern part of the Middle Haddam quadrangle. Both units are well exposed along or near the power transmission line shown in figure 2 (H I), where they form a prominent ridge.

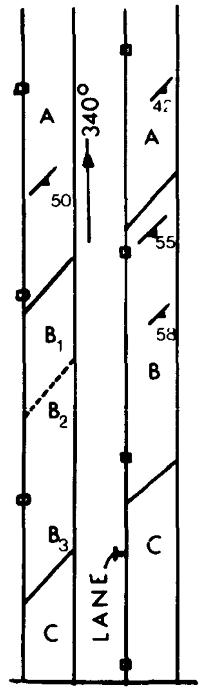
Route 9--southbound lane, eastern side

A Light-gray quartz-feldspar-biotite gneiss with biotite folia. At northern end layers of muscovite-biotite schist with sillimanite-quartz nodules, biotite schist, rusty muscovite schist, and coticule lenses.

B_1 Rusty muscovite-biotite schist and gneiss. Large garnet in some layers. Sulfides and sulfates conspicuous on fresh and weathered surfaces, respectively.

B_2 Coarse garnet-biotite rock with associated schist with sillimanite-quartz nodules and diamond-shaped amphibolite boudins.

B_3 Same rock as B_1 with thin (10 cm) planar amphibolite and fine-grained biotite-quartz-feldspar gneiss with pyrite laminae.



Route 9--northbound lane, eastern side

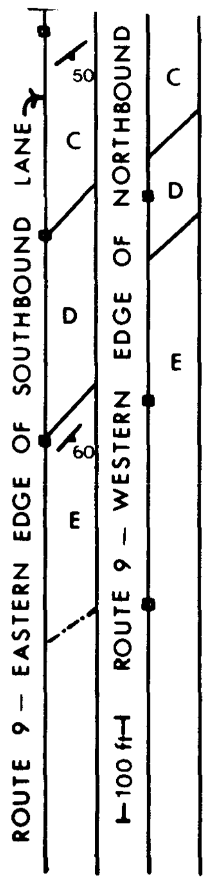
A Light-gray quartz-feldspar-biotite gneiss with biotite folia; calcite and pyrite present. Layers of silvery muscovite schist and gneiss. Mineralogy: Quartz, plagioclase, microcline, muscovite, biotite (Z = 5Y 6/4), calcite, epidote, pyrite, sphene.

B Rusty muscovite-biotite schist and well bedded muscovite-quartz schist. Large (1-2 cm) garnet in some layers in foliation plane. Layer of amphibolite boudins. Muscovite-quartz schist mineralogy: Quartz-muscovite, biotite (Z = 10YR 5/8), plagioclase, garnet, pyrite.

C Well bedded gray and greenish-gray quartz-plagioclase-biotite gneiss with poikiloblastic garnet and black tourmaline. Layers of amphibolite boudins and a 2-ft thick layer of muscovite schist are interbedded with gneiss. Thin (5 cm) layer of epidote in rectangular boudins.

D Greenish-gray gneiss, some with a pin-stripe appearance. Contains thin lenses and laminae of calcite marble. Thickest marble layer 10 cm thick. Thin muscovite schist layer and thin garnet calc-silicate layer present.

E Rusty muscovite-biotite schist.



C Gray quartz plagioclase-biotite gneiss with poikiloblastic garnet and minor epidote and muscovite. Muscovite layers present.

D Northern end: epidote amphibolite: Dark-gray amphibolite: hornblende, plagioclase, quartz, biotite calcite with green lenses of epidote, calcite, diopside rock. Southern end: Greenish-gray fine-grained hornblende gneiss with conspicuous pin-stripe appearance. Individual thin layers making up pin stripes consist of:
1) Hornblende, quartz, plagioclase, calcite, sphene, epidote.
2) Quartz, plagioclase, hornblende, garnet, calcite.
3) Quartz, plagioclase, biotite.

E Rusty muscovite-biotite schist.

Fig. 6. Sections across the Collins Hill Formation, seen as viewed from above, along Route 9. Northern ends of sections are approximately 900 ft southeast of the intersection of Route 9 and Filly Road, as measured along Route 9.

The lower unit (Obc) in the sequence is a bedded garnet-quartz rock (coticule) that consists of thin layers (millimeter-to-centimeter thick) of fine-grained spessartite-quartz granofels. Plagioclase, biotite, and hornblende are present in some layers, but the rocks are essentially aggregates of very small (less than 0.05-0.1 mm) garnet crystals and quartz. Such rocks are designated as *coticule* by most geologists working in New England. More detailed information, including chemical and modal analyses of this unit and others like it, has recently been compiled by Kim (1975).

The upper unit (Oba) is a fine-grained layered black amphibolite consisting of hornblende, plagioclase, quartz, and magnetite/ilmenite. It commonly contains distinctive plagioclase megacrysts, which stand out as white crystals on a black background. The bulk of the rock is a very fine-grained (0.1 mm) aggregate of hornblende and plagioclase. The "megacrysts" (0.5 mm x 3.0 mm) are mosaic aggregates of strikingly zoned plagioclase grains (individuals, 0.5 mm). This layered amphibolite is interbedded with the coticule and with less well layered black amphibolites containing pods and lenses of green epidote.

Schist of East Hampton

The Schist of East Hampton, a biotite-muscovitic schist, was given this name by Eaton and Rosenfeld (1972). It was mapped in the northeastern corner of the Haddam quadrangle on the basis of exposures in the contiguous quadrangles. In the Deep River quadrangle it was mapped as Brimfield Schist (Lundgren, 1963). Lenses (isoclinal folds) of similar rock were seen within the Monson Gneiss and also have been designated by the symbol *Oeh.*

"Calc-silicate rocks and schists of Bodkin Rock"

Eaton and Rosenfeld (1972) mapped a unit consisting of biotite-muscovite schist, calc-silicate granofels, and gray plagioclase gneiss as "calc-silicate rocks and schists at Bodkin Rock" and showed it in their stratigraphic section as a unit overlying the Collins Hill Formation. This unit is very poorly exposed in Haddam I; examples must be sought in the Middle Haddam quadrangle.

Pegmatite (p)

Coarse-grained pegmatite consisting of quartz, microcline, and plagioclase is abundant throughout the quadrangle. Masses display many forms and clearly are of several different ages. The largest, and presumably youngest, masses shown on the map are mostly pink pegmatites, which are at least partly discordant with respect to the structure of the adjacent rocks. The pegmatites typically contain conspicuous muscovite and crystals of microcline, commonly as graphic granite, that are at least 0.5 m in maximum dimension. The best known of these younger discordant pegmatites is that at Gillette Quarry; at one time it was a commercial pegmatite (see Cameron and others, 1954). Where these younger pegmatites cut orthoamphibole rocks of the Middletown Formation, the pegmatites invariably are sheathed in an envelope of biotite representing a reaction product of K-bearing fluid and orthoamphibole.

Other pegmatite masses occur as gently dipping tabular masses (Route 9 cuts in the Monson), irregular masses filling zones along gently dipping faults (Route 9 cuts, East Haddam Connector, DR IV), and as irregular folded and/or boudinaged masses in all the rock units. All these are as old or older than the major pegmatites described above.

Diabase (J-Trd)

The Higganum diabase dike can be traced from the Connecticut River southward to the vicinity of Interchange 8 of Route 9. The dike cannot be seen in an interval along Ponset Brook (H II and V, fig. 2) but it can be traced continuously from the southern end of this interval to the quadrangle border (H VII). In H VII the dike is offset along a fault and reappears in the Durham quadrangle (D IX). Diabase is also present in a small dike cutting Monson Gneiss in roadcuts on Route 9 north of the Christian Hill Road bridge.

The diabase has not been studied in detail; however, two exposures deserve special mention. The first comprises all the exposures made in the construction of Interchange 8, especially those in the exit ramp from the southbound lane and in the channel constructed for Ponset Brook (see figure 8a for map). The largest cuts, and the natural exposures near them, illustrate the ridge-forming properties of the diabase and its well developed columnar jointing. The contact between diabase and country rock is well exposed on the crest of the ridge between the southbound lane and the southbound exit of Route 9. The exposures in the man-made channel of Ponset Brook display contrasting facies of the dike and the contact between dike and pegmatite. Rock in the channel (eastern side) appears to comprise two types gradational into one another, one a finer grained, darker gray rock, the other a coarser grained, lighter gray rock. Both appear to be part of the intrusive dike. The finer grained, darker gray rock is a diabase; it consists of laths of plagioclase embedded in aggregates of augite. Hypersthene phenocrysts are conspicuous. Magnetite-ilmenite, biotite, and interstitial graphic granite are the other principal constituents. However, the coarser grained, lighter gray rock consists of quartz, biotite, and potassium-feldspar, with angular intergrowths of plagioclase and potassium feldspar and of feldspar with quartz. On the western side of this channel, diabase (gray) appears to cut pegmatite (pink but with greenish feldspar). The gray rock here is not true diabase but is also a peculiar quartz-plagioclase rock with angular intergrowths of the two minerals; it presumably is comparable with the coarser rock seen in the channel and is part of the dike. The "pegmatite" is a coarse-grained rock consisting of large round quartz grains set in a matrix that appears to be altered microcline and plagioclase. The "plagioclase" is in lathlike or rectangular brownish crystals.

The second exposure of special interest is a small one at the western contact of the dike in H II. This exposure is north of "old" Route 9 (Middlesex Turnpike on the quadrangle topographic map) at an elevation of about 90 ft above sea level. Here aphanitic black dike rock appears to cut pinkish granite, but the contact relations are such that in some places the pinkish granite appears to cut the diabase. The aphanitic black dike rock in thin section (fig. 7) is a rather striking and unusual porphyritic rock, consisting of perfectly euhedral plagioclase crystals and somewhat less well formed and much larger augite crystals. Hypersthene crystals appear in some thin sections and, very rarely, olivine crystals are present. The matrix (white in the negative print, fig. 7) is nearly opaque and very fine grained, and appears to be altered glass. The "granite" cut by the dikes is coarser grained quartz-feldspar rock in which most of the feldspar is thoroughly altered (sericitized) plagioclase. At the contact this rock has a micro-breccia appearance, with angular fragments of rock in a matrix of small quartz grains.

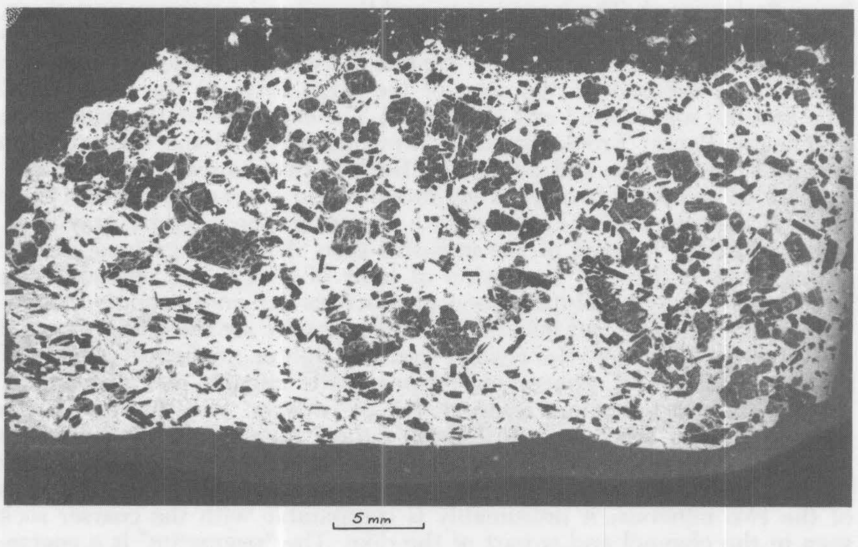


Fig. 7. Negative print of full thin section of porphyritic and altered "glassy" facies of the diabase dike. White is opaque matrix, small black rectangles are plagioclase, and larger black grains are augite. Location: H II, eastern side of road north of old Route 9 (Connecticut grid coordinates 654,560 ft E; 242,400 ft N.)

General relationships

The Haddam quadrangle displays parts of complicated folds at the southern end of the Bronson Hill anticlinorium, structures that have been described earlier (Lundgren, 1963, 1964; Lundgren and Thurrell, 1973; Dixon and Lundgren, 1968). In addition, the northern extensions of these structures were illustrated by Eaton and Rosenfeld (1972) and were interpreted in some detail in cross sections by Snyder (1970).

The major folds are seen most clearly from the map pattern of the upper surface of the Monson Gneiss (fig. 2). The central feature is the Killingworth dome, a large antiformal mass of Monson Gneiss. The Monson Gneiss also forms the core of the Monson anticline, a narrow anticline along the eastern edge of the quadrangle. The two anticlines are separated from each other by the Ivoryton synform, which is occupied by rocks younger than the Monson Gneiss. All these major folds are cut by the diabase dike. High-angle faults cut all structures, including the dike.

The internal structure of each of the three major folds is complicated and not fully understood. As seen in individual outcrops, each major fold contains tightly folded rock units. Many outcrops display evidence of two or more episodes of folding. Samples of these relationships showing two episodes of folding are presented in this report, but the evidence from these samples has not been fully integrated into an interpretation of large-scale structure. Such integration will require careful structural analysis over an area including the Essex, Haddam, Middle Haddam, and Marlborough quadrangles (see index map, fig. 1). The samples of fold relationships and problems are presented here to stimulate such analysis.

Major structures

MONSON ANTICLINE

The Monson anticline extends north-south along the eastern edge of the quadrangle. It is a structure of regional importance extending from the Essex quadrangle north to the Massachusetts border and beyond. The anticline has a core of Monson Gneiss, flanked on both sides by the Middletown Formation and the muscovitic schists of the Collins Hill and Brimfield (East Hampton of Eaton and Rosenfeld, 1972) formations. Thin septa of Middletown Formation and of East Hampton Schist or equivalents within the Monson (H III) are inferred to represent the keels of isoclinal synclines within the larger anticline, as has been particularly well illustrated by Snyder (1970) for the Monson anticline 15-20 km north of the Haddam quadrangle. Thus, as Snyder's cross sections illustrate, the Monson anticline includes within it many smaller isoclinal anticlines and synclines. The axial surfaces of all these folds now have the same approximately N-S trend.

The Monson anticline has previously been interpreted as the root zone of a rather large-amplitude partially recumbent fold, and Snyder (1970) has followed and developed this interpretation in his sections across the anticline in the Marlborough quadrangle. No new evidence bearing on this interpretation is apparent in the Haddam quadrangle. However, since the publication of the Deep River report (Lundgren, 1963), some new details of the internal structure of the Monson anticline have been seen in the Haddam quadrangle and in highway cuts made in the adjacent Deep River quadrangle. These are described below.

Isoclinal folds in Monson amphibolite are well displayed in Haddam VI. Here their hinges plunge steeply E or SE. A strong rodlike lineation is present in exposures of these folds; it is parallel with and commonly created by the hinge regions of the small folds. The same lineation is evident in the flanking quartzite (Omuq).

Additional information on structures within the Monson anticline is now available in the circular exit cut made on the western side of Route 9 in the Deep River quadrangle (DR IV) at the East Haddam connector. Here, as in H VI, isoclinal folds in amphibolite are present, but there are other younger folds as well. They are best displayed on the western wall of the circular cut. This wall cuts across the noses of a series of folds in amphibolite; layering in amphibolite has an overall N-S trend and dips steeply. These folds have the following characteristics: The folded surfaces are striated and have a slickensidelike appearance. The axial surfaces have highly variable orientation but tend to be gently dipping. The hinges are almost horizontal and aligned approximately N-S. The folds are more open than any others along the Monson anticline. They appear to be flexural slip folds formed in steeply dipping layers; they modify all other folds and are the youngest seen along the Monson anticline. They are associated with and cut by irregular faults that have variable but commonly horizontal orientation. These faults truncate the steeply dipping layering, and the layers are sharply offset along them. Some of the faults are filled with pegmatite. Similar relationships are seen within the Killingworth dome. These young folds and thrust faults are believed to be not genetically related to the Monson anticline but, rather, to late events affecting the entire area.

KILLINGWORTH DOME

Large-scale structure. The Killingworth dome is an antiform of Monson Gneiss almost completely surrounded by younger rocks (fig. 2). It appears to be a true anticline; the oldest rocks lie in the core and are overlain by younger rocks. It is not the simple dome of intrusive rock that Mikami and Digman (1957) thought it to be, nor is it a simple anticline formed in a single episode of folding. Both its large-scale form and its internal structure are the result of several superimposed deformations. To understand them it is helpful to consider first the large-scale form and then some of the details of internal structure.

The northern end of the dome looks like a simple N-plunging antiform. Middletown Formation dips away from the axial surface of this antiform on both eastern and western sides and dips N at the northern end of the dome. However, this antiform broadens to the south, and in the southern part of the Haddam quadrangle the Monson Gneiss extends across the quadrangle and across much of the Durham quadrangle as well. Thus, in southern Haddam and adjacent Durham quadrangles the antiform looks more like a broad dome. This broadening is at least partially the result of uplift in the coastal zone, uplift that modified all the older structures that trend N-S, north of this coastal belt (see Lundgren and Thurrell, 1973; Lundgren and Ebblin, 1972). Thus, at the very least, the Killingworth dome is a product of interference between N-S trending antiforms and E-W trending coastal antiforms. One would expect the Monson Gneiss of the dome, and the surrounding units as well, to display small-scale structures reflecting the effects of these and other deformations. Such small-scale structures are abundant and demonstrate that the units within and around the dome have a complex structural history, a history not yet fully worked out but deserving of some discussion.

Internal structure. It is convenient to divide a description of the internal structure of the dome and adjacent units into two parts, one dealing with the portion lying within H VII-IX and the other with the part seen best in H I, II, and IV. All the exposures in the southern part (H VII-IX) are natural outcrops, whereas exposures in the northern part include some rather spectacular roadcuts. Exposures in much of the southern part display rock that is assumed to be located deeper in the dome than that to the north and northwest. Much of this rock is rather weakly foliated, with few conspicuous layers. The foliation is gently dipping for the most part; dips range from 0°-25°. As poor as these exposures are, many of them display folds which demonstrate that the gently dipping foliation commonly is axial planar to folds formed when an older foliation was deformed. Where the younger foliation cuts the older at a low angle, about 10°-20°, the rock has a rather massive appearance, modified only by weathering along the two apparent foliation directions. Pegmatite folia and quartz veins also lie in the axial planes of these folds. Exposures in the western part of the southern segment of the dome display numerous folds, including some rather large isoclinal folds, where the relationship between younger foliation and older is clearly seen as the two foliations are parallel on the limbs of the folds but the younger cuts across the older in the axial-plane region.

Exposures in the area that includes H I, II, IV, and V display a greater variety of layered rocks than do those to the south. They contain a great variety of small-scale structures. Those within the Monson are described first. Within a broad belt of Monson, parallel to the diabase dike and at least 2 km wide, the following features seem generally to be present. The layered rocks display isoclinal folds, and they also display large asymmetric folds. Discontinuous layers or lenses of biotite-muscovite schist closely resembling the East Hampton Schist of Eaton and Rosenfeld (1972) are found within this belt of folded rock. This belt also contains rock mapped as *Omml* in H II. Thus it appears that this belt of Monson contains remnants of younger overlying rocks folded into the Monson. Although these relationships were first recognized in natural exposures, they are much more strikingly displayed in the roadcuts made in the construction of Route 9, and it is these cuts that are used for illustration.

Route 9 transect. The series of roadcuts in the Monson Gneiss made during the construction of Route 9 illustrate recumbent folds and low-angle and high-angle faults—structural features that appear to pervade much of the northern part of the Killingworth dome. They are not shown very clearly in natural exposures; artificial exposures are invaluable in revealing the true complexity of the structure. In fact, inspection of the largest artificial exposures shows that, in this area, the possibility of interpreting the structure by studying natural exposures is very limited.

The Route 9 roadcuts provide materal for a much more detailed structural analysis than that carried out for this report, where the goal is to present observations that can stimulate and guide detailed analyses by others and a structural interpretation that will suggest lines of future investigations. In this report the exposures are illustrated by drawings made from composite roadcut photographs, assembled to show as much of each rock face as possible, and then traced onto a single sheet. Each such composite is necessarily distorted, and no attempt has been made to correct these distortions. Many structural details, not clearly shown on the original photographs, were greatly clarified by close-up photographs. Some of these are included in this report and, wherever possible, were used to fill in details of the composite drawings. The greatest potential value of the drawings is their use as maps from which sub-areas can be selected for further study. They also convey the over-all relationship among various small features, relationships not easily understood, if at all, from natural exposures. These "maps" also show the extraordinary heterogeneity of structure here; this heterogeneity cautions against making inferences from isolated natural exposures.

Three successive structure sections across the Monson/Middletown and their locations and orientations are shown in figure 8 (in pocket). (Details are shown in fig. 10.) The sections are given the designations used in field notes. Each section displays large folds having gently dipping axial surfaces, a variety of smaller folds, low-angle and high-angle faults, and boudinage. Because, by chance, each section is oriented at approximately a right angle to the hinges (axes) of the largest folds, most folds are seen in profile. In the following descriptions, the largest features are discussed first and are then used as the reference framework for detailed descriptions.

The middle of the three sections (205C) is described first because it is the simplest and clearest. It displays (fig. 8c) recumbent folds that are outlined by black amphibolite layers and a layer of gedrite-bearing plagioclase gneiss. The largest fold appears to have an amplitude of at least 30 m. Some of the amphibolite layers that outline this fold can be traced as single layers over the entire face of the cut; others split laterally into two or more layers. This largest fold is not seen in its entirety, and its full form is a matter of conjecture. Three forms are possible, given the shape of the smaller folds in the outcrop and the relationships in the other cuts: (1) The fold may simply be an asymmetric Z-fold (fig. 9a). (2) It may be a large recumbent isoclinal fold (fig. 9b). (3) It may be a recumbent fold having a truncated lower limb (fig. 9c). Evidence from section 205E (fig. 8d) suggests that the largest fold has a truncated lower limb, as represented by figure 9c.

The smaller scale structural features associated with the large fold are parasitic folds or are smaller scale versions of the larger fold. Asymmetric Z-folds (fig. 10a) and symmetrical M-folds (fig. 10b) have axial surfaces oriented approximately parallel with that of the largest fold. Layers in the hinge or axial-surface region of some of the recumbent folds show small-scale folding of the contacts (fig. 10c). The thin, nearly horizontal limbs of the recumbent folds show boudinage, indicating extension in the near-horizontal direction. This boudinage was accomplished by small-scale normal faulting.

Some of the individual structures seen in 205C can be traced through the "center island" of Route 9 to section 205B (not shown). However, these particular structures cannot be traced to section 205A. That section (fig. 8b) shows recumbent folds comparable with those in 205B, C, but the folds have forms that differ from those in 205B, C. It appears that 205A exposes rocks at a slightly higher structural level. Exposures at section 205G (not illustrated) show some of these folds in the third dimension because the face of the section is nearly parallel to the hinges of small folds.

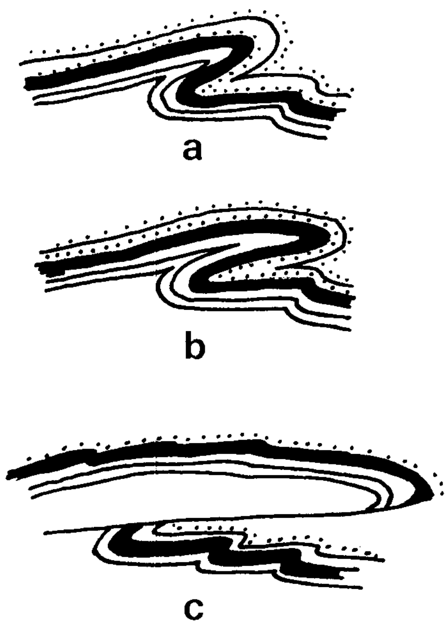
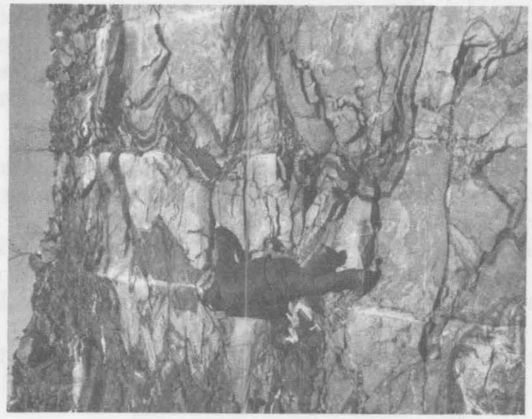


Fig. 9. Structural interpretations of recumbent fold shown in figure 8b:

a. Z-fold

b. Isoclinal fold

c. Truncated fold



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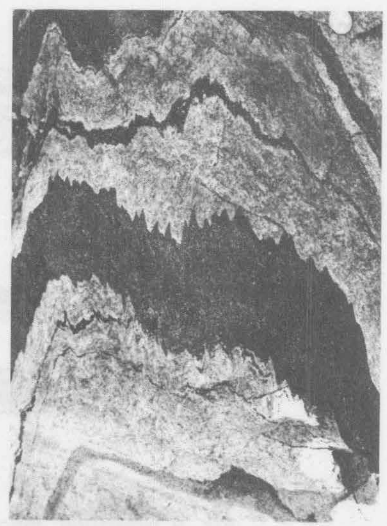

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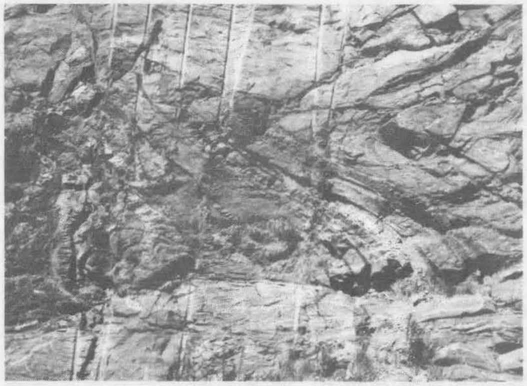


d

e

Fig. 10. Details of structure in sections shown in figures 8c,d:

a. Z-fold seen in figure 8c

b. M-folds seen in figure 8c

c. Folded contact from nose of fold beneath geologist's foot in figure 10a

d. Folded and faulted Middletown (section shown in fig. 8d). Triangular block bounded by upper and lower faults displays folds in three dimensions.

e. Detail from figure 10d, showing truncation of folded layers by lower fault.

If we attempt to trace the structures of 205A-C southwestward through 205D and 205E, we find the same large-scale relationship of Z-folds and M-folds, and a great deal more complexity as well, especially along the lower part of 205E. The lower part of 205E, which is exposed along an entrance ramp, is located well below the level of exposure on the main highway. The major relationship of interest here is the truncation of folds along a more-or-less plane surface marked "lower fault" on figure 8d. This triangular block of folded rock is also bounded by an apparent fault above, marked "upper fault" on figure 8d. The lower fault separates Middletown rocks above, which are folded, from Monson below, in which the foliation is approximately parallel with the lower fault. The folded rocks and their relationship to the two faults are shown in greater detail in figures 10d and 10e. The folds shown in these figures display an axial plane cleavage parallel to the lower fault.

These recumbent folds and associated low-angle faults are merely samples of recumbent folds in the Monson Gneiss and Middletown Formation in the northern part of the Killingworth dome. Many others may be seen in the hills west and north of these roadcuts, wherever axial plane symbols appear on the map. Still others may be seen in other road cuts on Route 9 farther north.

Interpretation of sections. There are at least three separate elements of structural interpretation to which the Route 9 cuts may contribute: 1) The interpretation of the geometric and genetic relationships between the recumbent folds and the lower boundary of these folds (the contact between the Middletown Formation above and the Monson Gneiss below), 2) the interpretation of the areal extent, within the Killingworth dome, of the type of features seen in the Route 9 cuts, 3) the interpretation of the geometric and temporal relationship between these rather large recumbent folds and other large folds within the quadrangle and the region. These other large folds include the set of major folds having axial surfaces oriented N-S; this set includes the Killingworth dome, the Ivoryton synform, the Monson anticline, and the Chester syncline.

1) Relationship between recumbent folds and the lower boundary of the fold "packet:" The lower boundary of the fold packet (the contact between Middletown Formation and Monson Gneiss) appears to be a thrust fault on which recumbent folds of Middletown Formation were thrust over Monson Gneiss. This interpretation is shown in fig. 9c. It is based on evidence of a sharp truncation of folds along this contact, on the extensive disruption of blocks of Middletown above this contact, and on the abrupt difference in structure on either side of it. These features suggest that this thrust faulting was a more brittle type of deformation than was the recumbent folding. Close examination shows that all folds in the vicinity of the Middletown/Monson contact are indeed truncated sharply at this contact (fig. 10d, e). Because of this, cataclastic rocks would be expected, like those so well displayed elsewhere in the region along the Honey Hill and other faults (Lundgren and Ebblin, 1972). However, such features are absent. This is surprising because of the sharpness of the structural discordance. If recumbent folding and faulting were concomitant in these rocks, as I believe they were, then these processes must have been followed by substantial recrystallization that obliterated any traces of cataclastic fabric.

2) *Areal extent of Omml within the Killingworth dome:* The entire belt of rocks mapped as *Omml* northeast and southwest of the Route 9 cuts is interpreted as a mass of infolded Middletown. This mass cannot be traced northeastward to connect with *Omml* in the Ivoryton synform, and it appears that it must be truncated by a high-angle fault, as indicated on plate 1. The termination of this mass of *Omml* to the southwest is less clear, because outcrop is very poor.

3) *Relationship of folds in the Omml inlier to other major folds:* The recumbent folds displayed within *Omml* in the inlier are matched by comparable recumbent folds in the Monson Gneiss, especially along the northern edge of the inlier, as may be readily seen in roadcuts along Route 9 between Route 81 and Christian Brothers Road, suggesting that the inlier is indeed "folded into" the Monson Gneiss. The axial surfaces of all folds within this infold are not parallel to the axial surfaces of the major folds—Killingworth dome, Ivoryton synform, Monson anticline —and the formation of those folds must be separated in time from the formation of the recumbent folds seen in the inlier. I believe that the recumbent folds antedate the formation of the Ivoryton synform. If so, the preservation of sharply discordant structures such as the "lower fault" is surprising, as noted above.

IVORYTON SYNFORM

The Ivoryton synform separates the Killingworth dome from the Monson anticline (figs. 2, 11). The synform was first named for relationships seen in the Essex quadrangle (Lundgren, 1964, p. 29), and the basic interpretation presented there is still valid. The basic shape of the synform is outlined by the upper surface of the Monson Gneiss; plan view and inferred cross sections are shown in figure 11. This synform is the southern termination of a syncline along the western side of the Monson anticline that has been mapped by Snyder (1970) in the Marlborough quadrangle and by Eaton and Rosenfeld (1972) in the Middle Haddam quadrangle. Within those quadrangles the synform is filled with Collins Hill Formation; in the Haddam quadrangle this core of Collins Hill Formation terminates southward. As shown in figure 4, the synform is filled entirely with rocks younger than the Monson. This interpretation contrasts with my earlier ones (Lundgren, 1963, 1964), which showed Monson Gneiss, albeit partly gedrite bearing, within the synform. It has not been possible to re-examine the area of the synform within the Deep River and Essex quadrangles, but the Monson Gneiss (m_{CL}) of these reports is reclassified in figure 11 as Middletown (Omu) and Collins Hill (?) (Ogcl). The structure within the synform apparently is complex, and the stratigraphic relationships of the rock units within it may have been equally complex, as is seen most easily by examining the pattern of several rock units and their relationship to one another, as shown in several somewhat schematic cross sections across the synform. The basic form is defined by the present shape of the upper surface of the Monson Gneiss;

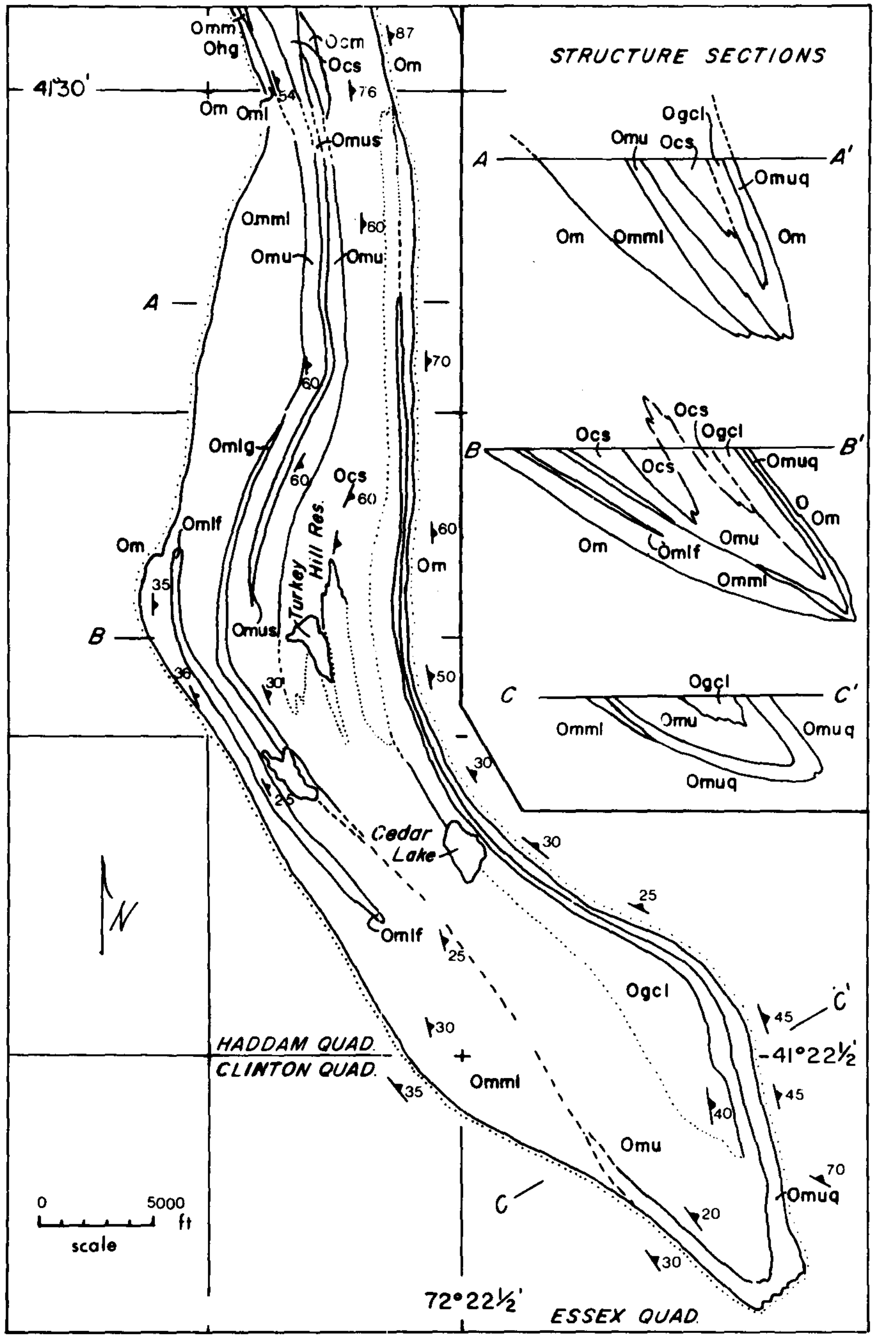


Fig. 11. Geologic map of the Ivoryton synform with structure sections. Letter symbols are those used in plate 1 and figure 3. As in that figure, symbols north of 41°30′ are Eaton and Rosenfeld's (1972) symbols.

this form is treated here as established fact. Therefore, we will focus on relationships shown by the units within the synform.

Cross-section AA′ (fig. 11) illustrates the synformal shape of the upper surface of the Monson Gneiss and the strong east-west asymmetry within this synform. The lower and middle Middletown (Omml), so important on the western side, apparently are not present on the eastern. Upper Middletown (Omu) is present on both sides; however, on the eastern side the typical upper Middletown is separated from the Monson by quartzite and schist shown as *Omus*. Collins Hill Formation is shown as simply filling the core of the synform. (Note, however, that *Omus* might be assigned to the Collins Hill Formation.) Several interpretations of this asymmetry are allowable. An unconformity could be present within the Middletown section at the stratigraphic level of *Omuq*, or *Omml* could have been eliminated on the eastern side by thinning and/or faulting on the steep or overturned limb of the synform. There is no basis at present for favoring one of these.

This asymmetry is maintained in any cross section south of AA′. In addition, sections such as BB′ suggest that there are one or more antiform/synform pairs within the larger synform. For example, *Omu* east of Turkey Hill Reservoir appears to occupy an antiformal core that splits *Ocs*. Given the excellent section of Collins Hill Formation on Route 9 just north of this (see fig. 6), one would expect either to recognize repetition of this entire section east of the *Omu* antiform or to find large isoclinal folds within the Route 9 section shown in figure 6. However, examination of that section showed very few folds on the scale of the roadcut, and efforts to demonstrate repetition of the Route 9 section were frustrated by poor exposure away from the roadcut.

All cross sections within the Haddam quadrangle replicate what is shown in AA′ and BB′. A section across the synform in the Essex and Deep River quadrangles (see fig. 11, section CC′ and also Lundgren, 1964) suggests some problems that will be resolved, if at all, only by detailed stratigraphic examination of units shown in figure 11 within the Deep River and Essex quadrangles as *Ogcl, Omu,* and *Omml*. As shown in CC′, there is strong asymmetry except for *Omuq*. However, as the dotted-line contacts on the map suggest, the relationships among these three or four units are not well established here. This is because each of these units, which is rather distinctive to the north, becomes less and less distinctive as it is traced southward. This may be seen from examination of the maps of the Deep River and Essex quadrangles (Lundgren, 1963, 1964) which were the first to be made for this region and in which I simply showed the core of the synform as Monson Gneiss (m_{CL}).

The reader familiar with multiple-fold events, such as those demonstrated in the next section (Superimposed folds in *Obc*), will note that the interpretation presented thus far for the Ivoryton synform is deceptively simple, relying as it does on one set of folds (axial surfaces trending N-S, hinges plunging gently N). Evidence from some exposures, notably in *Omu* west of Turkey Hill Reservoir, indicates that there are at least two sets of folds that set up interference patterns and that there are faults of many different ages that inevitably create complications scarcely suggested by the cross sections. Given this outcrop-scale information, assiduous efforts were made to find one good marker unit within the Middletown that could be traced well enough to document fold interference on a larger scale. These efforts were unsuccessful. This is the reason for treating the larger pattern simply, while recognizing ample fold interference at a smaller scale. Further evidence on this is found in the next section, dealing with multiple folding of a remarkable marker unit seen higher in the section and thus not present, unfortunately, in the Ivoryton synform.

Superimposed folds in Obc

The most remarkable record of folding in the area is found in the units on the northwestern flank of the Killingworth dome, especially in the coticule unit (Obc). This record is very well displayed in the Haddam and Durham quadrangles and presumably in the Middle Haddam quadrangle as well. Individual outcrops commonly display two sets of superimposed folds, and these folds commonly are seen in three-dimensional exposures. Some are so extraordinary that geologists and students visiting them should rely on a camera instead of a hammer for carrying out the investigation.

A variety of fold types are represented; among them are isoclinal, open, asymmetrical, and chevron. These types are seen in combination, and detailed work would be required systematically to establish the temporal relationships among them. Examples are given here.

The over-all trend of the coticule unit may be seen from the map. Isoclinal folds are well displayed (fig. 12a); their axial surfaces are parallel to the main trend of the layering, and they are assumed to be the oldest folds. All exposures showing isoclinal folds in combination with other folds show the isoclinal folds to be the older of any pair. In exposures within the Haddam quadrangle that show two sets of folds, the principal set comprises younger folds, rather open and generally symmetrical. These younger folds have certain distinguishing characteristics illustrated in figures 12b,c,d. The folded surfaces display slickensidelike features suggesting slip along bedding surfaces during folding (fig. 12b). The thickness of the layers in the most open folds is nearly constant (figs. 12c,d), indicating concentric folding. The biotitic layers form packs of chevron folds filling the space under the folded coticule layers. In some of these folds the over-all concentric character is not preserved in the hinge regions of the folds (fig. 12d). Plastic deformation in some of these hinge regions accounts for departures from the overall concentric form (Spratt, 1976). The axial surfaces of these open folds generally dip 15°-30° S or SE; the hinges generally are aligned within 10° of horizontal, with azimuths in the range 3° ± 5° or 210° ± 5°. These open folds are believed to be the youngest folds observed. They antedate the emplacement of at least one generation of pegmatites. This is shown by an exposure in a brook in H I in which delicate open-fold structures are preserved within the pegmatite, indicating that the open folds were formed, and then the pegmatite was emplaced, preserving the folds within the pegmatite.

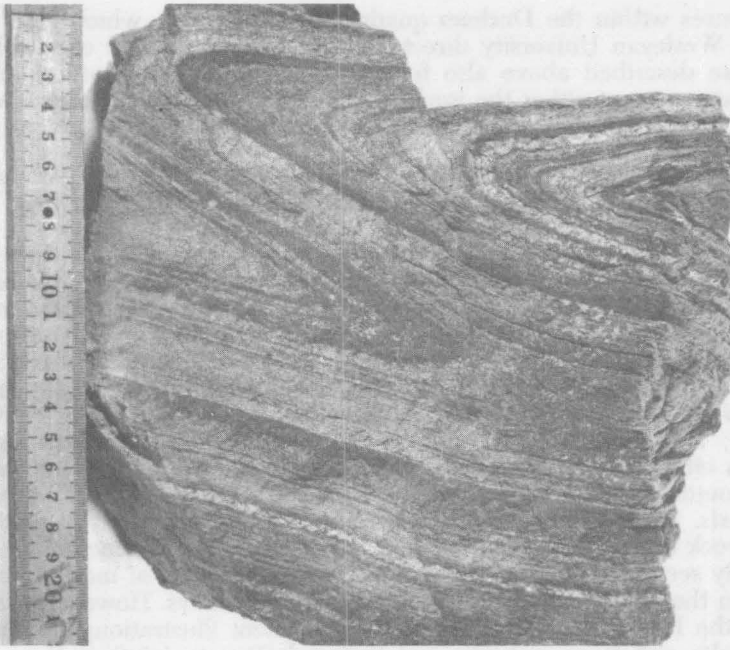
Exposures within the Durham quadrangle (D III), to which Jelle de Boer of Wesleyan University directed me, show clearly that open folds like those described above also fold the axial surfaces of rather large folds that represent either the isoclinal set of folds or a set of folds intermediate in age between the isoclinal set and the open folds.

Joints, fracture zones, and faults

Almost all bedrock exposures display joints (plane fracture surfaces); the orientation of many of the largest are mapped on plate 1 (see also Mikami and Digman, 1957). These joints have many orientations and origins; some are parallel to the axial surfaces of folds, some are clearly associated with faulting, and some with larger structural features or events not readily identifiable. Some outcrops display very closely spaced joints of several different orientations. Such closely jointed rock is unstable, and many of the linear valleys with conspicuous joint-face walls on either side probably are underlain by it. The major joint faces seen in outcrops along such valleys are generally oriented parallel to the valley axis. Some of these valleys are underlain not simply by closely jointed rock but by faults and fracture zones, which, unlike the joint sets, are rarely seen in outcrop. They are inferred from offset of marker units and from the alignment of very prominent linear valleys. However, roadcuts in the Haddam quadrangle provide excellent illustrations of small-scale faults and fracture zones and their relations to jointing. Because these may help the reader to understand the larger scale relationships, they are illustrated and described in some detail.

The faults and fracture zones are seen in exposures made along Route 9. Figures 13a,b illustrate a fracture zone in Monson Gneiss. This zone is about 25 cm wide; both walls are parallel joint faces with a steplike or zig-zag surface. Within the fracture zone most of the rock is friable granular or even claylike material, forming a matrix for lenses of Monson Gneiss that do not appear to have been rotated or much displaced. Pegmatite folia crossing this zone do not seem to be offset or displaced. Thus, the zone is referred to as a fracture zone to indicate that the rock is rather thoroughly broken and pulverized, although significant displacement cannot be demonstrated. This zone lies within a wider zone of closely jointed Monson, and the walls of this wider zone are large joint faces approximately parallel to the fracture zone. Thus, in natural exposure we see only the walls of the wider zone, which very likely are the walls of a linear valley. The inner zone would never be seen in natural exposure. Thus we can expect that many linear valleys are underlain by material such as that shown in figure 13a.

Fgures 13c,d illustrate a fault-fracture zone (location 205E, fig. 8a). Here a narrow tabular zone of pastelike greenish material is mapped as a fault. This material has no strength and is rapidly eroded. It is bordered by a broader zone of friable, closely fractured rock that contains anastamosing sheets of the green material. This broader zone is flanked by very closely jointed Monson. The tabular zone is mapped as a fault on plate 1, but it is difficult to determine the offset of rocks on opposite sides. It, too, illustrates that a natural exposure would show



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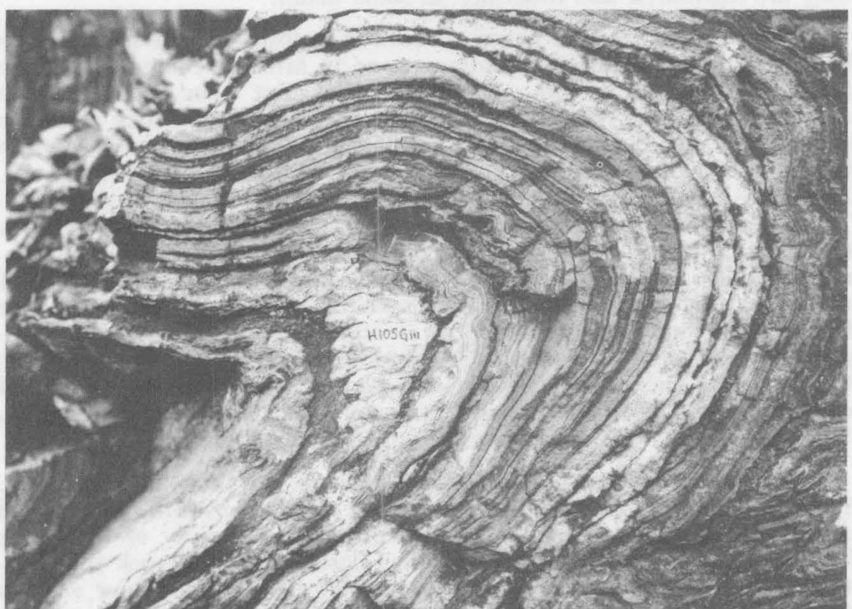

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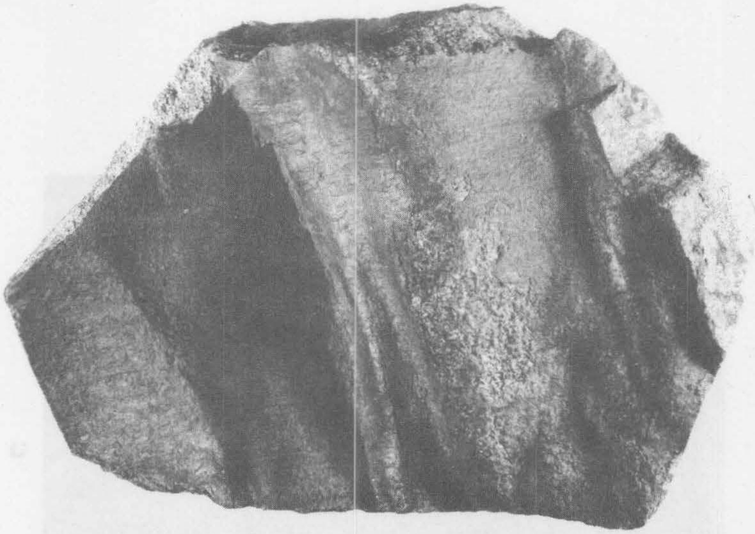

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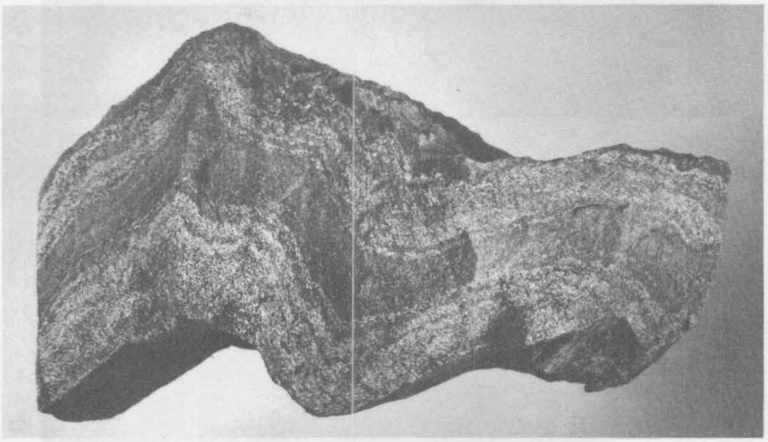

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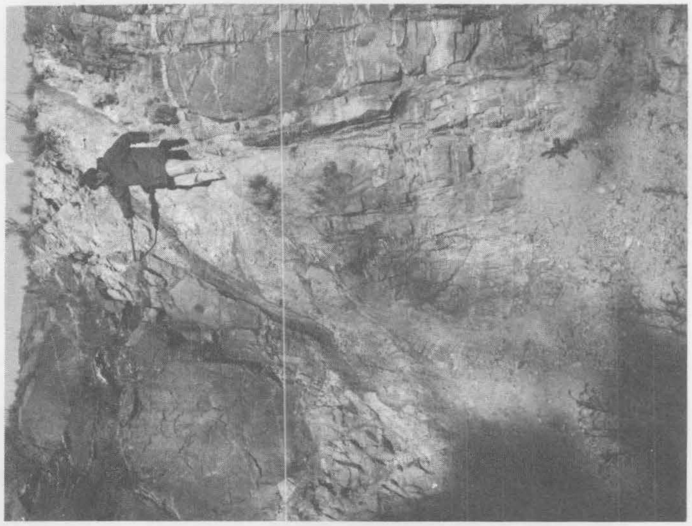
Fig. 12. Folds in coticule of "metavolcanic rocks of Bodkin Rock" (H III, 238,000 ft W; 645,000 ft N).

a. Isoclinal folds (oldest folds); scale in centimeters. (Photograph on opposite page)

b. Concentric folds (younger folds, which fold the isoclinal folds of fig. 11a). Tape label in axial-plane region is 2 in. long. (Photograph on opposite page.)

c. View of "slickensides" on folded surfaces of modified concentric fold (width of sample, 6 in.)

d. Modified concentric fold, showing area of plastic deformation in axial-plane region (marked by arrow; same sample as in fig. c)



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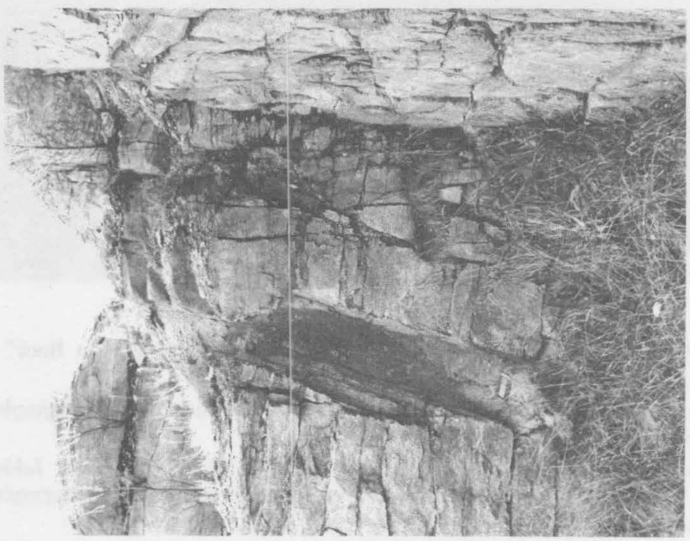

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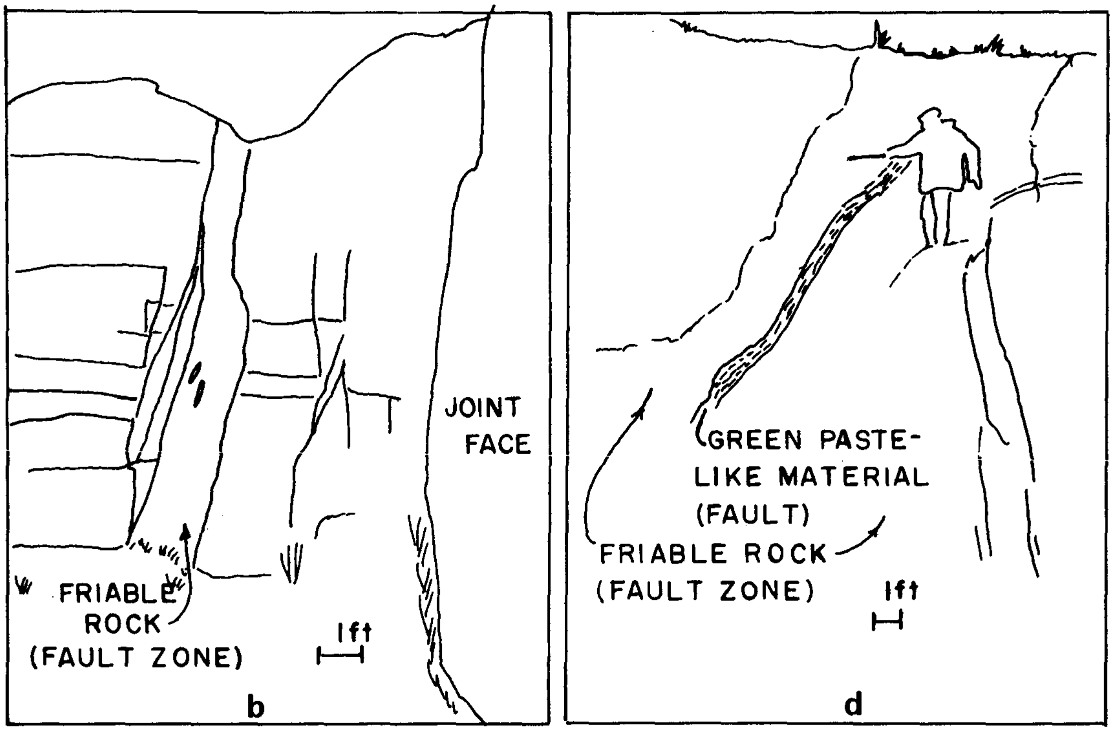

Fig. 13. Fault zones in Monson Gneiss

a. Zone of finely broken and friable Monson Gneiss marking inferred fault zone; no measurable displacement. Route 9, center island, 0.6 mi. south of Christian Brothers Road.

b. Sketch of *a*

c. Fault marked by green plastic rock material within zone of finely broken, highly friable Monson Gneiss. Southbound entrance to Route 9 at Route 81.

d. Sketch of *c*

only the closely jointed rock on either side; the central zone might be marked by a valley. In this case, the main joints would not be parallel with the valley.

A third type of fault-fracture zone is shown in the Collins Hill Formation (location of fig. 6). Here a zone of crumpled, crenulated, and friable rock lies parallel to the layering in adjacent units. This zone appears to be a fault zone, and the rock in it is so erodible that it would never be seen in natural exposure.

All these examples prepare us to examine the evidence for larger scale faulting. Although faults must be numerous, only four are shown. Two offset the diabase dike; one offsets the *Omlf* unit in the Middletown, and one may truncate *Omml*. Each is marked by a linear valley and must be underlain by a zone of friable rock like the fault zones shown in figure 13. Other linear valleys are clearly apparent in the vicinity of these two faults; these valleys must be underlain by erodible material and probably are underlain by fracture zones and/or faults. The largest valley is that of Candlewood Brook; one would expect it to be a fault valley, although it might be underlain by an erodible stratigraphic unit, as, unlike those noted above, this valley parallels the contact between Middletown and Monson.

APPLICATIONS OF GEOLOGIC INFORMATION

The most important practical information provided by the map (pl. 1) is the location of bedrock outcrops. As most of the field work was done in a single summer month when vegetation was at its peak, the original mapping did not locate every bedrock exposure. Because of this, the outcrop map prepared during bedrock mapping was combined with outcrop maps prepared during the mapping of the surficial geology of the Haddam quadrangle. Thus, the outcrop map shown here is the same as that by Flint (1978).

The relative erodibility of various major rock units is suggested by the topography and by the relative outcrop abundance of various rock types. Diabase and coticule are the most resistant, Monson or Monson-like Middletown intermediate in resistance, and much of the Middletown and most of the Collins Hill Formation the least resistant. Thus, diabase and coticule are very well exposed and form prominent ridges; muscovite schist and calcite-bearing rocks are very poorly exposed and are marked by topographically low areas. These observations can be supported by direct observations of the changes that take place in rocks after they have been exposed in newly made roadcuts.

Experience with roadcuts in the various units and with drilling indicates that micaceous units (for example, schists of Collins Hill Formation) containing significant amounts of sulfide can be expected to weather rapidly and to be quite unstable, physically and chemically. Sulfides (apparently pyrrhotite before pyrite) weather rapidly to sulfates, and exposures become coated with sulfates. The schist disintegrates and is rapidly eroded. The cutting through or dumping of rock debris from such units can be expected to have a significant effect on local stream quality, an effect whose duration is not known. This seems to have been demonstrated by Beaver Meadow Brook, which became quite rusty following construction of Route 9, with the excavation of a large volume of sulfide-bearing schist and amphibolite.

Any linear topographic feature on the map should be regarded as a zone underlain by rock lacking in coherence and strength. This is true whether or not the zone is shown as a fault (see section on faults, fracture zones, and joints).

The pegmatites shown on plate 1 are only a sample of the thousands of pegmatites in the quadrangle. Several of them were quarried at one time or another; the best known is the Gillette pegmatite (Cameron and others, 1954); others in H I and H VI are not known to be described anywhere and have been long abandoned. The diabase was taken from several quarries both north and south of Route 9 close to Route 81, but these quarries, too, have long been abandoned.

GEOLOGICAL EVOLUTION

Generalized schemes of the evolutionary stages in the development of the bedrock structure in this region have been presented in reports on other quadrangles indexed in figure 2. The Haddam quadrangle has much in common with some of these quadrangles, and its bedrock evolution must include events affecting rocks in the contiguous quadrangles. With the completion of the basic 1/24000 mapping in this region, it has become apparent that this evolution may be more complicated than was originally recognized. Now we can see that there certainly were three or more episodes of folding, and there apparently were two or more stages of metamorphic-mineral development. In addition, there were at least two episodes of late metamorphic and post metamorphic instrusive activity, and significant high-angle faulting. No one has yet ordered the fold events affecting the rocks of eastern Connecticut in a manner comparable with schemes for the equivalent rocks to the north (see Thompson and others, 1968) or to the west (see, for example, Stanley, 1964). Furthermore, interpretations of the geological evolution of a key area between the Haddam quadrangle and the area described by Thompson and others are radically different from those based on the fold model that they assumed (see Peper and others, 1975). I have chosen here to present a chronology of events in the evolution of the bedrock of the Haddam quadrangle that separates events known with some certainty from those that seem significant but whose relation to other events is not well established. The framework is provided by events recognized in the Middle Haddam quadrangle as well as in the Haddam quadrangle.

We begin with the most recent events, because these are the most accurately dated and subject to the least ambiguity. As we move backward through geologic time, we see that each successively older event must be masked by the events of more recent date. This discussion is best read in conjunction with an examination of table 1.

The intrusion of the diabase dike is dated as Late Triassic or possibly Early Jurassic. Armstrong and Besancon (1970) obtained K-Ar ages for

Table 1.—Sequence of events in the Haddam and Middle Haddam quadrangles

Age	Event in Middle Haddam quadrangle	Comparable event in Haddam quadrangle
Late Triassic and younger	High-angle faulting	Faulting of the diabase dike
Late Triassic, possibly Jurassic $\geqslant 193 \pm 12$ m.y. B.P.	Intrusion of diabase dike (Higganum dike)	Intrusion of diabase dike (Higganum dike and offshoots)
Permian 261 ± 4.3 m.y. B.P.	Intrusion of Strickland Quarry pegmatite	Intrusion of Gillette Quarry pegmatite
Pennsylvanian 285 ± 10 m.y. B.P.	Intrusion and metamorphism of Maromas Granite Gneiss	Not recognized with certainty in Haddam quadrangle
post Lower Devonian	Folding of Clough, Fitch, and Littleton on N-S axial surfaces	Major N-S synform
	Amphibolite facies metamorphism	Amphibolite-facies metamorphism
		Earlier fold events; relative timing uncertain.
Silurian/ Lower Devonian	Deposition of Clough, Fitch, and Littleton	Not represented in Haddam quadrangle
	------ UNCONFORMITY ------	
Ordovician	Deposition of the shale-carbonate sequences, including Collins Hill Formation and Bodkin Rock sequence.	
	Deposition of mixed pyroclastics, flows, and manganese-bearing cherts of the Middletown Formation	
	Deposition of volcanic parts of Monson Gneiss. Intrusive parts of Monson largely or totally emplaced prior to deposition of Middletown Formation	

two samples from locality 205 (see fig. 8a) of 192 ± 12 and 194 ± 12 million years (m.y.) before the present (B.P.). These ages are post-Triassic, but Armstrong and Besancon note that the rocks may be older than the K-Ar age. However, palynological evidence indicates that the tholeitic basalt lava *flows* of the Connecticut Valley are Early Jurassic (Robinson and others, 1978) and thus the diabase dikes on the margin of the Connecticut Valley may be Early Jurassic as well.

The next oldest event is the emplacement of the youngest pegmatites represented by the Gillette quarry pegmatite (H III). The time of emplacement of these youngest pegmatites has been well established by a long series of studies of pegmatites from the Strickland Quarry and the Spinelli Quarry (see review by Brookins, 1970). The Strickland Quarry pegmatite contains uraninite crystallized 261 ± 4.3 m.y. B.P. (Brookins, 1970). These pegmatites have not been metamorphosed or deformed but they did affect mineral crystallization in the immediately adjacent wall rock; thus they provide an end point for metamorphism and deformation at this level in the crust.

The next oldest event is the emplacement of the Maromas Granite Gneiss in the Middle Haddam quadrangle. Brookins places this at 285 ± 10 m.y. B.P. This event apparently included intrusion and some metamorphism and deformation in a large area of the Middle Haddam quadrangle. It has not been identified directly in the Haddam quadrangle but it is assumed to have left some effect.

As we move backward in time beyond the emplacement of the Maromas, the events known with greatest certainty are those of sedimentation. These can be ordered with some confidence and geologic ages assigned with decreasing confidence, the older the units become. The listing of sedimentation and volcanism in table 1 is self explanatory.

When we turn to structural and metamorphic events we confront more difficult problems. Clearly the evidence from the Middle Haddam quadrangle establishes that there is a major folding event on N-S axial surfaces which is post-Lower Devonian and prior to 285 ± 10 m.y. B.P. This event is accompanied by amphibolite-facies metamorphism. The key units (Clough, Fitch, and Littleton) are not present in the Haddam quadrangle, but the event must be represented because of the continuity of the Collins Hill Formation in the Ivoryton synform. The major structural questions remaining are: What fold events preceded the folding event noted above and what fold events postdate it? For those that precede this event there is an additional question: Which preceded the deposition of the Clough (Silurian) and which postdate the Littleton (Lower Levonian)?

It has been suggested (see sections on structural geology) that recumbent folding (maximum scale unknown) precedes folding on N-S axial surfaces. Isoclinal folding within and around the Killingworth dome includes the recumbent folding and probably includes folds formed during the formation of the N-S-trending anticline. Late folding, at least on the periphery of the dome, is illustrated in the coticule unit. It represents the last fold event to affect these rocks. Uplift of the coastal region is apparently responsible for the shape of the southern part of the Killingworth dome. This uplift seemingly took place in the interval between 285 and 250 m.y. B.P. The major mineral assemblages in all these rocks must have formed during the metamorphic event that affected the Littleton Formation, but it seems almost mandatory that they were affected earlier in the Late Ordovician.

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