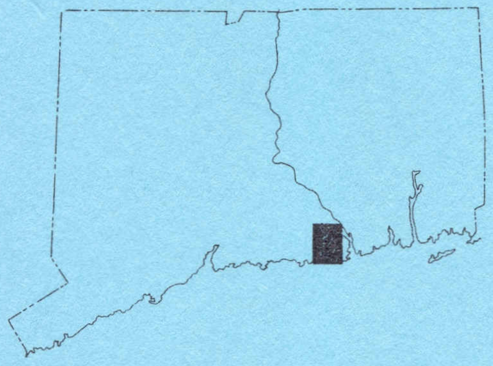
The Bedrock Geology of the Essex Quadrangle

WITH MAP

Open Map

Open Figure 2

BY LAWRENCE LUNDGREN, JR.



STATE GEOLOGICAL AND NATURAL HISTORY SURVEY
OF CONNECTICUT

A DIVISION OF THE DEPARTMENT OF AGRICULTURE
AND NATURAL RESOURCES

1964

QUADRANGLE REPORT NO. 15

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by

Lawrence Lundgren, Jr.

ABSTRACT

Bedrock in the Essex quadrangle comprises the following units, from oldest to youngest: Unnamed quartz-feldspar gneisses associated with the Clinton granite gneiss (pink, biotite granite gneiss of uncertain age); New London (?) granite gneiss (interbedded granitic gneiss and amphibolite); Monson gneiss (plagioclase-quartz gneisses); Middletown formation (anthophyllitic plagioclase-quartz gneisses and amphibolite); metamorphosed ultramafic rocks; Putnam gneiss (upper part) and Brimfield formation (laterally equivalent facies of a biotitic schist unit); Hebron formation (calc-silicate gneiss and quartz-biotite gneiss). All these rocks contain pegmatite. One new chemical analysis and 36 modal analyses are presented. The age of these rocks ranges from Cambrian? or even Precambrian to Ordovician or possibly Silurian (Hebron formation).

Rocks below the base of the Putnam gneiss (upper part) and the Brimfield formation are exposed in the Killingworth, Clinton, and Selden Neck domes and the Monson anticline; those above are exposed in the Chester syncline, a major isoclinal syncline separating the domes from one another. The axial plane of the Chester syncline is complexly folded. The complex structural configuration of the major stratigraphic units is evident in the topography, which is controlled in detail by the relative erodibility of the rock units.

A sillimanite-orthoclase isograd crosses the map from west to east; it separates biotite-sillimanite-muscovite schist to the north from biotite-sillimanite-orthoclase schist to the south. The isograd is discordant with respect to the trend of major stratigraphic and structural units.

The present structures and mineral assemblages are principally the result of high-grade metamorphism and contemporaneous doming and plastic flow that affected the rocks during the Middle or Late Paleozoic at some time prior to 265 million years B. P.

INTRODUCTION

The bedrock geology of the Essex quadrangle (fig. 1) has never been mapped on a large scale before, and the small-scale geologic maps of Percival (1842), Rice and Gregory (1906), Gregory and Robinson (1907), Foye (1949), and Rodgers and others (1956) do no more than suggest the geologic relationships in this small area of complicated structure. The stratigraphic and structural relationships of the rock units in the Essex quadrangle cannot be grasped satisfactorily without some knowledge of the major geologic features of eastern Connecticut; the reader is referred to the following

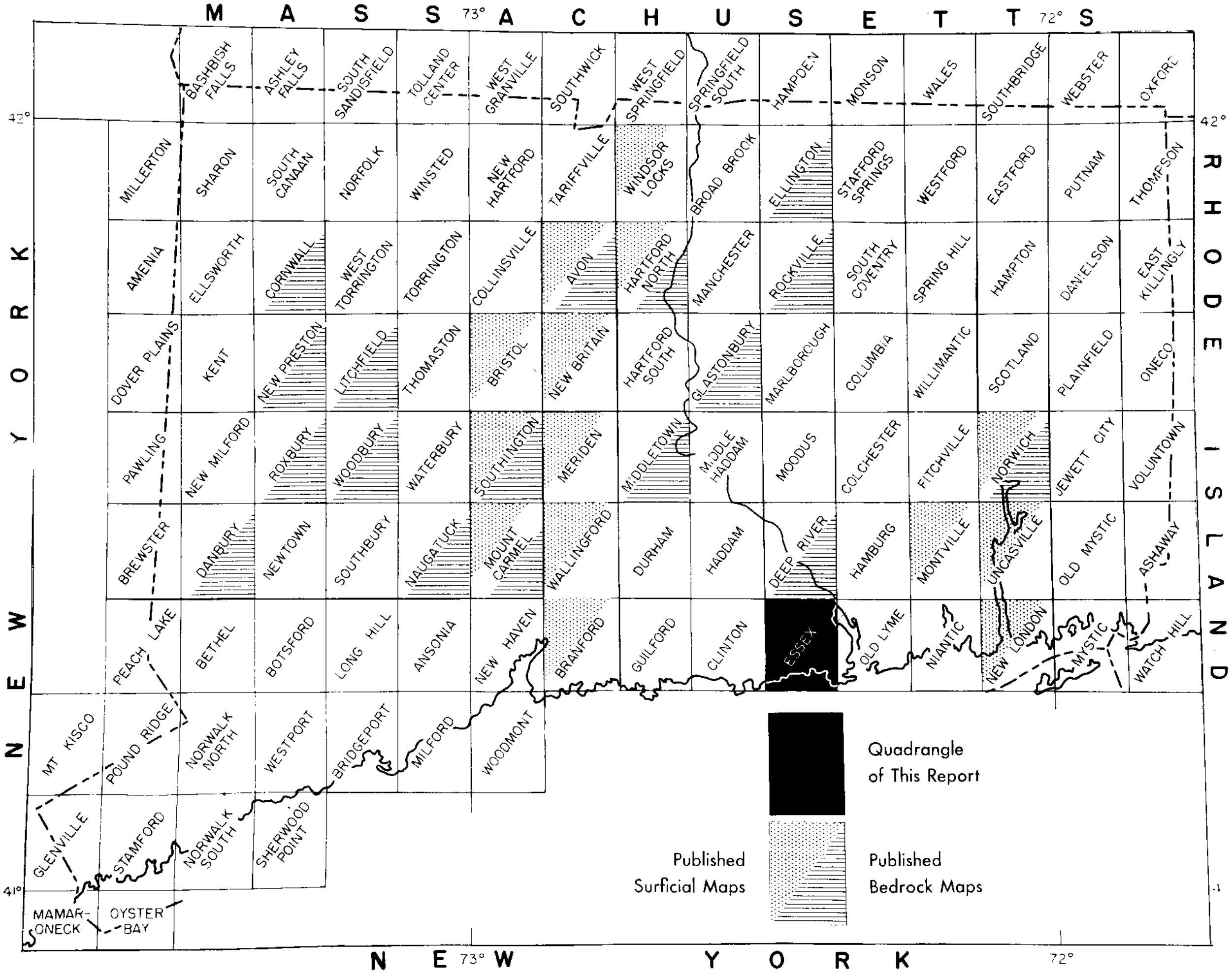

Fig. 1. Index map of Connecticut showing the location of the Essex quadrangle, and of other published quadrangle maps. See appendix for list of published maps.

papers for this information (Rodgers and others, 1959; Lundgren, 1962a and 1963) and to figure 2.

The maps and text of this report are modified from an unpublished dissertation (Lundgren, 1957) in which the stratigraphic nomenclature differed from that used here. I am grateful to Matt Walton and John Rodgers of Yale for their comments on the dissertation manuscript and to G. L. Snyder, Richard Goldsmith, L. P. Ashmead, G. P. Eaton, and J. L. Rosenfeld for making available preliminary maps of surrounding quadrangles and for discussions of stratigraphic and structural problems in the region. The Connecticut Geological and Natural History Survey supported the field work, done in 1956 and 1958-59, and together with the Geological Society of America paid for thin sections and a chemical analysis.

To facilitate the locating of geologic and geographic features, the quadrangle has been divided into ninths. Locations are indicated

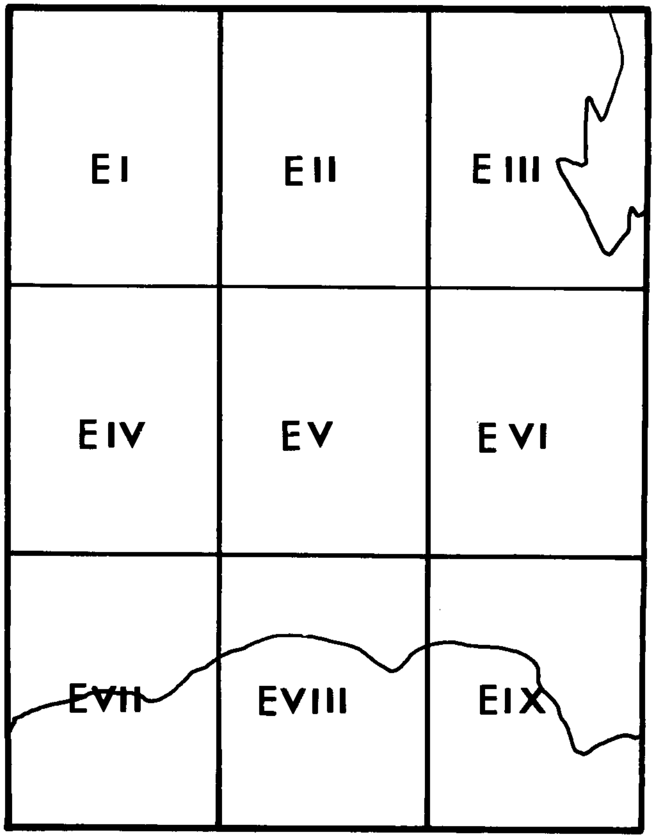

Fig. 3. Index map showing the division of the Essex quadrangle into ninths designated by Roman numerals.

throughout the report using the notation in figure 3 to indicate the ninth in which each location is to be found.

ROCK UNITS

Nearly all of the rock units exposed in the Essex quadrangle are continuous with units in the Deep River quadrangle (fig. 2), and the stratigraphic names used in this report are consistent with those used in the report on that quadrangle (Lundgren, 1963). In general, contacts between rock units in the Essex quadrangle are less accurately located than contacts between the same units in the Deep River quadrangle, because bedrock is less well exposed, particularly in the southern two thirds of the quadrangle, and because the metamorphic grade is higher in the Essex than in the Deep River quadrangle.

The descriptions of rock units are based on a study of approximately one hundred thin sections. Pleochroic colors of minerals as seen in standard thin section and colors of hand specimens of rocks are described throughout the report by the most nearly similar color on the Rock Color Chart distributed by the Geological Society of America. The modal analyses of most of the rocks are good samples of the hand specimens from which the thin sections were taken.

Where the mineralogy of a rock is indicated by a series of hyphenated mineral names (for example, quartz-biotite-garnet gneiss) the first mineral in the series is the most abundant of those listed. Rocks in which one or two accessory minerals are distinctive are described with the accessory mineral(s) before the hyphenated term (for example, graphitic biotite-sillimanite schist). The rock units are described in order from youngest to oldest except for rocks which are possibly intrusive; these are described last.

Hebron formation

The Hebron formation is exposed along a narrow sinuous belt in the Essex quadrangle; it has been traced north along this belt through the Deep River quadrangle to the type locality of the Hebron gneiss (Rice and Gregory, 1906, p. 140). In the Essex quadrangle, the Hebron consists of layered calc-silicate gneiss and quartz-biotite-plagioclase gneiss. The calc-silicate gneisses, which are the more abundant, are dark-greenish-gray medium-grained rocks consisting of abundant quartz, plagioclase (labradorite), reddish-brown biotite, and variable amounts of diopside or hornblende or both these calc-silicate minerals (table 1, modal analyses 1 to 3). Potassium feldspar is present in some samples, and zircon, sphene, graphite, pyrite, and calcite are common accessory minerals. The quartz-biotite gneisses are equigranular rocks consisting of abundant quartz (40 to 50 percent), plagioclase (oligoclase), and reddish-brown biotite. They do not contain garnet, in contrast with similar rocks in adjacent stratigraphic units.

TABLE 1. — Modal analyses of the Hebron formation

	1	2	3
Specimen no.	E 161-5	E 112-6	E 181-6
quartz	29.5	37.9	39.3
plagioclase	42.2	37.8	18.8
sericite[1]	—	—	14.8
biotite	21.7	19.8	8.3
diopside	5.4	4.2	—
hornblende	—	—	9.7
chlorite	—	—	3.1
K-feldspar	—	—	4.6
opaque accessory	0.9	0.1	0.5
nonopaque accessory	0.3	0.2	0.9
N[2]	15.5	27.9	17.6
E[2]	24.5	24.2	31.9

[1] Sericite is fine-grained muscovite present within plagioclase grains.

[2] N and E are coordinates giving the location of each sample. N is in thousands of ft north of lat 41°15′ N; E is in thousands of ft east of long 72°30′ W.

Brimfield formation

The Brimfield formation is exposed in two distinct belts and in an isolated circular area around Vincent Pond (fig. 3, E IV). The Brimfield in the main belt adjacent to the Hebron formation may be traced north through the Deep River quadrangle to the type locality of the Brimfield schist of Emerson (1898 and 1917). The rocks mapped as b_{PL} on plate 1 are continuous with schist in the Deep River quadrangle described informally as the Pine Ledge belt of Brimfield (Lundgren, 1963). The rocks in the Pine Ledge belt and around Vincent Pond are correlated with the Brimfield in the main belt on the basis of physical similarity and apparent similarity of stratigraphic position with respect to the older units.

The Brimfield consists of garnetiferous biotitic schists interbedded with subordinate garnetiferous quartz-feldspar gneiss, amphibolite, quartzite, bedded garnet-quartz rock, and anthophyllitic gneiss, all of which are described below.

BIOTITIC SCHISTS

Rust-stained micaceous schists are characteristic of the Brimfield formation, but they rarely are seen to advantage in natural outcrops, as they are so weathered and so friable that outcrops are small and specimens from them are poor. The only exposures of fresh schist are in recently opened roadcuts, notably at Interchange 64 of the Connecticut Turnpike where the cut was opened in 1956. When these schists are exposed to the atmosphere they rapidly deteriorate, primarily through the oxidation of iron and manganese in pyrite and garnet.

TABLE 2. – Modal analyses of the Brimfield formation

	Biotitic schists							
	1	2	3	4	5	6	7	8
Specimen no.	35A-6	58-6	111-6	4A-8	27-9	3-0	36-6	56-6
quartz	31.4	46.6	37.3	43.7	46.5	34.8	36.2	–
plagioclase	8.0	10.0	23.9	4.7	25.8	1.5	15.2	23.6
biotite	32.5	10.9	24.4	22.6	15.1	38.2		
orthoclase	7.9	16.5	6.1	5.1	8.2	0.7	–	–
sillimanite	12.4	7.3	4.0	15.6	0.9	22.1	–	–
garnet	6.2	7.8	4.0	7.5	3.4	2.6	46.7	–
hornblende	–	–	–	–	–	–	–	41.7
diopside	–	–	–	–	–	–	–	34.0
opaque accessories	1.4	0.9	0.1	0.8	0.1	–	–	0.3
nonopaque accessories	0.2	–	–	–	–	–	1.9	0.3
N[1]	22.75	16.3	27.1	15.6	15.4	28.0	22.9	15.9
E[1]	18.35	11.3	23.7	3.0	27.55	21.8	19.5	12.5

[1] N and E are coordinates giving the location of each sample. N is in thousands of ft north of lat 41°15′ N; E is in thousands of ft east of long 72°30′ W.

North of the sillimanite-orthoclase isograd (pl. 1, in pocket), the Brimfield, seen only in scattered outcrops, apparently consists of graphitic biotite-muscovite-garnet schist. Rocks in these outcrops generally display mineral assemblages and textures indicative of extensive alteration. Chlorite and rutile are obvious alteration products of biotite. Muscovite is present in large flakes and also as an alteration product of plagioclase and possibly sillimanite. The assemblage muscovite-sillimanite-orthoclase is represented in at least one outcrop north of the isograd, but this appears to be an unusual and anomalous assemblage.

The schists in the principal belt of Brimfield south of the isograd are coarse-grained migmatitic schists in which laminae rich in biotite and sillimanite are interleaved with more resistant laminae rich in quartz, feldspar, and garnet. The same type of schist probably underlies the central part of the Vincent Pond basin (fig. 3, E IV).

All samples of schist contain abundant quartz (table 2, modes 1 to 6), and they generally contain from 20 to 40 percent dark-reddish-brown biotite. Plagioclase, typically antiperthitic oligoclase or albite, and orthoclase ($2V_X = 45$ to $60°$; optically monoclinic; single $\{131\}$ reflection in X-ray diffractometer patterns) generally are the next most abundant minerals after biotite, although some samples contain no feldspar. Prismatic sillimanite is present in nearly every outcrop; it is common in biotitic and quartzo-feldspathic laminae, giving the rocks a silky sheen. Garnet is present in nearly every sample; it is in the form of conspicuous, large, sieve-textured grains up to one inch in diameter. It rarely displays crystal faces, and it is coated with yellow-brown iron oxides. Graphite is a common accessory; it occurs in flakes 5 mm or more in maximum dimension. Pyrite is an equally common accessory, but it is not present in much of the highly weathered schist.

BEDDED GARNET-QUARTZ ROCK

Thin-bedded, fine-grained, equigranular, pink to pale-reddish-purple garnet-quartz rock is a distinctive component of the Brimfield, particularly in association with biotitic schist. Excellent outcrops may be seen in cuts on the north side of the Connecticut Turnpike at Interchange 64 and in natural exposures immediately to the north. These rocks (table 2, mode 7) consist of quartz and small dodecahedra of manganiferous garnet, and accessory plagioclase, graphite, and pyrite. Weathered specimens are coated with dark-brown to black manganese oxides. Similar rocks in Massachusetts have been described by Emerson (1898, p. 174; 1917, p. 43) as coticule, and the name gondite apparently has also been used. The more descriptive name used above is to be preferred.

GARNETIFEROUS QUARTZ-FELDSPAR GNEISS

Garnetiferous quartz-feldspar gneisses are an important but poorly exposed constituent of the Brimfield formation from Pequot

Swamp (fig. 3, E V) south to Westbrook (E VII). Most of the feldspathic gneiss, as seen in the vicinity of Ingham Hill (E VI), is well foliated, medium-grained inequigranular quartz-plagioclase-orthoclase-biotite-garnet gneiss containing between 15 and 25 percent biotite and garnet. Garnet is conspicuous in large sieve-textured grains; biotite is abundant in folia interleaved with feldspathic layers. Thin layers of amphibolite, quartzite, and sillimanitic schist are interleaved with the gneiss. Light-gray aplitic granite and pegmatite containing conspicuous garnet also are found with the gneiss, but exposures are so inadequate that the relative importance of these rocks in the belt mapped as *bqf* (pl.1) cannot be determined.

AMPHIBOLITE AND CALC-SILICATE GNEISS

Layered amphibolites are common in the Brimfield formation. They generally are well bedded, coarse-grained, dark-greenish-black, hornblende-plagioclase rocks containing variable amounts of diopside, garnet, and sphene. Ellipsoidal nodules rich in garnet and diopside are common, and some layers of amphibolite are spotted with large red garnets up to one inch in diameter. Diopsidic amphibolite (table 2, mode 8) generally displays a laminar structure marked by light-colored laminae rich in diopside. These laminar diopsidic amphibolites grade laterally into relatively massive non-diopsidic amphibolites or into sharply layered amphibolite gneisses. The amphibolite gneisses consist of black layers of hornblende-plagioclase amphibolite interleaved with light-colored layers consisting of quartz, plagioclase, garnet, and potassium feldspar. Striking outcrops of amphibolite gneiss are exposed at Interchange 65 of the Connecticut Turnpike and south of it and west of Pequot Swamp (fig. 3, E VI).

Dark-greenish-black graphitic calc-silicate gneiss (quartz-diopside-calcite-biotite-plagioclase) and diopsidic calcite marble are found with amphibolite in several places, particularly in the Vincent Pond basin and west of Bushy Hill Pond. Marble undoubtedly is more important than is evident from outcrops. Large blocks of marble occur as erratics in glacial drift south of Vincent Pond; the most likely source is the Brimfield in the Vincent Pond basin.

ANTHOPHYLLITIC GNEISS

Anthophyllitic and cordieritic quartz-plagioclase gneiss is found with amphibolites in the Brimfield formation west of Pequot Swamp (fig. 3, E V and VI). The anthophyllitic gneisses are light-gray quartz-plagioclase rocks in which prisms of olive-gray anthophyllite are scattered through an equigranular matrix. Masses of nearly pure anthophyllite rock are found in the gneisses and adjacent to the amphibolites. These anthophyllitic gneisses are similar to gneisses elsewhere included in the Middletown formation; they are mapped with the Brimfield because they are interbedded with sillimanitic biotitic schist.

QUARTZITE

Quartzite interbedded with sillimanitic biotitic schist occurs at the contact between the Brimfield formation and the Monson gneiss west of Pequot Swamp (fig. 3, E VI), where it is medium-grained, vitreous, light-gray rock consisting of more than 80 percent quartz. Plagioclase, orthoclase, garnet, biotite, magnetite, and sillimanite constitute the remainder of most samples. Sillimanite is prominent in many outcrops, in nodular and sheetlike masses of intergrown quartz and sillimanite that stand in relief on outcrop surfaces. Muscovite is present locally, apparently as an alteration product of sillimanite.

Putnam gneiss (upper part)

The Putnam gneiss has been traced north and northeast to the Norwich quadrangle (Snyder, 1961) to meet rocks known to be continuous with the upper part of the type Putnam gneiss (Rice and Gregory, 1906, p. 129-132; Snyder, 1961; Dixon and others, 1962). In the Essex quadrangle, the Putnam gneiss (upper part) is primarily a migmatitic biotitic schist unit in which well bedded calc-silicate gneisses and garnetiferous quartz-biotite gneisses are important toward the top of the sequence.

BIOTITIC SCHISTS

The most important type of rock in the Putnam north of the sillimanite-orthoclase isograd is well foliated, dark-gray, coarse-grained biotitic schist (table 3, modes 1 to 5) in which quartz (30 to 50 percent), oligoclase or andesine (20 to 30 percent) and biotite (20 to 30 percent; $Z =$ brownish black or grayish brown) are the principal minerals. Muscovite and garnet are minor constituents; magnetite and sillimanite are common and conspicuous accessory minerals.

These muscovitic schists are heterogeneous rocks in which layers and lenses rich in quartz and plagioclase grade into laminae rich in biotite. Layers and lenses of gray to pink, fine- to coarse-grained granitic rock are interleaved with the muscovitic biotitic schists; the boundary between these microcline-bearing layers and the adjacent schist is generally sharp. Biotitic foliation surfaces commonly are matted with sillimanite needles, and many layers of schist are spotted with nodular masses of quartz laced with silky sheaves of sillimanite needles. These rocks are particularly well exposed in the vicinity of the power transmission line (not shown on plate 1) that crosses the south end of Book Hill (fig. 3, E II, III).

Rust-stained, graphitic biotite-muscovite schist is interbedded with the migmatitic biotitic schist, but it is neither as abundant nor as well exposed. Graphitic schist evidently is more muscovitic than are the biotitic schists and generally contains pyrite and abundant sillimanite.

TABLE 3. – Modal analyses of the Putnam gneiss (upper part)

	Biotitic schists								Calc-silicate gneiss							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15[1]	16[2]
Specimen no.	9-9	11-9	16-9	17-9	6-9	22-9	43-9	97-6	75-6	77-6	5-8	10-9	19-9	20-9	78-6	157-5
quartz	76.6	32.2	42.3	42.1	48.6	37.4	30.2	35.4	32.6	29.1	37.3	41.3	27.7	33.9	48.7	45.7
plagioclase	17.0	36.8	25.6	32.0	24.3	25.0	33.5	–	37.7	40.0	38.0	31.6	46.4	36.6	21.2	45.0
biotite	20.7	27.6	31.4	25.2	24.7	21.6	24.9	38.2	16.9	10.7	11.0	18.9	13.5	12.1	30.4	8.0
muscovite	0.2	1.6	–	–	1.4	–	–	–	–	–	–	–	–	–	–	–
sillimanite	0.5	–	–	–	0.8	2.7	1.0	19.2	–	–	–	–	–	–	–	–
orthoclase	–	–	–	–	–	8.8	10.4	–	–	–	–	–	0.4	–	–	0.2
garnet	–	–	–	0.7	–	4.3	–	5.5	–	–	–	–	–	4.1	0.5	–
diopside	–	–	–	–	–	–	–	–	12.7	3.2	–	5.4	11.2	–	–	–
hornblende	–	–	–	–	–	–	–	–	15.7	15.7	13.6	1.9	–	12.8	–	–
opaque accessories	0.1	1.8	0.7	–	0.1	–	–	1.7	–	–	–	–	–	–	–	0.5
nonopaque accessories	0.3	–	–	–	0.1	–	–	–	–	1.3	0.1	0.9	0.8	0.6	0.1	0.2
N[3]	41.3	40.0	37.4	37.4	41.3	18.4	33.4	16.45	18.8	18.7	20.1	40.65	30.9	31.3	16.25	28.85
E[3]	22.0	21.75	24.7	24.7	22.0	33.5	31.5	22.55	30.1	28.35	32.85	20.95	33.8	33.2	26.2	27.6

[1] Garnetiferous quartz-biotite gneiss.

[2] Quartzo-feldspathic gneiss.

[3] N and E are coordinates giving the location of each sample. N is in thousands of ft north of lat 41°15′ N; E is in thousands of ft east of long 72°30′ W.

South of the sillimanite-orthoclase isograd, the biotitic schists and graphitic schists are characterized by the presence of intergrown sillimanite and orthoclase (table 3, modes 6 to 8). Muscovite is not present in most samples, but occurs in some, ordinarily as an obvious alteration product of feldspar. These biotitic schists containing sillimanite and orthoclase have much the same migmatitic appearance as the muscovitic schists north of the isograd. However, in outcrops in which sillimanite and orthoclase are important minerals, quartz-plagioclasse-orthoclase laminae are intimately interleaved with and grade into biotitic schist laminae. Sillimanite occurs throughout; garnet is present in large irregular grains. A small exposure on the north side of the Connecticut Turnpike at the east edge of the quadrangle, immediately east of Interchange 67, illustrates the essential features of these migmatitic schists.

QUARTZ-BIOTITE-FELDSPAR GNEISSES

The upper half of the Putnam gneiss (upper part) consists of well bedded gneisses in which modal amounts of quartz + feldspar (70 ± 5 percent) and biotite (15 ± 5 percent) are relatively uniform even though the type and abundance of the other minerals vary markedly. These gneisses are mapped on plate 1 as a single unit (*pg*) consisting of interbedded calc-silicate gneiss, garnetiferous quartz-biotite gneiss, and quartzo-feldspathic gneiss, distinguished on the basis of the accessory mineralogy and physical appearance and described below. The prevalence of a particular type of rock is indicated on the map by adding an appropriate letter symbol within the map unit shown as *pg*. These gneisses are interleaved with extraordinarily abundant pegmatite throughout the area of outcrop in E VI (fig. 3), and the stratigraphic identity of these rocks is all but lost in many outcrops.

Calc-silicate gneiss. The calc-silicate gneisses are dark-gray or dark-greenish-gray, quartz-plagioclase (andesine or labradorite) -biotite (Z = reddish brown) rocks containing moderate amounts of diopside or hornblende (Z = light olive brown), or both, as well as accessory sphene (table 3, modes 9 to 14). Pyrite, pyrrhotite, graphite, microcline, and garnet are accessory minerals in some samples. These gneisses are much like the Hebron calc-silicate gneisses, but they are interbedded with biotitic schists and the other rocks described below that are not represented in the main belt of Hebron gneiss.

Garnetiferous quartz-biotite gneiss. The garnetiferous quartz-biotite gneisses are dark-gray, equigranular rocks consisting of quartz, plagioclase (oligoclase or andesine), and reddish-brown biotite (20 percent or more) and minor but conspicuous garnet (table 3, mode 15). The presence of garnet is a useful basis for distinguishing these gneisses from the similar, but nongarnetiferous quartz-biotite gneisses in the Hebron formation. The garnets are typically in the form of lenticular, sieve-textured grains that stand in conspicuous relief on weathered surfaces and foliation planes (Connecticut Turnpike north of Beacon Hill; fig. 3, E VI).

These garnetiferous gneisses are interbedded with sillimanitic biotitic schist.

Quartzo-feldspathic gneisses. The well bedded calc-silicate and garnetiferous gneisses occur with more nearly massive gneisses in which biotite is somewhat less abundant (table 3, mode 16). These gneisses generally contain substantial microcline or orthoclase, and are associated with irregular layers of pegmatite, so that it is difficult to distinguish possibly intrusive from possibly stratigraphic units. Isolated fragments of layers of amphibolite and calc-silicate gneiss are evident in large outcrops, and at least part of the quartzo-feldspathic gneiss displays small-scale intrusive relationships in relation to the calc-silicate gneisses.

AMPHIBOLITE

Dark-gray plagioclase-hornblende amphibolite in thin, discontinuous layers is a minor element of the Putnam, particularly at or near the contact between that formation and Monson gneisses and in quartzo-feldspathic gneiss. No Putnam amphibolite is shown on plate 1.

BEDDED GARNET-QUARTZ ROCK

Thin-bedded, fine-grained, pink garnet-quartz rock identical with garnet-quartz rock in the Brimfield formation is interbedded with Putnam biotitic schists in one locality (west of the crossing of the N. Y. N. H. and H. Railroad tracks and Bokum Hill Road; fig. 3, E III). It is too small to be shown on plate 1.

Middletown formation

Three separate belts of rock are mapped as Middletown formation. The belt that extends both north and northwest from Ivoryton (fig. 3, E II) is continuous with the type Middletown gneiss of Gregory (Rice and Gregory, 1906; Lundgren, 1963). The belt that extends north from Mill Pond in Centerbrook (E II) is separated from the belt of type Middletown by the Monson gneiss as is the Middletown around the Vincent Pond basin (E IV).

In the Essex as in the Deep River quadrangle, the Middletown formation is distinguished by the association of rust-stained anthophyllitic gneisses with a variety of quartz-feldspar gneisses and amphibolite. Here, too, it is difficult in some places to separate the Middletown from adjacent Monson gneiss and Brimfield formation. Anthophyllitic gneisses and amphibolites interbedded with sillimanitic schists have been mapped as part of the Brimfield; minor anthophyllitic gneiss in predominantly clean-weathering quartz-plagioclase gneiss has been mapped as part of the Monson.

The rocks in the two principal belts of the Middletown formation are much the same, and it is not necessary to describe them separately. The rock types described below have been grouped on the map because they are so intimately associated with one another that any large outcrop will display several of the types of rock described below.

TABLE 4. — Modal analyses of plagioclase gneisses of the Middletown formation [1] and Monson gneiss [2].

	1	2	3	4	5	6	7	8
Specimen no.	E 284	E 132-6	E 142-5	E 146-5	E 122-6	E 1-8	E 2-6	E 24-6
quartz	40.9	44.8	32.8	23.6	32.1	31.2	32.6	4.7
plagioclase	55.6	39.6	57.2	55.3	52.7	55.2	39.9	54.6
K-feldspar	—	—	—	1.4	1.0	1.1	7.3	—
biotite	—	10.8	—	12.5	9.6	10.9	13.1	—
hornblende	—	—	—	7.2	4.8	—	7.0	0.3
anthophyllite	1.0	4.7	—	—	—	—	—	—
cummingtonite	—	—	9.1	—	—	—	—	—
diopside	—	—	—	—	—	—	—	33.7
garnet	—	—	—	—	—	—	0.2	—
scapolite	—	—	—	—	—	—	—	3.2
opaque accessories[3]	2.0	0.1	0.4	0.2	0.2	1.4	0.2	2.3
nonopaque accessories	0.2	0.2	0.1	0.2	0.2	0.2	0.2	1.2
N[4]	41.4	40.45	43.7	43.5	39.75	38.0	18.65	32.4
E[4]	8.5	12.0	17.0	21.7	24.0	6.0	6.9	6.5

[1] Modal analyses 1 and 2 are anthophyllitic gneisses in the Monson of the Ivoryton synform, close to the contact with the Middletown. Analysis 3 is cummingtonitic Middletown.

[2] Modal analyses 4 through 7 are plagioclase-quartz gneisses of the Monson gneiss; analysis 8 is a calc-silicate layer in the Monson.

[3] Opaque accessories are magnetite-ilmenite in all but analysis 8 in which pyrite is the opaque mineral.

[4] N and E are coordinates giving the location of each sample. N is in thousands of ft north of lat 41°15′ N; E is in thousands of ft east of long 72°30′ W.

ANTHOPHYLLITIC GNEISS

Rust-stained quartz-plagioclase gneisses containing olive-gray (5Y 3/2) prismatic anthophyllite (table 4, modes 1, 2) are the most distinctive rocks in the Middletown formation. They are particularly well exposed east of Bushy Hill Pond (fig. 3, E I) and in the area between Comstock Pond and Lord Pond (E II). They are crudely foliated, coarse-grained gneisses in which anthophyllite commonly occurs in schistose biotite-anthophyllite laminae which are particularly conspicuous in tightly folded gneiss, as the laminae thicken in the crests of minor folds. Dark-red garnet is a common accessory mineral; it also occurs in lenses consisting of garnet, quartz, and tourmaline. Cordierite is present locally; it is identifiable only in thin section, so that numerous sections would have to be examined to obtain a satisfactory estimate of its distribution and abundance.

Lenses and isolated masses of nearly pure anthophyllite rock are present in a few places. The most accessible outcrop is in a roadcut at the 260-ft contour on Route 80 east of Post Hill (BM 355; E I), where a mass of anthophyllite rock consisting of large (1 to 2 in.), olive-gray anthophyllite prisms in a matrix of quartz, plagioclase, and biotite lies in folded quartz-plagioclase gneiss.

CUMMINGTONITIC GNEISS

Cummingtonitic gneisses are less common than anthophyllitic gneisses and more difficult to recognize in outcrop. They are light-gray, quartz-plagioclase rocks in which biotite and prisms of dusky-yellow-green cummingtonite occur as minor minerals (table 4, mode 3). These cummingtonitic layers are interbedded with amphibolite layers, so that they ordinarly appear as sharply banded gneisses in outcrop. The cummingtonite is conspicuous in thin section, because it displays well developed polysynthetic twinning.

AMPHIBOLITE AND DIOPSIDIC MARBLE

Amphibolites, associated with diopsidic marble, are important elements of the Middletown formation. The amphibolites are dark-greenish-black, hornblende-plagioclase rocks that commonly contain diopside and calcite. Typically they are interleaved with light-colored quartz-feldspar layers and therefore are strikingly banded in outcrop. Diopsidic amphibolites generally display a laminar structure made evident by the contrast between the pale-green diopsidic laminae and the black hornblendic laminae. As the diopsidic laminae commonly are calcitic, they tend to be etched out on outcrop surfaces, leaving hornblendic laminae standing in relief.

NODULE-BEARING QUARTZ-FELDSPAR GNEISS

Quartz-plagioclase-biotite-muscovite or quartz-plagioclase-orthoclase gneisses containing nodular masses and lenses of quartz and sillimanite are prominent in the Middletown formation, as indicated by the + symbol in belts of Middletown on plate 1. They are best displayed east of Bushy Hill Pond (fig. 3, E I), where they are interbedded with anthophyllitic gneiss, and along the south rim of the Vincent Pond basin (E IV) where they are close to the contact between the Brimfield and the Middletown formations.

GARNETIFEROUS QUARTZ-FELDSPAR GNEISSES

Quartz-plagioclase-biotite gneisses spotted with erratically distributed garnets are common associates of the anthophyllitic gneisses. The garnets are subhedral to euhedral crystals up to one-half inch in diameter generally standing in relief on outcrop surfaces.

BEDDED GARNET-QUARTZ ROCK

Well bedded pale-reddish-purple garnet-quartz rocks are interbedded in the Middletown formation with the various quartz-feldspar gneisses and amphibolites. They are indistinguishable from similar rocks in the Brimfield formation.

Monson gneiss

The major part of the Monson gneiss in the Essex quadrangle occupies the southeastern part of the Killingworth dome and two offshoots from the dome, one extending north from Ivoryton along the Monson anticline, the other extending southeast along the east flank of the Clinton dome and then east along the coast. Separate belts of Monson gneiss are exposed in the southwest part of the Selden Neck dome (fig. 3, E III) and in the Ivoryton synform northwest of Ivoryton (E I, II).

Here, as in the adjacent quadrangles, the rocks mapped as Monson are heterogeneous quartzo-feldspathic gneisses in which modal quartz + plagioclase together constitute 80 percent or more of the volume of most specimens, with microcline ordinarily a minor constituent. The bulk of the Monson gneiss evidently is a one-feldspar gneiss; it has been designated as plagioclase gneiss (Lundgren, 1962a) to indicate this.

These plagioclase gneisses are mapped as Monson gneiss because they can be traced north along the Monson anticline to Monson, Massachusetts, the type locality of the Monson gneiss of Emerson (1898, 1917), which is a plagioclase gneiss at the type locality (Lundgren, 1963). The rocks in the Ivoryton synform probably represent uppermost Monson, but their structural relationship to the main part of the Monson gneiss has not been established with certainty.

The mineralogy, physical appearance, and modal constitution of rocks mapped as Monson gneiss vary markedly. This undoubtedly reflects the heterogeneity of the pre-metamorphic complex from which the present Monson gneiss evolved, but it also reflects compositional and textural differences resulting from metamorphism, metasomatism, and deformation.

The most nearly representative exposures of Monson gneiss are in a zone some 2,000 ft wide along the east side of the Monson anticline north of Mill Pond (E II) and in a zone of comparable width in the outer part of the Selden Neck dome (E II, III). The extensive exposures in these zones display relatively monotonous light-to medium-gray, quartz-plagioclase gneisses in which the gneissic structure is determined by variations in the abundance of biotite and hornblende. Thin layers of black amphibolite accentuate the foliation. These amphibolites commonly occur in open or isoclinal folds or in well developed boudin.

Modal analyses (table 4, modes 4 to 7) of representative samples of the most common type of plagioclase gneiss demonstrate that plagioclase (andesine) generally is the most abundant mineral (more than 50 percent), with quartz next (30 ± 5 percent). Mafic minerals generally constitute 10 to 20 percent in the modes. Biotite (Z = brownish black) normally is more abundant than hornblende (Z = olive gray). Magnetite is a common accessory mineral, and sphene is common in hornblendic gneiss.

Hornblendic and biotitic plagioclase gneisses in the southeastern part of the Killingworth dome display some mineralogic and textural features different from the Monson to the north. At Horse Hill, the Ledges, and Dee Pond (E IV) the hornblendic gneisses are veined with pink and white pegmatite in irregular veins parallel to the foliation and irregular dikes discordant to the foliation. Potassium feldspar is more common in the gneisses here (table 4, mode 7); it occurs in large perthite crystals scattered through the gneiss and in less conspicuous small grains interstitial to the major minerals. Garnet is conspicuous in many outcrops, in round grains 5 mm or more in diameter. Foliation is not very well developed in some of this gneiss, but a weak lineation marked by streaks of biotite and hornblende is evident.

The Monson in the southeastern sector of the Killingworth dome includes many thin layers of a variety of rock types not evident in the Monson to the north. The rocks are much better exposed in this part of the dome than in its north and northwest portions, and the Monson may be as heterogeneous elsewhere as it is here. These layers are shown in plate 1 simply as metasedimentary layers (*ms*) in the Monson to indicate that they are undoubtedly of sedimentary origin. They include rust-stained graphitic biotite-sillimanite-orthoclase schist in small outcrops in the bottom of such narrow defiles as those clearly shown on the geologic map (pl. 1) in the area between the Ledges and Vincent Pond (E IV). These schists are associated with thinly bedded biotitic amphibolite, quartzite, calc-silicate granofels (table 4, mode 8), and marble. Layers of hornblende gneiss containing more than 10 percent garnet are found with these other rocks, and bedded garnet-quartz rock is present in at least two places.

New London (?) granite gneiss

New London (?) granite gneiss in the northeast ninth of the quadrangle is continuous with granitic gneisses in the Deep River quadrangle that separate the Monson gneiss above from the Plainfield formation below. These gneisses were designated as New London (?) granite gneiss (Lundgren, 1963), because they are similar to the New London granite gneiss of Gregory (Rice and Gregory, 1906; Gregory and Robinson, 1907) and appear to occupy the same stratigraphic position. Rocks on Salt Island (fig. 3, E VIII) are shown as New London (?) granite gneiss also.

The bulk of the New London (?) granite gneiss consists of medium-grained, equigranular, light-gray or pinkish, magnetite-bearing quartz-plagioclase-microcline-biotite gneiss. Biotite typically is of minor importance (less than 5 percent) and occurs in inconspicuous small flakes disseminated evenly through the rock. This magnetite-bearing gneiss forms smoothly rounded outcrops in which little or no internal structure is evident.

The magnetite-bearing gneisses commonly are interleaved with thin layers of amphibolite, hornblendic plagioclase gneiss, and pink alaskitic granite and pegmatite, so that many outcrops display a sharply banded surface. The layers generally are from 1 to 5 in. thick. Contacts between adjacent layers of any two types are sharp in some places, gradational in others. The best outcrops of such rock are on Salt Island in Long Island Sound, but good examples are displayed along the east side of Book Hill Road immediately south of the intersection marked 164 on the map, plate 1 (E III).

Clinton granite gneiss

The Clinton granite gneiss in the Clinton dome (fig. 3, E VII) is continuous with the Clinton granite of Mikami and Digman (1957, p. 25), which they described as "a poorly foliated granite with microcline the predominate feldspar." In the Essex quadrangle, the Clinton granite gneiss is a pink biotitic granite gneiss similar to the rocks mapped as Sterling granite gneiss in the Deep River quadrangle. The term Clinton applies to pink granitic gneiss occupying the same position in relation to the major stratigraphic units as the Sterling and may be regarded as part of the Sterling to which a local name has been applied. Areas in which pink granitic gneiss is the principal rock exposed are indicated on plate 1 by letter symbol *c;* a representative modal analysis (sample E-201-6) is as follows: quartz (34.9)—plagioclase (30.0)—microcline (28.0)—biotite (6.6)—magnetite (0.2)—nonopaque accessories (0.2).

The pink granite gneisses are interleaved with a variety of quartzo-feldspathic gneisses, amphibolites, and garnetiferous biotitic and hornblendic gneisses and schists that collectively constitute the next stratigraphic unit beneath the New London (?) granite gneiss or Monson gneiss. These rocks are exposed only in isolated outcrops; areas in which such outcrops are to be found are designated on plate 1 by letter symbol *g*.

The best exposures illustrating the relationships between the Clinton granite gneiss and the associated gneisses are to be seen in the extensive cut on the Connecticut Turnpike west of Interchange 64, at the border between the Essex and Clinton quadrangles. The west end of this cut, in the Clinton quadrangle, displays medium-grained, equigranular, pink granite gneiss in which biotite is of subordinate importance. This rock is interleaved with gray plagioclase-quartz-biotite-hornblende gneisses; contacts between granite and adjacent gray gneiss are sharp and discordant. Although this facies of the Clinton granite is easily distinguished from the adjacent rocks, pink granitic gneisses containing more biotite are not so easily distinguished, and contacts are not sharp. The more biotitic granite gneisses, commonly stained with very dark red hematite spots, are common in the part of the cut in the Essex quadrangle, and they appear to grade into gray quartz-plagioclase-biotite gneisses streaked with microcline or orthoclase and veined with coarse pink pegmatite. These gray gneisses are strikingly migmatitic; they are interbedded with more distinct layers of amphibolite, biotite-hornblende schist, and biotite-garnet gneiss which are continuous across the entire outcrop except where boudin are developed.

Thus the contact between the Clinton granite gneiss and the adjacent rocks is represented by a broad zone in which the predominance of granite diminishes with increasing distance from any mass of relatively uniform granite.

Ultramafic rock

One small mass of coarse-grained, greenish-black rock consisting largely of calciferous amphibole and lesser amounts of clinopyroxene and olivine has been mapped as ultramafic rock.

This ultramafic rock occurs as a lens in amphibolite in Monson plagioclase gneiss along the Monson anticline (fig. 3, E II). Amphibole constitutes more than 70 percent of most specimens, as stubby prisms up to half an inch long. The amphibole is faintly pleochroic ($Z =$ pale yellow green), index of refraction $= 1.652 \pm .003$, optic axial angle $= 88 \pm 2^\circ$, and $Z \wedge c = 17^\circ$—optical properties appropriate for an aluminous actinolite. The amphibole in intricately intergrown with large grains of diopside displaying broad $\{100\}$ twin lamellae. Rounded grains of magnesian olivine are scattered throughout and may constitute more than 20 percent in some samples. Scattered flakes of biotite and granules of green spinel are present locally. A chemical analysis of this rock is given in table 5. The carbonate found in the analyzed block was not present in sections from adjacent slabs.

A single small outcrop of ultramafic rock is present along the Putnam-Monson contact south of the power transmission line (not

TABLE 5. – Chemical analysis[1] of specimen[2] of ultramafic rock
(H. B. Wiik, analyst)

$SiO_2 = 46.90$
$TiO_2 = 0.17$
$Al_2O_3 = 6.79$
$Fe_2O_3 = 2.48$
$FeO = 8.48$
$MnO = 0.18$
$MgO = 18.50$
$CaO = 12.97$

$Na_2O = 0.81$
$K_2O = 0.00$
$P_2O_5 = 0.00$
$H_2O+ = 0.81$
$H_2O- = 0.00$
$CO_2 = 1.45$
Total = 99.54

[1] In percents by weight.

[2] Coordinates of sample location: 40,400 ft north of lat 41°15′ N and 15,200 ft east of long 72°30′ W.

shown on pl. 1) that crosses Book Hill (border between E II and III) north of Centerbrook. This ultramafic apparently consists of orthopyroxene, anthophyllite, and talc in addition to actinolite.

Pegmatite

Granitic pegmatite is abundant in nearly every rock unit in the quadrangle. The pegmatites shown on plate 1 are those large enough and sufficiently resistant to erosion to show some topographic expression, making it feasible to map them; they are only a small part of the total amount of pegmatite. Pegmatite in dikes and in layers and lenses intimately interleaved with the various rock units probably constitutes a far greater volume. The pegmatites were not examined in detail; the following statements are based on field observations and a study of relatively few thin sections.

Discrete masses of pegmatite are most abundant in zones of tightly folded rock, particularly in schistose units in which resistant beds such as amphibolite or bedded garnet-quartz rock are present. This assertion is based on the observed abundance of pegmatite in tightly folded schists of the Brimfield formation in the west end of the Westbrook syncline (fig. 3, E IV) and in Vincent Pond basin (E VI). Elongate pegmatite masses, few of them mappable, also are particularly abundant in tightly folded Hebron calc-silicate gneisses along the Chester syncline.

Although pegmatite dikes with nearly planar walls are particularly common in the quartzo-feldspathic gneisses such as the Monson and the Clinton, they are found in all units. Many outcrops of Monson gneiss in the extreme southeastern part of the Killingworth dome (E IV, V) are cut by a network of narrow, sharply discordant pegmatite dikes. Outcrops of Monson gneiss on the power transmission line across the south end of Book Hill (E III) are cut by discordant pegmatite dikes that are not bounded by planar walls but rather by an irregular contact, so that these dikes display a well developed pinch-and-swell structure.

Conformable layers and lenses of pegmatite are commonplace, and most rock units have a migmatitic aspect, particularly south of the sillimanite-orthoclase isograd. The most conspicuously migmatitic units are the schists in the Putnam gneiss and the Brimfield formation, the calc-silicate gneisses in the Putnam (E VI), the Monson gneiss along the coast, and the biotitic and hornblendic gneisses in which the Clinton granite gneiss occurs. Pegmatite layers and lenses are quite distinct in some outcrops; in others they grade into the adjacent rock so that no sharp boundary can be seen. One of the most striking exposures of migmatitic gneiss to be seen in the quadrangle is the exposure along the shore at Salt Works Bay (E VIII).

All of the pegmatites are primarily assemblages of quartz, potassium feldspar, and sodic plagioclase. However, the accessory mineralogy, texture, and color of the pegmatites seem to be related in some degree to the type of rock in which the pegmatite is found and to the structural relationship between it and the adjacent rocks. Some of the more obvious examples on which this statement is based are described below.

Pegmatite in Brimfield biotite-sillimanite-orthoclase-garnet schist generally is white, structurally conformable, and intimately interleaved with the schist. It commonly contains large orthoclase or microcline perthite crystals set in a finer grained matrix of antiperthitic albite, quartz, orthoclase, biotite, sillimanite, and garnet. Biotite, in small flakes and large crystals inches in diameter, is generally the only mica, but muscovite is present in places, apparently as an alteration mineral. Sillimanite, in silky sheaves of prismatic crystals, and garnet, in large red crystals, are conspicuous and are scattered throughout. The distribution of these sillimanitic pegmatites is a useful guide to the distribution of sillimanitic schist that is not well exposed.

Pegmatites in biotitic schists in the Putnam gneiss south of the sillimanite-orthoclase isograd are similar to those in the Brimfield as described above, except that sillimanite is even more conspicuous, commonly appearing in resistant masses intergrown with quartz. North of the isograd conformable pegmatites in the Putnam contain biotite and muscovite; the contact surface of these pegmatites is spotted with nodules of quartz-sillimanite intergrowths, but sillimanite does not appear to occur within the pegmatites. Here, too, the distribution of sillimanitic biotitic schist could be mapped on the basis of the distribution of pegmatite containing sillimanite or covered with sillimanitic nodules.

Pegmatite in sharply discordant sharp-walled dikes in the Putnam gneiss, Monson gneiss, and Clinton granite gneiss seems to display some marked differences in comparison with the bulk of the structurally concordant pegmatites. Discordant pegmatite generally is pink and appears to be rich in pink microcline perthite, so rich that in many outcrops the pegmatite appears to consist of quartz and microcline perthite with only minor albite and tourmaline. Pink pegmatites are notable as the only pegmatites in which cavities lined with euhedral crystals have been seen. Pink pegmatite in dikes in the Turnpike cut west of Menunketesuck River (E VII) displays cavities lined with euhedral crystals of quartz and perthite. Similar cavities have been observed in pink pegmatite at two other localities where the contact relationships are not clear. One is in a marble bed in Monson gneiss just south of Mt. Tom (E IV); the other is in the Brimfield on the east shore of Pequot Swamp (E VI) close to the telephone line shown on the map (pl. 1).

The observations presented above do not mean, for example, that all pink pegmatites are discordant, nor are they intended to imply that all the pegmatite in the Brimfield and Putnam has a common origin and mineralogy. Much more detailed study of the mineralogy, chemical composition, and age of various types of pegmatite would be required to evaluate some of the inferences reached from field observations.

STRATIGRAPHIC RELATIONSHIPS AND RELATIVE AGES OF ROCK UNITS

The stratigraphic relationships and apparent ages of the rock units in the Essex quadrangle are essentially similar to those of the Deep River quadrangle (Lundgren, 1963). The stratigraphic sequence is listed in table 6 together with the probable geologic age of each stratigraphic unit. Contact relationships and the conventions followed in mapping some of these units are discussed below.

The contact between the Hebron formation and the schists of the Brimfield formation is sharp and easy to map, but the contact between the Hebron and the Putnam gneiss is not. Calc-silicate gneisses in the upper Putnam are similar to rocks mapped as Hebron; all such gneisses known to be interbedded with sillimanitic biotitic schist have been included in the Putnam, consistent with the procedure followed in mapping the Deep River quadrangle (Lundgren, 1963). Thus the contact between the Putnam and the Hebron appears to be gradational. The Brimfield and the Putnam (upper part) are regarded as approximately equivalent. The Hebron, Putnam, and Brimfield constitute a coherent sequence of rocks that can be distinguished as a group from the sequence of older rocks on which they were deposited.

The complex of rocks older than the Brimfield-Putnam-Hebron sequence may have served as the basement on which these units were deposited, but no primary evidence of an unconformity between the two sequences has been found. The contact between the Putnam and the underlying Monson is sharp and generally is easy to map. The contact between the Brimfield and the underlying Middletown formation is not so easy to map, as the two units appear to interfinger along strike. This relationship is assumed to result

TABLE 6. — Sequence and geologic ages of stratigraphic units

PROBABLE AGE[1]	NAME
Silurian? or Ordovician	Hebron formation
Middle Ordovician?	Brimfield formation = Putnam gneiss (upper part)
Ordovician?	*Ultramafic rock*[2] Middletown formation Monson gneiss New London granite gneiss
Ordovician or older	*Clinton granite gneiss*[2] Unnamed gneisses associated with Clinton granite gneiss

[1] After Dixon and others (1962) and Lundgren (1962a, 1963).

[2] Probably intrusive, although metamorphosed; listed above all rock units that almost certainly are older.

from the short-range facies changes common in sequences of intermixed sedimentary and volcanic rocks. As a matter of convenience, the amphibolite and anthophyllitic gneisses that are interbedded with sillimanitic biotitic schist have been included in the Brimfield formation; they are indistinguishable from like rocks mapped as Middletown formation and undoubtedly have the same origin; presumably they were volcanic rocks.

The Middletown formation itself appears to grade into the Monson gneiss, and is regarded as the uppermost part of a major sequence of which the greater part is Monson gneiss. Just as the Middletown represents the upper part of this sequence, so does the New London (?) granite gneiss represent the lower part, and the New London grades upward into the Monson.

The relation of the rocks below the New London to the New London-Monson-Middletown sequence is not known. The Clinton granite gneiss does appear to be intrusive into these oldest rocks; its age relative to the New London and younger units is not known, because it is not found in contact with any of them.

STRUCTURAL GEOLOGY

The major structural elements in the Essex quadrangle are continuations of structural elements in the Deep River quadrangle or the Guilford 15-minute quadrangle (fig. 2; Lundgren, 1962a; Mikami and Digman, 1957). These elements are domes and anticlines of quartzo-feldspathic gneiss and a complexly folded syncline in which the mantle sequence is found.

Domes and anticlines

The map pattern of the Monson gneiss reflects the position of the four structural highs in which it appears. Although each of these highs is described as a separate structural unit, in the Essex quadrangle they have been cut deeply enough by erosion to show the continuity of the Monson gneiss from one structural unit to the next. The principal structural puzzle in the Essex quadrangle is understanding the manner in which these structures merge with one another and the relation of the apparent configuration of the mantle to the domes.

SELDEN NECK DOME

The Monson gneiss exposed in the vicinity of Essex (fig. 3, E III) lies in the southwest sector of the Selden Neck dome (Lundgren, 1962a, 1963), an elongate dome or doubly plunging anticline that trends approximately east-west (fig. 2). The axial plane of this anticline dips north, and the Monson structurally overlies the younger Putnam gneiss in the vicinity of Essex.

MONSON ANTICLINE

Between Mares Hill (E II) and Valley Regional School (E II), the Monson gneiss is exposed in what has been described as the root zone of a major recumbent anticline, previously designated as the Monson anticline (Lundgren, 1962a, 1963). This supposed root zone can be traced from Mares Hill north through the Deep River quadrangle and into Massachusetts. In the Essex quadrangle, the axial plane dips east at ground level; it is vertical or dips west in the northern part of the Deep River quadrangle.

KILLINGWORTH DOME

The Monson gneiss exposed in most of the western half of the quadrangle (fig. 3, E I, IV, V) marks the southeastern sector of the Killingworth dome, which has been regarded as a rather broad and internally uncomplicated dome of plagioclase gneiss (Mikami and Digman, 1957). It is evident from plate 1 that this is not true within the Essex quadrangle where the dome displays a complicated internal structure.

The supposed root zone of the Monson anticline merges with the Killingworth dome in the vicinity of Mares Hill (E II), which is unfortunately an area of negligible outcrop. This merger is marked by the termination of the belts of Brimfield and Middletown formations that separate the Monson anticline from the Killingworth dome north of Ivoryton (E II). The V-shaped belt of Brimfield and Middletown, described below as the Ivoryton synform, is one of the primary structural complications superimposed on the basic structure of the Killingworth dome.

The circular map pattern of marker units in the Monson gneiss around Vincent Pond (E IV) reflects another structure superimposed on the dome; it is discussed below as the Vincent Pond basin.

In view of these superimposed structures, this part of the Killingworth dome is perhaps better described as an anticlinorium, which may be regarded as a dome by ignoring the structural details established by large-scale mapping. These details are evident only where marker units are present and where exposures are excellent; where marker units are absent or where exposures are poor, the structure of the Monson appears to be quite simple.

CLINTON DOME

The Monson gneiss exposed between Chapman Pond (fig. 3, E VII) and Old Saybrook (E IX) marks the northern flank of a structural high that trends east-west parallel with the coastline. This high probably is an anticline, the axis of which lies in Long Island Sound. The Clinton dome (E VII) (Mikami and Digman, 1957) represents a local high superimposed on this anticline in which rocks older than the Monson are exposed.

Synclines

The domes are separated from one another by a relatively narrow belt in which the mantle sequence is exposed; this belt marks the position of the Chester syncline, the major syncline separating adjacent structural highs. The other places in which rocks younger than the Monson are exposed must also mark the position of essentially synclinal structures. Each of these synclinal structures is described below, beginning with the Chester syncline.

CHESTER SYNCLINE

The narrow belt of Hebron formation separating the Monson anticline from the Selden Neck dome marks the approximate position of the axial plane of the Chester syncline, which has been described as a recumbent isoclinal syncline (Lundgren, 1962a, 1963; Dixon and others, 1962), a syncline with a complexly folded axial plane. The Brimfield formation and Putnam gneiss are regarded as opposed limbs of this syncline.

The segment of the Chester syncline lying between the north edge of the quadrangle and Centerbrook (E III) appears to be quite simple (section *AA′*, pl. 1) ; the axial plane dips steeply to the east at ground level. South of Centerbrook, the configuration of the syncline is more complicated as is evident from the sinuous map plan of the Brimfield, Hebron, and Putnam. The interpretation of this structure is not straightforward, because the outcrop is least adequate where the structure appears to be most complicated, and no marker units are present in the Putnam to aid in elucidating the structure in the east-central ninth of the quadrangle.

The possible structural relationships of the mantle south of Centerbrook must be considered in relation to the assumed structure (fig. 4) of the Chester syncline to the north. The part of the syn-

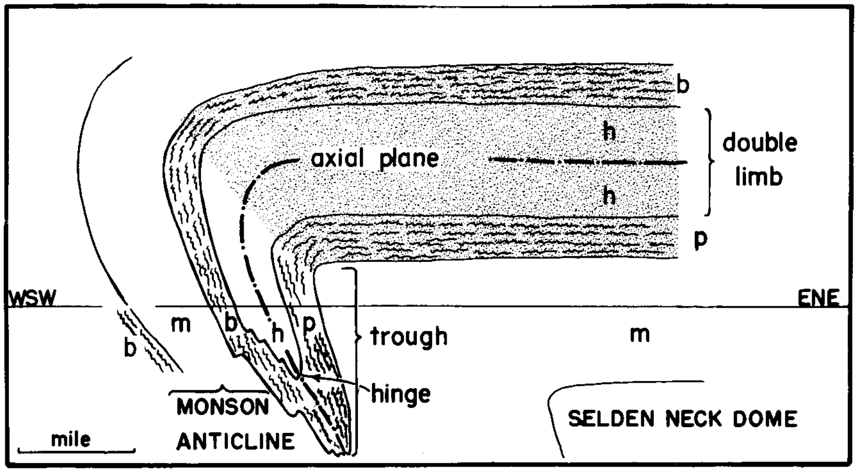

Fig. 4. Section across the Chester syncline in the Deep River quadrangle illustrating the terminology used to designate different parts of the structure.

cline exposed between the Monson anticline and the Selden Neck dome will be referred to as the *trough*; it is in normal position, and the axial plane dips steeply to the east. The line of sharpest flexure in the Hebron formation will be referred to as the *hinge line* (= axis) of the primary syncline. In the Deep River quadrangle, part of the syncline is recumbent, and the axial plane, as marked by the Hebron formation,[1] is nearly horizontal. Given this interpretation, the principal question to be considered is whether the configuration of the Hebron and adjacent units in the southern two-thirds of the Essex quadrangle can be understood solely as the result of flexures superimposed on the trough of the Chester syncline or whether part of the pattern is the result of folding of the recumbent part. The configuration of the Brimfield and Putnam is described first as a means of locating structural elements superimposed on the primary structure of the Chester syncline. Then the pattern of the Hebron formation is considered in relation to these superimposed structures.

The Brimfield formation forms the west limb and the Putnam gneiss the east limb of the Chester syncline north of Centerbrook. South of Centerbrook, the Brimfield is warped around and under the southern margin of the Killingworth dome, partially separating it from the Clinton dome. Thus the Brimfield forms a broad anticline on the southeastern flank of the Killingworth dome, and it lies in an overturned syncline between the Killingworth and Clinton domes (fig. 7a and section *BB′*, pl. 1); this syncline, shown as the Westbrook syncline, plunges east. South and east of Centerbrook,

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[1] The Hebron formation is regarded as a double limb of the syncline (McKinstry, 1961, p. 561). That is, it occurs in an isoclinal fold so tightly appressed that the innermost unit is folded against itself, the next younger unit squeezed from the core.

the Putnam is warped around and under the Selden Neck dome. Thus this part of the Putnam has an anticlinal structure related to the dome.

As the Brimfield and Putnam are limbs of the Chester syncline, each fold evident in the Brimfield or Putnam must be reflected in the configuration of the axial plane of the Chester syncline or the position of the trough of the syncline. As indicated above, the map pattern of the Hebron formation is the best clue to the configuration of the axial plane of the Chester syncline. Three alternatives may be considered; the evidence does not appear adequate to allow a choice to be made with complete confidence.

The pattern of the Hebron formation may be considered to result from the bending of the trough of an existing isoclinal fold (or of the pinching of the mantle between the domes as they developed). In either case, the part of the syncline exposed in the Essex quadrangle represents a folded but non-recumbent syncline, the trough of which extends only a few thousand feet below the surface. The

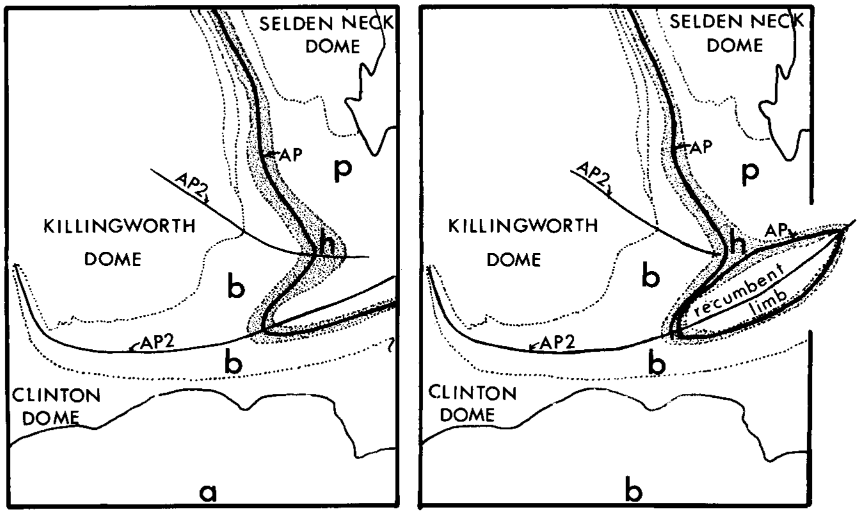

Fig. 5. Alternative interpretations of the configuration of the axial plane of the Chester syncline in the Essex quadrangle.

a. Interpretation based on the assumption that only the trough of the primary syncline is affected by cross folds. *AP* is the axial plane of primary syncline; *AP2* indicates trace of axial plane of cross fold.

b. Interpretation based on the assumption that both the trough and the recumbent part of the primary syncline are affected by cross folds. *AP* is the axial plane of primary syncline. Expected pattern of the Hebron formation is schematic. *AP2* indicates trace of axial plane of cross fold.

recumbent part, if present initially, is not represented in the quadrangle, having been removed by erosion. This interpretation, tacitly followed in earlier discussions (Lundgren, 1962a) accounts for the essential features of the map pattern of the key units, but is difficult to reconcile with the interpretation that the rocks on the north side of the Selden Neck dome represent the recumbent part of the Chester syncline.

A second interpretation is required if the pattern of the Hebron formation (fig. 3, E VI) resulted from folding of the recumbent part (see fig. 4) of the Chester syncline. The recumbent axial plane of the Chester syncline would have been folded down along the eastern segment of the axis of the Westbrook syncline. The map pattern of the axial plane of the Chester syncline that is required by this structure is illustrated in figure 5b. Calc-silicate units in the Putnam are shown in 5b as part of the Hebron formation, a representation followed in an earlier unpublished map (Lundgren, 1957). This interpretation is regarded as improbable but possible; it tacitly assumes that a recumbent fold first developed in the mantle (fig. 4), which was draped over the rocks now exposed in the Selden Neck dome. Later development of the dome would then have led to a pattern such as that illustrated in figure 5b.

A third interpretation is required if the pattern of the Hebron formation resulted from folding of the axial plane or double limb of the Chester syncline, folding the axial plane itself into a north-plunging recumbent fold, the core of which is occupied by the granitic rocks of the Selden Neck dome (fig. 6). Essential features of this interpretation are as follows:

1) The axial plane of the Chester syncline is recumbent above *and* below the core of the Selden Neck dome.

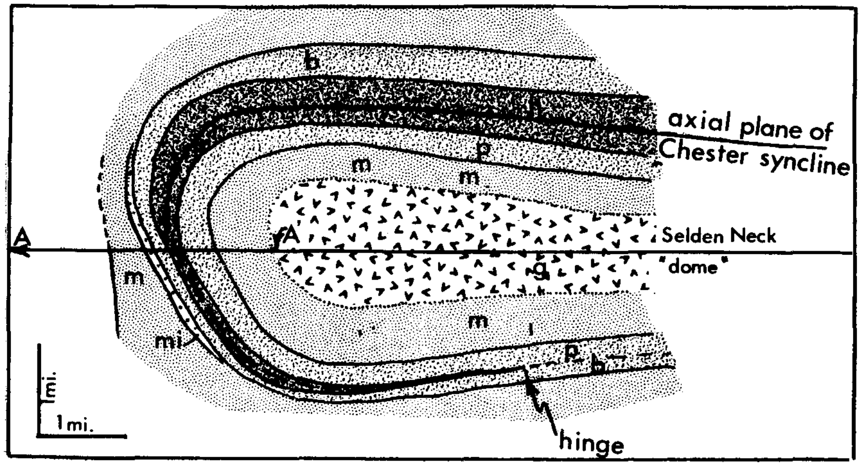

Fig. 6. Schematic structure section illustrating Selden Neck dome as a recumbent anticline. Line of section along *AA′* (pl. 1) but extending northeast into Deep River and Hamburg quadrangles.

2) The structure shown as the Selden Neck dome is, in reality, a north-plunging recumbent anticline.

3) The folded mantle must extend well under the rocks of the Selden Neck dome, as may be seen by comparing fig. 4 and fig. 6.

This interpretation is not discussed at length here, because a proper evaluation depends largely on detailed studies of the Chester syncline in the Hamburg and Old Lyme quadrangles and on regional studies over most of eastern Connecticut.

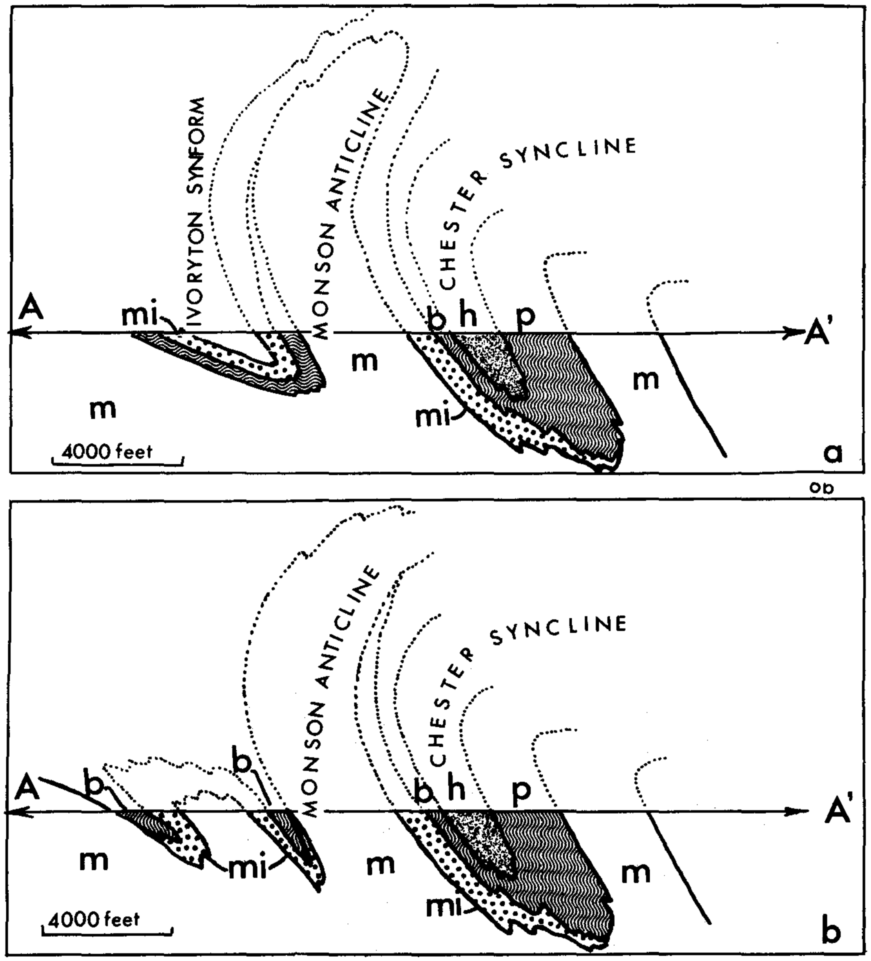

Fig. 7. Alternative structure sections across the Ivoryton synform.

a. Ivoryton synform shown as a true syncline. All rocks in this syncline are to be regarded as Middletown formation.

b. Ivoryton synform shown as an anticline. Brimfield formation on the flanks of this anticline occupies the double limb of an isoclinal fold that is itself tightly folded about a hinge at Ivoryton.

VINCENT POND BASIN

The nearly circular area of Brimfield formation at Vincent Pond is structurally an isolated, steep-walled basin superimposed on the southeast sector of the Killingworth dome (section *BB′*, pl. 1). The marker units in the Monson gneiss conform to this structure around the south side of the basin; they do not appear to close around the north side of the basin but extend northwest into an area of inadequate exposure.

IVORYTON SYNFORM

The V-shaped map plan of the Brimfield formation (Pine Ledge belt) and adjacent Middletown formation northwest of Ivoryton (fig. 3, E II) outlines a structure named the Ivoryton synform because this northwest-plunging structure has the apparent form of an open syncline. Two interpretations of the true structure of the Ivoryton synform have been suggested previously in a discussion of the Killingworth dome (Lundgren, 1963). Cross-sections illustrating these interpretations are shown in figure 7. The essential difference between them results from regarding the Brimfield as a layer within the Monson (fig. 7a) or as a tightly folded layer lying in the trough of an isoclinal syncline (fig. 7b) that has been folded sharply.

Minor structural features

The structures described above are typical of rocks that have been plastically deformed, presumably during the extensive recrystallization that is a part of the metamorphic process. Minor structural features, particularly folds and boudinage, provide the best direct evidence that the rocks have deformed plastically. The principal types of minor structures are described and illustrated below.

MINOR FOLDS

Minor folds are extensively developed in every foliated unit; they are particularly well developed in units in which a few thin layers of distinctive rock such as amphibolite, calc-silicate gneiss, or garnet-quartz rock are separated by thicker layers of relatively uniform rock of quite different mineralogy.

Open folds of small amplitude are outlined by thin amphibolite layers in Monson plagioclase-quartz gneiss (fig. 8a) exposed on a power transmission line that crosses the south end of Book Hill (fig. 3, E III). The gneiss itself is relatively structureless, and the extent to which it has been deformed might not be evident except for the amphibolite layers.

Isoclinal folds are best developed in schistose units or thin-bedded units such as calc-silicate Hebron gneiss. Excellent examples may be seen in the Putnam migmatitic schists immediately west of the

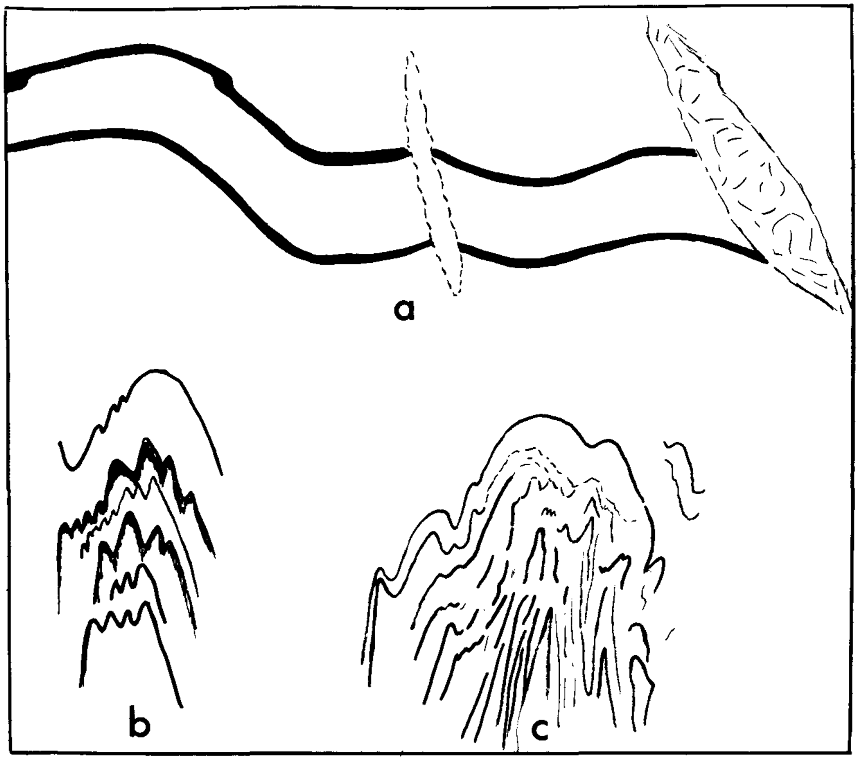

Fig. 8. Minor folds

a. Open folds in amphibolite layers (black) in Monson plagioclase gneiss. Power transmission line, Book Hill (fig. 3, E III), 39,200 ft N of lat 41°15′N and 24,000 ft E of long 72°30′W.

b. Minor folds in anthophyllitic gneiss outlined by anthophyllitic laminae (black). East of Comstock Pond (fig. 3, E II), 35,300 ft N of lat 41°15′N and 13,000 ft E of long 72°15′W.

c. Isoclinal folds in migmatitic biotitic schist (Putnam gneiss). Power transmission line (fig. 3, E II), 39,100 ft N of lat 41°15′N and 22,000 ft E of long 72°30′W.

outcrops noted above. The axial plane of these and most other isoclinal folds is parallel to the bedding trend of the adjacent beds; this is most easily demonstrated in outcrops of calc-silicate gneiss or amphibolite.

Chevron folds or crenulations are most numerous near the hinge line of major folds, and they appear to be the structural features most obviously related to the major structure. Amphibolite, anthophyllitic gneiss (fig. 7b), and marble at the apex of the Ivoryton synform all display innumerable chevron folds, and the axes of these folds appear to plunge in a common direction. A similar relationship is demonstrable in other zones of sharp flexure of the major stratigraphic units; three such zones are as follows: the west end of the Westbrook syncline south of the Ledges; the area in which the axis of the Chester syncline bends most sharply; and west of Pequot Swamp close to the telephone line shown on the map.

BOUDINAGE

Excellent examples of boudinage may be seen in quartzo-feldspathic gneisses in which amphibolite layers are present. Three examples are illustrated in figure 9. In each illustration, it is evident that cross-fractures formed in the amphibolite at the same time that the adjacent layers were thinned by plastic flow. This flow led to separation of the individual boudin from one another. Pegmatitic material occupies the neck area between adjacent boudin no matter what type of rock is adjacent to the boudin.

LINEATION

Linear structure, or lineation, generally consists of oriented prismatic minerals such as sillimanite, anthophyllite, and hornblende, all of which formed during metamorphism and deformation. Lineation is best developed in areas of fairly sharp flexure of individual beds or stratigraphic units. The most striking linear structure, displayed in Brimfield quartzite on the telephone line west of Pequot Swamp, consists of elongate nodules of intergrown quartz and sillimanite, which are aligned parallel to the axis of the anticline formed by the Brimfield here.

BEDROCK CONTROL OF TOPOGRAPHY

It is evident from plate 1 that the topography of the Essex quadrangle bears a detailed relationship to the configuration of the bedrock units and perhaps also to joints and faults cutting them. This relationship is partially masked where the cover of glacial outwash is extensive, notably in the southern part of the quadrangle, but it is so impressive that one suspects a bedrock control for any valley or low area filled with drift. The valley of Trout Brook is linear, narrow, and deep, as indicated by drilling in the stratified glacial drift that fills the bedrock valley, and it cuts across the strike of the rock units. Thus, the possibility that this valley is incised along a fault zone must be considered, although no primary evidence of a fault has been seen.

The relationship between topography and bedrock is impressively displayed in all but the southern tier of ninths, and it is clear that the relative erodibility of rock units exerts the primary control on the topography. The principal ridges and the highest hills are underlain by relatively uniform quartzo-feldspathic Monson or New London (?) gneiss. These ridges are all the more prominent because they are flanked by narrow valleys from which biotitic schists and marble have been removed. The pyritic and sillimanitic biotite-muscovite schists in the Brimfield and Putnam north of the isograd are among the most easily eroded rocks in the quadrangle, and the pyritic schists south of the isograd are possibly the most easily eroded bedrock units in eastern Connecticut. The extreme erodibility of the high-grade Brimfield appears to be related to the greater abundance of sillimanite, as sillimanitic folia tend to have virtually no coherence, even in fresh rock.

Thin beds of schist and marble in quartzo-feldspathic gneisses have left their mark on the topography where the cover of glacial drift is not extensive. This is clearly illustrated by the topography in the vicinity of the Vincent Pond basin, where the bedrock struc-

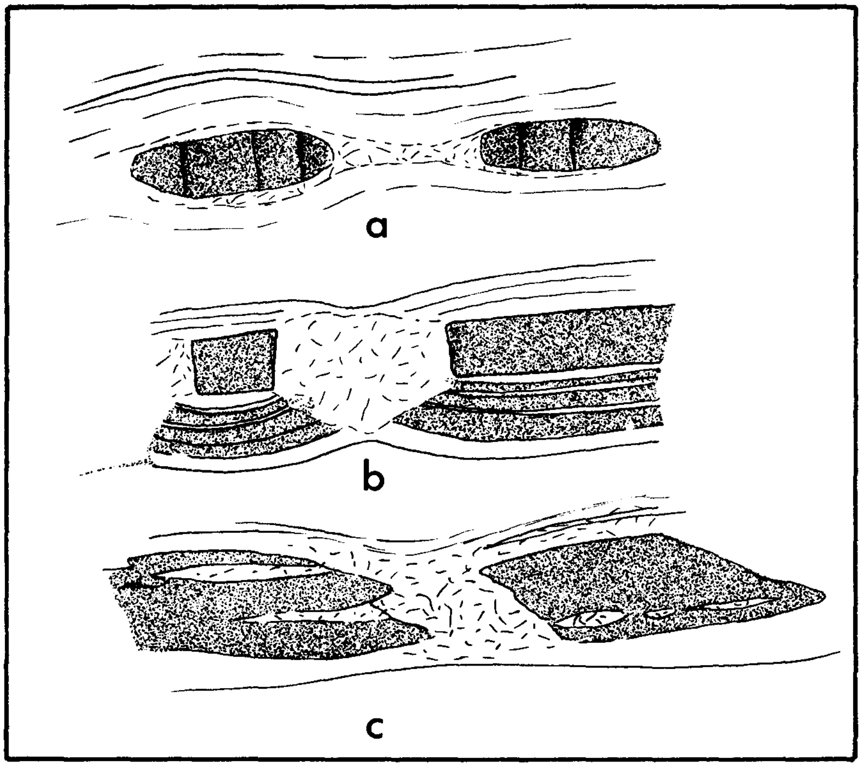

Fig. 9. Boudinage

a. Amphibolite boudins in migmatitic plagioclase gneiss. Amphibolite in stippled pattern, pegmatite in short-dashed-line area. Boudin approximately 2 ft long. Above Falls River (fig. 3, E II), 32,400 ft N of lat 41°15′N, and 12,000 ft E of long 72°30′W.

b. Amphibolite boudin in amphibolite gneiss. Stippled pattern is amphibolite. Separation of boudin approximately 18 in. Roadside outcrop on Route 153 south of Interchange 66 of Connecticut Turnpike.

c. Amphibolite boudin surrounded by pegmatite in migmatitic quartzo-feldspathic gneiss. South side of Connecticut Turnpike west of Interchange 64. Boudin is approximately 2 ft long.

(Note that foliation in each outcrop shown dips 25° or more; foliation is shown as horizontal in sketches for convenient comparison of the various types of boudin.)

ture is faithfully reflected in the topography, modified only slightly by rectilinear topography controlled by steep, north-trending joints.

After the Monson and New London gneisses, the calc-silicate gneisses of the Hebron formation and the Putnam gneiss are the next most resistant units, and each unit is marked by a subsidiary ridge. Small samples of calc-silicate gneiss appear to be even more resistant than Monson gneiss, but the calc-silicate gneisses are much better bedded and undoubtedly are eroded partly by fragmentation along bedding planes and joints.

The pegmatites, of course, are the most resistant of all the rocks, but because of their small area, they account for only minor details in the topography, particularly where they occur in rocks less resistant than the Monson and New London.

GEOLOGIC HISTORY

The geologic history of the rocks in the Essex quadrangle may have begun in the Cambrian or even the Precambrian. However, the effects of metamorphism and deformation impressed on these rocks during the later Paleozoic so thoroughly mask their original character that their early history cannot be inferred with confidence. The following outline of their probable geologic history is based on correlations and comparisons with less metamorphosed rocks of comparable age seen farther north along the Appalachian geosyncline (Lundgren, 1957).

During the Cambrian or the Precambrian, a major sequence of volcanic, clastic, and pyroclastic units was deposited; a sequence now represented by the New London (?) granite gneiss, the Monson gneiss, and the Middletown formation. The rocks below the New London (?) are not well enough exposed to justify discussing them. The New London (?) granite gneiss[2] may have been deposited as a thin but areally extensive unit consisting of rhyolite and dacite flows and pyroclastics interbedded with basalt. The Monson gneiss was deposited as a complex sequence consisting of andesites, quartz keratophyres, and basalts, as well as intrusives of like composition; it constitutes one of the major stratigraphic units in eastern Connecticut. The Middletown formation, which is genetically related to the Monson gneiss, probably was deposited as a discontinuous unit consisting of basaltic and andesitic pyroclastics, manganiferous bedded chert, and minor shale and limestone. The Clinton granite and the ultramafic rocks may have been intruded into this sequence during deformation prior to the deposition of the next younger unit; this is largely a matter of conjecture, however.

The Brimfield formation and the Putnam gneiss (upper part) were deposited as geographically separate facies of a single major stratigraphic unit consisting of shale interbedded with subordinate quartz sandstone, limestone, andesitic and basaltic pyroclastics, and

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[2] In this discussion the formation names refer to the pre-metamorphic antecedents of each unit.

manganiferous bedded chert. The deposition of this pelitic unit represents a major change in the character of sedimentation, as volcanic rocks are of subordinate importance in the section above the base of the Brimfield and Putnam (upper part).

The Hebron formation, the youngest and possibly the least variable stratigraphic unit, was deposited as a sequence of well bedded siltstones, sandstones, and carbonate-bearing siltstones and sandstones. It may have been deposited as recently as the Silurian, but no firm evidence of its age has been presented to date.

The major part of the deformation and metamorphism that brought the rocks to their present state apparently took place during the Devonian or later, and it also appears that the development of the major structures was contemporaneous with metamorphism.

The key to the metamorphic history of the rocks is provided by a study of the assemblages in the Brimfield formation and Putnam gneiss. North of the sillimanite-orthoclase isograd, the sedimentary antecedents of the Brimfield and Putnam were metamorphosed into schists containing the assemblage sillimanite-muscovite-almandine; south of the isograd the same units were metamorphosed into migmatitic schists containing the assemblage sillimanite-orthoclase-almandine. Thus the grade of metamorphism increases from north to south: sillimanite-almandine-muscovite subfacies of the amphibolite facies north of the isograd, sillimanite-almandine-orthoclase subfacies south of it (Turner and Verhoogen, 1960, p. 548-549). This suggests that the mineral assemblages south of the isograd were formed at higher temperatures than those north of the isograd.

The occurence of sillimanite + orthoclase in schists south of the isograd in place of the chemically equivalent pair, muscovite + quartz, which is so common north of the isograd, has been interpreted (Lundgren, 1962b) as a consequence of the reaction:

$$\text{Muscovite} + \text{quartz} = \text{sillimanite} + \text{orthoclase} + \text{water}$$

Thus, a major step in the metamorphic history of these rocks was the dehydration of muscovite in muscovitic Brimfield and Putnam. As a consequence, the Brimfield and Putnam are more pervasively migmatitic, much coarser grained, and more heterogeneous south of the isograd than north of it. The orthoclase-quartz-plagioclase laminae in these migmatitic schists are the product of metamorphism; they were formed as a result of the reaction stated above.

The temperature of metamorphism of the rocks south of the isograd is estimated to have been 600° C or higher, and partial melting may have accompanied the dehydration of muscovite and even biotite, so that many of the pegmatite veins, dikes, and layers could have originated at the peak of metamorphism.

The major structural elements have been interpreted as the result of the vertical movement of masses of quartzo-feldspathic gneisses during the most recent high-grade metamorphism (Lundgren, 1962a). The minor structural features described above afford ample evidence that all the rocks were deformed plastically and subjected to differential flowage during this metamorphism. Unfortunately, this pervasive recrystallization and flowage has masked evidence of the earlier structural history of these rocks. However, one may suspect that the north-south trend of recumbent isoclinal folds such as the Monson anticline and Chester syncline was established in response to east-west compression during the early stages of post-Silurian metamorphism. In this event, the vertical movement of the domes may be regarded as a process that deformed pre-existing structures as well as establishing new ones. The present configuration of the Essex rocks thus is the result of a long and complicated history.

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APPENDIX

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The quadrangle reports listed below will be sent postpaid at $1.00 each, the quadrangle map alone for 25¢ postpaid. Residents of Connecticut shall add 3½ percent sales tax. Payment must accompany order. Make checks or money orders payable to Connecticut State Library. Quadrangle reports, and all other publications of the State Geological and Natural History Survey of Connecticut, are available without charge to public officials, exchange libraries, scientists, and teachers, who indicate, under their official letterhead, that these publications are required in their professional work. Established book dealers shall receive a 20 percent discount.

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2. The Geology of the New Preston Quadrangle: Part I. The Bedrock Geology, by Robert M. Gates, Ph.D.; Part II. The Glacial Geology, by William C. Bradley; 46 p., 14 pls., with charts and quadrangle map in color (Misc. Ser. 5), 1952.
3. The Bedrock Geology of the Woodbury Quadrangle, by Robert M. Gates, Ph.D.; 32 p., 8 pls., 1 fig., with quadrangle map in color, 1954.
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8. The Bedrock Geology of the Middletown Quadrangle, by Elroy P. Lehmann, Ph.D.; 40 p., 7 figs., with quadrangle map in color, 1959.
9. The Bedrock Geology of the Naugatuck Quadrangle, by Michael H. Carr; 25 p., 5 figs., with quadrangle map in color, 1960.
10. The Surficial Geology of the Wallingford Quadrangle, by Stephen C. Porter; 42 p., 18 figs., with quadrangle map in color, 1960.
11. The Bedrock Geology of the Cornwall Quadrangle, by Robert M. Gates, Ph.D.; 35 p., 5 figs., with quadrangle map in color, 1961.
12. The Surficial Geology of the Mount Carmel Quadrangle, by Richard F. Flint, Ph.D.; 25 p., 3 figs., with quadrangle map in color, 1962.
13. The Bedrock Geology of the Deep River Quadrangle, by Lawrence Lundgren, Jr., Ph.D.; 40 p., 6 figs., with quadrangle map in color, 1963.
14. The Surficial Geology of the Branford Quadrangle, by Richard F. Flint, Ph.D.; 44 p., 4 pls, 7 figs., with quadrangle map in color, 1964.
15. The Bedrock Geology of the Essex Quadrangle, by Lawrence Lundgren, Jr., Ph.D.; 37 p., 9 figs., with quadrangle map in color, 1964.

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Geologic Quadrangle No. 121. Bedrock Geology of the Roxbury Quadrangle, by Robert M. Gates, 1959.

Geologic Quadrangle No. 134. Bedrock Geology of the Avon Quadrangle, by Robert Schnabel, 1960.

Geologic Quadrangle No. 137. Surficial Geology of the Windsor Locks Quadrangle, by Roger Colton, 1960.

Geologic Quadrangle No. 138. Surficial Geology of the Uncasville Quadrangle, by Richard Goldsmith, 1960.

Geologic Quadrangle No. 144. Bedrock Geology of the Norwich Quadrangle, by George Snyder, 1961.

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