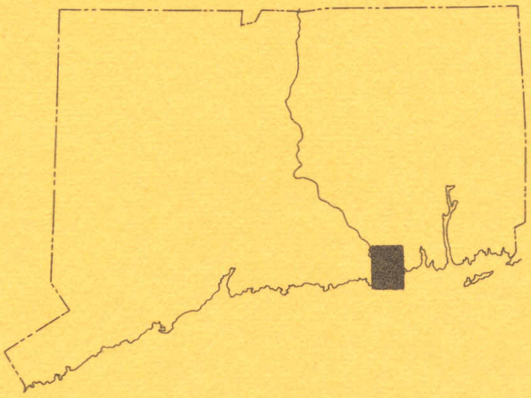
The Bedrock Geology of the Old Lyme Quadrangle

WITH MAP

Open Map

BY LAWRENCE LUNDGREN, JR.



STATE GEOLOGICAL AND NATURAL HISTORY SURVEY
OF CONNECTICUT

A DIVISION OF THE DEPARTMENT OF AGRICULTURE
AND NATURAL RESOURCES

1967

QUADRANGLE REPORT NO. 21

Migmatitic gneiss, Old Lyme Shores. The bands strike N-S. West is at the left of the photograph. The W-E dimension is 2 ft.

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BY LAWRENCE LUNDGREN, JR.
University of Rochester

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STATE GEOLOGICAL AND NATURAL HISTORY SURVEY OF CONNECTICUT

A Division of the Department of Agriculture
and Natural Resources

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The Bedrock Geology of the Old Lyme Quadrangle

by

Lawrence Lundgren, Jr.

ABSTRACT

Bedrock in the Old Lyme quadrangle comprises the following units from oldest to youngest: Plainfield Formation (lower unit–quartz-feldspar gneisses; middle unit–sillimanite schist; upper unit–quartzite and schist); Mamacoke Formation (schist, biotite quartz-feldspar gneiss); Ivoryton Group: New London and Monson Gneisses–quartz-feldspar gneisses); Tatnic Hill Formation (sillimanitic schist, calc-silicate gneiss, quartz-feldspar gneiss) and its equivalent, the Brimfield Formation (sillimanitic schist and gneiss, amphibolite); Hebron Formation (calc-silicate gneiss). Granitic gneisses designated as the Sterling Plutonic Group are interleaved with the Plainfield and Mamacoke Formations. Discordant granites (Westerly and Black Hall types) cut the Plainfield and Mamacoke.

The age of these metasedimentary rocks ranges from Cambrian (?) for the Plainfield to Middle Ordovician for the Brimfield Formation and possibly Silurian for the Hebron Formation. The discordant granites probably are Permian; the concordant granites of the Sterling Group are probably Devonian or older.

Rocks above the Ivoryton Group occur in the Hunts Brook syncline, an isoclinal syncline lying between two domes, the Selden Neck and Lyme domes. The axial surface of the Hunts Brooks syncline is folded around the Lyme dome. All the rocks, other than those in the Selden Neck dome and the younger discordant granites, were metamorphosed at temperatures in excess of 600°C and now belong to the sillimanite-orthoclase subfacies of the almandine-amphibolite facies of metamorphism.

INTRODUCTION

The Old Lyme quadrangle (SE quarter of the Saybrook 15-minute quadrangle) is located in the coastal region of eastern Connecticut where the Connecticut River empties into Long Island Sound (fig. 1). The Old Lyme quadrangle is the last of the four quadrangles that comprise the

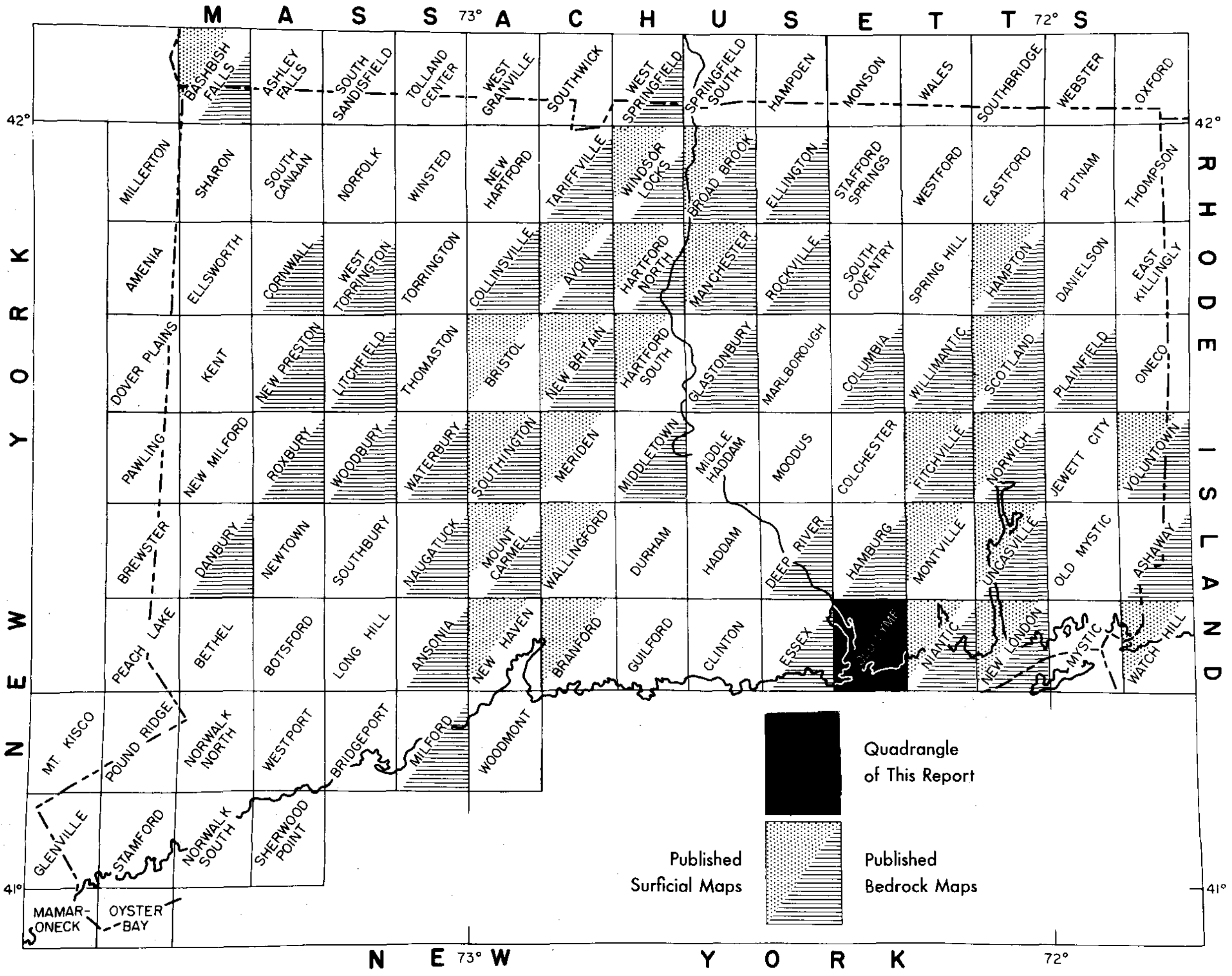

Fig. 1. Index map of Connecticut showing location of the Old Lyme quadrangle and of other published quadrangle maps.

Old Saybrook 15′ quadrangle (fig. 2) to be mapped. The Old Saybrook is notable because virtually all of the pre-Silurian units known to occur in eastern Connecticut are displayed within it; the Old Lyme is notable as the area in which some of the oldest rock units in the eastern part of the state are exposed. Most of the pre-Silurian stratigraphic units and

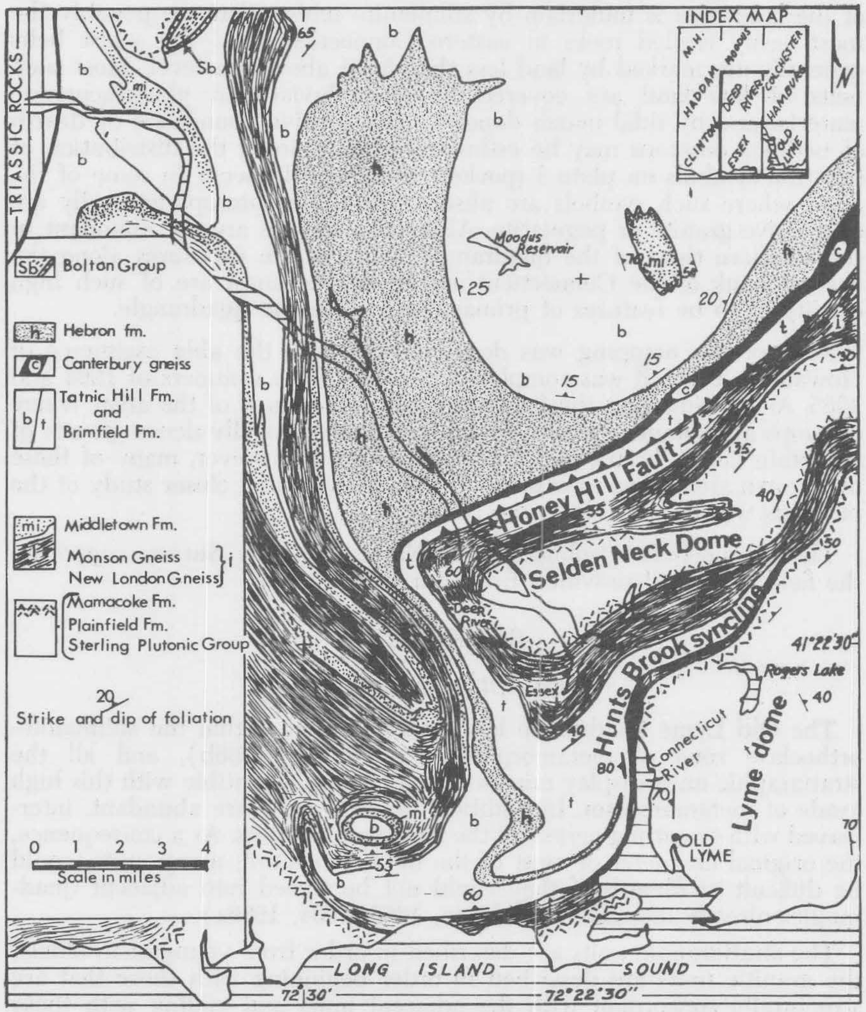

Fig. 2. Geologic sketch map of the Old Saybrook 15′ quadrangle (comprising the Deep River, Hamburg, Essex and Old Lyme 7½′ quadrangles) and contiguous areas to the north and west, illustrating the position of the Old Lyme quadrangle in the southeastern quarter of the Old Saybrook quadrangle. All mapping on this figure is by Lundgren, assisted by L. P. Ashmead, except for the Middle Haddam quadrangle (Rodgers and others, 1959).

most of the granitic units known in eastern Connecticut are exposed in the Old Lyme quadrangle.

Unfortunately, more than one third of the area of the quadrangle is covered by the Connecticut River and by Long Island Sound, and the percentage of the total land area in which bedrock is exposed is less than in the Hamburg quadrangle to the north (Lundgren, 1966a). Much of the land area is underlain by sillimanite schists that are possibly the most easily eroded rocks in eastern Connecticut, and the schist belts generally are marked by land less than 50 ft above sea level. Most such belts of low land are covered by glaciofluvial and glaciolacustrine material and by tidal marsh deposits. The relative abundance or dearth of bedrock outcrops may be estimated by examining the distribution of foliation symbols on plate 1 (pocket). Outcrops do occur in some of the areas where such symbols are absent, but these outcrops generally are of massive granite or pegmatite. Although outcrops are not abundant in the southern third of the quadrangle, some of the exposures along the eastern bank of the Connecticut and along the coast are of such high quality as to be features of primary interest in the quadrangle.

Most of the mapping was done in 1961 with the able assistance of Howard R. Pratt; it was completed in parts of the summers of 1964 and 1965. At the time that the field work was done, most of the areas where outcrops are common were covered by an exceptionally dense growth of mountain laurel, briars, and a variety of vines. However, many of these overgrown areas have now been partially cleared and closer study of the outcrops will be possible in the future.

The Connecticut Geological and Natural History Survey supported the field work and provided funds for thin sections.

ROCK UNITS

Descriptive procedures

The Old Lyme quadrangle lies almost entirely within the sillimanite-orthoclase zone of metamorphism (Lundgren, 1966b), and all the stratigraphic units display mineral assemblages compatible with this high grade of metamorphism. In addition, granitic rocks are abundant, interleaved with or cutting across all the stratigraphic units. As a consequence, the original character of most of the units is masked; many units would be difficult to identify if they could not be traced into adjacent quadrangles already mapped (Lundgren, 1963, 1964, 1966a).

The stratigraphic units are described in order from youngest to oldest; the granitic units are described in order beginning with those that are structurally concordant with the adjacent units and ending with those that are structurally discordant.

The location of an outcrop or sample is indicated by citing the ninth (for example, OL II) in which it occurs (see fig. 3), by citing the structural feature in which it occurs (for example, Hunts Brook syncline), or by giving its coordinates in thousands of feet east of the western edge of the quadrangle (XE) and north of the quadrangle's southern border (XN).

The descriptions of rock units are based on a study of approximately 250 thin sections. Colors of minerals as seen in thin sections of standard thickness (magnification 50X, plane-polarized light), and colors of hand specimens of rocks or minerals are described throughout the report by citing the most nearly similar color on the Rock Color Chart distributed

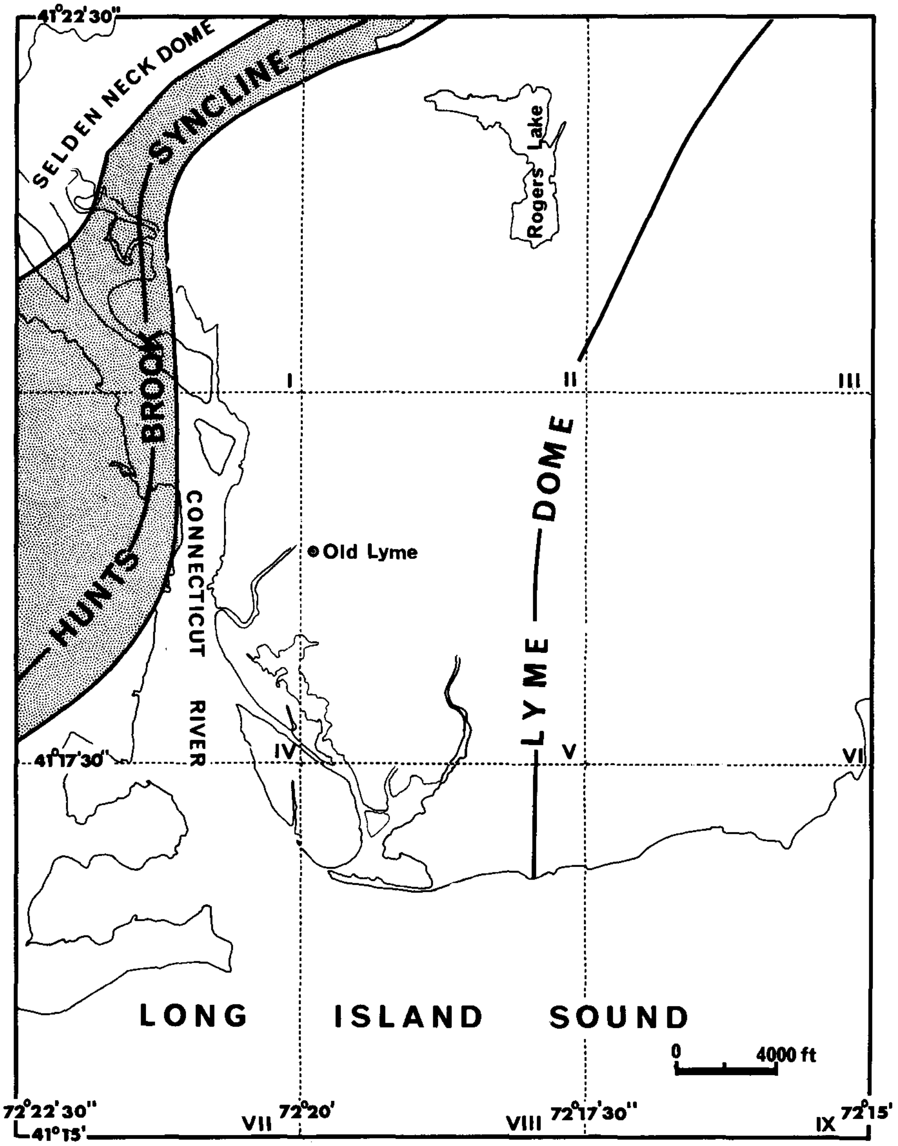

Fig. 3. Map of the Old Lyme quadrangle illustrating the division into ninths designated by Roman numerals, together with the distribution of major structural units.

Table 1.—Modal analyses[1] and mineral assemblages of rocks in the Hebron, Tatnic

	h	Otc	Otc	Otc	Otc	Otc	Otc	Otg
Sample no.	1	2	3	4	5	6	7	8
Field no.	1-9	1-8	16-0	140A	139	486B	74-8	449
quartz	51.2	43.6	34.0	24.8	34.0	x	x	42.2
plagioclase	25.0	33.6	33.2	38.8	37.4	x	x	44.2
microcline	----	----	0.8	----	----	----	x	x
biotite[5]	14.4	5.1	16.8	0.8	16.2	x	x	12.6
hornblende[5]	4.0	11.8	14.8	35.4	----	x	x	----
diopside	5.0	5.1	----	----	12.0	x	x	----
garnet	----	----	----	----	----	----	----	----
sillimanite	----	----	----	----	----	----	----	----
opaque[6]	x	x	x	0.2	x	x	x	1.0
other[6]	0.4	0.7	0.4	x	x	x	x	0.2
% An	38	45	80	55	----	56	65	38
XN[7]	22.15	23.6	44.85	22.3	29.95	45.35	40.1	40.6
XE[7]	3.6	2.35	11.3	2.2	4.1	13.15	5.35	5.1

---

[1] In volume percent; for samples 6 and 7 the symbol x indicates that the mineral is present, for the other samples that the volume percent of the mineral is less than 0.1.

[2] Map symbol (pl. 1) given in top line of table.

[3] 444A and 444B are adjacent folia in migmatitic schist.

[4] 5-9A and 5-9B are adjacent laminae in laminar amphibolite layer in the Brimfield Formation.

[5] Biotite color: samples 1-7 (Z=10R 4/6); samples 8, 9(Z=5YR 3/2); samples 10-14 (Z=10R 4/6). Hornblende color: samples 1-4, 6, 7 (Z=5Y 4/4); sample 16 (Z=5Y 5/4).

by the Geological Society of America (Goddard and others, 1948). Modal analyses listed in the tables or in figure 4 were made on thin sections in which both plagioclase and potassium feldspar were stained (Bailey and Stevens, 1960). Modal analyses (or modes) were obtained by counting 500 points on a grid of points 1.0 x 1.0 mm. A few of the modes were determined by H. R. Pratt (1962) as indicated in figure 4; all others were determined by the author. Pratt (1962) also presented additional modal analyses and a discussion of their precision and accuracy. The stated mode is a satisfactory measure of the composition of the thin section, but for these coarsely foliated migmatitic rocks the mode rarely is a satisfactory indicator of the composition of a large specimen. Modal analyses are listed for rocks that appear uniform in hand specimens and for rocks so coarsely foliated that a layer representing the metasediment can be sectioned separately from adjacent granite folia. The modes then are selected to indicate the kinds of rocks that occur in a map unit, but

Hill, and Brimfield Formations[2]

Otg	Otm	Otm	Obm	Obm	Obm	Obm	Obm	
9	10	11	12	13	14	15	16	Sample no.
448	444A[3]	444B[3]	4-9	401	2-9	5-9A[4]	5-9[4]	Field no.
37.2	75.4	28.6	50.5	21.3	39.5	----	----	quartz
34.0	4.3	15.2	26.8	39.3	25.5	14.8	27.0	plagioclase
----	8.6	6.6	10.1	2.2	3.5	----	----	microcline
28.6	4.2	23.2	8.1	31.4	22.8	----	----	biotite[5]
----	----	----	----	----	----	----	47.0	hornblende[5]
----	----	----	----	----	----	83.6	26.0	diopside
----	4.2	21.2	3.5	4.8	8.7	----	----	garnet
----	2.9	4.8	0.4	0.0	----	----	----	sillimanite
0.2	x	0.4	0.6	0.9	x	----	----	opaque[6]
x	0.6	x	x	0.1	x	1.6	x	other[6]
34	----	----	10	----	----	70	70	% An
40.0	42.25	42.25	19.05	19.05	19.5	18.4	18.4	XN[7]
4.2	5.85	5.85	1.3	1.3	3.05	1.4	1.4	XE[7]

[6] Opaque minerals: samples 1-7 (pyrite/pyrrhotite, graphite, magnetite); samples 8, 9 (magnetite); samples 10-14 (graphite, pyrite/pyrrhotite, magnetite). Other: apatite, zircon, sericite and in samples 1-7 and 15-16 sphene also present.

[7] Sample-location coordinates: XN numbers are thousands of ft N of S boundary of quadrangle; XE numbers are thousands of ft E of W boundary of quadrangle.

they give no indication of the relative abundance of the rock types in a map unit.

Hebron Formation

A narrow belt of calc-silicate gneiss in OL IV (fig. 3) is mapped as Hebron Formation (h), as it is continuous with the unit in the Essex quadrangle mapped as Hebron (Lundgren, 1964). Gneiss in this belt is similar to calc-silicate gneisses mapped as (upper) Tatnic Hill Formation (Otc). However, the calc-silicate gneisses mapped as Tatnic Hill are interleaved with garnetiferous schists and can be separated from the Hebron only where the schists are exposed. East of the Connecticut River, all the calc-silicate gneiss, including gneiss on strike with the Hebron, is mapped as Tatnic Hill, because garnetiferous schist is present in most outcrops of this calc-silicate gneiss.

The Hebron Formation comprises greenish- to dark-greenish-gray gneisses consisting of beds of calc-silicate granofels (Goldsmith, 1959)

1 to 3 in. thick. Such rock (table 1, sample 1) typically is an equigranular (1 mm) aggregate of quartz and plagioclase (An 40 to 60) spotted with pale-green granules of diopside, black grains of hornblende (Z = moderate olive brown), and flakes of biotite (Z = moderate reddish brown). Zircon, sphene, apatite, and pyrite (or pyrrhotite) are common accessory minerals; garnet is present in some samples. Adjacent beds differ chiefly in the relative abundance of diopside, hornblende, and biotite.

Tatnic Hill Formation

NOMENCLATURE AND DISTRIBUTION

Rock units on the west and northwest limb of the Hunts Brook syncline (pl. 1; fig. 3, OL I, II, IV) are mapped as Tatnic Hill Formation, because they are continuous with units in the Essex and Deep River quadrangles mapped as Putnam Gneiss (upper part)—units since renamed Tatnic Hill Formation by Dixon (1964; see also, Lundgren, 1966a). Here, as in the adjacent Essex and Hamburg quadrangles, the Tatnic Hill Formation consists of sillimanitic schists, which are most common in the lower part of the formation, and calc-silicate gneiss and biotitic quartz-feldspar gneiss, which are most abundant in, and probably restricted to, the upper part of the formation. Each of these units is mapped separately east of the Connecticut River. Although all are exposed west of the river, they cannot be mapped separately there because outcrops are too few.

CALC-SILICATE GNEISS (Otc)

The calc-silicate gneisses (Otc) are well exposed at and north of Interchange 68 of the Connecticut Turnpike (fig. 3, OL IV). They are sharply layered, gray to greenish-gray gneisses, individual layers being equigranular (½ to 1 mm) granofels consisting of more than 60 percent quartz plus plagioclase (mostly labradorite) and more than 25 percent mafic and calc-silicate minerals (biotite, hornblende, diopside). Biotite is present in most layers (table 1, samples 2-7); hornblende or diopside is present in every layer, and many layers contain both black hornblende and pale-green diopside granules. Sphene, zircon, and apatite are common; pyrite or pyrrhotite, graphite, and magnetite are fairly common. Muscovite, calcite, chlorite, and pale-green amphibole are common alteration products of feldspar and mafic minerals.

The Tatnic Hill calc-silicate gneisses are interbedded with layers of dark-gray garnetiferous biotite-quartz-plagioclase gneiss (see outcrops in OL II, NW of Uncas Lake–Hog Pond on pl. 1) spotted with red garnet up to 1 in. in diameter. This gneiss is similar in appearance to the calc-silicate rocks except for the presence of garnet, a mineral rare in calc-silicate rock here. Both the calc-silicate gneiss and garnetiferous gneiss generally are interleaved with folia of white or pink pegmatite 1 to 5 cm thick, which further accentuate the well developed compositional layering of the metasedimentary rock.

BIOTITIC QUARTZ-PLAGIOCLASE GNEISS (Otg)

A biotitic quartz-plagioclase gneiss unit (Otg) that separates *Otc* from *Otm* is best exposed in the NW corner of OL II (fig. 3). This unit comprises light- to dark-gray biotitic gneisses and subordinate amphibolite. The biotitic gneisses (table 1, samples 8, 9) are equigranular (1 to 2 mm) rocks consisting of 70 to 85 percent quartz plus plagioclase and 15 to 30 percent biotite. They contain numerous folia of pink or white pegmatite and layers of black amphibolite 1 in. to 1 ft thick. The amphibolite generally occurs in boudins, some of them separated from one another by a distance of 1 ft or more.

BIOTITE-GARNET-SILLIMANITE SCHIST (Otm)

The lowest unit in the Tatnic Hill Formation, adjacent to the Monson Gneiss, is migmatitic biotite-garnet-sillimanite schist (Otm) seen only in isolated outcrops in OL I (fig. 3). These schists are coarse-grained (2 to 5 mm), strongly foliated rocks in which micaceous biotite-sillimanite-garnet folia (table 1, sample 11) are interleaved with quartz-feldspar folia (table 1, sample 10). Crystals of orthoclase and garnet up to 1 in. in diameter are common. Some outcrops of this migmatitic-schist unit contain thin beds of quartzite and amphibolite.

Brimfield Formation

NOMENCLATURE AND DISTRIBUTION

The Brimfield Formation separates the rocks of the Lyme dome from the rocks in the axial region of the Hunts Brook syncline. The Brimfield mapped here is continuous with units in the adjacent Essex and Hamburg quadrangles mapped as Brimfield (Lundgren, 1964, 1966a). The Brimfield is not well exposed; most of its known rock types may be seen in a small area in OL IV (fig. 3) on the north and south sides of the railroad tracks (NYNH&H RR). Excavations made south of the tracks demonstrate that outcrops of the Brimfield present a misleading picture of the formation, because the sillimanitic schists and amphibolite uncovered in these excavations are rarely seen in outcrop.

MIGMATITIC SCHIST AND GNEISS

The principal type of rock seen in most outcrops (fig. 3, OL IV) is a coarse-grained migmatitic biotite schist and gneiss (table 1, samples 12-14) in which large (2 to 3 cm) poikilitic red garnets are conspicuous. Biotitic folia contain 5 to 10 percent garnet in large crystals set in a matrix of 60 to 70 percent quartz plus plagioclase and 20 to 30 percent biotite. White quartz-feldspar folia spotted with red garnets are interleaved with the biotitic folia. In many outcrops of this rock more than half of the outcrop consists of quartz-feldspar folia (Lundgren, 1966b, p. 440).

These biotite schists and gneisses are interbedded with layers of highly sillimanitic migmatitic schist, well displayed only in excavations. These layers are very coarse-grained rocks consisting of schist folia intimately interleaved with granite folia (Lundgren, 1966b, p. 441); they are so friable that samples suitable for thin-sectioning are difficult to obtain. The schist folia consist of biotite (Z = moderate reddish brown), red garnet (2 to 4 cm), prismatic sillimanite, quartz and feldspars, and coarsely crystalline graphite and pyrite. The granite folia contain the same minerals but quartz and orthoclase are the major constituents.

AMPHIBOLITE

A single layer of diopsidic amphibolite is exposed in an excavation in OL IV (fig. 3). In outcrop it is banded with dusky yellow-green stripes of diopside-plagioclase (table 1, sample 15) interleaved with greenish-black bands of hornblende-diopside-plagioclase (table 1, sample 16). This banding is broken by patches of nonfoliated white and green rock consisting of plagioclase, large (2 to 6 cm) crystals of dusky yellowish-green diopside, and 10-mm crystals of sphene. These patches, which have a pegmatitic aspect, probably occupy the necked areas between boudins but the exposure is not sufficient to demonstrate this.

Ivoryton Group

DISTRIBUTION

The Ivoryton Group (Lundgren, 1966a) is represented here by the Monson Gneiss and the New London Gneiss; the Middletown Formation is not present. The units of the Ivoryton Group lie along opposed limbs of the Hunts Brook syncline (fig. 3, OL I, II); they are continuous with units mapped as Monson Gneiss and New London Gneiss in adjoining quadrangles (Lundgren, 1964, 1966a).

MONSON GNEISS

The Monson Gneiss comprises light- to dark-gray, medium-grained (1 to 3 mm) biotitic and hornblendic plagioclase-quartz gneisses and subordinate thin (1 in. to 1 ft thick) layers of black amphibolite and pink alaskite. The most common types of rock are well displayed in the Selden Neck dome (OL I, NW corner). Close to the contact with the Brimfield (or Tatnic Hill) Formation, the Monson appears in sharply banded outcrops in which gray gneiss, black amphibolite, and fine-grained pink alaskite are interleaved with one another. This type of outcrop is well exposed along the shore at Lord Cove, east of Mink Island (OL I). Modal analyses (table 2) demonstrate that the Monson Gneiss here, as in contiguous quadrangles, is essentially a plagioclase-quartz gneiss containing little or no K-feldspar. They also illustrate that the alaskite layers are modally distinct from the bulk of the Monson.

NEW LONDON GNEISS

A narrow (500 ft wide) band of New London Gneiss is mapped south of Uncas Lake (Hog Pond on pl. 1; in fig. 3, OL II). The New London Gneiss consists of light-gray to grayish-pink, quartz-feldspar gneisses, which are interleaved with black amphibolite and pink alaskite layers. The New London is not easily separated from the Monson here, as both units are thin and both contain layers of amphibolite and alaskite. The quartz-feldspar gneisses of the New London generally are finer grained than those of the Monson, and they contain more than 10 percent K-feldspar in contrast with the Monson. They commonly are spotted with red hematite patches, which rarely are seen in any rocks other than the New London here. Modal analyses (table 2) illustrate the principal characteristics of the New London gneisses and the differences between them and those of the Monson Gneiss.

Mamacoke Formation

A narrow (600 ft wide) belt of Mamacoke Formation (see Lundgren, 1966a) separates the Ivoryton Group from the Plainfield Formation in the Lyme dome. There are so few outcrops in this belt that no clear picture of the Mamacoke can be obtained here. The only outcrops display nodular quartz-plagioclase-microcline-biotite gneiss, so named because of the presence of ellipsoidal nodules of quartz-sillimanite aggregate, and gray quartz-biotite-plagioclase gneiss striped with pink granite. Presumably, the belt in which no outcrops occur is underlain by the non-resistant schists and calc-silicate rocks common in the Mamacoke in the Hamburg quadrangle (Lundgren, 1966a).

Table 2.—Modal analyses[1] of rocks in the Ivoryton Group

	Monson Gneiss[2]						New London Gneiss[2]	
Sample no.	1	2	3	4	5[3]	6[3]	7	8
Field no.	445	488	480	481	491	446	483	482
quartz	28.0	32.2	23.8	25.4	34.8	14.2	33.2	22.2
plagioclase	50.8	45.4	54.4	50.8	24.2	31.4	28.2	35.0
microcline	----	4.4	3.8	0.4	39.4	----	37.6	37.6
biotite[4]	6.4	11.0	9.0	21.2	0.6	----	x	4.1
hornblende[4]	13.8	6.2	7.4	0.6	----	51.6	----	----
opaque	0.8	0.6	1.6	0.4	0.6	0.8	0.8	1.0
other	0.2	0.2	x	1.2	0.4	1.8	x	x
% An	36	40	30	26	----	45	----	----
XN[5]	42.45	35.1	44.85	44.8	35.5	41.25	44.6	44.65
XE[5]	5.7	6.3	16.8	16.9	5.95	4.75	16.85	17.0

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[1] In volume percent; the symbol x indicates that volume percent of mineral is less than 0.1.

[2] Samples 1-6 are Monson; samples 7, 8 are New London.

[3] Sample 5 is from a fine-grained alaskite layer; sample 6 is from an amphibolite layer.

[4] Biotite color in samples 1-4: Z=5Y 3/2; hornblende color: Z=5GY 3/2.

[5] Sample-location coordinates: XN numbers are thousands of ft N of S boundary of quadrangle; XE numbers are thousands of ft E of W boundary of quadrangle.

Plainfield Formation

DISTRIBUTION

All the rocks other than granite that lie within the area in the Lyme dome outlined by the Mamacoke Formation are mapped as Plainfield Formation. The rocks so mapped may be separated into three major units (fig. 4), each including many of the types of rock found in the other two:

Upper unit:	*Quartzite* and schist; subordinate amphibolite, biotite-quartz-feldspar gneiss, nodular gneiss.
Middle unit:	*Sillimanite schist and gneiss;* subordinate amphibolite, nodular gneiss.
Lower unit:	*Quartz-feldspar gneiss;* subordinate sillimanite schist, amphibolite, quartzite, calc-silicate granofels.

The upper unit, in which most of the quartzite is found, is continuous with the Plainfield Formation mapped in the southeastern part of the Hamburg quadrangle (Lundgren, 1966a). The middle and lower units appear to occupy a lower stratigraphic position than most of the units included in the Plainfield Formation of the Hamburg quadrangle. Probably they are sufficiently distinct from the upper unit to allow separation from it and assignment of formation rank—this could be done, however, only if outcrops were clearer, metamorphic grade lower, and volume of discordant and concordant granite less.

UPPER UNIT

The upper unit contains most of the quartzites seen in the Old Lyme quadrangle; it is separated from the Mamacoke Formation by biotite granite gneiss and from the middle unit by alaskite. Although only the quartzites are even moderately well exposed, most of the other types of rock associated with them may be seen between Hart Hill and Cranberry Ledge (fig. 3, OL III), as indicated below.

Quartzite (pq). Vitreous, white to light-gray rocks spotted with 1-mm grains of pink feldspar and brown biotite. Quartz (85 to 95 percent) in 3- to 4-mm grains; plagioclase (0 to 10 percent) in 0.2- to 0.4-mm granules partially altered to muscovite; brown biotite (2 to 4 percent) largely altered to chlorite; and muscovite (generally, but perhaps not entirely, an obvious product of alteration of feldspar) present in all samples.

Amphibolite. Grayish-black layers interbedded with quartzite and gneiss south of Hart Hill. Equigranular mosaic of hornblende (Z = dark yellowish green, 10GY 4/4; Y = moderate olive brown, 5Y 4/4) and plagioclase (labradorite) with minor reddish-brown biotite and magnetite-ilmenite.

Quartz-feldspar gneiss. Well foliated, quartz-feldspar rocks with biotite and garnet or biotite and hornblende as the principal other minerals.

Nodular gneiss (pn). Granular rocks consisting of quartz and orthoclase (with or without plagioclase) spotted with lenses and ellipsoidal nodules of quartz laced with sillimanite (E of Quarry Hill, OL I).

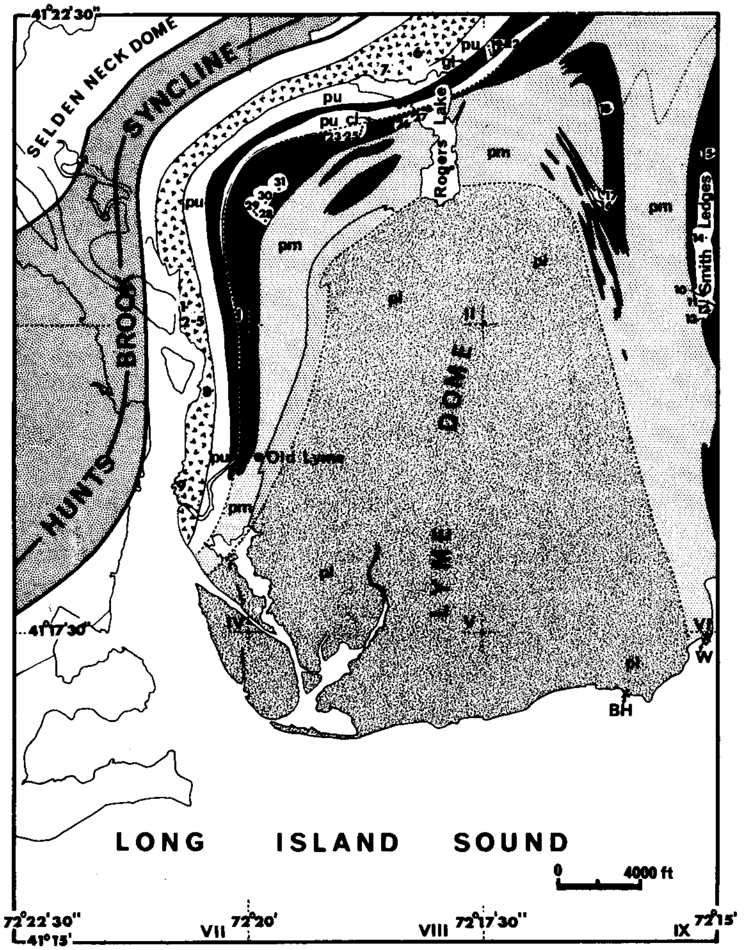

Fig. 4. Distribution of major units in the Plainfield formation together with the major types of granite. Upper, middle, and lower units of the Plainfield are designated by letter symbols *pu*, *pm*, and *pl*. Solid black indicates alaskite units of the Sterling; checked pattern indicates biotite granite gneiss unit. Numerals 1-27 indicate locations of modally analyzed samples (fig. 5). *BH* = exceptional exposure of Black Hall-type granite; *W* = exposures of Westerly type. Black Hall type present in all exposures in area mapped as lower Plainfield (pl); *cl* = Cranberry Ledge; *gl* = Game Ledge.

MIDDLE UNIT

The middle unit apparently is largely sillimanite schist and gneiss. It is not well exposed; its inferred position is marked by prominent belts of lowland flanking Lieutenant and Four Mile Rivers. Most outcrops of the middle unit occur where resistant granite layers crop out, particularly in the area in OL III and VI (fig. 3) north and south of U.S. Route 1. The layers of granite gneiss, granite pegmatite, and nodular granite form narrow ridges from which the sillimanite-rich schists have been stripped away by erosion (E and W sides of U.S. Route 1, OL III). Somewhat more resistant quartz-rich sillimanitic gneisses are moderately well displayed (OL III) in Stone Ranch Military Reservation (Camp Dempsey). Thin, discontinuous mafic amphibolite beds and quartzite lenses occur in isolated outcrops.

Sillimanite schists. Coarse-grained, friable, biotite-garnet-sillimanite schists coated with dark yellowish-orange or grayish-yellow stain. Garnets large (5 to 10 mm) and sieve-textured; sillimanite generally conspicuous in sheaves of silky white prisms. Schists are migmatitic and extremely heterogeneous; orthoclase-rich granitic folia common (table 3, sample 1).

Quartz-rich sillimanite gneisses. Medium-gray, generally equigranular, medium-grained (1 to 2 mm), quartz-rich rocks containing plagioclase and generally subordinate potassium feldspar. Sillimanite conspicuous on biotite-coated foliation surfaces; also present but not conspicuous in the granular quartz-feldspar rock. Garnets relatively rare; magnetite conspicuous in some samples. Quartz-sillimanite nodules present in some outcrops. Kyanite a rare accessory mineral (table 3, samples 3, 4).

LOWER UNIT

The rocks that occupy the core of the Lyme dome are treated here as the lower unit of the Plainfield Formation. These rocks are so pervasively migmatitic and so extensively disrupted by younger granites that the nature of their pre-metamorphic antecedents is even more obscure than that of most of the other stratigraphic units. The basis for this statement may be seen in every cut along the Connecticut Turnpike east of the Connecticut River and in the fine exposures along the coast, particularly at Point O'Woods and Old Lyme Shores (fig. 3, OL IX; frontispiece).

The major part of the lower unit consists of medium- to coarse-grained, gray, quartz-feldspar gneisses veined with pink and white granite. These gneisses are interleaved with layers of all the different types of rock described for the middle and upper units. These other types appear to be subordinate to the quartz-feldspar gneisses, occurring as thin and discontinuous layers in them. The lower unit may well include gneissic rocks that are metamorphosed intrusives, and it might be viewed by many geologists as "basement complex." The major rock types present in the lower unit are described separately:

Biotitic quartz-feldspar gneisses. At least half of the lower unit consists of light- to medium-gray, moderately well foliated, biotitic quartz-feldspar gneisses. Most of these gneisses have the following modal characteristics: Feldspar (40 to 60 percent) is about twice as abundant as quartz (20 to 40 percent) in modes of most samples (table 3, samples 5 to 12); biotite (10 to 20 percent) is the principal mafic mineral, and garnet (1 to 2 percent) and magnetite (1 to 2 percent) minor mafic minerals.

The principal mineralogic differences among the various outcrops of gray biotitic gneiss lie in the ratio of plagioclase to K-feldspar. Table 3 shows that some samples are plagioclase gneisses (samples 5 to 8) and others are microcline-plagioclase gneisses (samples 9 to 12). These cannot be distinguished satisfactorily in most outcrops. All are veined with pegmatite that contains much microcline, but the modally analyzed areas of each section were located so as to exclude pegmatite folia. Representative exposures may be seen at the following localities: Connecticut Turnpike—all cuts between Interchange 71 (fig. 3, OL VI) and a point 15,500 ft (measured along the turnpike) west of Interchange 71; NYNHH railroad cut west of BM 42 (OL VI); Old Lyme Shores (OL IX; see frontispiece).

Hornblendic quartz-feldspar gneisses. Medium-gray quartz-feldspar gneiss containing hornblende is also an important part of the lower unit. Much of the hornblendic gneiss is more nearly massive than the biotitic gneiss, and much of it may be metamorphosed intrusive rock. The hornblendic gneisses (table 3, samples 14, 15) are medium-grained (2 to 3 cm) rocks consisting of abundant plagioclase (40 to 50 percent), quartz (20 to 30 percent), microcline (3 to 7 percent), hornblende (10 percent), biotite (15 percent), and magnetite (1 percent). Representative exposures may be seen in the gravel pits south of the Connecticut Turnpike at Sawmill River (fig. 3, OL V); it is also present in some cuts cited in the preceding paragraph.

Other rock units. Each rock type described from the middle and upper units is present in the lower unit. The sillimanite and garnet schists and gneisses (table 3, samples 2, 8, 9), comparable to those described for the middle unit, are well exposed at the following localities: area around hill 198 in the SW corner of OL III (fig. 3), NW corner of OL VI, N of the power-transmission line and E of trail, and on the minor promontory W of Hatchett Point (OL IX).

Amphibolite appears to be separable into two types, one a "normal" amphibolite consisting of 50 percent hornblende ($Z = 5GY\ 3/2$), 40 percent plagioclase (An 65), and quartz, sphene, and magnetite; the other black, relatively massive rock consisting of hornblende ($Z = 5G\ 5/2$) (table 3, sample 17). Both types are exposed at the turnpike cut 3,000 ft west of Interchange 71. Amphibolite is also well exposed at Old Lyme Shores where it occurs in well developed boudins in migmatitic gray biotite gneiss (frontispiece). The boudins are rimmed with garnetiferous amphibolite or biotitic amphibolite. Broken folded masses of amphibolite may also be seen at the shore west of Hatchett Point.

Calc-silicate layers appear as lenses or broken layers of tough granofels of variable mineralogy. They are composed of quartz, plagioclase, and one or more of the following: hornblende, diopside, garnet, sphene (table 3, sample 16).

Table 3.—Modal analyses[1] of rocks in the Plainfield Formation[2]

	ps	pg	ps	ps	pg	pg	pg	pg	pg
Sample no.	1	2	3	4	5	6	7	8	9
Field no.	L175	L457	L436	L437	L464	L163	L450	L114	L127
quartz	18.0	33.4	68.2	67.8	27.6	30.6	35.6	20.6	34.6
plagioclase	17.3	11.6	20.4	18.4	59.8	49.8	46.2	47.0	34.8
microcline	17.3	9.5	3.2	1.4	1.2	1.4	----	----	18.0
biotite	34.3	28.4	8.2	11.0	9.2	15.6	17.2	31.8	12.0
hornblende	----	----	----	----	----	----	----	----	----
garnet	5.0	0.5	0.2	x	x	x	----	x	----
sillimanite	7.5	8.5	x	1.2	----	----	----	----	----
opaque	----	3.6	x	0.2	1.2	0.8	1.0	0.6	0.4
other	0.7	x	x	x	x	1.8	x	x	0.4
% An	----	----	----	----	32	----	38	36	----
XN[3]	30.3	12.3	37.9	38.8	25.85	----	25.05	24.15	13.3
XE[3]	29.95	18.2	27.6	27.6	16.2	----	19.25	23.6	19.1

[1] In volume percent; the symbol x indicates that volume percent of mineral is less than 0.1.

[2] Map symbols *ps* and *pg* are those of the map units (pl. 1) from which the analyzed samples were taken. An analyzed sample is not necessarily a sample of the principal or characteristic type of rock in its map unit—sample 22, for example, is from a schist layer in quartz-feldspar gneiss.

[3] Sample-location coordinates: XN numbers are thousands of ft N of S boundary of quadrangle; XE numbers are thousands of ft E of W boundary of quadrangle.

Sterling Plutonic Group

NOMENCLATURE

The rocks mapped as parts of the Sterling Plutonic Group are foliated granites within the Plainfield and Mamacoke Formations. Goldsmith (1966, p. 7) introduced the term Sterling Plutonic Group (see Lundgren, 1966a, p. 28) for the foliated granitic rocks in folded, apparently tabular masses more or less concordant with the structure of the adjacent rocks of the Plainfield and Mamacoke Formations. This is a useful term which applies to all the granites originally designated as Sterling Granite Gneiss (Rice and Gregory, 1906; Loughlin, 1910) except the younger granites (for example, Westerly granite), which are much younger than the foliated granites, as recognized long ago by Hawkins (1918). The term Lyme granite gneiss (Rice and Gregory, 1906, p. 149) is not used here as the Lyme is part of the Sterling.

pg	pg	ps	pg	pg	pg	pg	pg	pg	pg	
10	11	12	13	14	15	16	17	18	19	Sample no.
L461	L441	L473	L116	L170	L62	L111	L171	L78	L463	Field no.
26.6	39.8	29.2	18.2	20.4	28.0	39.2	2.0	29.4	29.8	quartz
44.6	26.8	30.2	48.0	45.0	44.2	53.6	5.0	26.2	36.6	plagioclase
17.6	17.6	26.2	15.6	6.8	3.6	----	----	0.8	4.4	microcline
9.8	12.8	11.8	17.0	15.0	14.2	----	2.5	25.8	26.8	biotite
----	----	----	----	11.2	8.2	4.2	90.0	----	----	hornblende
----	2.8	2.4	----	----	----	2.6	----	16.6	1.6	garnet
----	----	----	----	----	----	----	----	----	x	sillimanite
0.8	x	0.2	0.6	0.8	1.0	0.2	x	1.2	0.8	opaque
0.6	0.2	x	0.6	0.8	0.8	0.2	0.5	x	x	other
----	30	30	----	40	----	55	----	----	----	% An
26.55	15.65	25.3	25.7	24.45	20.35	24.3	26.8	25.55	26.25	XN^3
13.65	29.1	28.85	31.65	21.1	14.0	24.8	29.55	15.2	14.8	XE^3

BIOTITE GRANITE GNEISS (sgb)

A narrow belt of coarse-grained biotite granite gneiss, prominently displayed at Becket Hill (fig. 3, OL II) and Quarry Hill (OL I, IV; fig. 4), is mapped as (sgb) because it is continuous with granite mapped as *sgb* in the Hamburg quadrangle. This granite gneiss lies between the Mamacoke Formation and the Plainfield Formation and is interleaved with layers of Plainfeld. It does not crop out west of the Connecticut River in the Old Lyme quadrangle, but certainly extends west of the river to meet the unit mapped as Clinton granite gneiss in the Essex quadrangle (Lundgren, 1964, p. 17). Other belts of rock shown as *sgb* are similar to the Becket Hill-Quarry Hill belt on which the following description is based.

The bulk of the biotite granite gneiss is coarse-grained (3 to 5 mm), well foliated, orange-pink to yellowish-gray gneiss consisting of quartz (30 to 40 percent), feldspar (55 to 65 percent), and biotite plus hornblende (5 to 10 percent). Biotitic folia and flat grains of pink microcline and gray quartz are oriented parallel to one another; the resulting foliation locally is accentuated by layers of amphibolite or gray, biotitic gneiss. Microcline is more abundant than plagioclase in virtually all the samples (fig. 5, samples 1 to 9); the microcline-plagioclase ratio generally is greater than 3/2. All microcline is well twinned and microperthitic; plagioclase is well twinned oligoclase, myrmekitic (displaying quartz-plagioclase intergrowth) where in contact with microcline. Biotite (Z = dusky yellowish brown 10YR 2/2) is the principal mafic mineral in most samples; small dark-red garnets are common. Hornblende (Z = grayish olive green 5GY 3/2; Y = grayish olive 10Y 4/2) is present in belts of granite that contain 3 to 5 percent hornblende and subordinate biotite. Hornblende granite contains conspicuous zircon, apatite, allanite, and magnetite, and commonly is marked with red hematite spots.

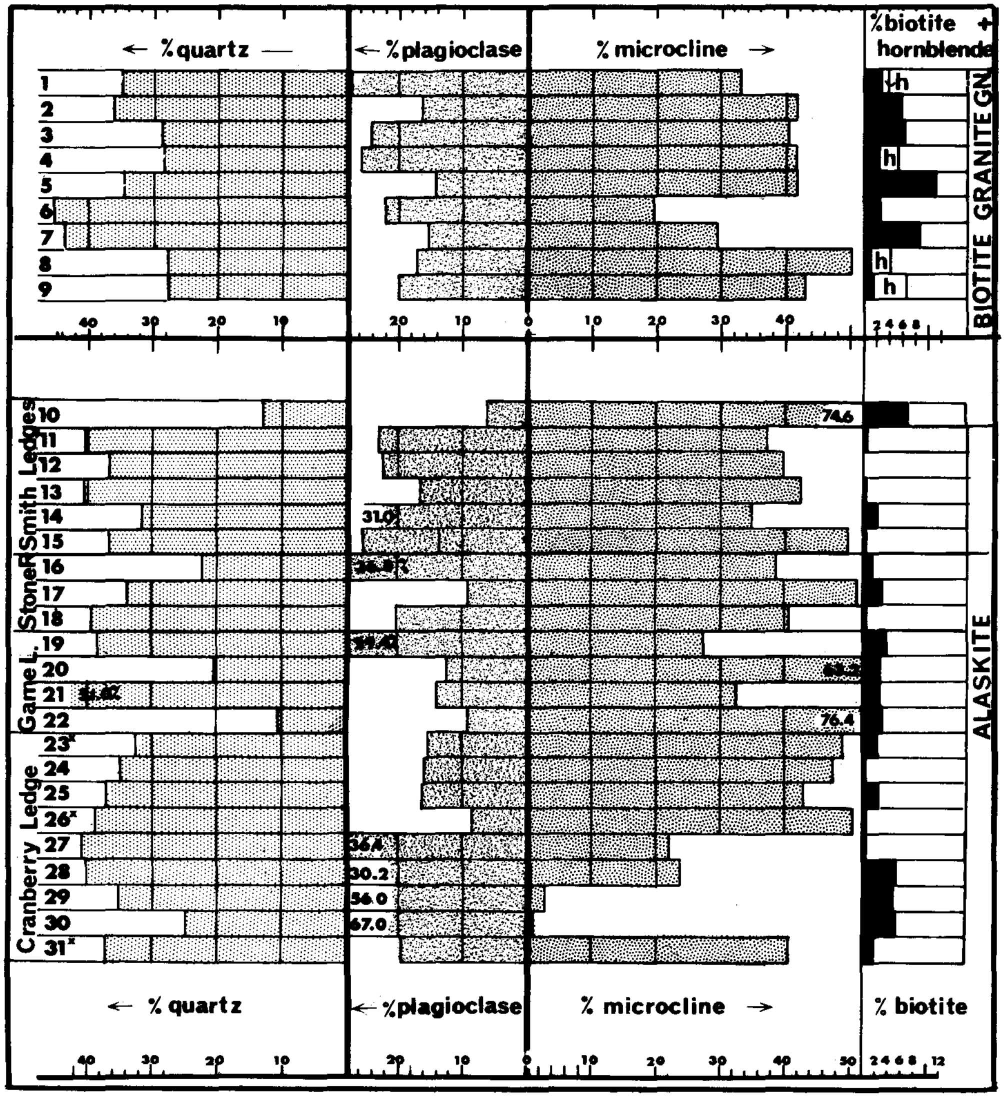

Fig. 5. Modal analyses of rocks in the Sterling Plutonic Group (see fig. 4 for locations).

ALASKITE

Within the Lyme dome, in the area bordered by the belt of biotite granite gneiss, weakly foliated alaskite is of major importance. The alaskite occurs in layers that form map patterns similar to those of the adjacent metasedimentary units. The thickest layers can be traced for miles along strike, as they form prominent ridges on which the alaskite is exposed in extensive outcrops. These ridges commonly are marked by cliff exposures on the side of the ridge closer to the axis of the Lyme dome. The smaller layers occur as lenses interleaved with a variety of rocks.

All of the alaskite masses have the following characteristics in common: They are orange-pink to grayish-orange, relatively equigranular, medium-grained (1 to 4 mm) aggregates of quartz, microcline microperthite, and plagioclase (generally An 20-25; less commonly An 12-20) containing less than 2 percent biotite and approximately 1 percent magnetite and a trace of garnet. Feldspars constitute more than 50 percent in each modal analysis (fig. 5); microcline generally is the more abundant feldspar. Hand specimens (3 × 4 in.) generally appear to be homogeneous and display only a weakly developed foliation; outcrops are less uniform, and foliation generally is evident, as marked by the parallel orientation of biotite flakes, quartz folia, and folia distinguished on the basis of grain size, modal composition, or both. Some of the major masses of alaskite are briefly described below, and modal analyses are presented in figure 5 to illustrate the variability in single masses of alaskite and the similarity of each mass to the others.

The *Smith Ledge belt* of alaskite is displayed along the eastern edge of the quadrangle. It is separated from other alaskite belts by sillimanite schists of the Plainfield Formation. Alaskite in this belt occurs in cliffs and rounded outcrops displaying weakly foliated to nearly massive, grayish-orange (10YR 7/4) rock consisting of quartz, feldspar, and 1 to 2 percent biotite. Many outcrops are stained a deeper moderate-reddish orange by iron oxides that appear in thin section as coatings along grain boundaries and cleavage cracks. Although most outcrops appear to be mineralogically uniform, modal analyses (fig. 5, samples 10 to 15) illustrate that some of the rock (samples 10, 15) is extremely rich in microcline. Foliation is well developed only near the contact between alaskite and the biotitic gneisses of the Plainfield, where alaskite folia are interleaved with folia of the gneisses to form a mixed rock. As the Smith Ledge belt is traced south into the Niantic quadrangle this type of mixed rock increases in importance.

The *Game Ledge belt* of alaskite forms a prominent ridge adjacent to a quartzite unit in the Plainfield Formation. This ridge extends from Game Ledge (fig. 3, OL III; fig. 5) across Rogers Lake and Hart Hill west to Rt. 156 (OL I); the alaskite forms a prominent ridge parallel with and adjacent to Rt. 156. Throughout its extent the ridge appears to be bordered by quartzite on one side and separated from the next belt of alaskite (Cranberry Ledge belt) by a thin metasedimentary unit consisting of garnetiferous biotite gneiss, amphibolite, and quartzite. The least biotitic alaskite is found next to the overlying quartzite; the most biotitic next to the underlying gneisses. Alaskite in this belt is medium-grained, weakly foliated to massive rock. Most samples are moderate orange pink to grayish orange pink although commonly stained moderate reddish orange on weathered surfaces. More than half the outcrops appear to contain less than 2 percent biotite; the remainder carry from 2 to 4 percent. The modal characteristics (fig. 5, samples 19-22) of rocks in this belt are similar to those in the Smith Ledge belt.

The *Cranberry Ledge belt* of alaskite forms a prominent ridge extending WSW from Cranberry Ledge to Myer Hill, SW across Saunders Hollow Road and S from there along Lieutenant River. The NE extension of this belt past Rogers Lake is less clearly marked, as the alaskite is mixed with other rocks and is difficult to map separately. This belt is the best exposed of all the alaskite masses, particularly at Cranberry Ledge and in broad bedrock slopes and cliffs between Town Woods Road and Saunders Hollow Road. These broad exposures illustrate the generally massive character of the alaskite and its apparent uniformity. Rocks from all these exposures appear similar except for slight differences in color and biotite content. However, modal analyses (fig. 5, samples 23-31) illustrate that part of the rock is plagioclase-quartz rock quite different from the typical alaskite. The plagioclase-quartz rock (fig. 5, samples 29, 30) is more biotitic than the typical alaskite such as samples 24 and 25 and is grayer; it may represent a layer of Plainfield Formation. It cannot be separated from typical alaskite in the field, however—it appears not to be a distinct layer in the alaskite but rather a "facies" of the alaskite.

The best exposed of the smaller masses of alaskite are those interleaved with sillimanite schist of the middle Plainfield in or near Stone Ranch Military Reservation (fig. 3, OL III and IV) on both sides of U.S. Rt. 1 (Post Road). These masses form narrow ridges that commonly are capped by pegmatite; they can be mapped readily because the schist is so much less resistant to erosion than is alaskite. Most of the alaskite in these ridges is more distinctly foliated and contains more garnet and sillimanite than those described above. Sillimanite is common in alaskite near contacts with sillimanite schist, and many masses of alaskitelike rock contain nodules of quartz-sillimanite aggregate that stand out in relief on outcrop surfaces. However, the modal analyses (fig. 5, samples 16-18) do not differ significantly from the bulk of the typical alaskites in other belts. Where alaskite and biotitic alaskite are interleaved with gray quartz-feldspar gneisses which are as resistant to erosion as the alaskite, then it is not possible to separate the two units on the map. These belts are shown as *sgm* to indicate that they appear to represent admixtures of granitic rock like that described above together with quartz-feldspar gneisses of the Plainfield Formation.

Younger granites and pegmatites

NOMENCLATURE

The Old Lyme quadrangle is notable for the extensive development of granite and pegmatitic granite that are structurally discordant and definitely younger than the folding and metamorphism, and younger than the foliated granites of the Sterling Group. These discordant granites mav be separated into two types that may, in fact, be merely different facies of intrusive granite emplaced after the completion of folding and metamorphism. One is designated here as Westerly type, after the Westerly granite of Emerson (1917, p. 230-231) of Westerly, Rhode Island. The second is here named informally Black Hall type for its occurrence in the MacCurdy Quarry near Black Hall (fig. 3, OL V)—it was first described by Kemp (1899, p. 366) and more completely by Dale and Gregory (1911, p. 100-102). Neither type forms individual masses large enough to be shown on the map (pl. 1). However, the central part of the Lyme dome is extensively transected by Black Hall type, and the granite probably occupies 25 percent of the area mapped as lower Plainfield.

WESTERLY TYPE

Narrow, discordant dikes of fine-grained granite are well exposed at Point O'Woods (fig. 3, OL IX, VI) but have not been seen elsewhere in the quadrangle. Most of the dikes are between 4 in. and 4 ft wide, but at least one is more than 25 ft wide. The contacts of most are not plane surfaces; the strike azimuth of those that are nearly planar appears to lie between 60° and 90°, and the dip of the contacts to be steeper than 70°S. These dikes cut all other rock units exposed in the quadrangle; they resemble most closely the pink variety of dike rock quarried at Millstone Point, Niantic quadrangle, which Kemp (1899, p. 366-367) and Dale and Gregory (1911, p. 110) equated with the Westerly granite of Westerly, Rhode Island. Therefore these dikes are regarded here as representatives of the westernmost occurrence of granite dikes comparable to those at Westerly (Lundgren, 1966c).

These dike rocks are fine-grained (½ to 1 mm grains) and equigranular, very pale-orange to moderate-orange-pink rocks spotted with red hematite patches. They are quartz-monzonites, Type II* granite in Chayes' (1957) classification, in which plagioclase and microcline are about equally abundant, and they are modally similar to the Westerly granite (table 4, samples 1, 2). Plagioclase is oligoclase, extensively altered to muscovite; microcline is moderately well twinned but not visibly perthitic. Neither feldspar displays crystal faces generally. Micrographic intergrowths of microcline and quartz are evident in thin section, and large (6 to 12 in.) crystals of microcline with quartz (graphic granite) surrounded by fine-grained granite are seen in outcrop. Biotite (Z = moderate to light olive brown, 5Y 4/4 to 5Y 5/6) is largely altered to chlorite. Muscovite occurs in flakes 1 to 2 mm across and in smaller grains as alteration products of plagioclase and microcline. Zircon, magnetite, hematite, and apatite are the principal accessory minerals.

Some of the dikes display cavities lined with euhedral quartz and muscovite, and boulders and fragments of similar rock have been seen in which the cavities contain euhedral feldspar and hematite crystals as well. The rocks containing these cavities are richer than normal in microcline, they do not contain biotite, and muscovite is conspicuous (table 4, sample 3).

Table 4.—Modal analyses[1] of Westerly-type granite

No.	Field no.	quartz	plagioclase	microcline	biotite	muscovite	opaque
1	429.1	31.0	30.4	32.2	5.2	1.0	0.2
2	----[2]	27.8	32.9	32.7	3.7	1.9	1.0
3	428	26.0	27.2	41.8	----	3.8	1.2

[1] In volume percent; volume percent of all minerals except those listed in the table is less than 0.1.

[2] Average of 16 thin sections of Westerly granite (Chayes, 1950, p. 384).

BLACK HALL TYPE

This is a pegmatitic biotite granite described briefly by Kemp (1899, p. 366, 374) as the Lyme pink, on the basis of exposures in quarries in Old Lyme and South Lyme (Niantic quadrangle). The MacCurdy Quarry in Old Lyme, near Black Hall, was described in more detail by Dale and Gregory (1911, p. 100-102). This quarry is now overgrown, and much better exposures may be seen along the coast, notably at a small promontory west of Hatchett Point (fig. 3, OL IX) or along the Connecticut Turnpike. The rock was used for breakwaters at Old Lyme Shores (OL IX) and Rocky Neck State Park (Niantic quadrangle); these breakwaters provide an excellent display of the essential character of this rock.

The Black Hall type of granite displays an extreme range of grain size, texture, and relationships with the metasedimentary units and older granites, so that no written description is entirely satisfactory. The most distinctive type of rock, which is regarded here as characteristic Black Hall type, is the one figured by Kemp (1899, pl. 41, fig. 1). It occurs in discordant dikes that cut all the fold structures cleanly. The most discordant parts of these dikes are aligned E-W and dip steeply, but they merge with rock that displays irregular but discordant contacts with the adjacent Plainfield. This variety is massive, exceptionally coarse-grained rock, moderate orange pink (10R 7/4) except for patches of white feldspar, gray quartz, and black biotite. The biotite commonly is in randomly oriented laths up to 1 ft long; they give the rock its most easily recognized attribute (see Kemp, 1899, pl. 41). Pink microcline, partly in distinct crystals up to 1 ft in maximum diameter, appears to be the dominant mineral. Many of the microcline crystals are intergrown with quartz. Quartz and plagioclase appear to be subordinate to microcline; they occur interstitial to or intergrown with larger microcline crystals.

The coarsest facies grades into fine-grained granite within the area of single outcrops (shoreline outcrops west of Hatchett Point, fig. 3, OL IX). These outcrops suggest that the Black Hall type and the Westerly type are genetically related variants of a single intrusive granite. They do not appear to be genetically related to the Sterling granites, as Loughlin (1910) had inferred, because they cut the foliated granites, they do not contain garnet (as do the foliated granites), and, unlike the foliated granites, they contain graphic granite. A detailed study of some concordant masses of alaskite in the middle Plainfield unit, containing cavities lined with feldspar and quartz, might show that they actually are variants of the younger granites and differ from the bulk of the Sterling alaskite.

STRUCTURAL GEOLOGY

The dominant structural feature in the quadrangle is the Lyme dome (pl. 1; fig. 3), which is outlined by the contact between the Brimfield Formation and the Monson Gneiss. The broad internal structure of the dome is indicated by the pattern of the middle unit of the Plainfield Formation and the alaskite units (fig. 4) and by the foliation pattern (pl. 1). The distribution of stratigraphic units demonstrates that the dome is a NE-plunging anticline having an axial surface that trends N-S except in OL III (fig. 3) where it trends NE. The trend of the axial surface south of the coast line may be nearly E-W as suggested by the E-W trend of the Plainfield Formation west of the Connecticut River in OL VII. The Plainfield and overlying units trend west across the Essex quadrangle (Lundgren, 1964) into the Clinton and Killingworth domes. The southern portion of those domes, like the Lyme dome, are hidden beneath Long Island Sound. These relationships suggest that the Lyme dome and the Clinton dome are linked by an E-W anticline lying beneath Long Island Sound.

The Lyme dome thus has the appearance of a relatively simple anticline developed in a normal sequence of stratigraphic units. However, the dome is surrounded or mantled by a folded isoclinal syncline, the Hunts Brook syncline (Goldsmith, 1961; Lundgren, 1966a), developed in the younger stratigraphic units. Only a small segment of this syncline is exposed in the Old Lyme quadrangle. Work in adjacent quadrangles by Goldsmith (1961) and Lundgren (1966a, fig. 3) has shown that the axial surface of the Hunts Brook syncline is folded around the Lyme dome, so that this surface has the same anticlinal form as each of the stratigraphic units. The existence of this major folded fold suggests the possibility that units within the Lyme dome also occur in major folded folds, as yet unrecognized. Small isoclinal folds having amplitudes as large as 10 ft are evident in large outcrops (fig. 6) within the dome, and it is therefore evident that larger isoclines may be present. This possibility must be kept in mind in evaluating the inference that the rocks in the core of the Lyme dome are the oldest rocks in eastern Connecticut, an inference that might not be valid if it were to be shown that rocks in the dome are not in normal stratigraphic order.

Small-scale folds and mineral lineations are not particularly well developed in the Old Lyme quadrangle in comparison with their development in the Hamburg or Deep River quadrangles. This is at least partly determined by the smaller area of outcrop of units such as the Hebron Formation in which small folds are particularly well displayed. It is also determined by the high grade of metamorphism, as the pervasively migmatitic rocks commonly display irregular folds and crenulations (see frontispiece), but folds developed prior to the formation of the mig-

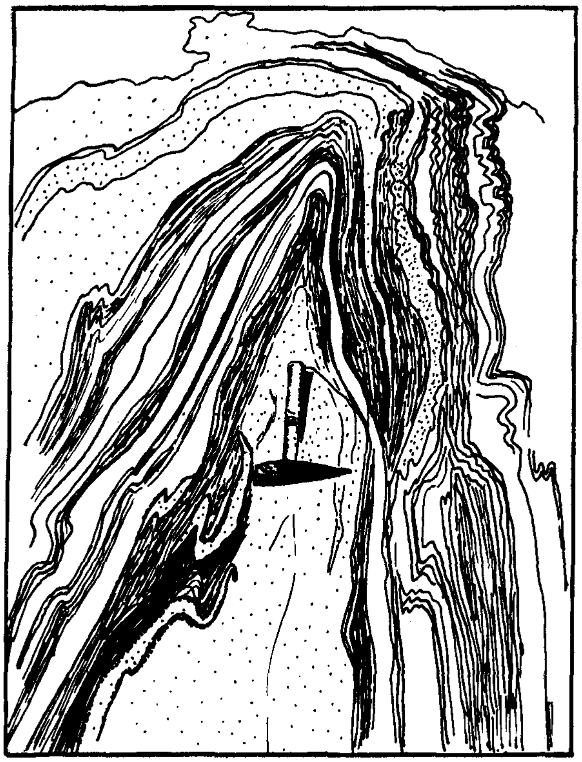

Fig. 6. Isoclinal fold in Plainfield Formation; Point O'Woods (fig. 3, OL VI).

matites apparently have been obscured or obliterated. Careful structural studies would be required to distinguish and recognize minor folds older than the crenulations developed during and after migmatite formation; no such work has been done to date.

Joints were not studied systematically. It appears, however, that joints are best developed in the granites of the Sterling Plutonic Group, and that the best developed set of joints includes clean, nearly vertical joints having a strike azimuth lying between 20° and 340°. Another relatively prominent set includes steeply dipping joints having strike azimuth between 80° and 100°. These E-W joints commonly are filled with pegmatite and granite (fig. 7), in contrast with the N-S joints, which generally are not filled.

BEDROCK CONTROL OF TOPOGRAPHY

The topography of the Old Lyme quadrangle, like that of the Hamburg quadrangle to the north (Lundgren, 1966a, p. 38-39) has a rather

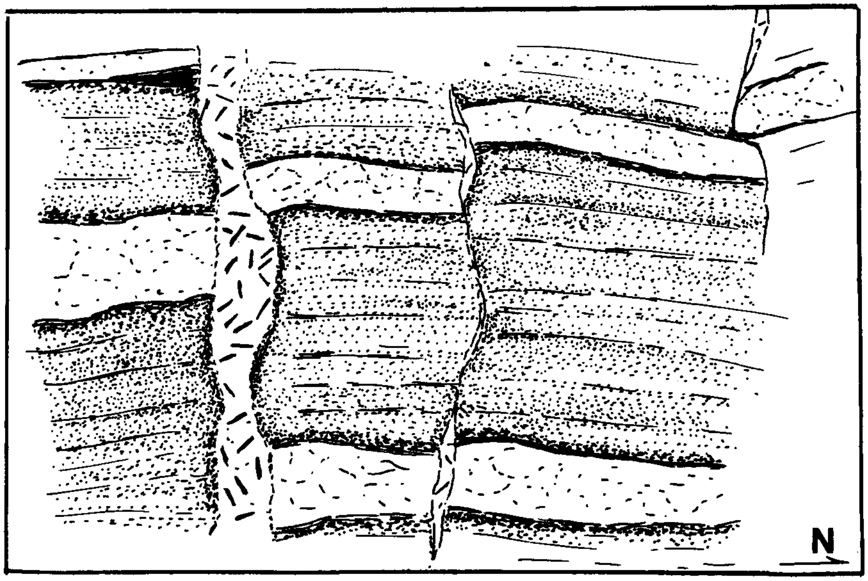

Fig. 7. Pegmatite-filled minor faults in migmatitic Monson Gneiss on the shore of the Connecticut River at Lord Cove, 34,900 ft north of southern boundary of quadrangle and 6,150 ft east of western boundary of quadrangle.

fine texture, clearly determined by the distribution of bedrock units and the development of joints in these units. Only at the mouth of the Connecticut River is the topography determined more by the distribution of Pleistocene and Recent deposits of unconsolidated sediment than by the distribution of bedrock units.

The superimposed topographic and bedrock geologic maps of plate 1 illustrate that the principal ridges are developed on granites of the Sterling Plutonic Group and that the local relief is greatest where these granites are bordered by schists of the Plainfield Formation (e.g., Smith Ledges, fig. 3, OL III). Furthermore, these maps illustrate that the local relief is greatest where steeply dipping units trend north-south (e.g., OL II, V, west of Lieutenant River). Much of the topography within the Lyme dome (OL V) illustrates this relationship on a small scale, as narrow ridges of granite and gneiss are separated by narrow, steep-walled valleys from which friable schist has been almost completely removed.

Although the distribution of bedrock units is the primary control of topography, some of the local details in the topography reflect the presence of relatively well developed sets of joints, particularly in the granites. The topography in OL II, for example, clearly reflects the NE trend of rock units and the presence of well developed, nearly vertical joints that strike N or NNW. Locally, steeply dipping E-W joints are sufficiently well developed to be reflected in the topography, but their effect appears to be relatively minor.

All the relationships described above suggest that the relief on the buried bedrock surface may be as much as 100 ft or more beneath the surface of the valleys such as those of Lieutenant and Fourmile Rivers.

ECONOMIC GEOLOGY

The only bedrock units to have been of economic importance in the past are the biotite granite gneisses of the Sterling Plutonic Group and the Black Hall-type granite. The biotite granite gneisses were once quarried at several sites on Quarry Hill (fig. 3, OL I, IV); the Black Hall-type granite was quarried in the 19th century at the MacCurdy Quarry (Dale and Gregory, 1911, p. 100-101). Here, as in the Hamburg quadrangle (Lundgren, 1966a), the granites of the Sterling Plutonic Group constitute a potential source of sized aggregate.

Perhaps of greater, if less obvious, economic importance is the observation that the topography reflects the distribution of bedrock units. Although the exposed bedrock is largely resistant granite and gneiss, it is clear that much of the quadrangle is underlain by extremely friable schists and that one should assume that each linear valley is underlain by such rock until drilling proves otherwise. Thus any tunnels or deep bedrock excavations presumably would have to be lined, as the sillimanite-biotite schists have little strength as compared with the granites and gneisses.

GEOLOGIC EVENTS

The Old Lyme Quadrangle displays what may be the oldest rocks (Cambrian or Precambrian lower Plainfield) and the youngest granites (post-Pennsylvanian (?) Westerly type). Thus, the rocks exposed here might be expected to provide clues to the entire Paleozoic history of this area. However, the major metamorphic event so profoundly affected most units that the nature of the antecedents of the metamorphic rocks and of the sequence of older events affecting these rocks are obscured. Because of this, no attempt is made here to outline systematically the mutual relationships among inferred metamorphic, intrusive, and structural events. Some of the most clearly recognizable events are named and the inferred relative or absolute age indicated.

The most recent intrusive events include the emplacement of granitic melt in steeply dipping E-W fractures to form Westerly-type granite and Black Hall-type granite. These events are regarded as Pennsylvanian or Permian, because these granites probably are equivalents of the Westerly and Narragansett Pier granites of SW Rhode Island, which are definitely post-Middle Pennsylvanian (Quinn and others, 1957) and probably post-Pennsylvanian (Hurley and others, 1960). They are also regarded as events postdating the folding and regional metamorphism, because the younger granites transect all visible fold structures and all foliated structures in the migmatitic rocks (fig. 7). Any other intrusive events, including the emplacement of possibly intrusive parts of the Sterling Group, the Ivoryton Group, and the lower Plainfield were contemporaneous with, or older than, the major metamorphism and folding, as all other granitic rocks are foliated and folded in concordance with the metasedimentary units (frontispiece).

Evidence for two distinct metamorphic events can be recognized. The principal metamorphic event (Lundgren, 1966b) was one in which migmatites were formed and most of the present mineral assemblages developed. It took place at a temperature of more than 600° C, when all the rocks were at a depth of 20 km or more. During this metamorphism, muscovite and biotite reacted to eliminate muscovite from previously muscovitic rocks, the biotite in these rocks decreased, and sillimanite and garnet increased. Garnet was formed in a variety of rocks, including most of the foliated granites of the Sterling Group. At this time, many of the micaceous units were partially melted; granitic melt was injected into these and other units, and most stratigraphic units were converted into well foliated migmatitic gneisses in which sillimanite + orthoclase is a common mineral pair.

The other metamorphic event consisted of mineral reactions leading to the development of delicate microscopic intergrowths of biotite and quartz, biotite and feldspar, and plagioclase and quartz, and to the pseudomorphous replacement of garnet by biotite, quartz, and plagioclase. This is designated here as a *thermal event*; it postdates the major metamorphism and folding; it either antedated or was contemporaneous with the emplacement of Black Hall-type granite—evidence for it is present only in rocks in the Lyme dome that are transected by Black Hall granite. This thermal event may be equivalent to the Permian thermal event recognized by Zartman and others (1966) and by Faul and others (1963). It presumably resulted as the rocks were being uplifted, as it must have occurred at a pressure so low that garnet was unstable. If the thermal event is Permian or Late Pennsylvanian, then the regional metamorphism and concomitant deformation must be Middle Pennsylvanian or older. Zartman and others (1966) have held that the major regional event that affected rocks now exposed north of 41° 30′ N lat in eastern Connecticut was Devonian. However, there is no direct evidence in the coastal rocks to indicate that the metamorphism of the coastal rocks was necessarily Devonian (Lundgren, 1966c).

Few of the temporal relationships between any one structural event and other structural, metamorphic, or intrusive events can be inferred with confidence. The development of the major folds may have been accomplished in several discrete stages beginning with the formation of a recumbent syncline (Hunts Brook syncline), culminating with the refolding of the Hunts Brook syncline as a consequence of the formation of the Lyme dome, and terminating with faulting, fracturing, and upwarping of the coastal rocks. The development of the Lyme dome is assumed to have been the last major folding event; the formation of the Hunts Brook syncline could be as recent as Devonian but as old as Upper Ordovician, as the youngest rocks included in it are Middle Ordovician (?).

All the events described above are more recent than the deposition of the sedimentary and volcanic parents or antecedents of the metamorphic rocks. As a consequence, the nature of the parent rocks is even more obscure than in most other areas in eastern Connecticut. However, the depositional history recorded here for the time period between the deposition of the Mamacoke Formation and the deposition of the Hebron

Formation is assumed to be similar to that inferred for the Hamburg quadrangle (Lundgren, 1966a, p. 39). Thus the Monson and New London are inferred to be metamorphosed andesitic and dacitic volcanics and associated intrusives, the Brimfield and Tatnic Hill to be metamorphosed shales in which thin carbonate units were present, and the calc-silicate gneisses of the Tatnic Hill and Hebron Formations to be metamorphosed carbonate-bearing siltstones.

The nature of the pre-metamorphic Plainfield and Mamacoke is largely obscure. The upper part of the Plainfield clearly consisted of interbedded shale and quartz-sandstone; such rock also constituted a minor part of the lower Plainfield. However, the bulk of the lower Plainfield is not clearly metasedimentary and may include both meta-volcanic and meta-intrusive units. These units probably were quartz-dioritic and granodioritic in composition, whether volcanic or intrusive.

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