Prepared in cooperation with the
State of Connecticut, Department of Environmental Protection,
Geological and Natural History Survey

Bedrock Geologic Map of the Old Lyme Quadrangle, New London and Middlesex Counties, Connecticut

By Gregory J. Walsh, Robert B. Scott, John N. Aleinikoff, and Thomas R. Armstrong

Pamphlet to accompany

Scientific Investigations Map 3052

Supersedes USGS Open-File Report 2006–1296

2009

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1–888–ASK–USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1–888–ASK–USGS

Cover: View across the Connecticut River looking southwest toward Saybrook Point from Great Island. Outcrop is biotite gneiss of the Old Lyme Gneiss. Photograph by Janet R. Stone.

Suggested citation:
Walsh, G.J., Scott, R.B., Aleinikoff, J.N., and Armstrong, T.R., 2009, Bedrock geologic map of the Old Lyme quadrangle, New London and Middlesex Counties, Connecticut: U.S. Geological Survey Scientific Investigations Map 3052, 2 sheets, scale 1:24,000, 25-p. text. (Supersedes USGS Open-File Report 2006–1296.)

Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)

Bedrock Geologic Map of the Old Lyme Quadrangle, New London and Middlesex Counties, Connecticut

By Gregory J. Walsh,[1] Robert B. Scott,[2] John N. Aleinikoff,[2] and Thomas R. Armstrong[3]

Introduction

The bedrock geology of the Old Lyme quadrangle consists of Neoproterozoic and Permian gneisses and granites of the Gander and Avalon terranes, Silurian metasedimentary rocks of the Merrimack terrane, and Silurian to Devonian metasedimentary rocks of uncertain origin. The Avalon terrane rocks crop out within the Selden Neck block, and the Gander terrane rocks crop out within the Lyme dome. The Silurian to Devonian rocks crop out between these two massifs.

Previous mapping in the Old Lyme quadrangle includes the work by Lundgren (1967). Lundgren's report provides an excellent resource for rock descriptions and detailed modal analyses of rock units that will not be duplicated in this current report. New research that was not covered in detail by Lundgren is the focus of this report and includes

- Evaluation of the rocks in the core of the Lyme dome in an effort to subdivide units in this area.
- Structural analysis of foliations and folds in and around the Lyme dome.
- Geochronology of selected units within the Lyme dome.
- Analysis of joints and the fracture properties of the rocks.

Mapping completed in adjacent or nearby areas includes the Hamburg quadrangle to the north (Lundgren, 1966a), the Niantic quadrangle to the east (Goldsmith, 1967a), the Essex quadrangle to the west (Lundgren, 1964; R.B. Scott, written commun., 2003), the Deep River quadrangle to the northwest (Lundgren, 1963), the Montville quadrangle to the northeast (Goldsmith, 1967b), and parts of the Deep River and Essex quadrangles (Wintsch, 1994).

The results of this report represent mapping by T.R. Armstrong in 2001 and by G.J. Walsh and R.B. Scott in 2002. J.N. Aleinikoff conducted the geochronology by sensitive high-resolution ion microprobe (SHRIMP). A detailed discussion of the tectonics, geochronology, and structural evolution of the Lyme dome is presented in Walsh and others (2007).

[1]U.S. Geological Survey, Montpelier, VT 05601.

[2]U.S. Geological Survey, Denver, CO 80225.

[3]U.S. Geological Survey, Reston, VA 20192.

Stratigraphy

The metamorphic and igneous rocks in the Old Lyme quadrangle range in age from Neoproterozoic to Permian. These rocks are discussed from youngest to oldest and include (1) Permian igneous rocks, (2) Silurian to Devonian metasedimentary rocks, (3) Silurian metasedimentary rocks of the Merrimack terrane, (4) Neoproterozoic metaigneous rocks of the Avalon terrane, (5) Neoproterozoic metaigneous rocks of the Gander terrane, and (6) Neoproterozoic metasedimentary and metavolcanic rocks of the Gander terrane. Some formation and rock unit names are consistent with Lundgren (1967) or Rodgers (1985) with modifications to agree with standard U.S. Geological Survey (USGS) nomenclature. Names have been changed or abandoned where new mapping or isotopic or geochronologic data invalidate previous assignments of nomenclature. Table 1 summarizes nomenclature used in this and in previous maps.

Igneous Rocks of Permian Age

In the Old Lyme quadrangle, igneous rocks of Permian age include the Westerly Granite, granite pegmatite (Pp), alaskite and granite gneiss (Pa), granite gneiss (Pg) and migmatite gneiss (PZmig).

Westerly Granite

The Westerly Granite (Gregory, 1906; Feininger, 1963) occurs as straight-walled, undeformed tabular dikes that intrude units in the Lyme dome. The dikes are shown by strike and dip symbols on the geologic map. Chemical analysis of one dike (sample OL294A, fig. 1*A*) shows that it is peraluminous calc-alkaline granite (table 2, fig. 2). Eight dikes of Westerly Granite were observed during mapping. The dikes are generally steeply dipping (dips range from 47°–82°) and have variable strikes (fig. 3). The dikes range in thickness from 0.1 to 2.0 meters (m). Lundgren (1967) noted that the

Table 1. Summary of stratigraphic nomenclature used in this and previous maps.

[Labels in parentheses indicate map unit designators. —, not applicable]

Lundgren (1967)	Rodgers (1985)	This report
Westerly type (+)	Westerly Granite (Pw)	Westerly Granite.
Black Hall type (pe, pg)	Narragansett Pier Granite (Pn)	Granite pegmatite (Pp).
Sterling Plutonic Group[1] (sga, sgba, sgm)	Hope Valley Alaskite Gneiss (Zsh) of the Sterling Plutonic Group[1]	Alaskite and granite gneiss (Pa).
—	—	Granite gneiss (Pg).
—	—	Migmatite gneiss (PZmig).
Tatnic Hill Formation (Ot, Otg)	Tatnic Hill Formation (Ota)	Schist and gneiss at Obed Heights (DSoh, DSohrs).
Brimfield Formation (Obm)	Brimfield Schist (Obr)	Old Saybrook schist (DSos).
Tatnic Hill Formation (Otc)	Hebron Gneiss (SOh)	Hebron Formation (Sh).
Monson Gneiss (Om)	Rope Ferry Gneiss (Zwr)	Rope Ferry Gneiss (Zwr, Zwra).
Sterling Plutonic Group[1] (sgb)	Potter Hill Granite Gneiss (Zsph) of the Sterling Plutonic Group[1]	Granite gneiss at Becket Hill (Zgb).
—	—	Granodiorite gneiss at Johnnycake Hill (Zgd, Zgdh).
Monson Gneiss (Om)	Rope Ferry Gneiss (Zwr) of the Waterford Group	Granodiorite gneiss at Lord Hill (Zgdl, Zgdla).
Plainfield Formation (p, ps, pg, pq, pa)	Plainfield Formation (Zp, Zpq)	Old Lyme Gneiss (Zo, Zos, Zog, Zoq, Zolq, Zoa).

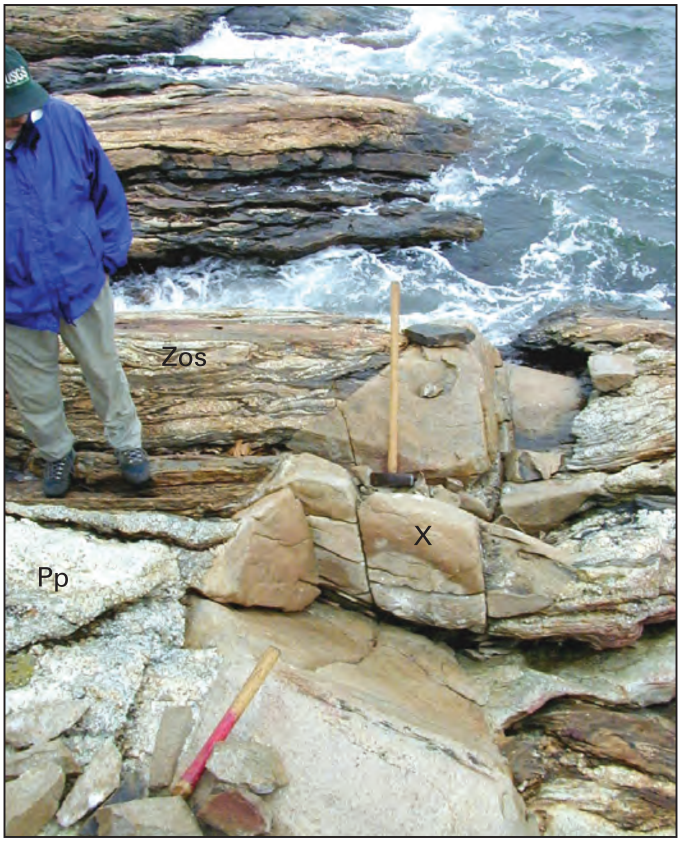
[1]U.S. Geological Survey usage is Sterling Plutonic Suite (Hermes and Zartman, 1985).

dikes exposed at Point O'Woods, the only ones that he saw, have a generally east-northeast trend. Our mapping agrees with Lundgren at Point O'Woods, but dikes with other orientations were found throughout the southern part of the quadrangle. Goldsmith (1988) noted that Westerly Granite dikes in southeastern Connecticut and southern Rhode Island also have variable strikes but that the dips are moderate to gentle to the south-southeast—gentler than we observed in the Old Lyme area. Goldsmith (1988) also noted that large dikes observed in quarries generally have irregular contacts and are not straight-walled tabular features like those seen in smaller outcrops. A SHRIMP U-Pb age from igneous zircon cores of 275±4 Ma (mega annum, million years ago) from a sample of Westerly Granite at Point O'Woods (sample OL294A, table 3; Walsh and others, 2007) provides a Permian age and closely agrees with a TIMS (thermal ionization mass spectrometry) age of 276±7 Ma (Zartman and Hermes, 1987). Typical exposures of the Westerly Granite dikes occur along the shore of Long Island Sound at Point O'Woods (fig. 1*A*).

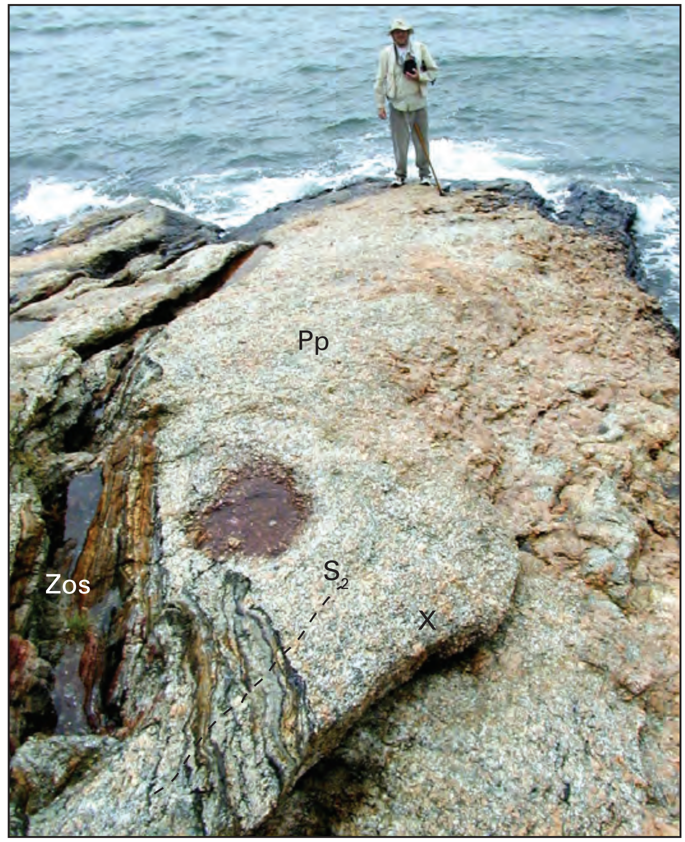
Granite Pegmatite

Granite pegmatite (Pp) occurs throughout the Lyme dome. Lundgren (1967, p. 21) mapped 15 pegmatite bodies on the eastern flank of the Lyme dome as "Black Hall type" granite pegmatite (Lundgren's "pe" unit). Lundgren informally used the name "Black Hall type" for pegmatite exposed at the MacCurdy quarry in Old Lyme. The rock at the MacCurdy quarry is described as a biotite granite pegmatite (Kemp, 1899; Dale and Gregory, 1911; Lundgren, 1967). The quarry is located on the east bank of the Duck River, approximately 400 m north of Lyme Station and 1,000 m north-northwest of Black Hall (sheet 1). Lundgren (1967) reported that the pegmatite, although not mapped separately, constituted 25 percent of his Old Lyme Gneiss (his "pg" unit) in the core of the Lyme dome, and we generally agree with this estimate, although we use the name "Old Lyme Gneiss" for rocks formerly mapped as Plainfield Formation. Rodgers (1985) assigned the pegmatite in the core of the Lyme dome to the Narragansett Pier Granite ("Pn" on the State map) after its use in Rhode Island (Nichols, 1956; Feininger, 1968). We map the rocks as unnamed granite pegmatites because they are not contiguous with mapped Narragansett Pier Granite in eastern Connecticut and Rhode Island, although they may be correlative in age and chemistry. Furthermore, although we agree with Lundgren's description of the rock at the MacCurdy quarry, the principal rock type at Black Hall is the granodiorite gneiss at Johnnycake Hill (Zgd on sheet 1), so the name "Black Hall" is not appropriate.

The granite pegmatite occurs as straight-walled tabular dikes and non-foliated to weakly foliated irregular intrusive bodies in the Lyme dome. The dikes are shown by strike and dip symbols and the intrusive bodies are shown as map units (Pp) on the geologic map (sheet 1). In general, the irregular intrusive bodies are sills that intruded subparallel to the dominant foliation (S_1) in the country rocks. Chemical analysis of one sample (OL294B, fig. 1*B*) shows that it is peraluminous calc-alkaline granite (table 2, fig. 2). The dikes are generally steeply dipping (dips ≥60°, after Mabee and others, 1994), but some shallowly dipping dikes also were observed (fig. 1*C*). Of 39 measured dikes, 36 dip ≥45°. The principal strike direction of 36 moderately to steeply dipping dikes suggests that these tabular bodies have a preferred east-west orientation (fig. 3). Hozik (1988) notes a similar east-west trend for most of the Narragansett Pier Granite dikes and the largest Westerly Granite dikes in Rhode Island. A SHRIMP U-Pb age from igneous zircon cores of 288±4 Ma from a sample at Point O'Woods (sample OL294B, table 3; Walsh and others, 2007) provides a



A



B

C

Figure 1. *A*, Westerly Granite dike in the Old Lyme Gneiss at Point O'Woods (sample site for OL294A shown by X). *B*, Medium- to coarse-grained Permian granite pegmatite in the Old Lyme Gneiss at Point O'Woods (sample site for OL294B shown by X). Dashed line shows trace of weakly developed cleavage (S_2) in the pegmatite and Old Lyme Gneiss. *C*, Dikes of Permian granite pegmatite in the Old Lyme Gneiss at an outcrop near Jericho; arrow shows location of hammer. The gently dipping dikes postdate the steeply dipping dikes in this photograph. Rock unit abbreviations: Old Lyme Gneiss sillimanite schist (Zos), biotite gneiss (Zo), and granite pegmatite (Pp). The dominant foliation in all photographs is S_1. Locations for all photographs given in table 4 and shown on geologic map (sheet 1).

Permian age. The sample collected at Point O'Woods comes from a medium- to coarse-grained weakly foliated pegmatite (fig. 1*B*). Field evidence shows that the Westerly Granite dikes postdate the pegmatites, but their similar chemistry, similar age, and the local gradational margins between the two suggest that the Westerly is closely related to the pegmatite, supporting findings of earlier workers who linked the Westerly Granite with the Narragansett Pier Granite (Lundgren, 1967;

Table 2. Major and trace element geochemistry of rocks from the 7.5-minute Old Lyme quadrangle, Connecticut.

[Major oxides determined by wavelength-dispersive X-ray fluorescence spectrometry of lithium tetraborate fused beads; analyst, D.F. Siems, USGS. All iron reported as Fe_2O_3. Trace-element abundances determined by inductively coupled plasma spectrometry (ICP40); analyst J.R. Budahn, USGS. Normative-mineral compositions calculated using Easy Norm v. 1.0 (http://web.tiscali.it/no-redirect-tiscali/geoware). Methods and error limits described in Taggart (2002)]

Sample no.	OL293	OL294A	OL294B
Map unit	Granodiorite gneiss at Johnnycake Hill (Zgd)	Westerly Granite dike	Granite pegmatite (Pp)
Major oxides, in weight percent, and loss on ignition			
SiO_2	67.4	72.1	71.6
Al_2O_3	15.0	14.5	16.0
Fe_2O_3	4.47	1.99	0.69
CaO	2.98	1.03	1.50
MgO	2.18	0.35	0.17
MnO	0.08	0.02	0.01
K_2O	2.80	5.34	5.93
Na_2O	3.18	3.15	3.38
TiO_2	0.68	0.27	0.09
P_2O_5	0.17	0.09	<0.05
Loss on ignition	1.00	0.55	0.42
Total	99.94	99.39	99.84
Normative-mineral composition, in weight percent			
Q	26.36	29.66	25.49
or	16.54	31.55	35.04
ab	26.91	26.65	28.6
an	13.78	4.58	7.15
C	1.69	1.86	1.4
hy	5.6	0.9	0.44
fs	5.77	2.59	0.91
mt	0.86	0.38	0.13
il	1.29	0.51	0.17
ap	0.37	0.2	0.11
Total	99.17	98.88	99.44
Trace elements, in weight percent			
Al	8.2	7.6	8.2
Ca	2.2	0.73	1
Fe	2.8	1.2	0.43
K	2.4	4.4	4.7
Mg	1.3	0.21	0.094
Na	2.6	2.3	2.6
P	0.079	0.036	0.012
Ti	0.41	0.13	0.04

Sample no.	OL293	OL294A	OL294B
Map unit	Granodiorite gneiss at Johnnycake Hill (Zgd)	Westerly Granite dike	Granite pegmatite (Pp)
Trace elements, in parts per million			
Ag	<2	<2	<2
As	<10	<10	<10
Au	<8	<8	<8
Ba	720	2130	1480
Be	2	2.1	2.9
Bi	<10	<10	<10
Cd	<2	<2	<2
Ce	86	200	59
Co	13	2.9	2.2
Cr	51	<1	1.2
Cu	<1	3.3	2
Eu	<2	<2	<2
Ga	17	22	19
Ho	<4	<4	<4
La	44	116	30
Li	23	17	11
Mn	600	166	59
Mo	<2	<2	<2
Nb	23	21	20
Nd	32	60	23
Ni	25	4	<2
Pb	18	59	56
Sc	12	3.4	<2
Sn	<5	<5	<5
Sr	328	236	466
Ta	<40	<40	<40
Th	17	68	21
U	<100	<100	<100
V	78	15	5.8
Y	16	12	4
Yb	1.3	<1	<1
Zn	76	37	9.1
Total	99.17	98.88	99.44

Description of sample locations (NAD27 datum):

OL293—Granodiorite gneiss at Johnnycake Hill (Zgd), 41°18′03″ N.; 72°19′22″ W. Railroad cut on northern side of Penn Central railroad near Black Hall.

OL294A—Westerly Granite dike, 41°17′30″ N.; 72°15′06″ W. Outcrop on Long Island Sound at Point O'Woods (see fig. 1*A*).

OL294B—Granite pegmatite (Pp), 41°17′30″ N.; 72°15′06″ W. Outcrop on Long Island Sound at Point O'Woods (see fig. 1*B*).

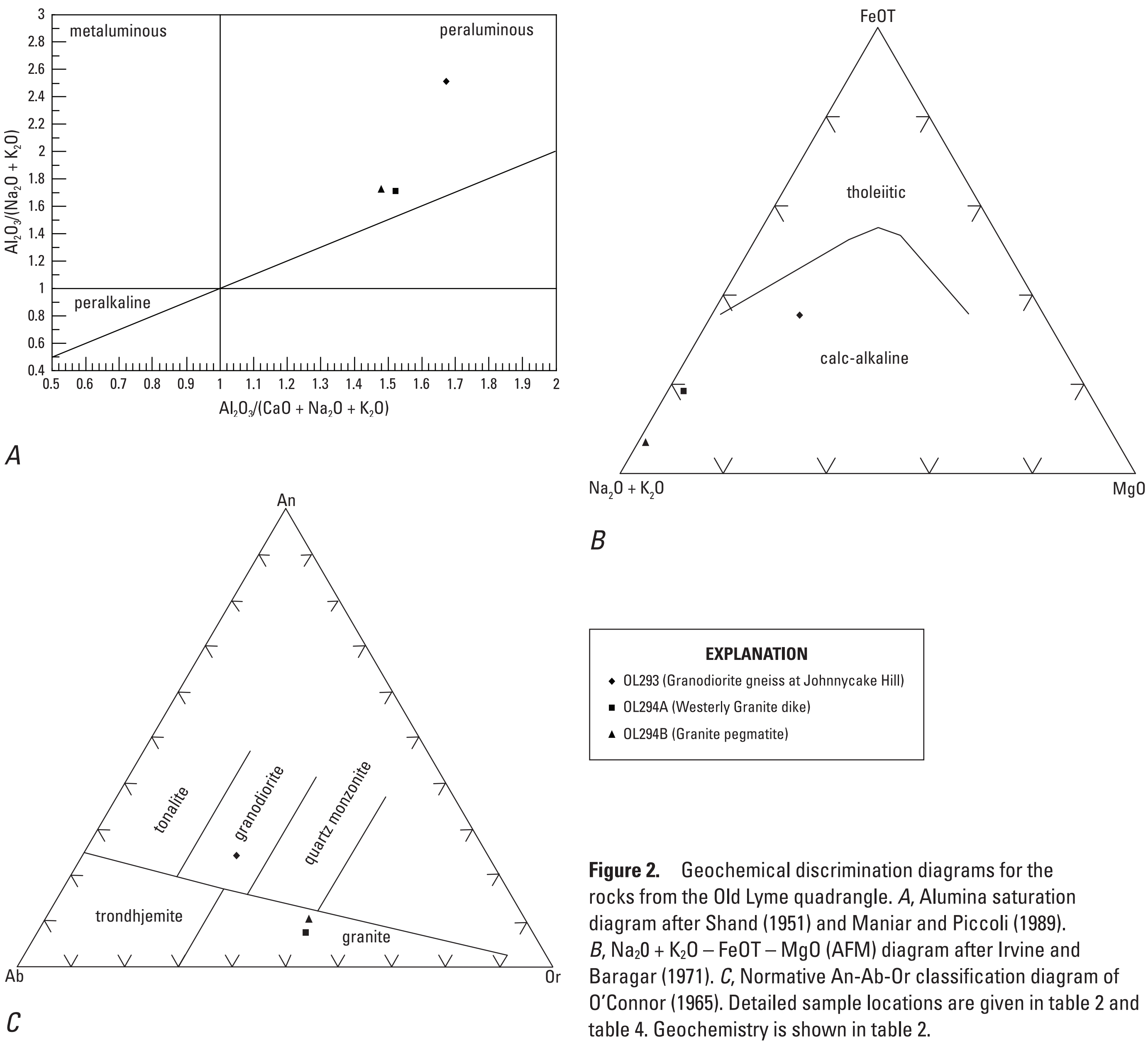


Figure 2. Geochemical discrimination diagrams for the rocks from the Old Lyme quadrangle. *A*, Alumina saturation diagram after Shand (1951) and Maniar and Piccoli (1989). *B*, $Na_2O + K_2O$ – FeOT – MgO (AFM) diagram after Irvine and Baragar (1971). *C*, Normative An-Ab-Or classification diagram of O'Connor (1965). Detailed sample locations are given in table 2 and table 4. Geochemistry is shown in table 2.

Buma and others, 1971; Zartman and Hermes, 1987; Skehan and Rast, 1990). Typical exposures of the granite pegmatite occur along the shore of Long Island Sound at Point O'Woods and at the promontory south of Little Pond. Pegmatite is present, however, at virtually every outcrop.

Alaskite and Granite Gneiss

Alaskite and granite gneiss (Pa) occurs as large sills and irregular intrusive bodies into the rocks of the Old Lyme Gneiss in the Lyme dome. The rock generally exhibits a strongly developed foliation, but locally it is coarse grained and poorly foliated. The foliation developed within the gneiss has the same relative age as the dominant foliation within the host rocks of the Old Lyme Gneiss, and it is mapped as S_1.

Lundgren (1967) mapped similar rocks as units "sga," "sgba," and "sgm" of the Sterling Plutonic Group. On the State map, Rodgers (1985) agreed with Lundgren and further subdivided Lundgren's units as Potter Hill Granite Gneiss and others as Hope Valley Alaskite Gneiss. Our mapping suggests a compositional similarity with some of the rocks mapped as the Neoproterozoic Sterling Plutonic Group[4] (Rodgers, 1985), but a SHRIMP U-Pb zircon age from the alaskite and granite gneiss is 290±4 Ma (sample OL291, table 3; Walsh and others, 2007), indicating the rock is Permian in age. We, therefore, have abandoned the use of the names Sterling Plutonic Group (or Suite), Potter Hill Granite Gneiss, and Hope Valley Alaskite Gneiss for the alaskite and granite gneiss (Pa). Instead, we

[4]USGS usage is "Sterling Plutonic Suite" (Hermes and Zartman, 1985).

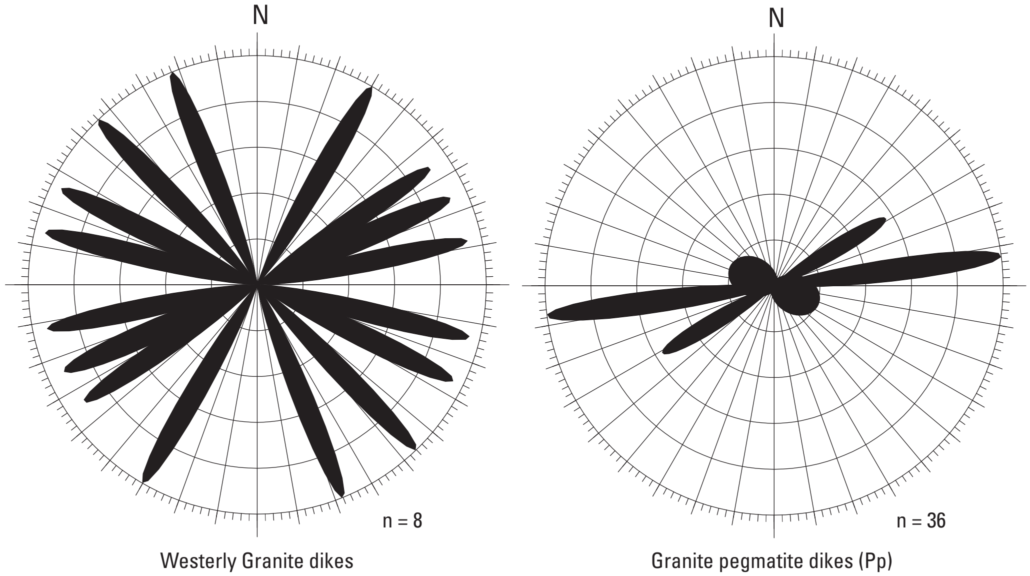


Figure 3. Azimuth-frequency diagrams for dikes of Westerly Granite and granite pegmatite with dips ≥45°. North is marked by “N”; the number of points in the dataset is indicated by “n.” Data are plotted by using Structural Data Integrated System Analyser (DAISY, version 3.41) software by Salvini (2002).

map them as unnamed Permian intrusive rocks. The presence of foliated early Permian intrusive rocks in this part of Connecticut suggests that other rocks mapped as Sterling Plutonic Group in southern Connecticut (Rodgers, 1985) need to be re-evaluated. Because modal abundances of alaskite gneiss overlap with those of the granite gneiss at Becket Hill (Zgb), a degree of uncertainty in identification of granitic units exists. The granite gneiss at Becket Hill generally contains more biotite. Typical exposures of the alaskite and granite gneiss occur at Cranberry Ledge, Game Ledge, Smith Ledges, and the unnamed ridges west of Lower Millpond and Upper Millpond. The dated sample was collected from a roadcut on Talcott Farm Road (not labeled on base map) approximately 400 m east of State Route 156 at the latitude of Calves Island.

Granite Gneiss

In the western part of the map, the granite gneiss (Pg) occurs as S_1-foliation-parallel sill-like bodies in the schist and gneiss at Obed Heights (DSoh). Unequivocal crosscutting relations with the surrounding Obed Heights rocks were not observed, but sharp contacts and generally discordant layering in the enclosing metasedimentary rocks suggest that the granite gneiss bodies are intrusive sills. In the Essex quadrangle, Lundgren (1964) mapped the southernmost of the two bodies as quartzofeldspathic gneiss of the Putnam Gneiss (his “pgf”). Lundgren (1967) did not show this unit on his map of the Old Lyme quadrangle, but we have traced it from the hill southeast of Obed Heights Reservoir, south of the dam, and into the adjacent Essex quadrangle, where it matches outcrop locations of his “pgf” unit. The northernmost belt is exposed across the quadrangle boundary in a residential area along Fordham Trail road (road neither mapped nor labeled on base map). This rock resembles granitic phases of the alaskite and granite gneiss (Pa), but contains more biotite and less K-feldspar than the Pa unit. Because of similarities with phases of the Pa unit, and because it has the same relative age in relation to the S_1 foliation of the Pa unit, we interpret this rock as Permian granite sills.

Migmatite Gneiss

The migmatite gneiss (PZmig) unit is exposed in the southeastern part of the map. There, the rock consists of 75 percent or more of leucocratic migmatite and granitic gneiss with lesser screens of biotite gneiss and schist of the Old Lyme Gneiss. Locally, only traces of melanocratic schlieren are present within the migmatite unit making it difficult to identify the original host rock, and for this reason the unit is mapped separately from the Old Lyme Gneiss. The leucosomes within this unit resemble the rocks of the alaskite and granite gneiss (Pa) and the rock is interpreted as a Permian-age migmatite of a Neoproterozoic protolith. Although migmatitic rocks are present at virtually every outcrop throughout the Old Lyme Gneiss in the Lyme dome, the percentage of migmate is generally less than 50 percent and is insufficient to mask the character of the host rock. Typical exposures of PZmig occur in the railroad cut on the northern side of the Penn Central tracks, north of Point O’Woods.

Silurian to Devonian Metasedimentary Rocks

The Silurian to Devonian rocks crop out between the Gander and Avalon terranes exposed in the Lyme dome and Selden Neck block, respectively. These rocks were previously mapped as Ordovician Tatnic Hill Formation, Brimfield Formation, or Brimfield Schist (Lundgren, 1967; Rodgers, 1985). Recent ages on detrital zircons from rocks within this belt, but outside this quadrangle, suggest that these rocks are Late Silurian to Early Devonian and were deposited at about 420 to 415 Ma (Wintsch and others, 2004, 2007; J.N. Aleinikoff, written commun., 2007). The authors report that detrital zircons from the Merrimack terrane have ages from Mesoproterozoic, Ordovician, and Silurian sources. Wintsch and others (2007) report that the zircons from the Tatnic Hill Formation in the Putnam-Nashoba terrane have a similar distribution of ages and show a strong Devonian metamorphic overprint not found in the Merrimack terrane samples. Owing to the new ages and considerable uncertainties regarding the extent of rocks previously mapped as Tatnic Hill and Brimfield, we have abandoned the use of the names Tatnic Hill and Brimfield for the rocks in this quadrangle. Here we use new, informal, local names of "schist and gneiss at Obed Heights" and "Old Saybrook schist" to describe these rocks.

Schist and Gneiss at Obed Heights

The schist and gneiss at Obed Heights is a heterogeneous suite of rocks that we map as two separate units: (1) gneiss, schist, amphibolite, and calc-silicate gneiss (DSoh) and (2) rusty weathering schist and schistose gneiss (DSohrs). Lundgren (1967) and Rodgers (1985) mapped these rocks as Tatnic Hill Formation. The DSoh unit extends from the Nehantic State Forest into the adjacent Essex quadrangle to the west. The DSohrs unit only occurs in the northwestern part of the map. Lundgren (1967) concluded that the northernmost part of his belt (his Tatnic Hill Formation) contains a rock unit he mapped as "Otm" that is similar to the rocks south of the Hebron Formation (his Brimfield Formation "Obm," our Old Saybrook schist "DSos"). Our mapping does not find this rock unit (DSohrs) to be as extensive as Lundgren indicated; it is restricted to a 50- to 75-m-wide and 1.2-km-long belt south of, and structurally below, the Rope Ferry Gneiss (Zwr) in the Selden Neck block.

SHRIMP analyses of detrital zircons from the schist and gneiss at Obed Heights from locations outside the Old Lyme quadrangle indicate a maximum deposition age of about 420 Ma (J.N. Aleinikoff, written commun., 2007). The zircons were metamorphosed several times in the late Paleozoic. No Neoproterozoic zircons with Gander or Avalon ages were found. The depositional age of the protolith of the schist and gneiss at Obed Heights is between about 420 and 415 Ma, or Late Silurian to Early Devonian.

Old Saybrook Schist

The Old Saybrook schist (DSos) is a sillimanite-plagioclase-biotite-K-feldspar-quartz schist. It is the southernmost schist unit encountered at the northern limit of the Lyme dome, north of the granodiorite gneiss at Lord Hill. The schist extends from Uncas Pond to Old Saybrook.

The rocks of the Old Saybrook schist were previously mapped in the Old Lyme quadrangle as Ordovician Brimfield Formation by Lundgren (1967) or Brimfield Schist by Rodgers (1985). Both Lundgren and Rodgers interpreted these rocks as facies equivalents of the Ordovician Tatnic Hill Formation, separated only by the rocks of the Silurian Hebron Formation in the core of the Hunts Brook syncline, despite an apparent lack of symmetry across the syncline. The new ages by Wintsch and others (2004) and J.N. Aleinikoff (written commun., 2007) suggest that a syncline may not exist here, and instead suggest that many rocks are the same age—Silurian to Devonian.

SHRIMP analyses of detrital zircons from the Old Saybrook schist from locations outside the Old Lyme quadrangle indicate a maximum deposition age of about 415 Ma, and maybe younger than about 420 Ma, suggesting that the age of the rock is Silurian to Devonian. Sources for the detrital zircons are about 900 to 550 (Gander and Avalon ages) and about 1,600 to 1,000 (Laurentian ages).

Silurian Metasedimentary Rocks of the Merrimack Terrane

The Hebron Formation forms a continuous belt of rocks within the belt of more schistose rocks between the Lyme dome and Selden Neck block. Rodgers (1985) mapped the Hebron "Gneiss" from the Hamburg quadrangle southward across the Connecticut River into the Essex quadrangle. In the Old Lyme quadrangle, however, Lundgren (1967) did not map the Hebron Formation east of the Connecticut River. Instead, Lundgren considered the interlayered minor garnet-bearing gneiss and calc-silicate gneiss to be the Tatnic Hill Formation (his "Otc" unit). Detrital zircons from a sample of the Hebron Formation collected in the Nehantic State Forest north of the access road (sample OL292) have SHRIMP U-Pb ages consistent with a Silurian depositional age of the unit; therefore, we map these rocks as Hebron Formation east of Connecticut River as does Rodgers (1985).

Neoproterozoic Metaigneous Rocks of the Avalon Terrane

Rope Ferry Gneiss

The Rope Ferry Gneiss (Zwr) is a granodioritic gneiss exposed in the Selden Neck block. The rock is considered an orthogneiss owing to the generally homogeneous texture. The rock may be metavolcanic or metaplutonic, or both. Rare amphibolite stringers could be either highly attenuated basaltic volcanic rock or they could be attenuated mafic inclusions in a pluton. Wintsch (1985) interpreted similar mafic inclusions in the Rope Ferry Gneiss of the Essex quadrangle as xenoliths or deformed mafic dikes. The generally well-layered, locally pinstripe appearance suggests that most of the Zwr unit in the Old Lyme quadrangle is a metavolcanic orthogneiss. Granodioritic gneiss interpreted as an intrusive phase of the Rope Ferry Gneiss from the Essex quadrangle (Wintsch, 1985) yielded a U-Pb zircon age by conventional analysis of 620±3 Ma (Wintsch and Aleinikoff, 1987). Recent SHRIMP analyses of zircons from the same sample of Rope Ferry Gneiss indicate that a more accurate age is 598±5 Ma (J.N. Aleinikoff, unpub. data, 2003).

Neoproterozoic Metaigneous Rocks of the Gander Terrane

Three informal map units, granodiorite gneiss at Lord Hill, granite gneiss at Becket Hill, and granodiorite gneiss at Johnnycake Hill, consititute the Neoproterozoic metaigneous rocks of the Gander terrane. The three map units consist largely of metaintrusive orthogneiss.

Granodiorite Gneiss at Lord Hill

The granodiorite gneiss at Lord Hill (Zgdl) is exposed along the northwestern margin of the Lyme dome. The rock is considered an orthogneiss due to the generally homogeneous texture. The rock is strongly foliated and has a slabby weathering texture. It contains small foliation-parallel horizons of amphibolite and lesser quartzofeldspathic biotite gneiss, interpreted as xenoliths, that resemble rocks found in the Old Lyme Gneiss. At three places the amphibolite horizons are mapped separately as Zgdla. Lundgren (1967) mapped this belt of rock as Monson Gneiss (his "Om" unit) along with other Monson Gneiss in the Selden Neck block. Rodgers (1985) changed Monson Gneiss in this area to Rope Ferry Gneiss (his "Zwr" unit) on the basis of correlations with rocks named by Goldsmith (1980) in the town of Waterford in the Avalon terrane. We assign the informal name "granodiorite gneiss at Lord Hill" because this rock is now mapped in the Gander terrane and not in the Avalon terrane. The gneiss is exposed on the summit of Lord Hill, on the northeastern slopes of Bills Hill, and on cliffs east of Mink Island. A SHRIMP U-Pb zircon age of 582±9 Ma (sample OL316, table 3) from the northeastern slopes of Bills Hill indicates that the rock is Neoproterozoic. The age is based on 17 analyses from 2 analytical sessions. The zircon population shows older ages of about 660 to 610 Ma that are interpreted as due to inheritance from peri-Gondwanan crystalline rocks. Although the rock is not exposed on the western side of the Connecticut River in this map, R.B. Scott (written commun., 2003) has mapped this rock in the adjacent Essex quadrangle. Lundgren (1964, 1967) also extended this belt of rocks across the river into the Essex quadrangle.

Granite Gneiss at Becket Hill

On the State map (Rodgers, 1985), the granite gneiss at Becket Hill (Zgb) was assigned to the Potter Hill Granite Gneiss of the Sterling Plutonic Group. Hermes and Zartman (1985) later redefined the Sterling Plutonic Group as the Sterling Plutonic Suite. The type locality for the Potter Hill Granite Gneiss is located in the Avalon terrane in Rhode Island (Feininger, 1965). We use the informal name, granite gneiss at Becket Hill, because the granite gneiss mapped here is located in the Gander terrane. The granite gneiss at Becket Hill intrudes the rocks of the Old Lyme Gneiss. The mapped extent of the granite gneiss at Becket Hill generally corresponds to Lundgren's (1967) "sgb" biotite granite gneiss unit of his Sterling Plutonic Group (table 1). A SHRIMP U-Pb zircon age of 611±8 Ma from a sample at Quarry Hill (sample OL290, table 3) further constrains a Neoproterozoic age obtained by Zartman and others (1988) of 634±29 Ma from a sample on Quarry Hill (their sample no. 2 PEC–707).

Granodiorite Gneiss at Johnnycake Hill

The granodiorite gneiss at Johnnycake Hill (Zgd) is a biotite-K-feldspar-quartz-plagioclase rock exposed in the core of the Lyme dome (fig. 4*A*, *B*). Locally the rock contains hornblende and was mapped as unit Zgdh (fig. 4*C*). This large map unit contains xenoliths of amphibolite mapped as amphibolite of the Old Lyme Gneiss (Zoa).This orthogneiss is interpreted as a pluton because of its massive texture and because it truncates units in the Old Lyme Gneiss. Two smaller map units of Zgd are exposed as sill-like bodies, one north of Jericho and

Table 3. Summary of U-Pb zircon ages from the Old Lyme quadrangle.

[Ages obtained by Sensitive High Resolution Ion Microprobe (SHRIMP) at Stanford University, Palo Alto, Calif.]

Sample no.	Map unit	Rock type	Age (Ma)
OL96[1]	Old Lyme Gneiss quartzite (Zoq)	Detrital zircons	About 2,127–925.
OL290[1]	Granite gneiss at Becket Hill (Zgb)	Igneous cores	611±8.
OL291[1]	Alaskite and granite gneiss (Pa)	Igneous cores	290±4.
OL292	Hebron Formation (Sh)	Detrital zircons	About 3,015–420.
		Metamorphic overgrowths	About 360 and 287.
OL293[1]	Granodiorite gneiss at Johnnycake Hill (Zgd)	Igneous cores	619±7.
OL294A[1]	Westerly Granite dike	Igneous cores	275±4.
		Metamorphic zircons	259±4.
		Monazite	271±3 and 259±2.
OL294B[1]	Granite pegmatite (Pp)	Igneous cores	288±4.
		Monazite	287±3 and about 263 and 260.
OL295[1]	Old Lyme Gneiss amphibolite (Zoa)	Metamorphic zircons	270±5 and 285±6.
OL316[2]	Granodiorite gneiss at Lord Hill (Zgdl)	Igneous cores	582±9.

[1]Ages from Walsh and others (2007).
[2]Ages from SHRIMP at Stanford and SHRIMP II at Research School of Earth Sciences, The Australian National University, Canberra, Australia.

another on the shore of Long Island Sound between White Sands Beach and Hawks Nest Beach at the Old Lyme Beach Club. This rock was not mapped by Lundgren (1967) but was briefly described (1967, p. 28) as "quartz-dioritic and granodioritic in composition, whether volcanic or intrusive" in the lower part of his Plainfield Formation, or our Old Lyme Gneiss. Rodgers (1985) reinterpreted Lundgren's (1967) map and identified the rocks in the core of the Lyme dome as a mixture of Plainfield Formation (our Old Lyme Gneiss), Potter Hill Granite Gneiss, and Narragansett Pier Granite (unit "Zp+Zsph+Pn?"). While there are a number of dikes and irregular intrusions of granite pegmatite similar to Narragansett Pier Granite in the area (fig. 4*A*), we recognize no mappable rocks like the Potter Hill Granite Gneiss (our granite gneiss at Becket Hill). A SHRIMP U-Pb zircon age of 619±7 Ma (sample OL293, table 3) indicates that the granodiorite gneiss is Neoproterozoic. The sample was collected from a railroad cut on the northern side of the Penn Central line, west of the pedestrian bridge in Black Hall, and resembles the rock shown in figure 4*B*. Chemically, the dated rock is a peraluminous calc-alkaline granodiorite (table 2, fig. 2).

Neoproterozoic Metasedimentary and Metavolcanic Rocks of the Gander Terrane

Recent Nd and Pb whole-rock isotopic data from rocks in southern Connecticut indicate that metaintrusive rocks in the core of the Lyme dome have different isotopic signatures from metaintrusive rocks in the Selden Neck block, and thus reflect different crustal sources (Wintsch and others, 2005; Aleinikoff and others, 2007). Rocks in the core of the Lyme dome have signatures that correlate with the Gander terrane of Newfoundland, and rocks in the Selden Neck block have signatures that correlate with the Avalon terrane. Additionally, U-Pb zircon ages from metaintrusive rocks in the Selden Neck block are around 590 Ma, whereas U-Pb zircon ages from metaintrusive rocks in the Lyme dome are around 620 Ma, suggesting an approximately 30 Ma age difference between metaigneous rocks in the two massifs (Wintsch and others, 2005; Aleinikoff and others, 2007). The differences in age and isotopic signatures are significant and suggest that rocks previously mapped as Avalon terrane rocks in the core of the Lyme dome are more appropriately correlated with Gander terrane rocks. For this reason, previous names for metasedimentary rocks within the core of the Lyme dome are not used in this report because all such names come from type localities within the Avalon terrane in eastern and southeastern Connecticut. Previous names for metasedimentary rocks in the Old Lyme quadrangle by Lundgren (1967) and Rodgers (1985) include the Plainfield Formation, the Mamacoke Formation, and the New London Gneiss. In this report, all of these rocks are mapped as members of the Old Lyme Gneiss. Table 1 shows nomenclature used in this and in previous reports.

The Old Lyme Gneiss contains the metasedimentary and metavolcanic rocks of the Lyme dome. Lundgren (1967) and Rodgers (1985) considered the sequence of Plainfield Formation, Mamacoke Formation, and New London Gneiss as metasedimentary and metavolcanic rocks representing a continuous stratigraphic succession from oldest to youngest, despite the high degree of metamorphic and igneous overprinting experienced by the rocks. Because sedimentary topping criteria are completely lacking in these rocks, and the contacts between the formations are occupied by metaigneous rocks, the true stratigraphic succession cannot be determined from field observations. Type localities for all three formations occur outside the Lyme dome in the Avalon terrane, and are, therefore, no longer considered part of the Lyme dome block. Detrital zircons from a quartzite in the Old Lyme Gneiss (Zoq, sample OL96, fig. 5*D*) yield a range of ages from 2,127 to 925 Ma suggesting that the time of deposition of the protolith of the Old Lyme Gneiss is Early Neoproterozoic or younger. The age of the quartzite is bracketed by the youngest detrital zircons at about 925 Ma and the oldest intrusive rocks that cut the Old Lyme Gneiss rocks at about 620 Ma (Walsh and others, 2007).

Old Lyme Gneiss

The name "Old Lyme Gneiss" is proposed here for metasedimentary rocks exposed in the core of the Lyme dome. The differences in isotopic signatures and ages between the Lyme dome rocks and the Selden Neck block, described earlier (Aleinikoff and others, 2007), support the interpretation that the rocks in the core of the Lyme dome belong to the Gander terrane, not the Avalon terrane, and thus previous Avalon-terrane names for these rocks are inappropriate. The name "Old Lyme Gneiss" is proposed because the town of Old Lyme underlies most of the core of the Lyme dome. Type localities for the Old Lyme Gneiss include Old Lyme Shores, Point O'Woods, Jericho, Amon Hill, the western slopes of Johnnycake Hill, roadcuts on I-95 between Exits 70 and 71, and the southwestern corner of Stone Ranch Military Reservation. Type localities for individual map units are included in the Description of Map Units.

Lundgren (1967) described the same basic subdivisions of the Old Lyme Gneiss that we show on our map (biotite gneiss, sillimanite schist, amphibolite, quartzite), but the geographic distribution of his units on his map do not match our findings. Lundgren's major metasedimentary units in the Lyme dome included, from the core of the Lyme dome outward, quartz-feldspar gneiss (pl on his fig. 4), sillimanite schist and gneiss with quartz-sillimanite nodules (pm on his fig. 4), and quartzite and schist with quartz-sillimanite nodules with quartzite and amphibolite (pu on his fig. 4). Lundgren (1967) designated these three units as lower (pl), middle (pm), and upper (pu) Plainfield Formation on the basis of their apparent stratigraphic position away from the core of the Lyme dome. Our mapping shows that there is no stratigraphic basis for Lundgren's lower, middle, and upper units because similar lithologies are present across the Lyme dome, with the possible exception that the thickest quartzites are present in

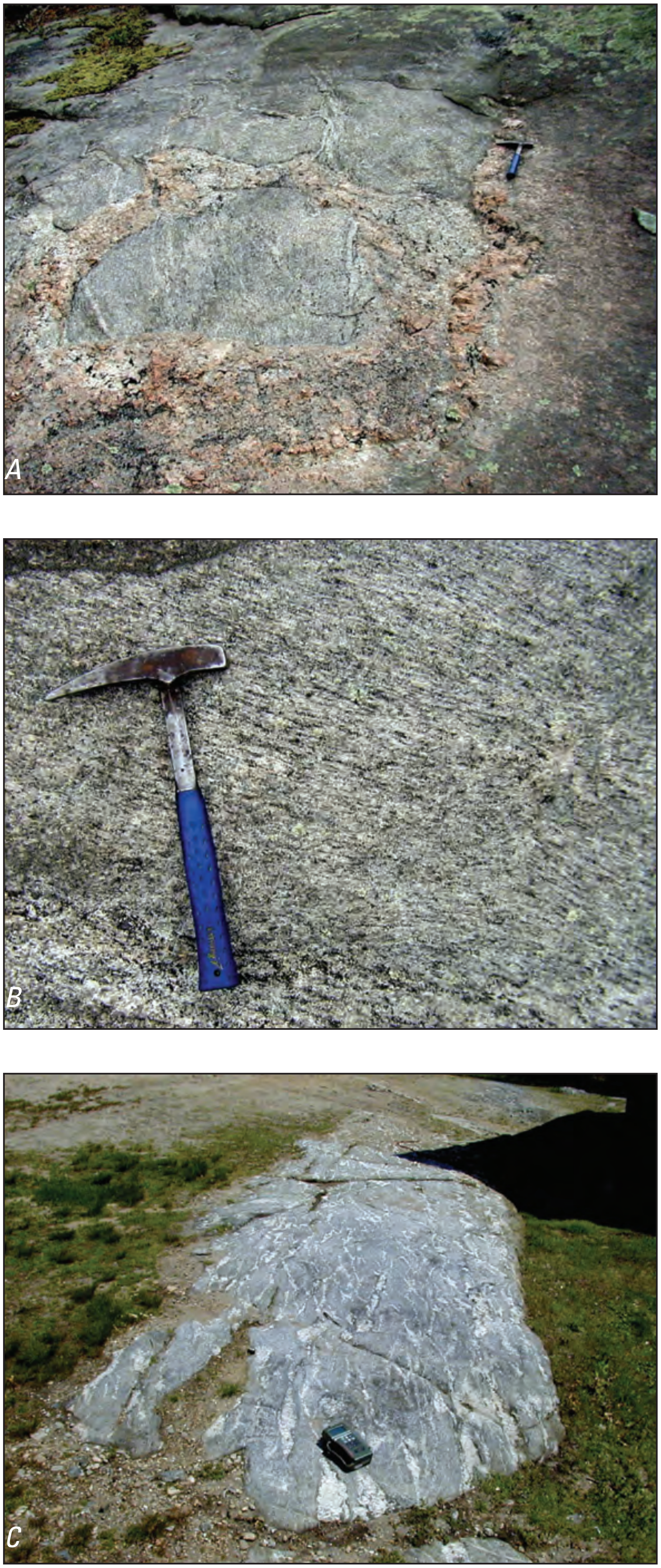


Figure 4. The granodiorite gneiss at Johnnycake Hill. *A*, The gneiss intruded by Permian granite pegmatite. *B*, Typical massive texture of the gneiss. *C*, Characteristic anastomosing leucosomes in the hornblende granodiorite gneiss (Zgdh). Locations for all photographs given in table 4 and shown on geologic map (sheet 1).

A

B

C

D

E

Figure 5. Rock types in the Old Lyme Gneiss. *A*, Sillimanite schist (Zos) with a thin interbedded layer of quartzofeldspathic biotite gneiss (under hammer) that is similar to the biotite gneiss unit (Zo); cross-section view looking north; west is to the left. *B*, Sillimanite-quartz segregations and downdip L_1 lineation (arrow) in the sillimanite schist (Zos); view perpendicular to foliation, looking north; west is to the left. *C*, Biotite gneiss (Zo) with thin interbedded layers of sillimanite schist and biotite-rich schist. The sillimanite schist resembles the Zos unit. Figures 5*A* and *C* illustrate the interbedded nature of the two main units, Zos and Zo, in the Old Lyme Gneiss; cross-section view looking north, west is to the left. *D*, Quartzite (Zoq) that is 2 m thick at detrital zircon sample site (X) at OL96; cross-section view looking downdip to the west; south is to the left. *E*, Garnetiferous biotite gneiss and schist (Zog) with abundant garnet porphyroblasts ranging up to 1.5 cm in diameter; downdip map view with north to the left. Locations for all photographs given in table 4 and shown on geologic map (sheet 1).

the northern part of the map. In addition, the core of the Lyme dome consists of intrusive granodiorite gneiss at Johnnycake Hill, not Old Lyme Gneiss. The major map units in the Old Lyme Gneiss are biotite gneiss (Zo) and sillimanite schist (Zos), and their distribution is subparallel to the dominant foliation in the rocks (S_1) and folded around the Lyme dome. The sillimanite schist (Zos, fig. 5*A*, *B*) can be distinguished and mapped separately from the biotite gneiss (Zo, fig. 5*C*) because the sillimanite schist (Zos) contains more biotite and sillimanite and fewer quartzofeldspathic gneiss layers. Layers of both rock types are present in the two map units: sillimanite schist layers in the biotite gneiss (Zo) and quartzofeldspathic biotite gneiss layers in the sillimanite schist (Zos) (fig. 5*A*, *C*). The two map units (Zo and Zos) are separated in the field on the basis of whether the quartzofeldspathic biotite gneiss is more abundant (Zo) or the sillimanite schist is more abundant (Zos). It was not possible to separate the two units on the basis of the percentage of sillimanite schist and biotite gneiss, because the two rock types are interbedded at most outcrops to a small degree (fig. 5*A*, *C*). The map distribution of the sillimanite schist unit (Zos) appears to be a function of the original character of a more pelitic protolith because the contacts are subparallel to the compositional layering seen in outcrops, but at the same time the Zos units are not continuous stratigraphic horizons. This latter observation is most likely the result of metamorphism as the mapped distribution of the Zos unit is a function of the abundance of sillimanite or fibrolite in outcrop. Burton and others (2000) found that detailed mapping of sillimanite-bearing schist in central New Hampshire produces map patterns that are a function of both the original stratigraphy and the metamorphic overprint, suggesting that although the rocks can be mapped, the resulting pattern is not related simply to original stratigraphy.

Lundgren (1967) mapped a small 0.1-km (kilometer)-wide by 2-km-long belt of New London Gneiss (his “nm” unit) just south of Uncas Pond (“Hog Pond” on his map), that we map within the gneiss at Lord Hill (Zgdl). The belt contains a light-pink to light-gray granodiorite to granite orthogneiss with much lesser amounts of paragneiss that resemble the biotite gneiss of the Old Lyme Gneiss (Zo). The submeter-scale foliation-parallel horizons of paragneiss could not be mapped separately, but are interpreted as deformed xenoliths of Old Lyme Gneiss (Zo). Interlayered amphibolites were reported in the New London Gneiss of Lundgren (1967), but only one was found during this mapping effort southwest of Uncas Pond, and it is shown on the map as Zgdla.

Lundgren (1967) mapped a belt of Mamacoke Formation (his “m” unit) along the northwestern flank of the Lyme dome that we map as Old Lyme Gneiss biotite gneiss (Zo). This belt is present in a single, poorly exposed, continuous horizon in the northern and western part of the map where it lies between the granodiorite gneiss at Lord Hill and the granite gneiss at Becket Hill. Because the lithology here is indistinguishable from other belts of biotite gneiss (Zo), we do not think that this belt of rocks can be separated from the rest of the Old Lyme Gneiss. Skehan and Rast (1990), summarizing earlier work by Lundgren (1966a), Goldsmith (1976, 1980, 1985), and Wintsch (1979), pointed out the similarities between the Plainfield and the Mamacoke Formations west of New London and suggested that the two formations were interlayered there. This belt also contains amphibolite that is mapped as Zoa, at least at one locality southeast of Uncas Pond. Lundgren (1967) did not extend this belt of rocks across the Connecticut River to the southwest, but showed an outcrop on Saybrook Point as a mixed unit of Plainfield and Mamacoke with intrusive rocks of the Sterling Plutonic Group (his “m+p+sg” unit). We map this outcrop as Old Lyme Gneiss biotite gneiss (Zo). Lundgren (1967) identified the difficulty in mapping his Mamacoke Formation in this belt because of the limited exposure, and we agree.

Structural Geology

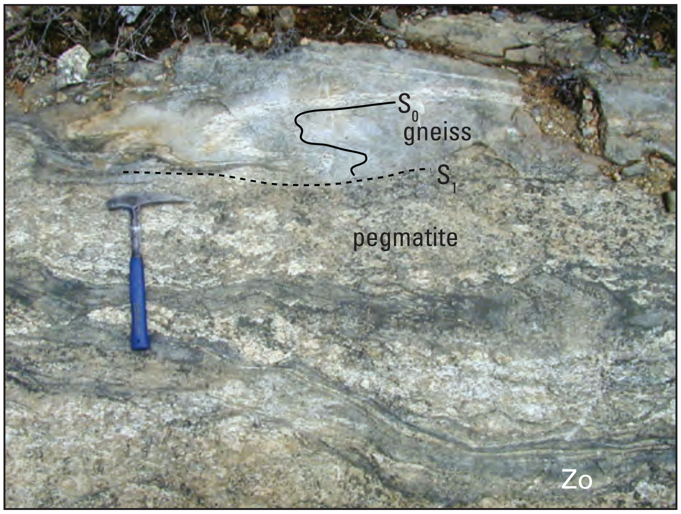
Ductile Structures

Three generations of ductile deformation and associated structures are recognized in the rocks of the Old Lyme quadrangle. The three generations are designated D_1, D_2, and D_3. The orientation of planar features is reported in right-hand rule.

D_1

The oldest deformational event (D_1) in the Old Lyme quadrangle is characterized by a penetrative gneissosity that is the dominant planar foliation in most rocks. This gneissosity, called S_1, is generally parallel to the gneissic layering in most outcrops. Locally S_1 is axial planar to rootless, outcrop-scale isoclinal folds (F_1) that deform a relict gneissic compositional layering (S_0) that is parallel to bedding in the metasedimentary rocks and some amphibolites (fig. 6*A*, *B*). The relict gneissic layering (S_0) is absent in the intrusive rocks. No folds older than F_1 were found. No map-scale F_1 folds were identified;

Figure 6 (on facing page). D_1 and D_2 structural features in the Old Lyme quadrangle. *A* and *B*, F_1 folds of S_0 compositional layering showing axial planar S_1 foliation. Photographs *A* and *B* show the biotite gneiss (Zo) and the amphibolite (Zoa), respectively, of the Old Lyme Gneiss. *C*, Downdip L_1 mineral lineations (parallel to hammer handle) in Old Lyme Gneiss biotite gneiss (Zo). *D*, Upright F_2 folds and S_2 cleavage deform gently dipping S_1 gneissosity in a xenolith of Old Lyme Gneiss biotite gneiss (Zo) within Permian granite and pegmatite (Pa). *E*, Upright F_2 folds deform S_1 gneissosity in the Old Lyme Gneiss sillimanite schist (Zos). Migmatitic leucosomes and granitic gneiss are parallel to S_1. *F*, F_2 and F_1 folds with axial planar S_1 and S_2 foliations in the Old Lyme Gneiss biotite gneiss (Zo). Locations for all photographs given in table 4 and shown on geologic map (sheet 1).


S0
gneiss
S1
pegmatite
Zo

A


S0
S1
Zoa

B


Zo

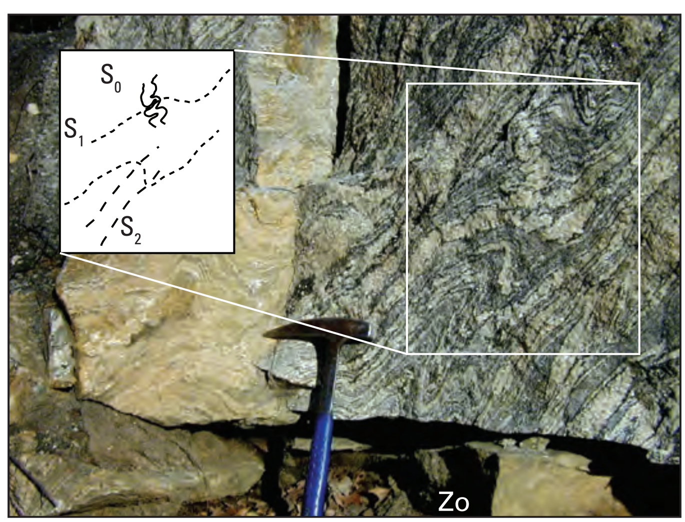
C


pegmatite
Zo
S1
S2

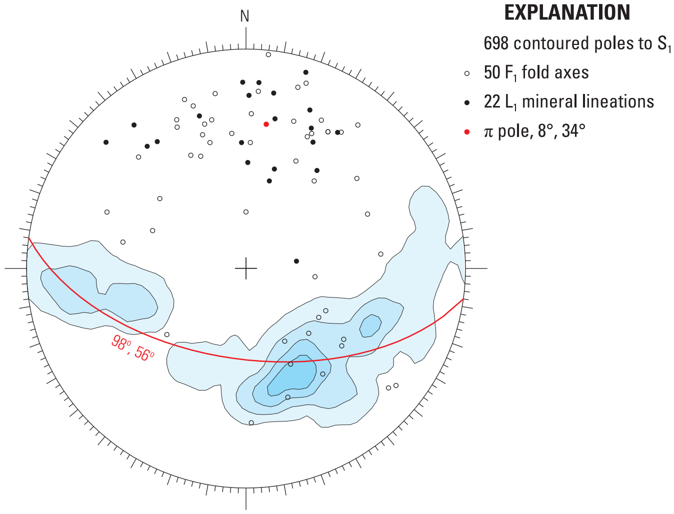
D


S1
Zos

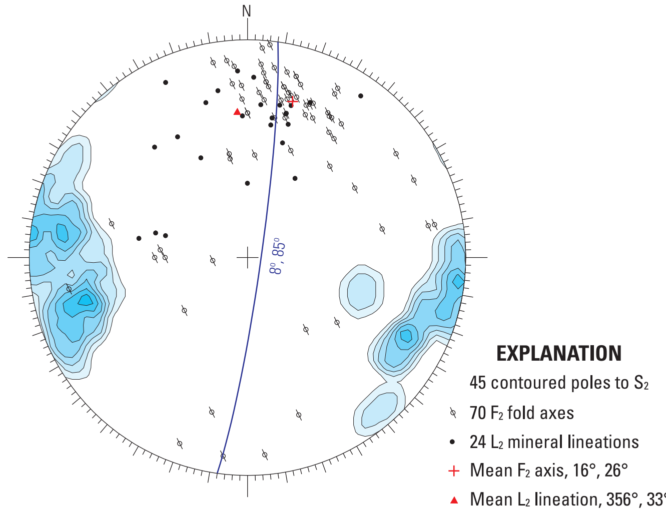
E


S0
S1
S2
Zo

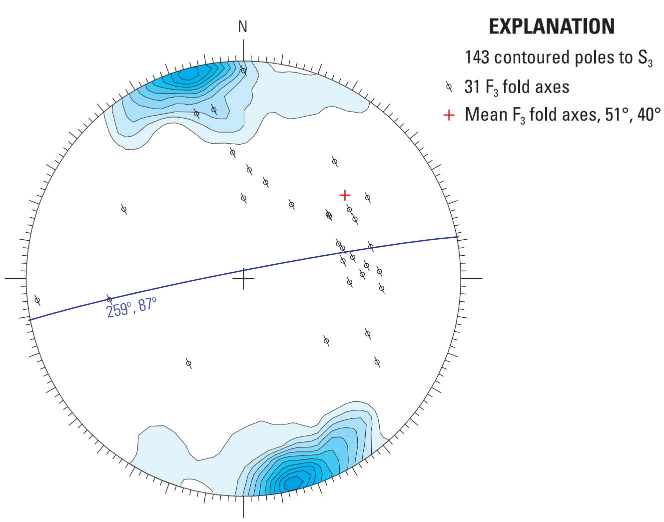
F



A



B



C

Figure 7. Lower hemisphere equal area projections of three generations of Alleghanian structures in the Old Lyme quadrangle. *A*, Contoured poles to S_1, linear F_1 fold axes and L_1 mineral lineations, best-fit great circle to poles (red), and π pole to best-fit great circle. *B*, Contoured poles to S_2 and linear F_2 fold axes and L_2 mineral lineations. The strike and dip of the average S_2 plane is indicated by the great circle (blue), and the point maxima for the linear data are indicated by a red triangle and plus sign. *C*, Contoured poles to S_3 and linear F_3 fold axes. The strike and dip of the average S_3 plane is indicated by the great circle (blue), and the point maximum for the linear data is indicated by a red plus sign. In all diagrams, north is marked by "N" and the contour interval is 2 percent. Data are plotted by using Structural Data Integrated System Analyser (DAISY, version 3.41) software by Salvini (2002). The notation for structural orientations that uses paired angles represents the horizontal component (strike or bearing) in the first value and the vertical component (dip or plunge) in the second value. For planar data, when compared with traditional notations, the structure orientation of 8°, 85°, would translate to N. 8° E., 85°SE., and 359°, 87° would translate to N. 01° W., 87° NE.

however, it is possible that some of the closures within the sillimanite schist (Zos) of the Old Lyme Gneiss could be the result of large-scale F_1 folding. The S_1 gneissosity predates emplacement of the Westerly Granite and Permian granite pegmatite (Pp) but postdates the youngest metasedimentary rocks, suggesting that it is the oldest fabric associated with the Alleghanian orogeny. The S_1 gneissosity is folded around the Lyme dome, and poles to S_1 define a great circle whose π pole plunges moderately to the north (fig. 7*A*). F_1 fold axes generally plunge down the dip of the foliation with a majority showing a northward trend. The bearing and plunge of F_1 fold axes varies across the map, however, as the result of folding around the Lyme dome and variations in the original orientation of F_1. Mineral lineations, as either aggregate or grain lineations (Passchier and Trouw, 2005), in the plane of S_1 (L_1) consist of quartz, plagioclase, K-feldspar, sillimanite, and (or) hornblende and, like the F_1 fold axes, generally trend steeply down the dip of S_1 and show a northward trend (figs. 6*C*, 7*A*).

D_2

The second deformational event (D_2) in the Old Lyme quadrangle is characterized by a variably developed cleavage to schistosity. This foliation, called S_2, is well developed in the schistose rocks and poorly developed to not present in the quartzofeldspathic gneissic rocks. Where S_2 is present in the gneissic rocks, it is locally a fracture cleavage (fig. 6*D*). The S_2 foliation predates the Westerly Granite and most exposures of the granite pegmatite. Where the granite pegmatite is finer grained, it is locally deformed and contains the S_2 foliation as a weakly developed cleavage (fig. 1*B*). The D_2 fabric postdates the Silurian and younger rocks. S_2 is attributed to the second deformational event of the Alleghanian orogeny. Locally S_2 is axial planar to outcrop-scale, upright, tight to open folds (F_2) that deform the dominant gneissic fabric (S_1) and older F_1 folds, and these folds are associated with the Lyme dome (fig. 6*D–F*). The average strike and dip of the S_2 foliation is 8°, 85°[5] (fig. 7*B*). The average bearing and plunge of F_2 fold axes and S_1/S_2 intersection lineations is 16°, 26°, and closely matches the orientation of the π pole (8°, 34°) to the great circle of deformed S_1 gneissosity (fig. 7*A*, *B*). The F_2 fold axes generally plunge to the north, but southward plunges occur locally, especially in the southeastern part of the map along the coast. Mineral lineations in the plane of S_2 (L_2) consist of aggregates of quartz, sillimanite, biotite, and (or) K-feldspar and are generally parallel to the F_2 fold axes.

While the Lyme dome is a D_2 structure that deforms S_1 and trends parallel to outcrop-scale F_2 folds with plunges to the north-northeast, the Selden Neck block is not related to D_2. In this quadrangle, S_1 foliation in the Selden Neck block strikes southwest and dips northwest, and occurs on the northwestern flank of the Lyme dome. The Selden Neck block is not a D_2 dome like the Lyme dome. Dixon and Lundgren (1968), and later Rodgers (1985), used the term "Selden Neck dome" on the basis of an apparent stratigraphic symmetry and interpreted that the rocks represented a southward-verging overturned anticline. This interpretation was questioned by Wintsch and others (1990) who introduced the idea that the Selden Neck rocks were fault bounded and renamed the feature the "Selden Neck block." Because the Rope Ferry Gneiss in the Selden Neck area is not exposed in a true dome, the term "Selden Neck block" from Wintsch and others (1990) is used in our report.

D_3

The third deformational event (D_3) in the Old Lyme quadrangle is characterized by boudinage and weak folding with associated fracture cleavage development (fig. 8). The foliation, called S_3, is well developed in the layered schistose and gneissic rocks and poorly developed to not present in the more massive gneissic rocks and young granites and pegmatites. The S_3 foliation was not observed in the Westerly Granite and the Permian granite pegmatite (Pp) because the cleavage is not penetrative, but pegmatite dikes locally intrude parallel to the S_3 cleavage suggesting that some of the dikes used the cleavage during intrusion (fig. 8*B*, *C*). The D_3 fabric postdates the youngest metasedimentary rocks. S_3 is attributed to the third deformational event of the Alleghanian orogeny. Locally S_3 is axial planar to upright, broad to open folds (F_3) that are associated with boudinage or pinch-and-swell structures (fig. 8*A*, *D*, *E*). The S_3 cleavage and F_3 folds generally deform the dominant gneissic fabric (S_1) but terminate within the granitic and pegmatitic layers within the metasedimentary rocks (fig. 8*D*, *E*). The average strike and dip of the S_3 cleavage is 259°, 87° (fig. 7*C*). The average bearing and plunge of F_3 fold axes and intersection lineations is 51°, 40°, but these linear elements show some variability due to the preexisting orientation of S_1 (fig. 7*C*).

Ductile Faults

Four thrust faults are mapped within the Old Lyme quadrangle, the Deep Creek fault, the Springdale Pond fault, the Olivers Hole fault, and the Ferry Point fault. The faults separate the Selden Neck block from the Lyme dome. The faults are parallel to the S_1 gneissosity and the contacts and are interpreted as D_1 features. The Deep Creek fault juxtaposes the Neoproterozoic Rope Ferry Gneiss (Zwr) in the Selden Neck block and the rocks of the schist and gneiss at Obed Heights (DSoh and DSohrs). The Deep Creek fault is exposed in the northwestern corner of the Old Lyme quadrangle, southeast of Deep Creek (fig. 9). Evidence for fault fabrics along the fault is not obvious, presumably because the fabric has been overprinted by subsequent metamorphism. DSohrs (rusty schist unit) occurs discontinuously along the Deep Creek fault and provides evidence for lower plate truncations. The Springdale Pond and Olivers Hole faults are conjectural. They juxtapose the rocks with the Silurian and Devonian sequence. These faults are conjectural because they are not exposed and there are no demonstrable upper or lower plate truncations. The Ferry Point fault places the Old Saybrook schist (DSos) over the granodiorite gneiss at Lord Hill (Zgdl), and it is conjectural because it is not exposed and there are no upper or lower plate truncations within this quadrangle. The arguments in favor of these major faults include the high degree of strain in this belt and the different isotopic signatures between metaigneous rocks in the Lyme dome and the Selden Neck block (Wintsch and others, 2005; Aleinikoff and others, 2007). A stratigraphic interpretation would be more difficult to defend because it would need to explain how the rocks of the Merrimack terrane were deposited between the rocks of the Avalon and Gander terranes, both below and above younger rocks. The transport direction of the faults is interpreted as generally north to northwest, parallel to the overall trend of L_1 lineations and F_1 fold axes. Wintsch and Sutter (1986) report a general southeast trend for transport on the Honey Hill fault associated with underplating of the Avalon terrane beneath the Merrimack and Putnam-Nashoba terranes. Wintsch and others (1990) suggest that the motion on their "Hunts Brook fault" and our Deep Creek fault was related to east-southeast transport of the Selden Neck block over the Lyme dome and that 5 to 10 km of displacement were possible. This general trend agrees with L_1 mineral lineations and F_1 fold axes from the northwestern part of our map.

[5]The notation for structural orientations that uses paired angles represents the horizontal component (strike or bearing) in the first value and the vertical component (dip or plunge) in the second value. For planar data, when compared with traditional notations, the structure orientation of 8°, 85°, would translate to N. 8° E., 85°SE., and 359°, 87° would translate to N. 01° W., 87° NE.

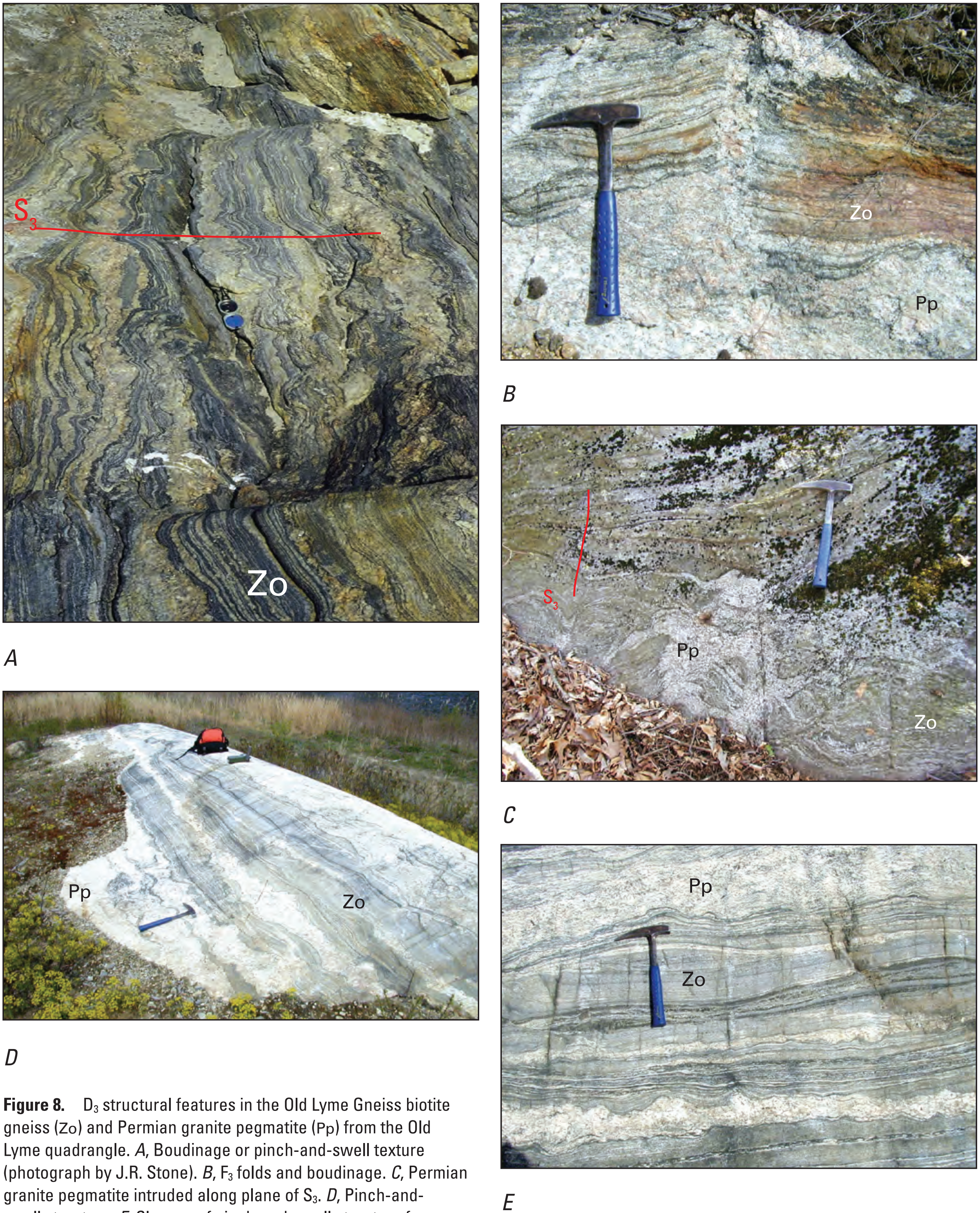


Figure 8. D_3 structural features in the Old Lyme Gneiss biotite gneiss (Zo) and Permian granite pegmatite (Pp) from the Old Lyme quadrangle. *A*, Boudinage or pinch-and-swell texture (photograph by J.R. Stone). *B*, F_3 folds and boudinage. *C*, Permian granite pegmatite intruded along plane of S_3. *D*, Pinch-and-swell structure. *E*, Closeup of pinch-and-swell structure from photograph *D* showing S_3 cleavage terminating in the pegmatite. In all photographs, S_3 is parallel to the hammer handle and (or) indicated by the red line. Locations for all photographs given in table 4 and shown on geologic map (sheet 1).

Figure 9. The Deep Creek fault (R.B. Scott pointing at the fault). Rocks to the left in the hanging wall are Rope Ferry Gneiss (Zwr), and rocks to the right in the footwall are rusty weathering schist and gneiss at Obed Heights (DSohrs). View is to the northeast, northwest is to the left. Location of this photograph given in table 4 and shown on geologic map (sheet 1).

Figure 10. Steeply dipping brittle normal fault in the granodiorite gneiss at Johnnycake Hill (Zgd). Fault is deeply weathered in a zone approximately 1 m thick. Fracture density decreases away from the fault. View looking west; south is to the left. The footwall is on the southern side of the fault (left). Location of this photograph given in table 4 and shown on geologic map (sheet 1).

Brittle Structures

The brittle structures in the area include faults, joints, and fractures developed parallel to gneissosity and cleavage (parting) (sheet 2). The orientation of joints measured in this study includes those with trace lengths greater than 20 cm (Barton and others, 1993). Joints were measured subjectively using methods described in Spencer and Kozak (1976) and Walsh and Clark (2000), and the data set includes the most conspicuous joints observed in a given outcrop. Joint data are plotted on rose diagrams (azimuth-frequency) and stereonets (lower hemisphere equal area projections) using Structural Data Integrated System Analyser (DAISY, version 3.41) software by Salvini (2002). The DAISY software uses a Gaussian curve-fitting routine that was first described by Wise and others (1985) for determining peaks in directional data (Salvini and others, 1999). These rose diagrams include strike data for steeply dipping fractures (dips >60°, after Mabee and others, 1994). Comprehensive analysis of brittle fracture data for paleostress analysis and hydrologic modeling was conducted by Zeitlhöfler (2003) and was not reproduced in this report.

Faults

Four minor outcrop-scale brittle faults were observed in the area and are shown by strike and dip symbols on sheet 2. All the faults were identified from slickensided surfaces. Of the four faults, two show normal relative motion, one shows left-lateral relative motion, and motion on the fourth could not be determined. The four faults dip steeply (>81°) and have variable strikes (5°, 249°, 124°, 254°). The two normal faults are characterized by approximately 1-m-thick zones of intense fracturing that decreases in intensity away from the fault (fig. 10). Zeitlhöfler (2003) found that normal faults were the most common brittle faults in his analysis of brittle fabrics in the region in and around the Old Lyme quadrangle. Two left-lateral faults were mapped in the northeastern part of the map. Fault surfaces in the northeastern part of the map, in the area of the two mapped left-lateral brittle faults, strike north and dip steeply east at 85°.

Joints

Joints measured in this study include fractures with no displacement that are not clearly associated with parting along a preexisting structure in the rock, such as foliation, axial surfaces, cleavage, and so on. Spacing of joint sets ranges from 5 cm (centimeters) to 7 m with an average of 1 m. Most joints are unmineralized, but a few contain trace patches of sulfide minerals and quartz. The connectivity of the joints is expressed as a percentage of blind (or "dead"), crossing, and abutting fractures after Barton and others (1993). The connectivity ratio in the data set is 43 percent blind, 37 percent crossing, and 20 percent abutting, suggesting moderate interconnectivity. The termination ratio is not representative of the entire data set, however, as it only includes joints where the termination could be unequivocally determined. Blind joints typically terminate within coarse pegmatite (fig. 11*A*), crossing joints transect all rock types (fig. 11*B*), and abutting joints terminate at foliation-parallel fractures called parting fractures (fig. 11*C*). In addition to recording joint termination, throughgoing joints that transect rather than terminate within the outcrop were recorded. Blind and abutting joints, by definition, cannot be throughgoing because their terminations

A

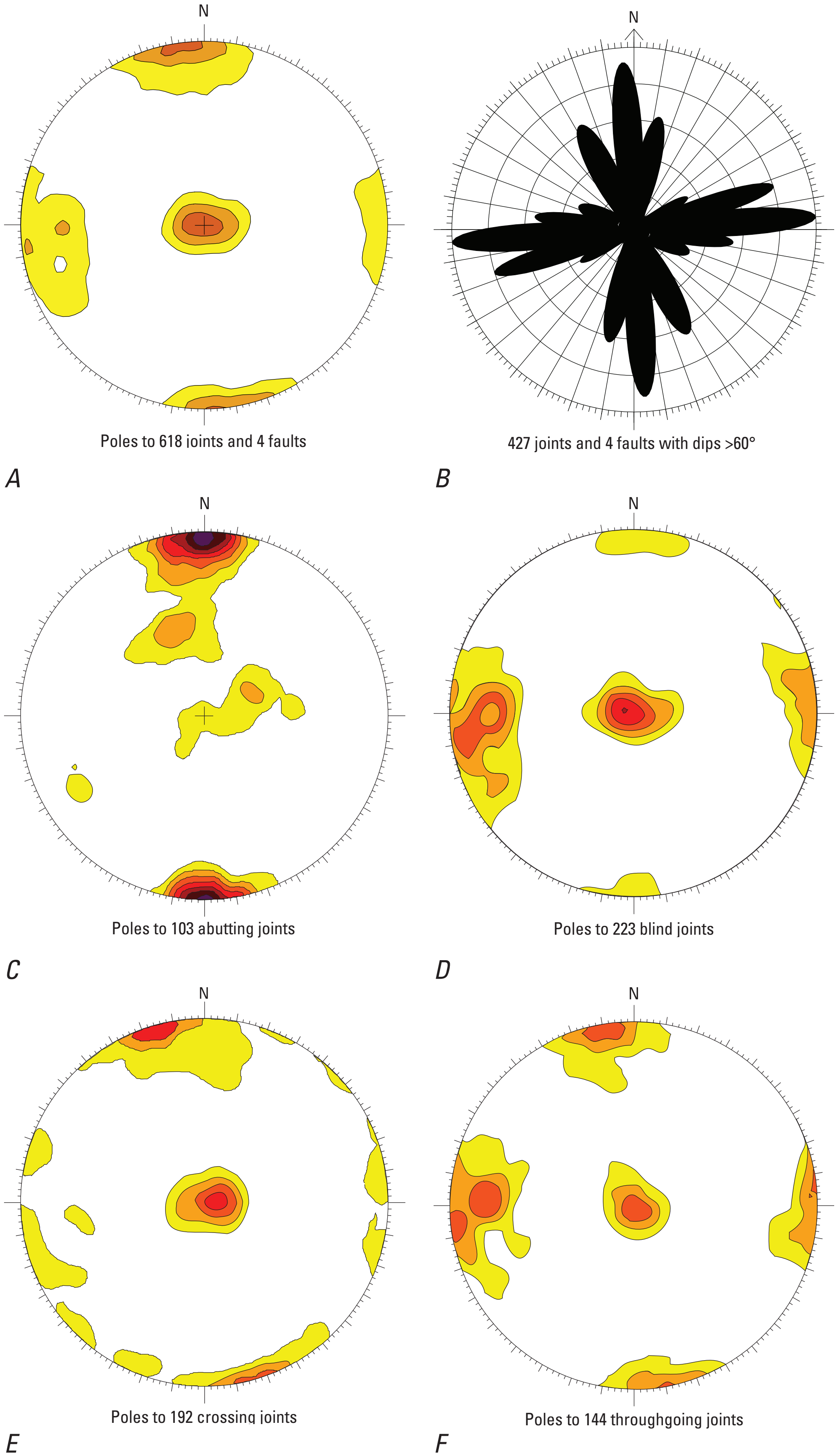
B

C

Figure 11. Photographs showing fracture characteristics in the Old Lyme quadrangle. *A*, Outcrop within the Old Lyme Gneiss biotite gneiss and amphibolite (dark rocks) shows that most joints terminate within or at the contact of the thicker layers of Permian granite pegmatite. These joints are parallel to S_3. *B*, East-west-trending joints parallel to S_3 in an I-95 northbound roadcut in the Old Lyme Gneiss biotite gneiss (Zo). The hammer handle is parallel to blind joints, and the cliff face is parallel to throughgoing joints. *C*, Foliation-parallel fractures or parting fractures (f), abutting joints (a), and crossing joints (x) in alaskite gneiss (Pa) at an outcrop in Rocky Neck State Park. The abutting joints in this photograph are generally representative of joints oriented parallel to the strike but perpendicular to the dip of the foliation. View is to the north; west is to the left. Locations for all photographs given in table 4 and shown on geologic map (sheet 1).

are visible in the outcrop, but crossing joints can be. Not all throughgoing joints are necessarily crossing, however, because if the throughgoing joint does not come in contact with other joints in the outcrop, the termination relations with other joints is not known. From 618 individual joint measurements, only 21 percent (127) are throughgoing indicating that most joints do not transect entire outcrops.

The majority of the joints observed in the area are steeply dipping, but gently dipping fractures or sheeting joints also are present, as shown by the tight concentration of poles in the center of the stereonet (fig. 12*A*, *C*–*F*). Joint orientations for the entire quadrangle show two dominant steeply dipping trends, east-northeast (86°±5°) and north-northwest (356°±6°) (fig. 12*B*), and the same trends are present in the subset of throughgoing joints (fig. 12*F*). Zeitlhöfler (2003) found the same two general trends in his regional analysis. Subsets of the joint data set separated by termination show different preferred orientations (fig. 12*C*–*E*). Abutting joints show a



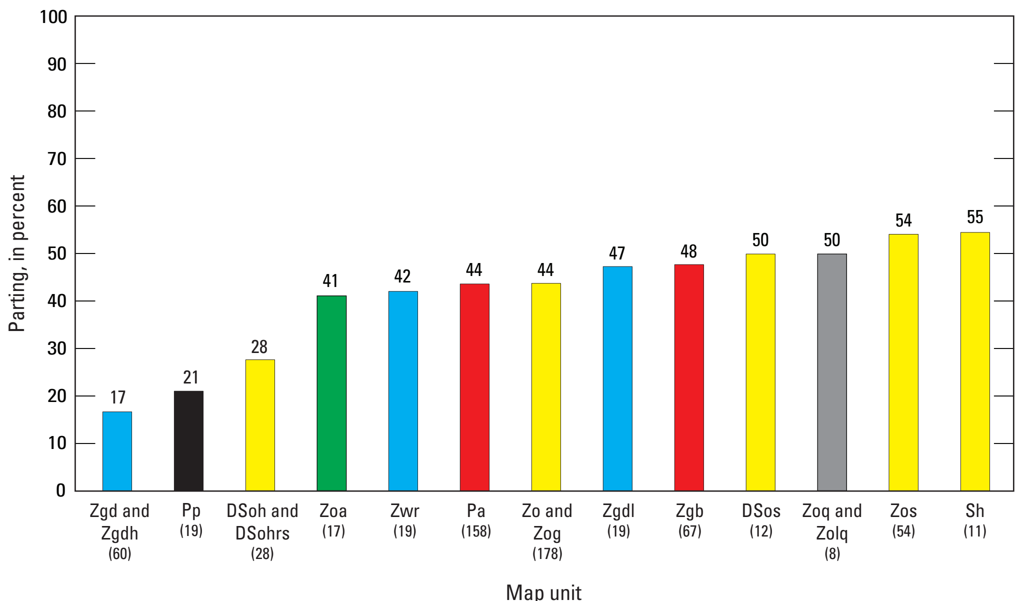
#	%	Nor. H.	azimuth	sd
1	14.3	100.0	86.0°	5.4°
2	15.2	91.1	356.2°	6.3°
3	10.7	78.5	72.7°	5.2°
4	11.1	59.7	12.7°	7.1°
5	13.1	61.0	332.6°	8.2°
6	7.5	50.7	277.5°	5.6°
7	2.4	25.3	349.2°	3.6°
8	6.2	26.5	292.8°	8.9°
9	4.1	28.1	58.9°	5.5°

Figure 12. Lower hemisphere equal area projection (stereonets) and normalized azimuth-frequency (rose) diagram of joints and brittle faults in the Old Lyme quadrangle. *A*, Stereonet for poles to all joints and faults. *B*, Rose diagram of joints and faults with dips >60°. The accompanying table shows trend number (#), followed by percent of total data per peak (%), peak height as a percentage of height of the tallest peak (Nor. H.), azimuth of each peak in degrees, and the standard deviation (sd) for each azimuth, in degrees, determined by a Gaussian curve-fitting routine. *C*, Stereonet for poles to abutting joints. *D*, Stereonet for poles to blind joints. *E*, Stereonet for poles to crossing joints. *F*, Stereonet for poles to throughgoing joints. In all diagrams, north is marked by "N." The contour interval in the stereonets is 2 percent. Data are plotted by using Structural Data Integrated System Analyser (DAISY, version 3.41) software by Salvini (2002).

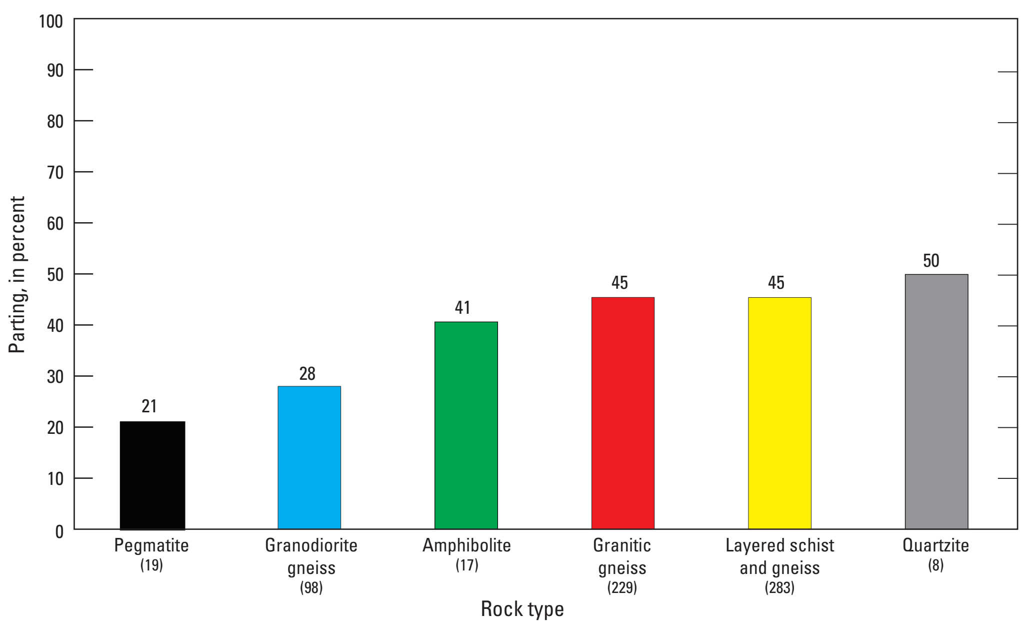
dominant steeply dipping east-west trend (fig. 12*C*). Blind joints show two dominant trends, steeply dipping east-northeast and subhorizontal (fig. *12D*). Crossing joints show two dominant trends, steeply dipping north-south and subhorizontal (fig. 12*E*).

Parting

In an effort to evaluate the control of rock type or preexisting structures on fracture development and orientation in the area, parting fracture data were collected along with structural measurements. The degree of parting is expressed as a percentage of the number of measurements that exhibit parting divided by the total number of measurements. Parting fractures were observed parallel to gneissosity, cleavage, axial surfaces of folds, and granite pegmatite dikes. In the database, planar structural features that exhibit parting as observed in the field at the point of measurement are assigned a “Y” which means “Yes.” Where these structures exhibit parting, their symbols are shown not only on the geologic map (sheet 1), but also on the brittle structure map (sheet 2) along with the standard brittle structures such as faults and joints. Parting data separated by relative age of ductile structure shows that the youngest (S_3) and oldest (S_1) surfaces exhibit a greater degree of parting than the intermediate surfaces (S_3 = 56 per-



A



B

Figure 13. Summary histograms of parting by map unit (*A*) and by rock type (*B*), expressed as a percentage of foliation or layer-parallel measurements that exhibit fracturing. The number on the top of each histogram represents the percentage, and the number at the bottom of each histogram represents the total number of measurements. Histograms in *A* are color coded by rock type shown in *B*. Map units PZmig and Pg are omitted from *A* because there are only four foliation measurements (three of the four show parting); both units are included in *B* in the granitic gneiss category.

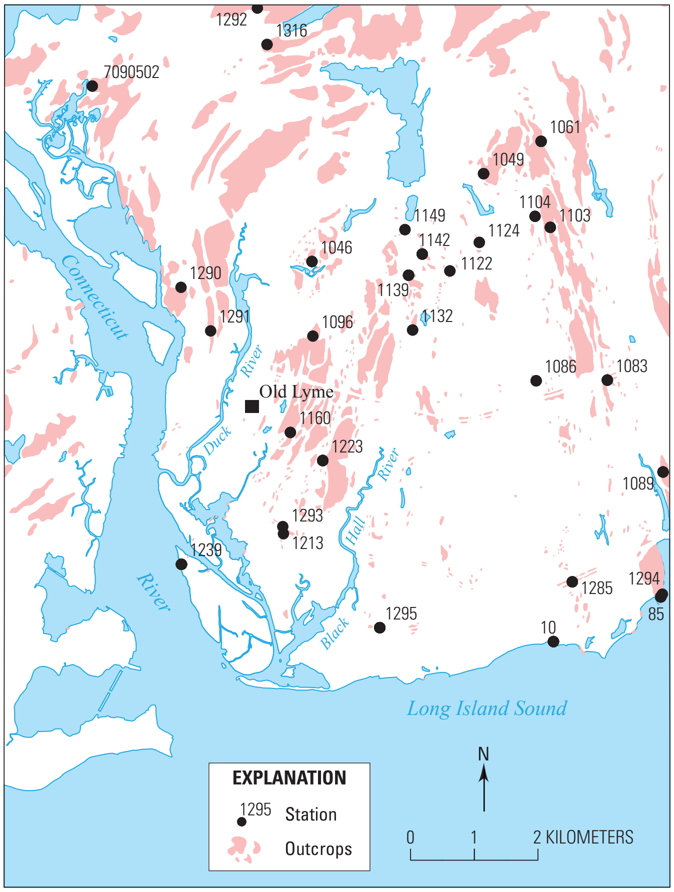


Figure 14. Station location map for U-Pb geochronology samples and photographs referred to in the report. See tables 3 and 4 for a summary of sample and figure numbers by station.

cent, S_2 = 17 percent, and S_1 = 33 percent). Parting in steeply dipping (dip >60°) younger surfaces is very well developed (S_3 = 95 percent and S_2 = 91 percent), whereas parting along steeply dipping S_1 (dip >60°) is developed to approximately the same degree as parting in the entire S_1 data set (36 percent). These findings suggest that the gneissic rocks in the area exhibit a significant amount of fracturing along preexisting surfaces. In fact 44 percent of all preexisting planar structures including gneissosity, cleavage, granite pegmatite dikes, and axial surfaces exhibit parting.

To assess whether primary layering or gneissosity (S_0 or S_1) controls parting in different rocks, parting data were separated by map unit and rock type for all cases of "gneissosity," "deformed gneissosity," and "layer parallel gneissosity" (fig. 13). The database contains 669 measurements of these three features, and 276 (41 percent) exhibit parting. The parting data by map unit show that most units exhibit between 41 and 55 percent parting (fig. 13*A*). The parting data by map unit show that granodiorite gneiss at Johnnycake Hill (Zgd), pegmatite (Pp), and schist and gneiss at Obed Heights (DSoh and DSohrs) exhibit the least parting in the area (fig. 13*A*). The pegmatite is rarely foliated and where parting exists, it generally occurs along the contact between pegmatite dikes and the country rock. The granodiorite gneiss at Johnnycake Hill is a moderately foliated rock, but its generally massive, unlayered texture inhibits parting. Thus, poorly foliated or massive igneous rocks exhibit the least parting along primary planar surfaces. When the map units are grouped by rock type (fig. 13*B*), parting data are similar for the remaining rock types (41–50 percent). Layered schist and gneiss and granitic gneiss show equal parting (45 percent), which suggests that the primary layering in the metasedimentary rocks and the well-developed foliation in the igneous rocks impart the same degree of layer-parallel fracturing to these rock types at this metamorphic grade.

Table 4. Locations of U-Pb geochronology samples and photographs referred to in the text.

["Station" corresponds to the unique location identifier in the GIS database. "East" and "North" indicate UTM coordinates zone 18 in NAD27 datum. Locations are plotted in figure 14 and are shown on geologic map (sheet 1)]

Station	East	North	Sample no.	Figure
10	728472	4573749		8*A*
85	730138	4574504		6*E*
1046	724488	4579623		6*B*
1049	727144	4581074		8*C*
1061	728048	4581609		5*B*
1083	729176	4577906		11*B*
1086	728073	4577859		5*A*
1089	730111	4576472		11*C*
1096	724537	4578438	OL96	5*D*
1103	728220	4580264		6*A*, 8*B*
1104	727987	4580424		8*D*, 8*E*
1122	726662	4579542		5*C*
1124	727085	4579987		5*E*
1132	726103	4578580		4*A*, 4*B*
1139	726011	4579443		1*C*
1142	726217	4579779		6*D*
1149	725954	4580156		6*C*
1160	724230	4576912		11*A*
1213	724177	4575297		4*C*
1223	724767	4576508		10
1239	722536	4574825		Cover
1285	728736	4574698		6*F*
1290	722440	4579140	OL290	
1291	722928	4578470	OL291	
1292	723506	4583570	OL292	
1293	724142	4575424	OL293	
1294	730160	4574550	OL294A, OL294B	1*A*, 1*B*
1295	725733	4573884	OL295	
1316	723860	4583010	OL316	
7090502	720945	4582262		9

Fracture Trend Analysis

The fracture trend analysis map on sheet 2 shows the distribution of fracture trends by domain. Domain boundaries occur parallel to geologic contacts and faults around the Lyme dome or at high angles to the geology-parallel boundaries, the latter of which are based on groupings of closely spaced outcrops where fracture measurements were collected. The domain boundaries were used to subdivide the outcrop data for spatial analysis, but may not necessarily separate rocks with distinctly different fracture trends (in other words, "fracture domains" of Mabee and Hardcastle, 1997).

Stereonets on the fracture trend analysis map depict all fracture data within a given domain, and rose diagrams show the azimuthal trends for the steeply dipping subset of fractures. Fracture trend orientations shown on the rose diagrams show principal trends generally ranging from north-south to east-west. A principal fracture trend is defined as having normalized peaks greater than 50 percent of the highest peak (Hardcastle, 1995). Each of these two principal directions matches the primary directions for the S_2 (north-south) and S_3 (east-west) foliations, suggesting that the major fracture directions in the area are inherited from the older ductile fabrics in the rocks. These two trends are most apparent in the domains around the Lyme dome. Domains 1 and 9 in the northwestern part of the map have northeastern and northwestern fracture trends that do not appear as principal trends in the other parts of the map, suggesting that the area northwest of the Ferry Point fault represents a separate fracture domain as defined by Mabee and Hardcastle (1997). Domains 1 and 9 may have distinctly different fracture trends because they are removed from the influence of the S_2 and S_3 structures present around the Lyme dome. Zeitlhöfler's (2003) study also found the same regional fracture domains, and he called them the Selden Neck Domain and the Lyme Dome Domain.

Metamorphism

The rocks in the Old Lyme quadrangle are metamorphosed to upper amphibolite facies conditions. Rocks in the Lyme dome experienced peak metamorphic conditions above the second sillimanite, or sillimanite-orthoclase, isograd. In this map, the second sillimanite isograd occurs in the Selden Neck block; however, we extrapolated its location on the basis of work by Lundgren (1966b, 1967) because the rocks of the Rope Ferry Gneiss are granodioritic, not pelitic, and contain virtually no sillimanite. Rocks in the northwestern corner of the map apparently experienced peak metamorphic conditions in the sillimanite-muscovite zone. Lundgren (1966b) estimated temperatures above 650°C for rocks in the sillimanite-orthoclase zone, and related the migmatites in the area to this event. This period of metamorphism has been attributed to the Alleghanian orogeny in the Avalon terrane (Lundgren, 1966b; Dallmeyer, 1982; Wintsch and Aleinikoff, 1987; Zartman and Hermes, 1987; Wintsch and others, 1992, 2003). Peak metamorphic mineral assemblages are associated with D_1 and D_2 structures in the area, as indicated by sillimanite and K-feldspar mineral growth in the L_1 and L_2 lineations. No evidence of polymetamorphism was found in the Gander terrane rocks, suggesting that the peak metamorphic conditions spanned the development of D_1 and D_2 structures, and hence they are also Alleghanian. SHRIMP ages from monazite (about 271–259 Ma) and metamorphic overgrowths on zircon (about 259 Ma) from the dated Westerly Granite and granite pegmatite samples at Point O'Woods suggest that Alleghanian post-tectonic heating continued through the development of D_3. Both the Hebron Formation and the schist and gneiss at Obed Heights contain zircons that have relict metamorphic overprints at about 360 to 350 Ma suggesting that the metasedimentary rocks between the Avalon and Gander terranes experienced Acadian metamorphism, and perhaps deformation, that has been completely reset by Alleghanian events.

References Cited

Aleinikoff, J.N., Wintsch, R.P., Tollo, R.P., and Unruh, D.M., 2007, Ages and origin of the Killingworth dome, south-central Connecticut; Implications for the tectonic evolution of southern New England: American Journal of Science, v. 307, p. 63–118.

Barton, C.C., Larsen, Eric, Page, W.R., and Howard, T.M., 1993, Characterizing fractured rock for fluid-flow, geomechanical, and paleostress modeling; Methods and preliminary results from Yucca Mountain, Nevada: U.S. Geological Survey Open-File Report 93–269, 62 p., 1 pl. in pocket.

Buma, Grant, Frey, F.A., and Wones, D.R., 1971, New England granites; Trace element evidence regarding their origin and differentiation: Contributions to Mineralogy and Petrology, v. 31, no. 4, p. 300–320.

Burton, W.C., Walsh, G.J., and Armstrong, T.R., 2000, Bedrock geologic map of the Hubbard Brook Experimental Forest, Grafton County, New Hampshire: U.S. Geological Survey Open-File Report 00–45, scale 1:10,000.

Dale, T.N., and Gregory, H.E., 1911, The granites of Connecticut: U.S. Geological Survey Bulletin 484, 137 p.

Dallmeyer, R.D., 1982, $^{40}Ar/^{39}Ar$ ages from the Narragansett Basin and southern Rhode Island basement terrane; Their bearing on the extent and timing of Alleghenian tectonothermal events in New England: Geological Society of America Bulletin, v. 93, no. 11, p. 1118–1130.

Dixon, H.R., and Lundgren, L.W., Jr., 1968, Structure of eastern Connecticut, *in* Zen, E-an, White, W.S., Hadley, J.B., and Thompson, J.B., Jr., eds., Studies of Appalachian geology; Northern and maritime: New York, Wiley Interscience Publishers, p. 219–229.

Feininger, T.G., 1963, Westerly Granite and related rocks of the Westerly-Bradford area, Field Trip G, *in* New England Intercollegiate Geological Conference, 55th Annual Meeting, Providence, R.I., Oct. 4–6, 1963, Guidebook: Providence, R.I., p. 48–55.

Feininger, Tomas, 1965, Bedrock geologic map of the Ashaway quadrangle, Connecticut-Rhode Island: U.S. Geological Survey Geologic Quadrangle Map GQ–403, scale 1:24,000.

Feininger, Tomas, 1968, The updip termination of a large dike of Westerly Granite and the regional distribution of the Westerly and Narragansett Pier Granites in Rhode Island and Connecticut: U.S. Geological Survey Professional Paper 600–D, p. D181–D185.

Goldsmith, Richard, 1967a, Bedrock geologic map of the Niantic quadrangle, New London County, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ–575, scale 1:24,000.

Goldsmith, Richard, 1967b, Bedrock geologic map of the Montville quadrangle, New London County, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ–609, scale 1:24,000.

Goldsmith, Richard, 1976, Pre-Silurian stratigraphy of the New London area, southeastern Connecticut, *in* Page, L.R., Contributions to the stratigraphy of New England: Geological Society of America Memoir 148, p. 271–275.

Goldsmith, Richard, 1980, Stratigraphic names in the New London area, southeastern Connecticut; A revision, *in* Sohl, N.F., and Wright, W.B., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1979: U.S. Geological Survey Bulletin 1502–A, p. 91–103.

Goldsmith, Richard, 1985, Honey Hill fault and Hunts Brook syncline, Trip C–4, *in* New England Intercollegiate Geological Conference, 77th Annual Meeting, New Haven, Conn., Oct. 4–6, 1985, Guidebook for fieldtrips in Connecticut and adjacent areas of New York and Rhode Island: Connecticut Geological and Natural History Survey Guidebook 6, p. 491–507. (Edited by R.J. Tracy.)

Goldsmith, Richard, 1988, Tectonic significance of dikes of Westerly Granite, southeastern Connecticut and southwestern Rhode Island: Northeastern Geology, v. 10, no. 3, p. 195–201.

Gregory, H.E., 1906, Manual of the geology of Connecticut: Connecticut State Geological and Natural History Survey Bulletin no. 6, 273 p.

Hardcastle, K.C., 1995, Photolineament factor; A new computer-aided method for remotely sensing the degree to which bedrock is fractured: Photogrammetric Engineering and Remote Sensing, v. 61, no. 6, p. 739–747.

Hermes, O.D., and Zartman, R.E., 1985, Late Proterozoic and Devonian plutonic terrane within the Avalon zone of Rhode Island: Geological Society of America Bulletin, v. 96, no. 2, p. 272–282.

Hozik, M.J., 1988, Tectonic implications of the brittle fracture history of the Permian Narragansett Pier Granite, Rhode Island, *in* Bartholomew, M.J., Hyndman, D.W., Mogk, D.W., and Mason, R., eds., Basement tectonics 8—Characterization and comparison of ancient and Mesozoic continental margins—Proceedings of the Eighth International Conference on Basement Tectonics, 1988, Butte, Montana: Boston, Kluwer Academic Publishers, p. 503–525.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, no. 5, p. 523–548.

Kemp, J.F., 1899, Granites of southern Rhode Island and Connecticut with observations on Atlantic coast granites in general: Geological Society of America Bulletin, v. 10, p. 361–382.

Lundgren, Lawrence, Jr., 1963, The bedrock geology of the Deep River quadrangle: State Geological and Natural History Survey of Connecticut Quadrangle Report no. 13, 40-p. text, 1 sheet, scale 1:24,000.

Lundgren, Lawrence, Jr., 1964, The bedrock geology of the Essex quadrangle: State Geological and Natural History Survey of Connecticut Quadrangle Report no. 15, 36-p. text, 1 sheet, scale 1:24,000.

Lundgren, Lawrence, Jr., 1966a, The bedrock geology of the Hamburg quadrangle: State Geological and Natural History Survey of Connecticut Quadrangle Report no. 19, 41-p. text, 1 sheet, scale 1:24,000.

Lundgren, L.W., Jr., 1966b, Muscovite reactions and partial melting in southeastern Connecticut: Journal of Petrology, v. 7, no. 3, p. 421–453.

Lundgren, Lawrence, Jr., 1967, The bedrock geology of the Old Lyme quadrangle: State Geological and Natural History Survey of Connecticut Quadrangle Report no. 21, 30-p. text, 1 sheet, scale 1:24,000.

Mabee, S.B., and Hardcastle, K.C., 1997, Analyzing outcrop-scale fracture features to supplement investigations of bedrock aquifers: Hydrogeology Journal, v. 5, no. 4, p. 21–36.

Mabee, S.B., Hardcastle, K.C., and Wise, D.U., 1994, A method of collecting and analyzing lineaments for regional-scale fractured-bedrock aquifer studies: Ground Water, v. 32, no. 6, p. 884–894.

Maniar, P.D., and Piccoli, P.M., 1989, Tectonic discrimination of granitoids: Geological Society of America Bulletin, v. 101, no. 5, p. 635–643.

Nichols, D.R., 1956, Bedrock geology of Narragansett Pier quadrangle, Rhode Island: U.S. Geological Survey Geologic Quadrangle Map GQ–91, scale 1:31,680.

O'Connor, J.T., 1965, A classification for quartz-rich igneous rocks based on feldspar ratios: U.S. Geological Survey Professional Paper 525–B, p. B79–B84.

Passchier, C.W., and Trouw, R.A.J., 2005, Microtectonics: Berlin, Springer, 366 p.

Rodgers, John, comp., 1985, Bedrock geological map of Connecticut: [Hartford] Connecticut Geological and Natural History Survey, 2 sheets, scale 1:125,000.

Salvini, Francesco, 2002, Structural Data Integrated System Analyser (DAISY, version 3.41): Rome, Italy, Universita degli Studi di "Roma Tre," Dipartimento di Scienze Geologiche, software available at http://host.uniroma3.it/progetti/fralab/Downloads/Programs/.

Salvini, Francesco, Billi, Andrea, and Wise, D.U., 1999, Strike-slip fault-propagation cleavage in carbonate rocks; The Mattinata fault zone, southern Apennines, Italy: Journal of Structural Geology, v. 21, no. 12, p. 1731–1749.

Shand, S.J., 1951, Eruptive rocks; Their genesis, composition, classification, and their relation to ore-deposits, with a chapter on meteorites (4th ed.): New York, John Wiley & Sons, 488 p.

Skehan, J.W., and Rast, Nicholas, 1990, Pre-Mesozoic evolution of Avalon terranes of southern New England, *in* Socci, A.D., Skehan, J.W., and Smith, G.W., eds., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 13–53.

Spencer, E.W., and Kozak, S.J., 1976, Determination of regional fracture patterns in Precambrian rocks—A comparison of techniques, *in* Hodgson, R.A., Gay, S.P., Jr., and Benjamins, J.Y., eds., Proceedings of the First International Conference on the New Basement Tectonics, Salt Lake City, Utah, June 3–7, 1974: Utah Geological Association Publication 5, p. 409–415.

Taggart, J.E., Jr., ed., 2002, Analytical methods for chemical analysis of geologic and other materials, U.S. Geological Survey: U.S. Geological Survey Open-File Report 02–223, version 5.0, http://pubs.usgs.gov/of/2002/ofr-02-0223/.

Walsh, G.J., and Clark, S.F., Jr., 2000, Contrasting methods of fracture trend characterization in crystalline metamorphic and igneous rocks of the Windham quadrangle, New Hampshire: Northeastern Geology and Environmental Sciences, v. 22, no. 2, p. 109–120.

Walsh, G.J., Aleinikoff, J.N., and Wintsch, R.P., 2007, Origin of the Lyme dome and implications for the timing of multiple Alleghanian deformational and intrusive events in southern Connecticut: American Journal of Science, v. 307, no. 1, p. 168–215.

Wintsch, R.P., 1979, Recent mapping in the Chester area, Connecticut, and its bearing on the Chester syncline [abs.]: Geological Society of America Abstracts with Programs, v. 11, no. 1, p. 60.

Wintsch, R.P., 1985, Bedrock geology of the Deep River area, Connecticut, *in* New England Intercollegiate Geological Conference, 77th Annual Meeting, New Haven, Conn., Oct. 4–6, 1985, Guidebook for fieldtrips in Connecticut and adjacent areas of New York and Rhode Island: Connecticut Geological and Natural History Survey Guidebook 6, p. 115–141. (Edited by R.J. Tracy.)

Wintsch, R.P., 1994, Bedrock geologic map of the Deep River area, Connecticut: Connecticut Geological and Natural History Survey, Open-File Map Series 94–1, scale 1:24,000.

Wintsch, R.P., and Aleinikoff, J.N., 1987, U-Pb isotopic and geologic evidence for late Paleozoic anatexis, deformation, and accretion of the late Proterozoic Avalon terrane, south-central Connecticut: American Journal of Science, v. 287, no. 2, p. 107–126.

Wintsch, R.P., and Sutter, J.F., 1986, A tectonic model for the late Paleozoic of southeastern New England: Journal of Geology, v. 94, p. 459–472.

Wintsch, R.P., Andrews, M.S., and Ambers, C.P., 1990, Thrust napping versus fold napping in the Avalon terrane of southeastern Connecticut, *in* Socci, A.D., Skehan, J.W., and Smith, G.W., eds., Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 209–233.

Wintsch, R.P., Sutter, J.F., Kunk, M.J., Aleinikoff, J.N., and Dorais, M.J., 1992, Contrasting P-T-t paths; Thermochronologic evidence for a late Paleozoic final assembly of the Avalon composite terrane in the New England Appalachians: Tectonics, v. 11, no. 3, p. 672–689.

Wintsch, R.P., Kunk, M.J., Boyd, J.L., and Aleinikoff, J.N., 2003, P-T-t paths and differential Alleghanian loading and uplift of the Bronson Hill terrane, south central New England: American Journal of Science, v. 303, no. 5, p. 410–446.

Wintsch, R.P., Aleinikoff, J.N., Scott, R.B., Walsh, G.J., Yacob, E.Y., and Stone, J.R., 2004, SHRIMP geochronology of detrital zircons from metasedimentary rocks in south-central Connecticut; Preliminary interpretations of the tectonic evolution of the Avalon terrane of southern New England [abs.]: Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 130.

Wintsch, R.P., Aleinikoff, J.N., Unruh, D.M., and Walsh, Greg, 2005, Evidence for tectonic wedging of Avalon terrane rocks into the Gander zone, southern New England [abs.]:

Geological Society of America Abstracts with Programs, v. 37, no. 1, p. 31.

Wintsch, R.P., Aleinikoff, J.N., Walsh, G.J., Bothner, W.A., Hussey, A.M., and Fanning, C.M., 2007, SHRIMP U-Pb evidence for a Late Silurian age of metasedimentary rocks in the Merrimack and Putnam-Nashoba terranes, eastern New England: American Journal of Science, v. 307, no. 1, p. 119–167.

Wise, D.U., Funiciello, Renato, Parotto, Maurizio, and Salvini, Francesco, 1985, Topographic lineament swarms; Clues to their origin from domain analysis of Italy: Geological Society of America Bulletin, v. 96, no. 7, p. 952–967.

Zartman, R.E., and Hermes, O.D., 1987, Archean inheritance in zircon from late Paleozoic granites from the Avalon zone of southeastern New England; An African connection: Earth and Planetary Science Letters, v. 82, no. 3–4, p. 305–315.

Zartman, R.E., Hermes, O.D., and Pease, M.H., Jr., 1988, Zircon crystallization ages, and subsequent isotopic disturbance events, in gneissic rocks of eastern Connecticut and western Rhode Island: American Journal of Science, v. 288, no. 4, p. 376–402.

Zeitlhöfler, M., 2003, Bedrock structure in southeastern Connecticut; Hydrologic implications: Middletown, Connecticut, Wesleyan University, unpublished M.S. thesis, 194 p.