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Bedrock Geologic Map of the Nashua South Quadrangle, Hillsborough County, New Hampshire, and Middlesex County, Massachusetts

By Gregory J. Walsh, Richard H. Jahns, and John N. Aleinikoff

Pamphlet to accompany

Scientific Investigations Map 3200

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)

Bedrock Geologic Map of the Nashua South Quadrangle, Hillsborough County, New Hampshire, and Middlesex County, Massachusetts

By Gregory J. Walsh,[1] Richard H. Jahns,[2] and John N. Aleinikoff[3]

Introduction

The bedrock of the Nashua South quadrangle consists primarily of Silurian metasedimentary rocks of the Berwick Formation. Regionally, the Berwick Formation is part of the Merrimack belt (Zen and others, 1983) or the Merrimack trough (Lyons and others, 1997). Recent work by Hussey and others (2010) discusses the ongoing problems with the stratigraphic position of the Berwick Formation and now suggests a correlation with the Central Maine sequence. This area of the Merrimack trough is referred to as the Rockingham subbelt (Robinson and Goldsmith, 1991) or the Rockingham anticlinorium (Billings, 1956; Goldsmith, 1991). The Rockingham anticlinorium lies east of the Nashua trough, but the boundary between the two is not well-defined (Goldsmith, 1991). The boundary may locally be a fault (Smith and Barosh, 1981) or occupied by the Hudson pluton (Walsh and Clark, 1999). The Nashua South quadrangle is located approximately 1 kilometer (km) north and west of the Clinton-Newbury fault and the rocks of the Nashoba zone. The metasedimentary rocks are intruded by a Late Silurian to Early Devonian diorite-gabbro suite, Devonian rocks of the Ayer Granodiorite, Devonian granitic rocks of the New Hampshire Plutonic Suite including pegmatite and the Chelmsford Granite, and Jurassic diabase dikes. All of the rocks except the Jurassic diabase dikes were deformed and metamorphosed during the Devonian Acadian orogeny. This work represents mapping by G.J. Walsh and R.H. Jahns and geochronology by J.N. Aleinikoff.

The purpose of this report is to present new data on the stratigraphic, structural, and geochronologic relations in the Merrimack belt. We present new geochronology results for the Ayer Granodiorite and Chelmsford Granite, which are scientifically significant because of problems associated with previously published ages of these rocks. The work was initiated in response to the study of a methane-yielding bedrock water well (location 2007–1399 on map) in the town of Tyngsborough, Mass. (Pierce and others, 2007).

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Previous Work

The 7.5-minute Nashua South quadrangle was formerly named the Tyngsborough quadrangle. Jahns mapped the New Hampshire part of the Tyngsborough quadrangle in 1951 and the Massachusetts part from 1939 to 1941. Jahns' unpublished manuscript maps of the quadrangle, showing geologic units, strike and dip of dominant foliation, and some outcrop locations, were obtained from the Richard Jahns Collection at the Branner Earth Sciences Library, Stanford University, Palo Alto, Calif. Jahns published a preliminary map (Jahns and others, 1959) covering the Massachusetts part of the Nashua South quadrangle. In 2006, Walsh checked and revised contacts and collected samples and structural data. In some places, outcrops visited by Jahns no longer exist due to subsequent development in the area over the last 60+ years.

Work in adjacent quadrangles includes 7.5-minute-scale mapping by Jahns and others (1959), Alvord (1975), Robinson (1978, 1981), Walsh and Clark (1999), Kopera (2006), and Kopera and others (2008) and 15-minute-scale mapping by Sriramadas (1966). A number of topical studies have focused on the Chelmsford Granite, and these papers are discussed later in the text.

Age of the Rocks

The Berwick Formation is considered Late Silurian (Wenlockian to Ludlovian) on the basis of U-Pb sensitive high resolution ion microprobe (SHRIMP) ages of detrital zircons as young as approximately 425 Ma (mega-annum) and the age of crosscutting intrusions dated at 414±3 Ma and 418±2 Ma (Wintsch and others, 2007). The intermediate to mafic rocks of the diorite-gabbro suite are correlated with the Exeter Diorite in New Hampshire, dated by conventional U-Pb zircon analysis at 406±1 Ma (Bothner and others, 1993) and with the Dracut Diorite, dated at approximately 408 Ma (Bothner, 1974). An Rb/Sr whole rock age of 473±1 Ma reported by Bothner and others (1984) and Gaudette and others (1984) is problematic because it is older than the maximum age of approximately 425 Ma for the Berwick Formation

(Wintsch and others, 2007). The intermediate to mafic rocks (map units DSdi and DSgn) have not been dated by modern methods, and the possibility exists that their ages may range into the Silurian; thus we consider them Late Silurian to Early Devonian. Wones and Goldsmith (1991) stated that the dioritic and gabbroic rocks intruded both the Berwick Formation and the Ayer Granodiorite, but the latter observation could not be confirmed here. The geochronology data suggest that the granodiorite phase of the Ayer Granodiorite and the ages of the Exeter and Dracut Diorites are approximately the same within uncertainty. The rocks of the Ayer Granodiorite are considered Early Devonian on the basis of a SHRIMP U-Pb zircon age of 407±4 Ma from the Devens-Long Pond facies (see geochronology section). The diorite-gabbro suite and the rocks of the Ayer Granodiorite are intruded by Devonian granitic rocks of the New Hampshire Plutonic Suite including pegmatite and the Late Devonian Chelmsford Granite. A SHRIMP U-Pb zircon age of 375±3 Ma from the Chelmsford Granite supports this age assignment (see geochronology section). The pegmatites occur as foliation-parallel sills and crosscutting tabular dikes. The youngest pegmatite dikes cut the Chelmsford Granite; their upper age limit is not known but is presumed to be Late Devonian or perhaps Permian. The age of the Jurassic diabase dikes is based on a correlation with the dated Medford diabase shown on the Massachusetts State map (Zen and others, 1983), which yielded a K-Ar biotite age of 194±6 Ma (Zartman and Marvin, 1991; Wones and Goldsmith, 1991). The dikes in this quadrangle are probably part of the regionally extensive Higganum-Holden-Onway dike that extends from southern Connecticut to Maine (McHone and Sundeen, 1995).

Stratigraphy

The metasedimentary rocks of the Berwick Formation (Sb) consist of interbedded biotite-plagioclase-quartz granofels with minor amounts of schist and calc-silicate rocks (fig. 1). The unit crops out widely in the northern two-thirds of the map and as thin belts, screens, or xenoliths in the Ayer and Chelmsford Granites in the south. Variability in the Berwick Formation is expressed by the percentage of laminated granofels and calc-silicate rocks. Locally, laminated varieties of the Sb unit are composed of closely spaced (millimeter to centimeter), white-weathering leucocratic quartz-plagioclase-calc-silicate layers alternating with gray, biotite-plagioclase-quartz granofels layers (fig. 1*A*, *B*). The laminations are subparallel to bedding and locally define the bed-parallel S_1 schistosity or second-generation S_2 foliation. In places, the Berwick Formation is not distinctly laminated, and it consists of well-layered granofels and more massive sandy granofels interbedded with minor amounts of schist (fig. 1*B*, *E*, *F*). The massive sandy granofels is well exposed at Interchange 3 on U.S. Route 3 (fig. 1*E*). Calc-silicate rocks occur as thin layers, lenses, boudins, veins, or isolated pods of granofels or foliated gneiss throughout the Berwick Formation (fig. 1*C*, *D*). The distribution of calc-silicate rocks could not be mapped; their abundance typically varies from approximately 5 percent, or less, up to about 30 percent. This variability is in contrast to what Sriramadas (1966) reported; he found about 5 percent in the lower member and about 15 percent in the upper member of the Berwick Formation, and we could not use the distribution or abundance of calc-silicate rocks as mapping criteria. The Berwick Formation here is similar to the Berwick Formation in the adjacent Windham quadrangle to the northeast (Walsh and Clark, 1999).

Polydeformed bedding consists of folded layering and boudins (fig. 1*F*). Sedimentary topping criteria such as graded bedding are rare (fig. 1*F*). No marker horizons were mapped in the Berwick Formation, thus making it difficult to determine the thickness and regional structure of the formation. Typical exposures of the Berwick Formation occur at roadcuts throughout the map area, especially along U.S. Route 3 and at a quarry on the western side of Bear Hill in the southwestern corner of the map.

A migmatitic version of the Berwick Formation (SbDc) occurs along the margin of the Chelmsford Granite. This zone of rock, as much as 1 km wide, consists of metasedimentary rocks with abundant injected foliation-parallel granite and pegmatite sills (fig. 2*A*). The unit consists of 50 to 75 percent granitic rock. Similar migmatitic rocks also occur where the Berwick Formation exhibits assimilation along the margins of xenoliths in granite and pegmatite, but these mixed zones are too small to map separately (fig. 2*B*).

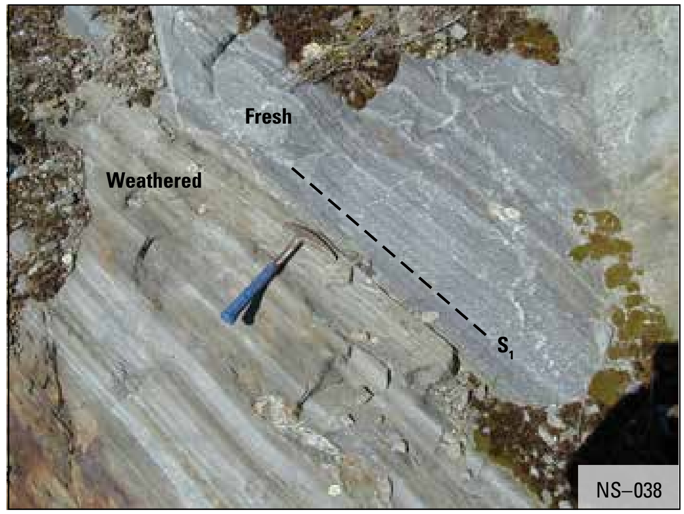
Igneous Rocks

Four phases of intrusive igneous rocks are present in the area: (1) a diorite-gabbro suite, (2) rocks of the Ayer Granodiorite, (3) rocks of the New Hampshire Plutonic Suite, and (4) Jurassic diabase dikes. The first three phases are meta-igneous rocks senso stricto, but the prefix "meta" has been omitted for brevity.

Figure 1 (facing page). Photographs of the Berwick Formation. *A*, Thin, tan and white laminations of quartz and plagioclase define the S_1 schistosity. S_1 is deformed by an F_2 fold, and the short-dashed line shows the S_2 axial planar foliation (station NS–009 in database). *B*, Well-layered granofels; here the layering defines the S_1 schistosity (station NS–038). *C*, Thin, folded calc-silicate laminations (CS) (station NS–115). *D*, Calc-silicate pods and boudins (CS) in granofels cut by granite and pegmatite dikes of the New Hampshire Plutonic Suite (station NS–115). *E*, Massive, thickly bedded sandy granofels; circled hammer for scale (station NS–150). *F*, Rarely observed graded bedding shows sedimentary topping direction (arrows show up), overturned beds, and thin metapelite horizons (dark colored) interlayered with metapsammitic granofels (light colored). Bedding (S_0) is locally isoclinally folded and deformed by boudinage and younger cleavage (S_2) (station NS–099). The locations of all figures with photographs are shown on the map with a camera icon. Station locations identified in the text are in the GIS database that accompanies this report. The GIS database contains additional photographs that are not used as figures in this report.

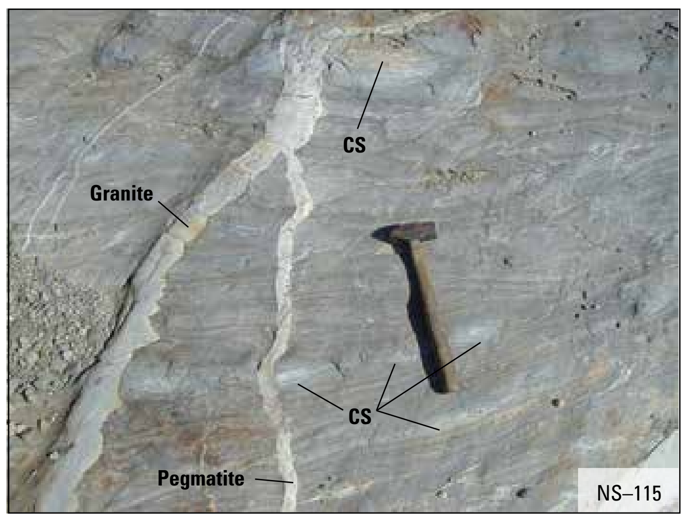
A. **Laminated**

B. **Layered**

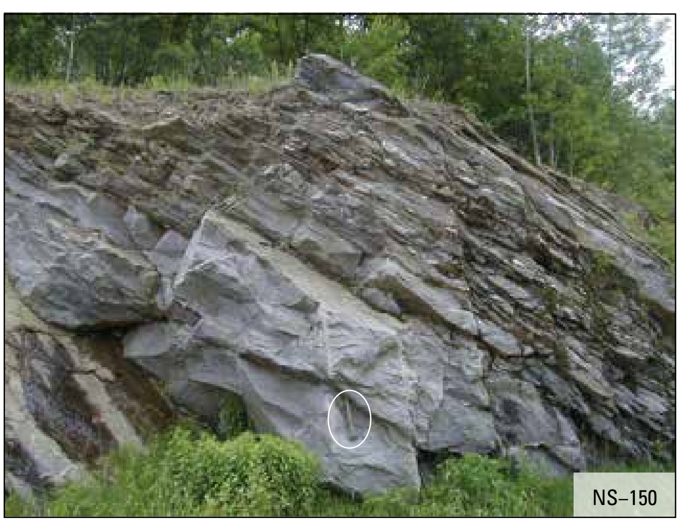


C. **Thin calc-silicate layers**

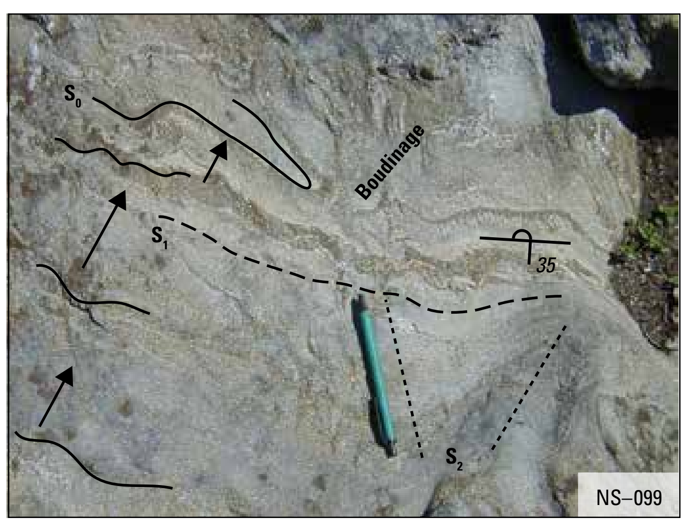
D. **Calc-silicate pods and boudins**



E. **Massive granofels**



F. **Graded bedding**



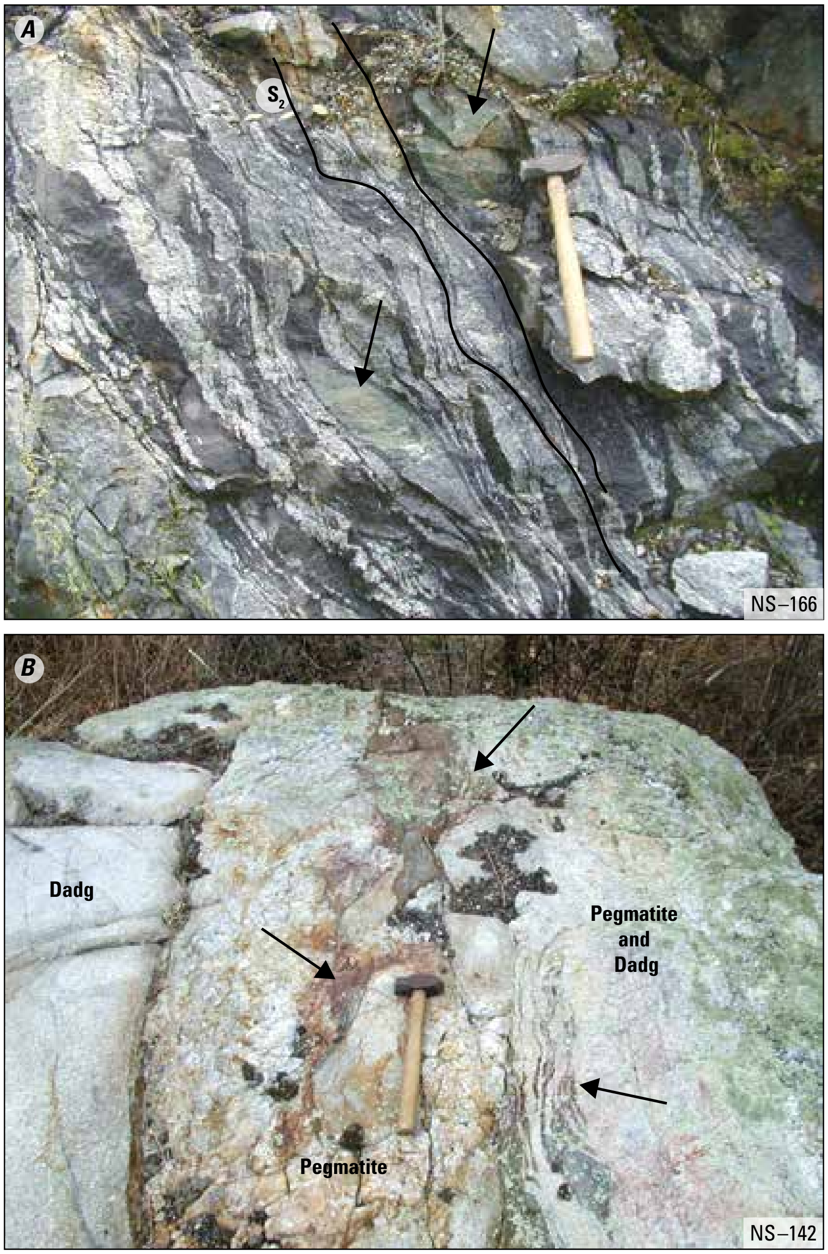


Figure 2. Photographs of migmatitic Berwick Formation. *A*, Interlayered leucocratic granitic and pegmatitic material (light colored) intrude the gray Berwick Formation parallel to the dominant foliation (S_2) in map unit SbDc. Arrows point to greenish calc-silicate pods (station NS–166). *B*, Screens of migmatitic Berwick Formation (arrows) along the margins of a New Hampshire Plutonic Suite pegmatite and biotite granodiorite (Dadg) of the Ayer Granodiorite (station NS–142).

Diorite-Gabbro Suite

Intermediate to mafic rock units include fine- to medium-grained diorite-gabbro (DSdi) and medium- to coarse-grained diorite-gabbro (DSgn). These rocks are equigranular, weakly foliated metadiorites and metagabbros (fig. 3*A*, *B*), although the composition of the plagioclase appears to be less than An_{50} in all cases. Considerable calcium exchange is evident in the coarse-grained rocks where plagioclase is saussuritized and titanite, epidote, and apatite are ubiquitous trace metamorphic minerals. Pyroxene was replaced by hornblende or fine-grained uralite, and minor amounts of serpentine in one sample (NS–040, table 1) suggest replacement of olivine. Modal compositions of the rocks are shown in table 1. Six small plutons (as much as 1 km^2) occur in the area, in addition to a number of smaller intrusions. The contacts with the adjacent units are not exposed. Outcrop-scale xenoliths of the Berwick Formation were observed in the pluton exposed along the eastern edge of the map in Pelham, and in the adjacent Pepperell quadrangle in the DSgn body west of Conant Road in Nashua. In several places the fine-grained unit (DSdi) is closely associated and interlayered with granodioritic rocks (Dadp and Dadg) of the Ayer Granodiorite, and some of these rocks may represent less-differentiated phases of the Ayer magma. Both the fine- and medium- to coarse-grained units are cut by two-mica granite and pegmatite dikes of the New Hampshire Plutonic Suite (fig. 3*C*).

The rocks of the diorite-gabbro suite are correlated with the Exeter Diorite and the Dracut Diorite (Lyons and others, 1997; Wones and Goldsmith, 1991; Zen and others, 1983) and a number of similar plutons in the Merrimack belt (Watts and others, 2000). Regional chemistry of this suite suggests that the rocks developed as arc-related magmas (Watts and others, 2000).

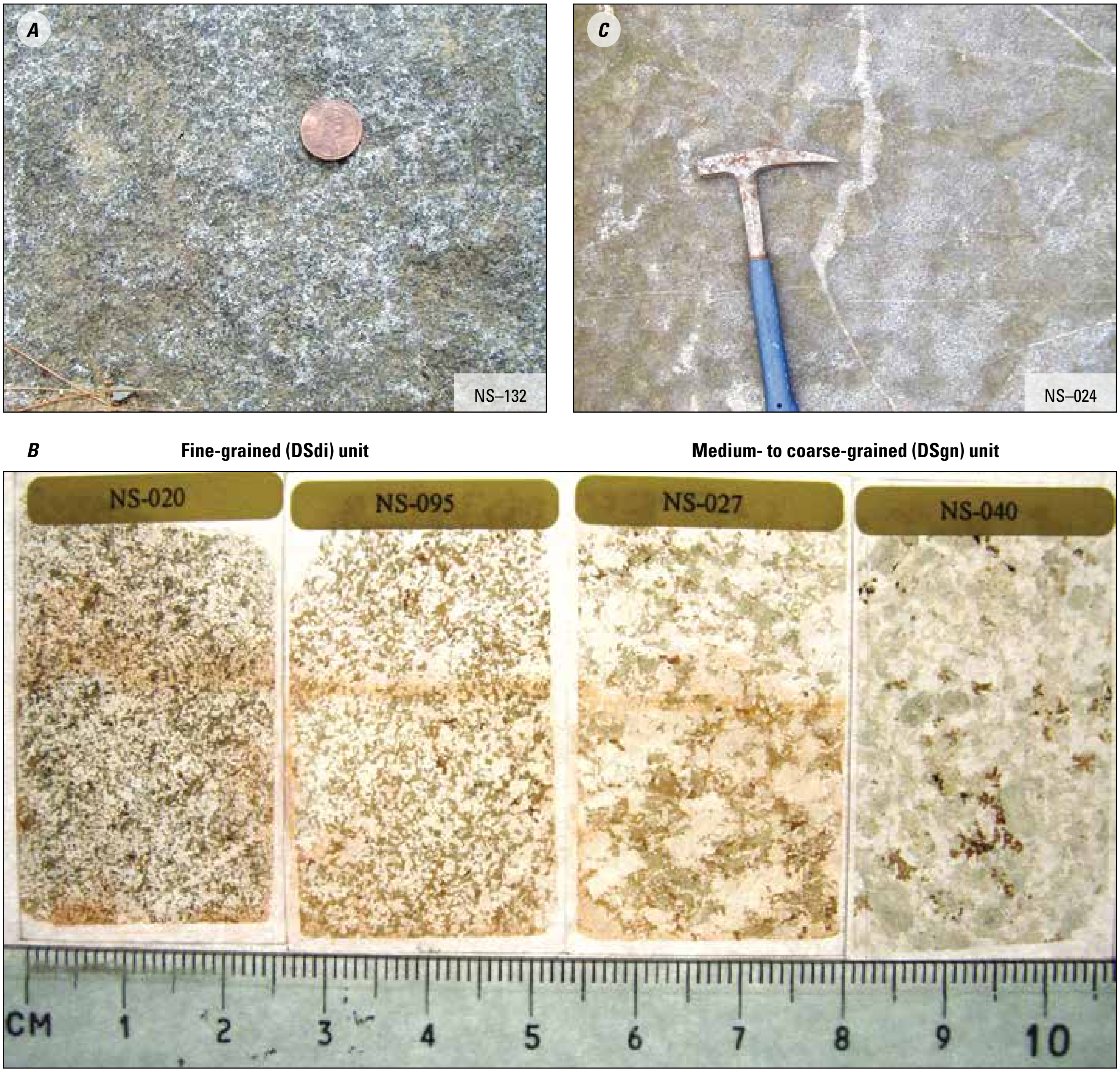


Figure 3. Photographs of the diorite-gabbro suite. *A*, Outcrop of the medium- to coarse-grained rock (DSgn) (station NS–132). *B*, Photomicrographs of entire thin sections showing the texture and grain size of the fine-grained (DSdi) and medium- to coarse-grained (DSgn) rocks. *C*, Outcrop of fine-grained diorite (DSdi) cut by granite dikes of the New Hampshire Plutonic Suite (station NS–024). The thicker dike in the center of the photograph is deformed by F_3 folds.

Ayer Granodiorite—Devens-Long Pond Facies

Mapped units of the Ayer Granodiorite include biotite granodiorite (Dadg), biotite granodiorite with microcline megacrysts (Dadp), and hornblende-biotite granite to tonalite (Dad) (fig. 4*A–D*). Granularity and the presence of hornblende are the two main criteria for separating the map units. The predominantly medium-grained equigranular rocks, Dadg and Dad, contain only trace amounts of deformed feldspar megacrysts found ubiquitously in the inequigranular Dadp. Detailed feldspar analyses suggest that the megacrysts are porphyroblasts consisting largely of microcline and minor plagioclase (Gore, 1976). Biotite and small amounts of muscovite, but no hornblende, are present in Dadg and Dadp. Hornblende

Table 1. Modal compositions and rock classifications of selected rocks from the diorite-gabbro suite.

[Modal compositions were based on a minimum of 200 point counts. The rock classifications were based on proportions of normalized quartz (Q), alkali feldspar (A), and plagioclase (P) as shown in the International Union of the Geological Sciences (IUGS) rock classification diagram (see fig. 5). tr, trace amount (less than 0.1 percent)]

Sample no.	NS–020	NS–095	NS–027	NS–040	NS–123	NS–125	NS–132
Grain size	Fine	Fine	Medium to coarse	Medium to coarse	Medium to coarse	Medium to coarse	Medium to coarse
Map unit label	DSdi	DSdi	DSgn	DSgn	DSgn	DSgn	DSgn
Points counted	212	212	216	213	207	211	207
Modal composition, in percent							
Quartz	0.9	5.7	9.3	0.0	4.8	1.9	0.5
Plagioclase	43.4	63.2	52.8	20.7	35.3	37.4	46.9
Alkali feldspar	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Biotite	21.2	17.0	12.0	11.7	11.1	14.2	7.7
Muscovite	0.0	0.0	0.0	0.0	0.0	3.8	0.5
Hornblende	28.8	10.4	8.8	64.8	48.8	40.3	38.2
Actinolite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	0.0	0.0	11.1	0.5	0.0	0.9	1.4
Opaques, including magnetite	1.9	0.9	0.0	1.4	0.0	0.5	1.4
Hematite	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Titanite	0.9	0.9	1.9	tr	tr	tr	2.4
Apatite	0.9	0.9	1.9	0.5	tr	tr	1.0
Epidote	tr	tr	tr	tr	tr	tr	tr
Clinozoisite	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Allanite	1.4	0.0	0.0	0.0	0.0	0.0	0.0
Saussurite	tr	tr	2.3	tr	tr	tr	tr
Garnet	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zircon	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Serpentine	0.0	0.0	0.0	0.5	0.0	0.0	0.0
Calcite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Rock classification							
Q	2	8	15	0	12	5	1
P	98	92	85	100	88	95	99
A	0	0	0	0	0	0	0
Rock type	Diorite	Diorite	Quartz diorite	Diorite	Diorite	Diorite	Diorite

is diagnostic of Dad. Modal compositions of selected rocks from the Ayer Granodiorite are shown in table 2 and plotted in figure 5. The rocks plot as quartz monzodiorite, tonalite, granodiorite, and monzogranite (fig. 5).

Rocks of the Ayer Granodiorite occur in three distinct belts. In the southwestern part of the map, all three units of Ayer Granodiorite are complexly interleaved with diorite-gabbro suite rocks (DSdi and DSgn). This area marks the northeasternmost extent of the Ayer pluton, which extends to the southwest into the Ayer quadrangle (Kopera, 2006). In the east-central part of the map, the Dadp and Dadg units are interleaved with the fine-grained diorite-gabbro unit (DSdi); this belt extends into the Lowell and Windham quadrangles (Jahns, 1942; Currier and Jahns, 1952; Jahns and others, 1959; Walsh and Clark, 1999). In the southeastern corner of the map, only the hornblende-biotite granite to tonalite (Dad) unit is mapped. Poor exposure limited our ability to identify and map other units of the Ayer Granodiorite.

At many places, xenoliths and large screens of the Berwick Formation were observed in the units of the Ayer Granodiorite (fig. 4*C*, *D*). Where exposed, the contacts along the margins of the plutons are generally sharp and locally marked by thin zones (as much as a few meters thick) of migmatization. These zones are characterized by abundant leucocratic and pegmatitic material and injected sills of granodioritic rock. All three units in the Ayer Granodiorite are cut by two-mica granite and pegmatite dikes of the New Hampshire Plutonic Suite (fig. 4*B*).

Chemically, the dated sample of Ayer Granodiorite (NS–187, Dadp) is a granodiorite that plots on the metaluminous-peraluminous limit (table 3, fig. 6*B*, *C*). The sample has fairly steep

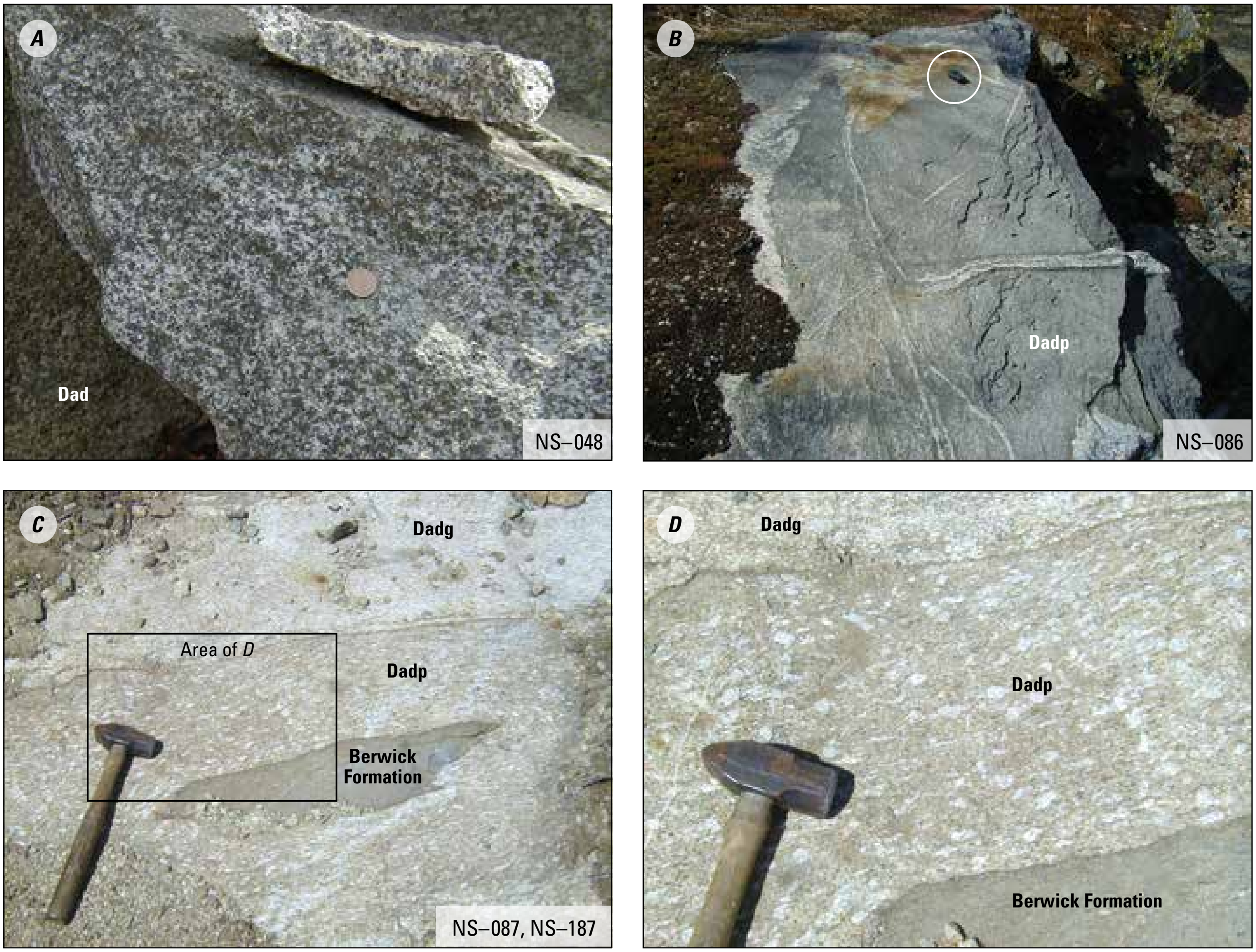


Figure 4. Photographs of the Ayer Granodiorite. *A*, Coarse-grained hornblende-biotite granite to tonalite (Dad) (station NS–048). *B*, Megacrystic biotite granodiorite (Dadp) cut by light-colored two-mica granite and pegmatite dikes of the New Hampshire Series Plutonic Suite; circled GPS receiver for scale (station NS–086). *C*, Map view of megacrystic biotite granodiorite (Dadp) at the dated sample locality (407±4 Ma) showing sharp contact with biotite granodiorite (Dadg) and xenolith of the Berwick Formation (Sb) (station NS–087, NS–187). *D*, Close-up of area shown in *C* showing microcline megacrysts in Dadp that have been deformed into augen. The S_2 foliation in *C* and *D* trends parallel to the long axis of the xenolith.

light rare-earth element abundances with normalized La values of approximately 150, relatively flat heavy rare-earth elements, and a prominent negative Eu anomaly (fig. 6*D*). The Nb versus Y tectonic discrimination diagram (fig. 6*F*) shows the rock as a syn-collisional granite, consistent with the chondrite-normalized rare-earth-element patterns.

In Massachusetts, this belt of rocks was mapped as the “Ayer Granite” by Zen and others (1983) after Emerson (1917). In New Hampshire, the rocks were mapped as “Ayer Granodiorite” by Lyons and others (1997) after descriptions by Jahns (1942) and Currier and Jahns (1952). Gore (1976) used the name “Devens-Long Pond Gneiss” for a phase of the “Ayer Crystalline Complex.” Zen and others (1983) and Wones and Goldsmith (1991) revised the name defined by Gore (1976) to “Devens-Long Pond facies of the Ayer Granite.” The type localities in the Ayer quadrangle include both inequigranular, porphyroblastic and equigranular varieties (Gore, 1976). Our data show the rocks here are dominantly granodioritic in composition, so we apply the name “Ayer Granodiorite” as used on the New Hampshire map (Lyons and others, 1997) and described by Jahns (1942) and Currier and Jahns (1952). In addition, we use the name “Devens-Long Pond facies” for the rocks of the Ayer Granodiorite because the rocks in the Nashua South quadrangle match the original description of Gore (1976) at the type locality. Furthermore, the belt of Devens-Long Pond facies of the Ayer Granodiorite northwest of the main belt of Chelmsford Granite is part of the Ayer pluton senso stricto and is contiguous along strike to the type locality approximately 10 km to the southwest (Gore, 1976; Kopera, 2006; Kopera and others, 2008). Rocks of the “Clinton facies” of the Ayer

Table 2. Modal compositions and rock classifications of selected rocks from the Ayer Granodiorite.

[Modal compositions were based on a minimum of 200 point counts. The rock classifications were based on proportions of normalized quartz (Q), alkali feldspar (A), and plagioclase (P) as shown in the International Union of the Geological Sciences (IUGS) rock classification diagram (see fig. 5). tr, trace amount (less than 0.1 percent)]

	Dated rock						
Sample no.	**NS–085**	**NS–048**	**NS–180**	**NS–063**	**NS–157**	**NS–087**	**NS–187**
Map unit label	**Dadg**	**Dad**	**Dad**	**Dad**	**Dad dike**	**Dadp**	**Dadp**
Points counted	**308**	**215**	**211**	**422**	**214**	**416**	**418**
Modal composition, in percent							
Quartz	26.6	22.3	14.2	19.9	11.2	14.7	31.6
Plagioclase	38.6	17.7	48.8	24.6	37.4	60.8	45.0
Alkali feldspar	8.1	30.7	0.5	28.4	13.6	10.8	10.8
Biotite	23.4	22.8	23.2	20.4	34.1	6.7	10.5
Muscovite	2.6	0.0	0.0	0.0	0.0	5.3	1.4
Hornblende	0.0	6.0	11.4	5.2	0.5	0.0	0.0
Actinolite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	0.6	0.0	0.0	0.2	0.5	0.0	0.5
Opaques, including magnetite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hematite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Titanite	0.0	0.5	1.4	0.7	0.9	0.2	0.0
Apatite	0.0	0.0	0.0	0.2	0.5	0.2	0.2
Epidote	0.0	0.0	0.5	0.2	0.5	0.0	0.0
Clinozoisite	0.0	0.0	0.0	0.0	0.5	1.2	0.0
Allanite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Saussurite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Garnet	0.0	0.0	0.0	0.0	0.5	0.0	0.0
Zircon	tr	tr	tr	tr	tr	tr	tr
Serpentine	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calcite	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Rock classification							
Q	36	32	22	27	18	17	36
P	53	25	77	34	60	70	52
A	11	43	1	39	22	13	12
Rock type	**Biotite granodiorite**	**Hornblende-biotite monzogranite**	**Hornblende-biotite tonalite**	**Hornblende-biotite monzogranite**	**Hornblende-biotite monzodiorite**	**Biotite monzodiorite**	**Biotite granodiorite**

Granodiorite mapped elsewhere contain large microcline megacrysts as much as 10 cm (centimeters) long (Gore, 1976; Zen and others, 1983; Wones and Goldsmith, 1991); rocks matching this description were not observed in the Nashua South quadrangle but occur in the adjacent Ayer and Westford quadrangles (Kopera, 2006; Kopera and others, 2008).

New Hampshire Plutonic Suite

Rocks of the New Hampshire Plutonic Suite occur as plutons, dikes, and sills of two-mica granite and granitic pegmatite. Two phases of the Chelmsford Granite (Dcgr and Dcfgr) and a pegmatite phase (Dp) are recognized and mapped in this quadrangle.

Chelmsford Granite

Rocks of the Chelmsford Granite are muscovite-biotite granites (Dcgr and Dcfgr). The main Chelmsford pluton is medium-grained granite (Dcgr) (fig. 7). The Dcgr granite locally exhibits internal compositional layering of light-gray and dark-gray granite that we interpret as flow banding (fig. 7). The flow banding is best viewed on quarry faces cut by a wire saw (fig. 7*A*–*C*). On the map we show the flow banding with a special strike and dip symbol only in the areas of the Fletcher and Le Masurier Quarries where it is distinct from the subsequent metamorphic foliation (S_2). Elsewhere on the map, the S_2 strike and dip symbol shows either the flow banding or the dominant metamorphic foliation, which is often

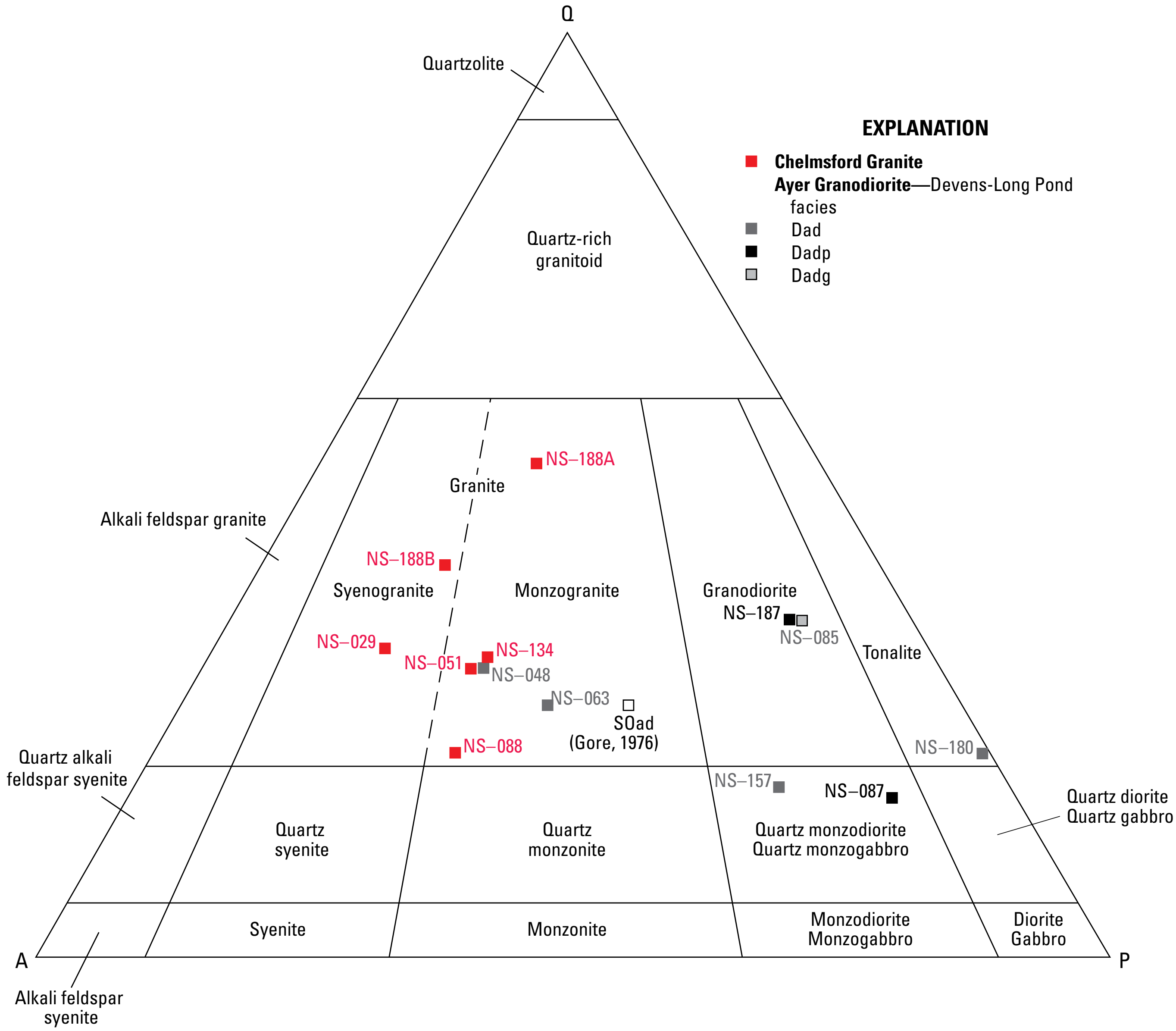


Figure 5. International Union of the Geological Sciences (IUGS) rock classification of samples of Ayer Granodiorite and Chelmsford Granite. The rock classification was based on proportions of normalized quartz (Q), alkali feldspar (A), and plagioclase (P). Modal composition data are shown in tables 2 and 4, respectively. SOad shows the average composition of Devens-Long Pond facies of Gore (1976).

indistinguishable away from the quarry faces. The banding in the rock led to earlier descriptions of the rock as gneiss (Dale, 1908, 1911, 1923), and the term “granite gneiss” is still used in the commercial granite industry. The light-gray and dark-gray bands in the granite have almost the same mineralogy, but the dark-gray bands contain less quartz and more biotite. Analyzed samples show that the light-gray granite, a monzogranite, contains more quartz and plagioclase, but less K-feldspar, muscovite, and biotite than the dark-gray granite, a syenogranite (samples NS–188A and NS–188B, respectively, table 4). In places, the lighter colored monzogranite intrudes the darker colored syenogranite by lit-par-lit injection (fig. 7*B*), and in the Chelmsford pluton, the lighter colored monzogranite is volumetrically more abundant. Minor amounts of muscovite granite, with trace amounts of biotite and garnet, occurs in the area but could not be mapped separately.

The compositional banding in the Chelmsford Granite has been noted by previous workers (Currier, 1937, 1947; Jahns, 1942, 1948; Currier and Jahns, 1952; Martin, 1973). Currier interpreted the banding as relict bedding from the host rock (Currier, 1937, 1947; Currier and Jahns, 1952), and Currier used this observation as partial evidence for in situ static metasomatic replacement as a mechanism of “granitization” for granite formation. Jahns (1942, 1948) disagreed, however, and interpreted the igneous rocks of both the Ayer and Chelmsford as injected magma. A detailed study of the Chelmsford Granite by Martin (1973) supports the magmatic origin for this rock. The composition of the darker colored

Table 3. Major, trace, and rare-earth element whole-rock geochemistry of the dated samples of the Ayer Granodiorite and Chelmsford Granite.

[Mass spectrometry analyses by SGS Canada Inc. Major oxide abundances by X-ray fluorescence (XRF) fused disk (SGS method XRF76Z). Trace- and rare-earth-element abundances by inductively coupled plasma (ICP) sodium peroxide fusion (SGS method ICM90A). Ma, mega-annum].

Sample no.		NS–187	NS–188A
Map unit label		Dadp	Dcgr
Map unit name		Ayer Granodiorite	Chelmsford Granite
	Detection limit	U-Pb zircon age this study (Ma)	
		407±4	375±3
Major oxide abundances, in weight percent, and loss on ignition			
SiO_2	0.01	70.1	75.7
Al_2O_3	0.01	14.2	12.9
Fe_2O_3T[1]	0.01	4.11	1.3
MgO	0.01	0.85	0.19
CaO	0.01	2.41	0.84
Na_2O	0.01	3.68	2.94
K_2O	0.01	3.62	5.61
TiO_2	0.01	0.51	0.12
P_2O_5	0.01	0.15	0.05
MnO	0.01	0.07	0.03
Cr_2O_3	0.01	<0.01	<0.01
Loss on ignition	0.01	0.24	0.25
Total	0.01	100	99.9
Trace- and rare-earth-element abundances, in parts per million			
Ba	0.5	286	152
Be	5	<5	<5
Cr	10	20	<10
Cu	5	<5	<5
Li	10	80	80
Mn	10	470	200
Ni	5	11	6
Sc	5	<5	<5
Sr	0.1	137	44.2
V	5	32	<5
Zn	5	70	30
Ag	1	<1	<1
As	30	<30	<30
Bi	0.1	<0.1	0.8
Cd	0.2	<0.2	<0.2
Ce	0.1	70.6	53.3
Co	0.5	4.3	1.1
Cs	0.1	4.1	5.6

Sample no.		NS–187	NS–188A
Map unit label		Dadp	Dcgr
Map unit name		Ayer Granodiorite	Chelmsford Granite
	Detection limit	U-Pb zircon age this study (Ma)	
		407±4	375±3
Trace- and rare-earth-element abundances, in parts per million—Continued			
Dy	0.05	2.68	2.48
Er	0.05	1.44	1.37
Eu	0.05	0.85	0.44
Ga	1	22	20
Gd	0.05	4.39	3.9
Ge	1	2	2
Hf	1	11	3
Ho	0.05	0.46	0.44
In	0.2	<0.2	<0.2
La	0.1	34.3	24
Lu	0.05	0.22	0.19
Mo	2	<2	<2
Nb	1	19	9
Nd	0.1	27.8	21.8
Pb	5	31	66
Pr	0.05	7.71	6.01
Rb	0.2	153	247
Sb	0.1	0.1	0.2
Sm	0.1	5.3	4.9
Sn	1	3	4
Ta	0.5	0.7	0.6
Tb	0.05	0.59	0.53
Th	0.1	15.9	13.3
Tl	0.5	1	1.6
Tm	0.05	0.16	0.15
U	0.05	3.11	9.65
W	1	<1	3
Y	0.5	12.6	12.3
Yb	0.1	1.2	1.1
Zr	0.5	341	92.1

[1]Fe_2O_3T, total iron calculated as Fe_2O_3.

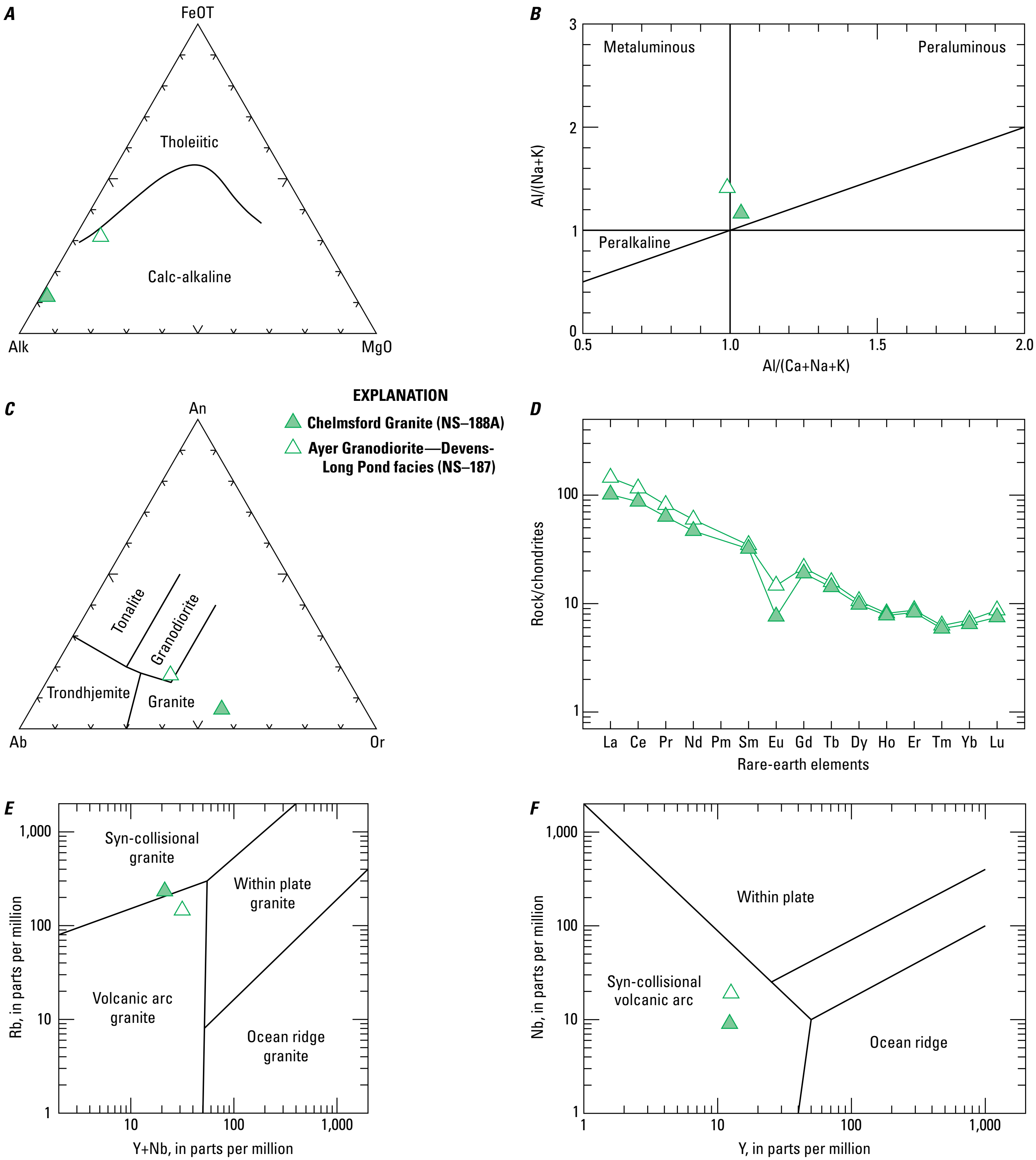


Figure 6. Major-, trace-, and rare-earth-element discrimination diagrams for the dated samples of the Ayer Granodiorite and Chelmsford Granite. *A*, Na_2O+K_2O(Alk)-FeOT-MgO (AFM) diagram after Irvine and Baragar (1971). *B*, Alumina saturation diagram after Shand (1951) and Maniar and Piccoli (1989). *C*, Normative An-Ab-Or classification diagram of O'Connor (1965) and Barker (1979). *D*, Rock-chondrite normalized rare-earth-element diagram after Sun and McDonough (1989). *E*, Rb versus Y+Nb and *F*, Nb versus Y tectonic discrimination diagrams after Pearce and others (1984). See text for discussion. An, anorthite; Ab, albite; Or, orthoclase.

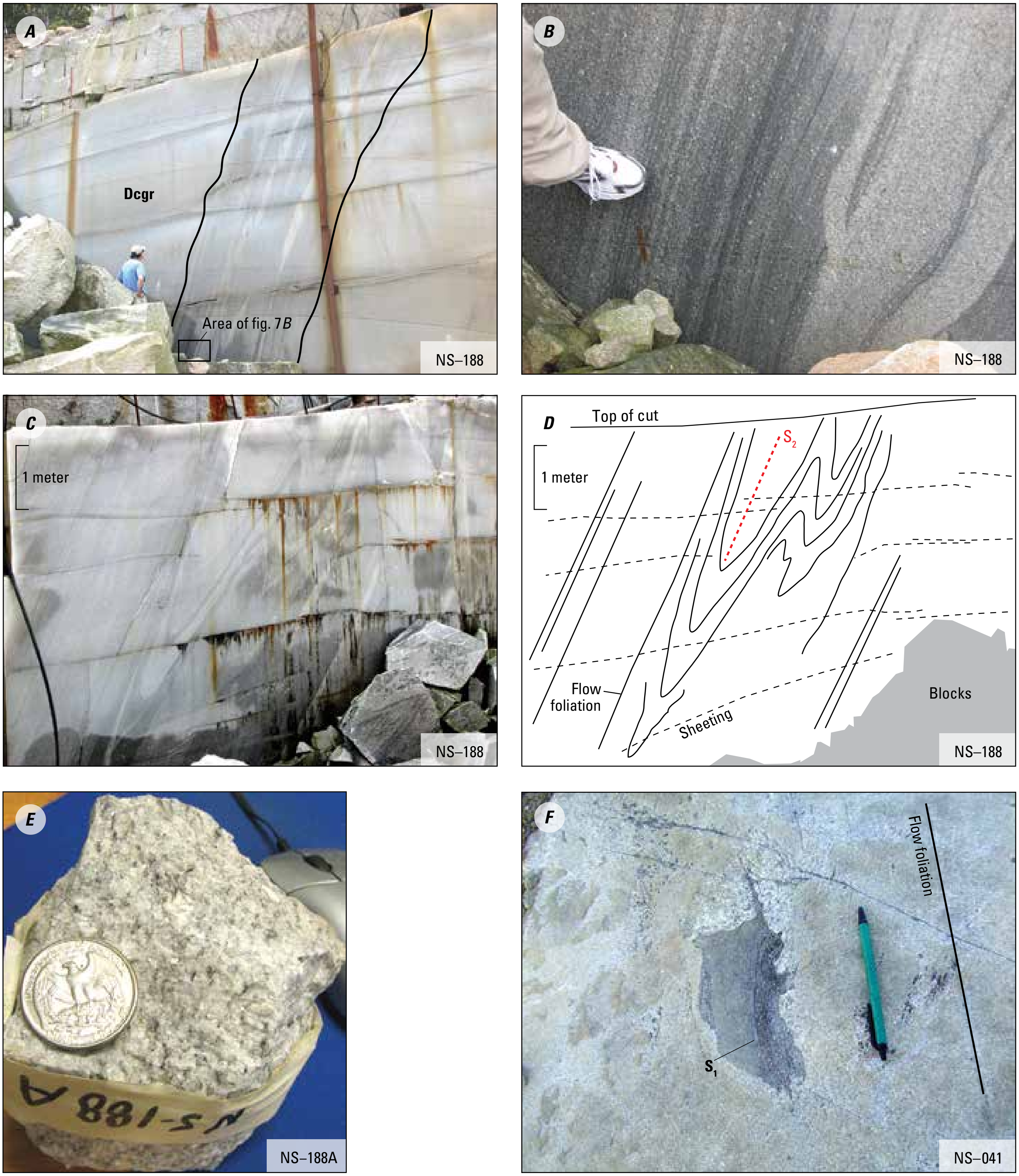

A
Dcgr
Area of fig. 7B
NS–188
B
NS–188
C
1 meter
NS–188
D
Top of cut
S_2
1 meter
Flow foliation
Sheeting
Blocks
NS–188
E
NS-188A
NS–188A
F
Flow foliation
S_1
NS–041

Table 4. Modal compositions and rock classifications of selected rocks from the Chelmsford Granite.

[Modal compositions were based on a minimum of 200 point counts. The rock classifications were based on proportions of normalized quartz (Q), alkali feldspar (A) and plagioclase (P) as shown in the International Union of the Geological Sciences (IUGS) rock classification diagram (see fig. 5). tr, trace amount (less than 0.1 percent); Ma, mega-annum]

				Dated rock		
Sample no.	**NS–051**	**NS–088**	**NS–134**	**NS–188A**[1]	**NS–188B**	**NS–029**
Map unit label	**Dcgr**	**Dcfgr**	**Dcgr**	**Dcgr**	**Dcgr**	**Dcgr**
Points counted	**212**	**396**	**205**	**891**	**831**	**475**
Modal composition, in percent						
Quartz	28.8	16.7	27.8	50.6	36.3	30.1
Plagioclase	23.6	21.2	23.4	19.1	15.3	14.1
Alkali feldspar	41.0	38.6	36.6	25.8	35.9	45.9
Biotite	2.8	11.6	5.9	1.2	6.0	6.3
Muscovite	2.4	9.8	5.9	1.8	4.7	2.9
Hornblende	0.0	0.0	0.0	0.0	0.0	0.0
Actinolite	0.0	0.0	0.0	0.0	0.0	0.0
Uralite	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	0.5	0.0	0.5	0.6	1.2	0.0
Opaques, including magnetite	0.0	1.3	0.0	0.0	0.5	0.2
Hematite	0.0	0.0	0.0	0.0	0.0	0.0
Titanite	0.5	0.0	0.0	0.0	0.0	0.0
Apatite	0.5	0.3	0.0	0.0	0.0	0.2
Epidote	0.0	0.0	0.0	0.0	0.1	0.0
Clinozoisite	0.0	0.5	0.0	0.7	0.0	0.0
Allanite	0.0	0.0	0.0	0.0	0.0	0.0
Saussurite	0.0	0.0	0.0	0.0	0.0	0.0
Garnet	0.0	0.0	0.0	0.2	0.0	0.0
Zircon	tr	tr	tr	tr	tr	0.2
Serpentine	0.0	0.0	0.0	0.0	0.0	0.0
Calcite	0.0	0.0	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
Rock classification						
Q	31	22	32	53	42	33
P	25	28	27	20	17	16
A	44	50	42	27	41	51
Rock type	**Muscovite-biotite monzogranite**	**Muscovite-biotite monzogranite**	**Muscovite-biotite monzogranite**	**Muscovite-biotite monzogranite**	**Muscovite-biotite syenogranite**	**Muscovite-biotite syenogranite**

[1]Dated rock = ~375 Ma.

Figure 7 (facing page). Photographs of the Chelmsford Granite. *A*, Sawn face through the granite (Dcgr) at the Le Masurier Granite Quarry in Westford, Mass. Cut is perpendicular to the foliation and layering and shows compositional banding interpreted as flow banding or flow foliation. The outlined area shows dark-gray syenogranite bounded by light-gray monzogranite. Modal compositions of the two rock types are shown in table 4—the light-gray rock is the dated rock, sample no. NS–188A; the dark-gray rock is sample no. NS–188B. *B*, Close-up of flow banding shown in *A*; here, the light-gray monzogranite crosscuts the dark-gray syenogranite. *C*, Another sawn face at the same quarry showing F_2 folds of folded flow foliation. Bar scale is approximately 1 meter. *D*, Sketch of *C*. An axial planar foliation defined by aligned micas is labeled as S_2. *E*, Hand sample of the dated rock, NS–188A. *F*, Xenolith of Berwick Formation granofels in a dike of Chelmsford Granite. The S_1 foliation is clearly cut by the granite; weakly developed flow foliation is visible at the right. The dike is located at station NS–041 in the adjacent Pepperell quadrangle.

syenogranite supports Jahns' original interpretation and shows that it is an igneous rock that intrudes and contains xenoliths of the Berwick Formation. Furthermore, layer-parallel foliation (S_1) observed in xenoliths of the Berwick Formation is truncated along the contacts with the granite (fig. 7*F*). The presence of abundant sills of the granite and granitic pegmatite along the margins of the Chelmsford pluton (unit SbDc), and throughout the Berwick Formation (for example, fig. 1*D*), provides evidence for magma injection by fracture and dike propagation—currently the most accepted mechanism of granite emplacement (for example, Clemens, 1998).

Modal compositions of the sampled rocks are shown in table 4. Samples of the Chelmsford Granite range in composition from syenogranite to monzogranite (fig. 5). Fine-grained two-mica granite (Dcfgr) is a volumetrically minor rock that is included as part of the Chelmsford Granite because its composition is similar to the granite in the Chelmsford pluton. The Dcfgr unit crops out within the Ayer Granodiorite and within the Berwick Formation on the northwestern side of the Chelmsford pluton; however, the contacts with the adjacent rocks are not exposed. The two exposures might be part of a dike that could not be mapped due to limited exposure.

Xenoliths of the Berwick Formation occur in the Chelmsford Granite at many places (fig. 7*F*); xenoliths of the Ayer Granodiorite are less abundant. The xenoliths are more numerous in dikes and along the margins of the Chelmsford pluton. Where exposed, the contacts along the margins of the plutons are marked by zones (a few meters to 1 kilometer wide) of injection migmatites characterized by abundant quartz veins and leucocratic pegmatitic material, perhaps due, in part, to the relatively high water content in the granite. The migmatitic zone contains abundant injected dikes and sills (fig. 2*A*). Our map shows this mixed zone of rock (SbDc) around the large Chelmsford pluton. The transitional nature of the contact of the Chelmsford pluton with the country rock also has been reported elsewhere (Jahns, 1942; Currier, 1947; Currier and Jahns, 1952; Jahns and others, 1959; Martin, 1973; Gore, 1976; Kopera and others, 2008).

Chemically, the dated sample of Chelmsford Granite (NS–188A, Dcgr) is mildly peraluminous (table 3, fig. 6*B*). The sample has fairly steep light rare-earth-element abundances with normalized La values of approximately 100, relatively flat heavy rare-earth elements, and a prominent negative Eu anomaly (fig. 6*D*). The Nb versus Y tectonic discrimination diagram (fig. 6*F*) shows the rock as a syn-collisional granite, consistent with the chondrite-normalized rare-earth-element patterns. Flagel and Hon (1988) report that the Chelmsford Granite, as a whole, is peraluminous.

Pegmatite

Dikes and sills of pegmatite (Dp) occur throughout the map. Older sills are subparallel to the foliation and locally boudinaged, and a number of these are mapped separately in the central part of the map near Interchange 1 on U.S. Route 3. Younger tabular dikes crosscut all Paleozoic rocks. The tabular dikes, shown on the map with red strike and dip symbols, range from 2 cm to 4 m thick and show somewhat variable orientations with moderate to steep dips, but an overall east-northeast-striking (81°), steeply dipping trend (fig. 8). This same trend was noted for the majority of pegmatite and aplite dikes in a detailed map of the Fletcher Quarry (R.H. Jahns, unpublished data, 1937).

Jurassic Dikes

Two Jurassic diabase dikes (Jd) cross the map. The dikes strike north-northeast and range from several meters to approximately 20 m in thickness. Locally, the dikes represent en echelon parts of a dike set that is traceable for approximately 30 km from the Ayer quadrangle in the southwest (Zen and others, 1983) to the Windham quadrangle in the northeast (Walsh and Clark, 1999). Regionally, the dikes are probably part of the Eastern North American dolerite province and represent the continuation of the Higganum-Holden-Onway dike, which may extend for 600 km from southern Connecticut to Maine (McHone and Sundeen, 1995).

Geochronology

Methods

Rock samples (~10 kilograms each) of the Devens-Long Pond facies of the Ayer Granodiorite and the Chelmsford Granite were collected for zircon U-Pb geochronology. Zircons were extracted by standard mineral separation procedures, including crushing, pulverizing, and concentrating heavy minerals by use of a Wilfley table, methylene iodide (density = 3.3 g/cm^3), and a magnetic separator. Individual zircons were hand picked using a binocular microscope, mounted in epoxy, ground to nearly half-thickness to expose internal zones, and polished using 6-micrometer (µm) and 1-µm diamond suspensions. All grains were imaged in transmitted and reflected light using a petrographic microscope and were imaged in cathodoluminescence (CL) (fig. 9*A*, *C*) using a scanning electron microscope.

Uranium-lead geochronology of zircon was performed using the U.S. Geological Survey/Stanford University sensitive high resolution ion microprobe-reverse geometry (SHRIMP–RG), following the methods of Williams (1998). The primary oxygen beam (4–6 nanoangstrom, nÅ) excavated a pit about 25 to 35 µm in diameter and about 1 µm in depth. The magnet cycled through the mass stations six times per analysis. Raw data were reduced by using Squid 1 (Ludwig, 2001) and were plotted by using Isoplot 3 (Ludwig, 2003). Measured $^{206}Pb/^{238}U$ are referenced to zircon standard R33 (419±1 Ma; Black and others, 2004). Concentrations of uranium are believed to be accurate to ±20 percent. Uranium-lead data are plotted on Tera-Wasserburg concordia plots (fig. 9*B*, *D*) to visually identify coherent age groups. A weighted average of selected individual $^{206}Pb/^{238}U$ ages (shown as insets within the concordia plots) was calculated to obtain a crystallization age for each sample.

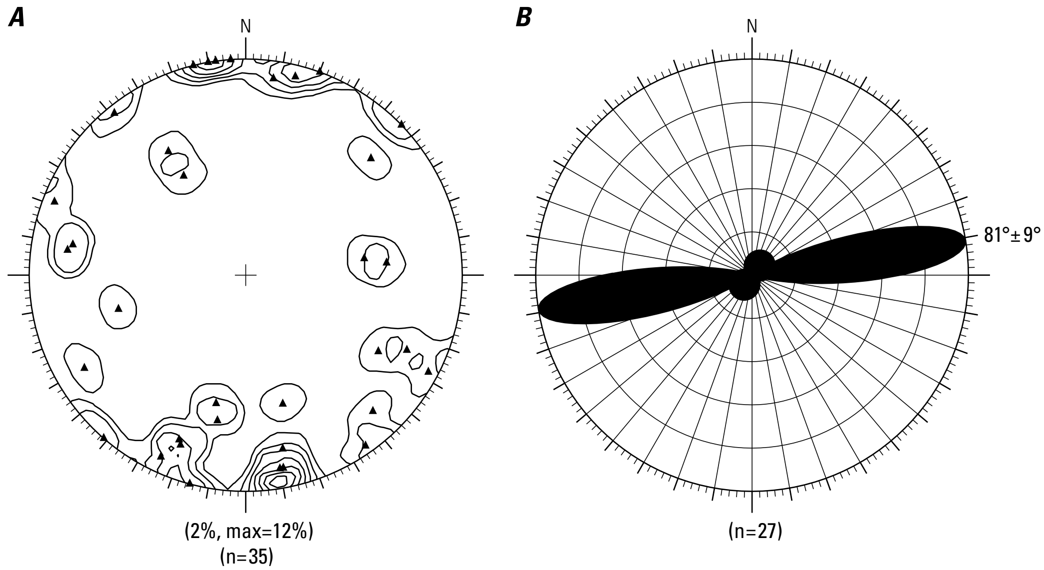


Figure 8. Lower hemisphere equal-area projection (stereonet) and azimuth-frequency (rose) diagram of pegmatite dikes. *A*, Poles (triangles) to strikes and dips of 35 pegmatite dikes. Contour interval, 2 percent; maximum is 12 percent. *B*, Azimuth-frequency (rose) diagram of 27 steeply dipping dikes (dip ≥60°). Data plotted in *B* are a subset of the data plotted in *A*. "N" indicates north, and "n" indicates the number of points in the dataset.

Results

Ayer Granodiorite

Zircons from the Devens-Long Pond facies of the Ayer Granodiorite (sample NS–187) are medium dark brown, euhedral, and have length-to-width (l/w) ratios of about 3 to 5 (fig. 9*A*). Most grains are somewhat deformed, with pitted and bent crystal faces. In CL, the zircons show broad cores with fine, concentric oscillatory zoning, indicative of igneous origin, and thin, discontinuous, dark metamorphic rims (fig. 9*A*). Fourteen analyses of cores yield a coherent age population with a weighted average of 407±4 Ma (fig. 9*B*), interpreted as the time of crystallization of the Devens-Long Pond facies of the Ayer Granodiorite. Four of five analyses of dark rims have very high uranium contents (~1,700 to 3,000 parts per million, ppm) and $^{206}Pb/^{238}U$ ages that are scattered and too old (~402–460 Ma; table 5), probably due to instrumental bias (Williams and Hergt, 2000). One relatively low-uranium (~350 ppm) rim yields a $^{206}Pb/^{238}U$ age of 378±4 Ma, which may be the time of formation of the metamorphic zircon overgrowths.

This new ~407 Ma age supersedes a conventional U-Pb zircon age of 433±5 Ma by Zartman and Naylor (1984). The ~433 Ma age was inconsistent with the recently reported detrital zircon ages as young as ~425 Ma from the Berwick Formation (Wintsch and others, 2007).

Chelmsford Granite

Zircons from the Chelmsford Granite (sample NS–188A) are light medium brown, euhedral, and have l/w ratios of 4 to 6. These grains are fairly pristine, with undeformed crystal faces and sharp terminations. The crystal morphology appears typical of igneous zircons produced in plutonic rocks, rather than zircons from metasomatic rocks (for example, Pointer and others, 1988; Hoskin and Schaltegger, 2003). As can be seen by CL imagery, some grains are composed primarily of oscillatory-zoned cores with thin, discontinuous, dark overgrowths, whereas other grains have small, remnant oscillatory-zoned cores and large dark, unzoned overgrowths (fig. 9*C*).

Twelve of 13 analyses of cores yield a coherent age population with a weighted average of 375±3 Ma (fig. 9*D*), interpreted as the time of crystallization of the Chelmsford Granite. Eight analyses of rims have very high uranium contents (~3,400–9,800 ppm). The $^{206}Pb/^{238}U$ ages are too old (for example, Williams and Hergt, 2000), but a weighted average of the $^{207}Pb/^{206}Pb$ ages yields an age of 377±15 Ma. Because of the large uncertainty in the age of the metamorphic overgrowths, we are unable to determine the difference in ages of the cores and rims. The radiogenic rims may partly explain why earlier conventional analyses of the Chelmsford Granite yielded a poorly constrained $^{207}Pb/^{206}Pb$ zircon age of 389±5 Ma (Zartman and Naylor, 1984). Keevil and others (1944) also noted the relatively high radioactivity in the accessory minerals in the Chelmsford Granite. The new ~375 Ma age supersedes the $^{207}Pb/^{206}Pb$ zircon age by Zartman and Naylor (1984) and obsolete Rb-Sr whole rock ages (Handford, 1965; Hayward, 1987).

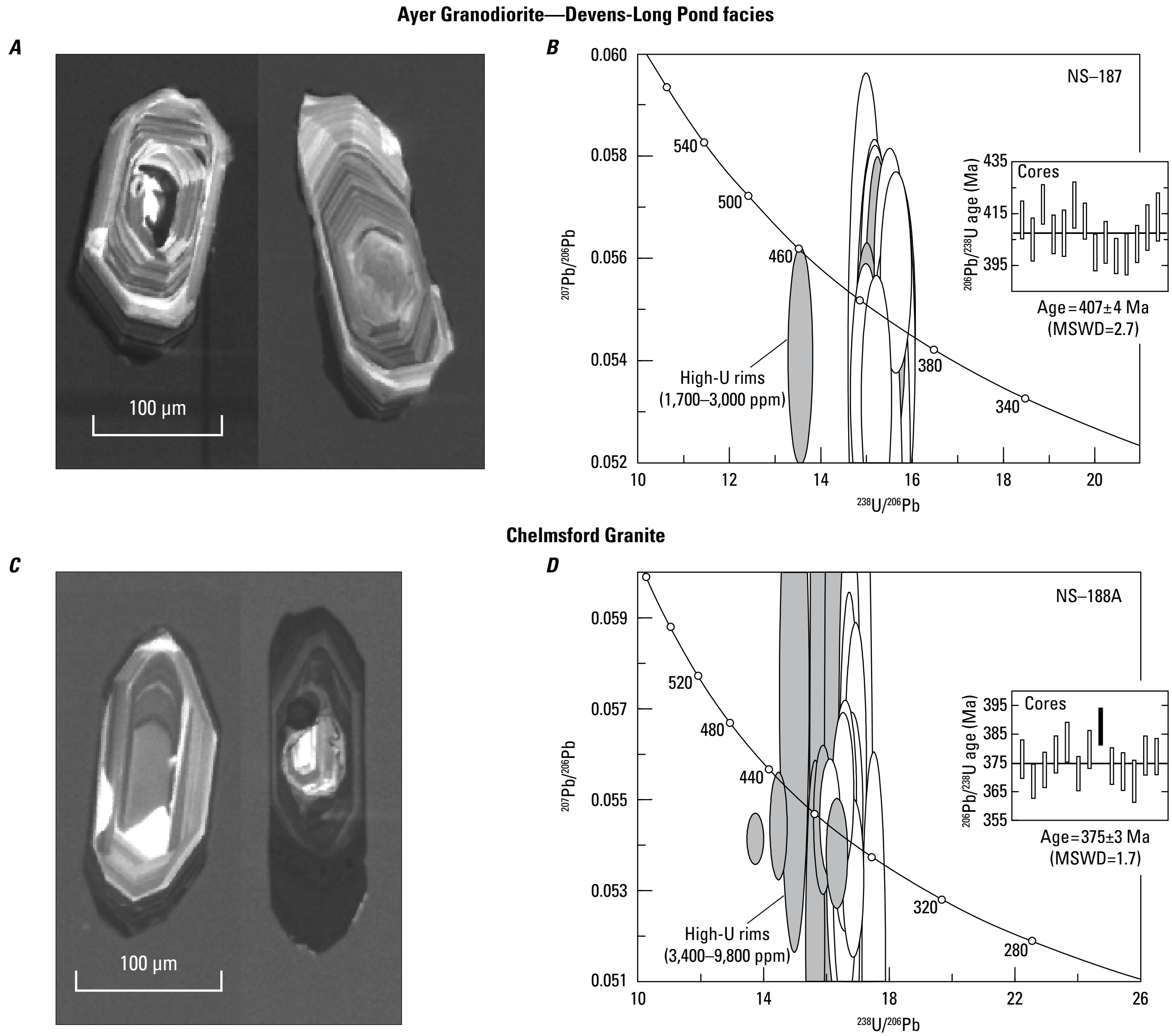


Figure 9. *A* and *C*, Cathodoluminescence images of representative zircons analyzed to determine a SHRIMP U-Pb zircon age of the Devens-Long Pond facies of the Ayer Granodiorite (*A*) and the Chelmsford Granite (*C*). *B* and *D*, Graphs showing SHRIMP U-Pb ages of zircon. The main figures (*B* and *D*) are Tera-Wasserburg concordia plots of the Devens-Long Pond facies of the Ayer Granodiorite and the Chelmsford Granite, respectively. White error ellipses are analyses used in weighted averages of selected $^{206}Pb/^{238}U$ ages (see insets) to determine the time of emplacement of igneous protoliths. Gray error ellipses show data from high-U rims. See text for discussion. The weighted average age for the Devens-Long Pond facies of the Ayer Granodiorite is 407±4 Ma (MSWD=2.7) and is interpreted to indicate an Early Devonian time of emplacement. The weighted average age for the Chelmsford Granite is 375±3 Ma (MSWD=1.7) and is interpreted to indicate a Late Devonian time of emplacement. Ages obtained by sensitive high resolution ion microprobe (SHRIMP) at Stanford University, Palo Alto, Calif. Ma, mega-annum; MSWD, mean square of the weighted deviates; µm, micrometer.

Table 5. SHRIMP U-Th-Pb data for zircons from igneous rocks of the Nashua South quadrangle, N.H.-Mass.

[Abbreviations: %, percent; ppm, parts per million; Ma, mega-annum; r, rim; c, core; §, 1-sigma error; NAD27, North American Datum of 1927]

Zircon, grain analysis	Measured $^{204}Pb/^{206}Pb$	Measured $^{207}Pb/^{206}Pb$	Common ^{206}Pb (weight %)	U (ppm)	Th/U	Age from $^{206}Pb/^{238}U$† (Ma)	Age from err§ (Ma)	Age from $^{207}Pb/^{206}Pb$ (Ma)	Age from err§ (Ma)	$^{238}U/^{206}Pb$†	err§ (%)	$^{207}Pb/^{206}Pb$†	err§ (%)
NS–187 (Ayer Granodiorite) [42°38'11.9" N., 71°28'00.0" W. in NAD27 datum]													
NS187–1.1r	0.000085	0.0569	0.34	348	0.45	378.0	3.7	437	48	16.53	1.0	.0556	2.2
NS187–2.1c	0.000081	0.0544	-0.08	561	0.35	412.6	3.6	338	41	15.16	0.9	.0532	1.8
NS187–3.1c	0.000156	0.0557	0.10	254	0.35	405.1	4.1	345	64	15.45	1.0	.0534	2.8
NS187–4.1c	0.000089	0.0546	-0.07	491	0.44	418.6	3.8	343	43	14.94	0.9	.0533	1.9
NS187–5.1c	0.000118	0.0553	0.06	461	0.35	407.1	3.7	354	58	15.36	0.9	.0536	2.6
NS187–6.1c	0.000099	0.0555	0.08	204	0.48	407.5	4.4	374	63	15.34	1.1	.0541	2.8
NS187–7.1c	0.000227	0.0573	0.27	245	0.38	418.3	4.4	372	93	14.94	1.1	.0540	4.1
NS187–8.1c	0.000068	0.0567	0.21	801	0.27	412.1	3.4	440	39	15.13	0.9	.0557	1.7
NS187–9.1r	0.000708	0.0638	1.08	2,038	0.21	416.4	3.3	349	47	15.02	0.8	.0535	2.1
NS187–10.1c	0.000000	0.0556	0.12	604	0.35	400.2	3.5	438	32	15.60	0.9	.0556	1.4
NS187–11.1c	0.000236	0.0552	0.05	296	0.34	404.0	4.0	276	85	15.52	1.0	.0518	3.7
NS187–12.1c	0.000240	0.0575	0.36	763	0.33	398.8	3.4	373	56	15.68	0.9	.0540	2.5
NS187–13.1r	0.000123	0.0562	0.18	2,973	0.39	401.9	3.2	387	37	15.55	0.8	.0544	1.6
NS187–14.1r	0.000152	0.0563	0.01	2,130	0.04	459.7	3.7	373	35	13.56	0.8	.0540	1.6
NS187–15.1r	0.000894	0.0664	1.41	1,695	0.04	410.1	3.3	341	80	15.25	0.8	.0533	3.5
NS187–16.1c	0.000000	0.0547	0.00	263	0.40	399.5	4.0	401	46	15.64	1.0	.0547	2.0
NS187–17.1c	0.000051	0.0566	0.22	554	0.35	403.4	3.6	446	35	15.46	0.9	.0558	1.6
NS187–18.1c	0.000439	0.0559	0.12	220	0.40	409.7	4.4	169	129	15.34	1.1	.0494	5.5
NS187–19.1c	0.000255	0.0567	0.21	182	0.48	413.7	4.6	328	91	15.12	1.1	.0530	4.0
NS–188A (Chelmsford Granite) [42°38'32.5" N., 71°25'12.8" W. in NAD27 datum]													
NS188–1.1r	0.000225	0.0571	0.35	4,935	0.01	383.0	3.2	363	21	16.35	0.9	.0538	0.9
NS188–2.1r	0.000014	0.0543	-0.21	8,519	0.01	453.7	3.5	376	10	13.75	0.8	.0541	0.4
NS188–3.1c	0.000000	0.0552	0.13	586	0.07	376.4	3.3	419	34	16.61	0.9	.0552	1.5
NS188–3.2r	0.000227	0.0579	0.41	4,565	0.01	393.2	3.0	393	28	15.90	0.8	.0545	1.2
NS188–4.1c	0.000582	0.0642	1.27	1,526	0.12	368.8	3.0	441	52	16.95	0.8	.0557	2.3
NS188–5.1c	0.000739	0.0671	1.62	1,355	0.12	372.7	3.0	466	86	16.76	0.8	.0563	3.9
NS188–6.1c	0.000000	0.0552	0.13	816	0.10	378.0	3.2	420	28	16.54	0.9	.0552	1.3
NS188–7.1c	0.000100	0.0547	0.05	546	0.25	382.2	3.4	338	47	16.39	0.9	.0532	2.1
NS188–8.1c	0.000591	0.0602	0.81	741	0.13	358.7	3.1	266	82	17.52	0.9	.0516	3.6
NS188–9.1r	0.000104	0.0559	0.06	9,045	0.01	430.6	3.2	388	20	14.49	0.8	.0544	0.9
NS188–10.1c	0.000120	0.0550	0.12	1,661	0.11	371.4	2.9	340	30	16.88	0.8	.0533	1.3
NS188–11.1c	0.000157	0.0560	0.22	681	0.07	379.7	3.3	358	47	16.49	0.9	.0537	2.1
NS188–12.1c	0.000000	0.0546	0.02	1,342	0.19	387.6	3.2	395	22	16.13	0.8	.0546	1.0
NS188–13.1r	0.006304	0.1491	11.63	9,814	0.05	415.1	5.2	505	90	14.99	1.3	.0574	4.1
NS188–14.1c	0.000287	0.0579	0.48	934	0.19	374.0	3.1	360	100	16.75	0.9	.0537	4.4
NS188–15.1c	0.000047	0.0555	0.18	605	0.15	372.1	3.2	404	35	16.81	0.9	.0548	1.6
NS188–16.1c	0.004534	0.1173	7.86	710	0.12	368.7	3.6	230	285	17.05	1.1	.0508	12.3
NS188–17.1r	0.039574	0.6312	71.40	4,379	0.87	392.6	18.5	167	605	16.03	1.4	.0494	25.9
NS188–18.1c	0.000131	0.0550	0.10	555	0.20	377.7	3.4	333	47	16.60	0.9	.0531	2.1
NS188–19.1r	0.006202	0.1436	11.06	5,881	0.01	384.5	4.2	318	274	16.30	0.9	.0528	12.1
NS188–20.1r	0.001389	0.0723	2.17	3,445	0.02	400.5	3.1	282	71	15.66	0.8	.0519	3.1
NS188–21.1c	0.000068	0.0550	0.11	974	0.15	377.3	3.1	373	33	16.59	0.8	.0541	1.5

†Corrected for common Pb. $^{206}Pb/^{238}U$ ages corrected for common Pb using the ^{207}Pb-correction method; $^{207}Pb/^{206}Pb$ ages and $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ corrected for common Pb using the ^{204}Pb-correction method based on the model by Stacey and Kramers (1975). Decay constants from Steiger and Jäger (1977).

Structural Geology

Ductile Structures

The relative ages of ductile structures in the Nashua South quadrangle are described in terms of (1) their relations to the dominant, or most visibly conspicuous, foliation at a given outcrop and (2) their interpreted age. In the accompanying geographic information system (GIS) database, the age of the dominant foliation or fold generation is assigned the relative age of "n." Older foliations or folds are assigned an age of "n–1," and younger foliations are assigned an age of "n+1." On the map and in the text, the interpreted age of the fabrics is assigned a number designation as follows:

- S_0 = bedding
- S_1/F_1 = First generation—Layer-parallel foliation and folds
- S_2/F_2 = Second generation—Schistosity to penetrative cleavage and folds
- S_3/F_3 = Third generation—Spaced cleavage, open folds, shear bands, and boudinage

The relative age assignment is an objective approach to describing fabrics at a single outcrop. This method is necessary because it is not always possible to unequivocally determine all the age relations at every outcrop during mapping, because not all the fabrics are present at every outcrop. At least three generations of ductile deformation are recognized and designated by their relative ages as D_1 to D_3.

The oldest deformation (D_1) is recognized by a layer- or bed-parallel schistosity (S_1) that occurs only in the Berwick Formation and contains rarely observed, locally refolded, isoclinal folds. Only in the hinge region of these folds is it possible to see bedding that is not parallel to a foliation (fig. 10). The layer-parallel schistosity is expressed by the parallel alignment of metamorphic minerals consisting mostly of biotite, quartz, plagioclase, and calc-silicate minerals (fig. 10*A*) and, locally, by leucocratic granitic and pegmatitic sills (fig. 11*A*). Where the Berwick Formation is well laminated, the laminations define S_1 (fig. 1*A*). Locally, this foliation is the dominant fabric in the rock and is assigned a relative age of Sn (fig. 10*B*). Where the layer-parallel foliation is the dominant foliation, its average strike and dip is 34°, 79° (in right-hand rule, or N. 34° E., 79° SE in quadrant format) (fig. 12*A*). More commonly, however, the S_1 foliation is deformed and transposed by a younger foliation (S_2) (fig. 11*A*). Compositional banding in the Chelmsford Granite (fig. 7*D*) is the oldest planar fabric in the granite, and it is interpreted as flow banding, not a deformational foliation. Although the banding predates younger F_2 folds, it postdates the S_1 foliation in the Berwick (fig. 7*F*) and is not correlated with it.

The second episode of deformation (D_2) produced a planar fabric that varies from a penetrative cleavage to a schistosity (S_2) in the Berwick Formation, a gneissosity in the Ayer Granodiorite, and a gneissosity in some of the plutonic rocks. The gneissosity is a well-developed foliation defined by aligned micas and recrystallized quartz and feldspar and, only locally, by compositional layering. Folds (F_2) associated with the second generation fabric deform S_1 and bedding in the Berwick Formation and flow banding in the Chelmsford Granite (figs. 11*A* and 7*D*, respectively). Currier and Jahns (1952, p. 114) mapped the banding and foliation (our S_2) in detail in the Fletcher Quarry in Westford, and our map shows representative symbols at the quarry. The F_2 folds vary from open to isoclinal with variable plunges (fig. 12*C*). Plunge directions vary across the map from northeast in the east-northeast, to west-southwest in the northwest, and southeast in the southwest parts of the map. The S_2 foliation and, to a lesser degree, S_1 are the dominant planar fabrics in the Berwick Formation (figs. 11*A*, *B*, 12*A*, *B*). Locally, these two planar fabrics are parallel, and it is difficult to discern one from the other. In places where only a single penetrative schistosity was observed and no crosscutting relative age relations were seen, a dominant foliation symbol is shown on the map. The average strike and dip of the dominant foliation, represented either by S_2 or by a composite S_1/S_2, is 33°, 80° (fig. 12*B*).

The youngest ductile fabric in the area (D_3) is recognized as widely distributed, weakly developed spaced cleavage, folds, shear bands, or boudinage (fig. 11*B*). Rarely observed gently dipping ductile shear bands postdate the foliation and flow banding in the Chelmsford Granite. A strike and dip symbol shows the location of measured shear bands at Interchange 34 on U.S. Route 3. Shear bands were also observed on the high walls of the Fletcher Quarry, but their orientation could not be readily measured. Folds are open and have gently to moderately dipping axial surfaces and gently plunging fold axes (fig. 12*D*). Boudinage is readily recognized by pinch and swell structure of granite or pegmatite layers (fig. 11*A*). Where tabular pegmatite or granite dikes crosscut both the Berwick Formation and the more rigid intrusive rocks, the D_3 boudinage is better developed in the relatively weaker metasedimentary rocks (fig. 11*B*). This observation not only demonstrates the competency contrast between relatively weaker and stronger rocks but also indicates that D_3 outlasted the intrusion of some relatively late tabular granitic dikes.

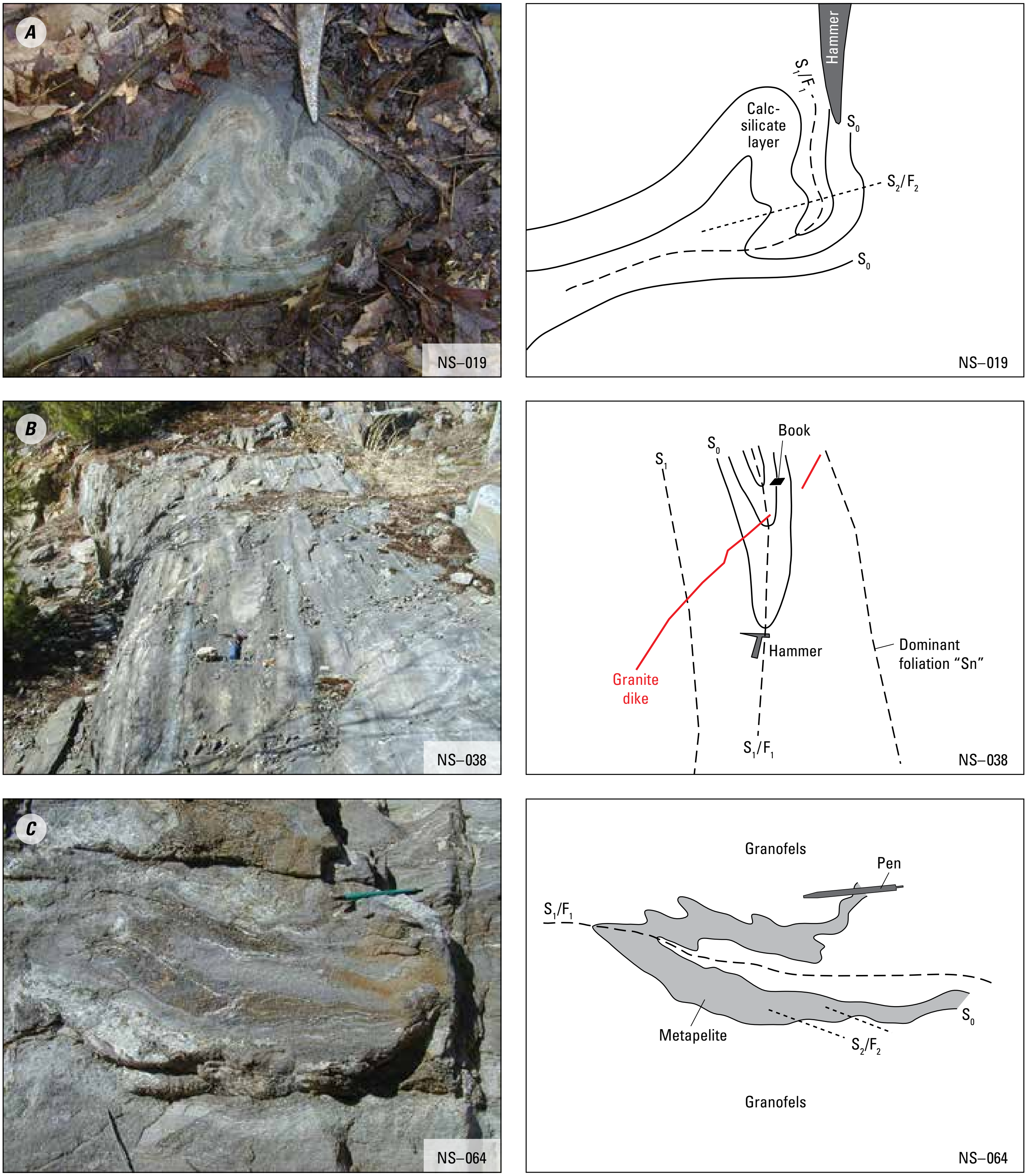


Figure 10. Photographs and companion sketches of relict D_1 structure in the Berwick Formation. *A*, Refolded calc-silicate layer showing two periods of folding (S_1/F_1 and S_2/F_2) and bedding (S_0). *B*, Outcrop-scale F_1 isoclinal fold. *C*, Gently warped F_1 fold showing thin layer of darker gray metapelite interbedded with granofels.

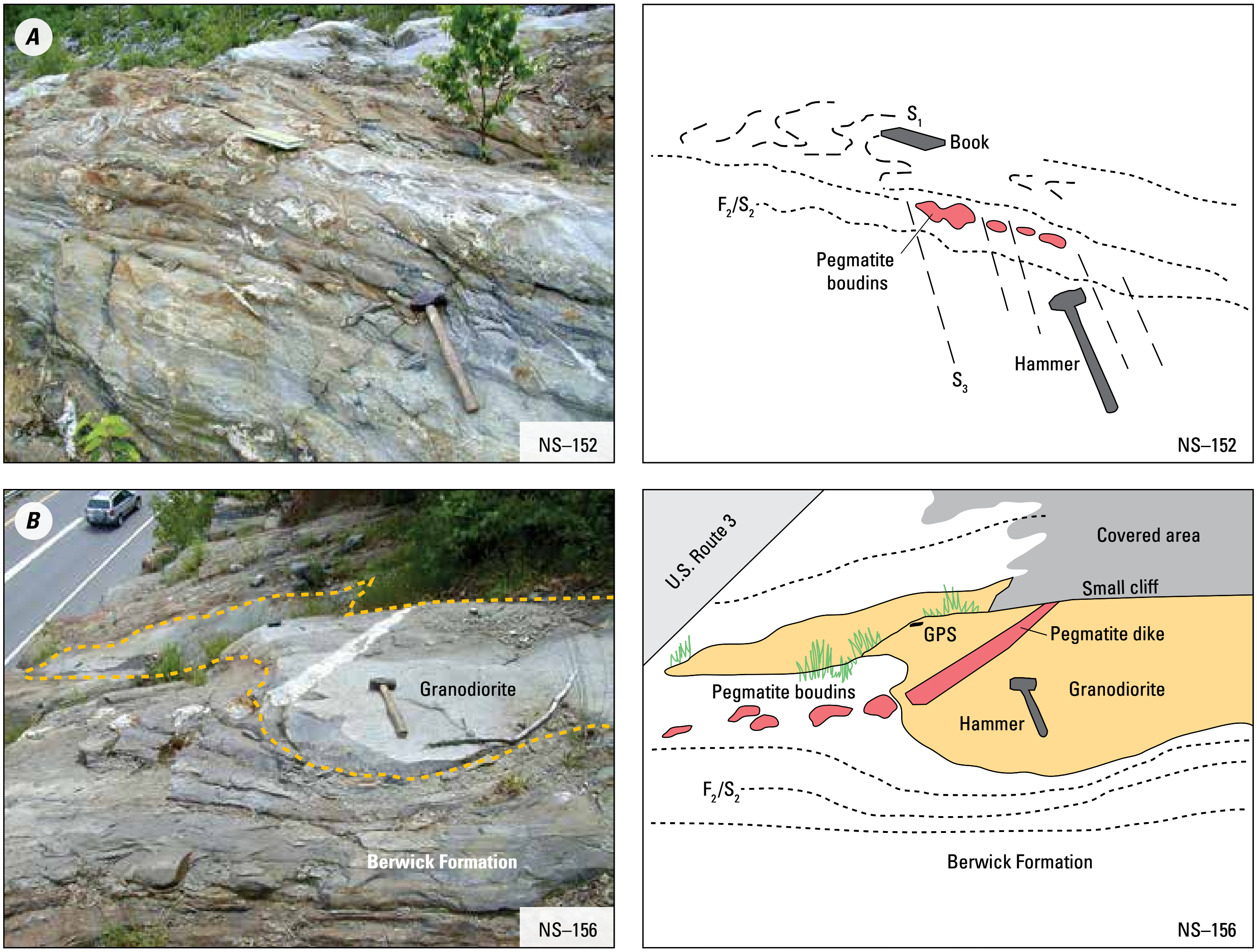


Figure 11. Photographs and companion sketches of D_2 and D_3 structures. *A*, Rare example of an outcrop in the Berwick Formation showing all three ductile fabrics: folded S_1 foliation, dominant S_2 foliation, and upright S_3 cleavage and associated boudinage. *B*, Granodiorite sill in the Berwick Formation cut by a tabular pegmatite dike. D_3 deformation shows the dike is boudinaged in the weaker metasedimentary rocks but generally undeformed in the granodiorite sill.

Brittle Structures

The planar brittle structures in this study are collectively called fractures. Fractures without displacement are separated on the basis of whether or not they are related to older fabrics in the metamorphic and igneous rocks as follows:

- *Parting fractures*: Occur where the rocks break, or part, along preexisting fabric (for example, Walsh, 2003). Parting fractures are related to older igneous or metamorphic fabrics due to structural inheritance and occur along axial surfaces of folds, cleavage, schistosity or gneissosity, contacts, dikes, and veins. Manda and others (2008) call these "foliation-parallel fractures" or "FPFs," but they occur along more than just foliation.
- *Crossing fractures*: Include joints and brittle faults that cross the metamorphic or igneous fabric of the rocks. Crossing fractures with displacement are brittle faults. Crossing fractures without displacement are joints.

The major fracture types are shown in figure 13. The orientation of measured joints 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 dataset includes only the most conspicuous joints observed in a given outcrop. Fracture data (fig. 14) are plotted on rose diagrams (azimuth-frequency) and stereonets (lower hemisphere equal-area projections) using DAISY software version 4.71.06 (Salvini, 2008). The software creates rose diagrams using a

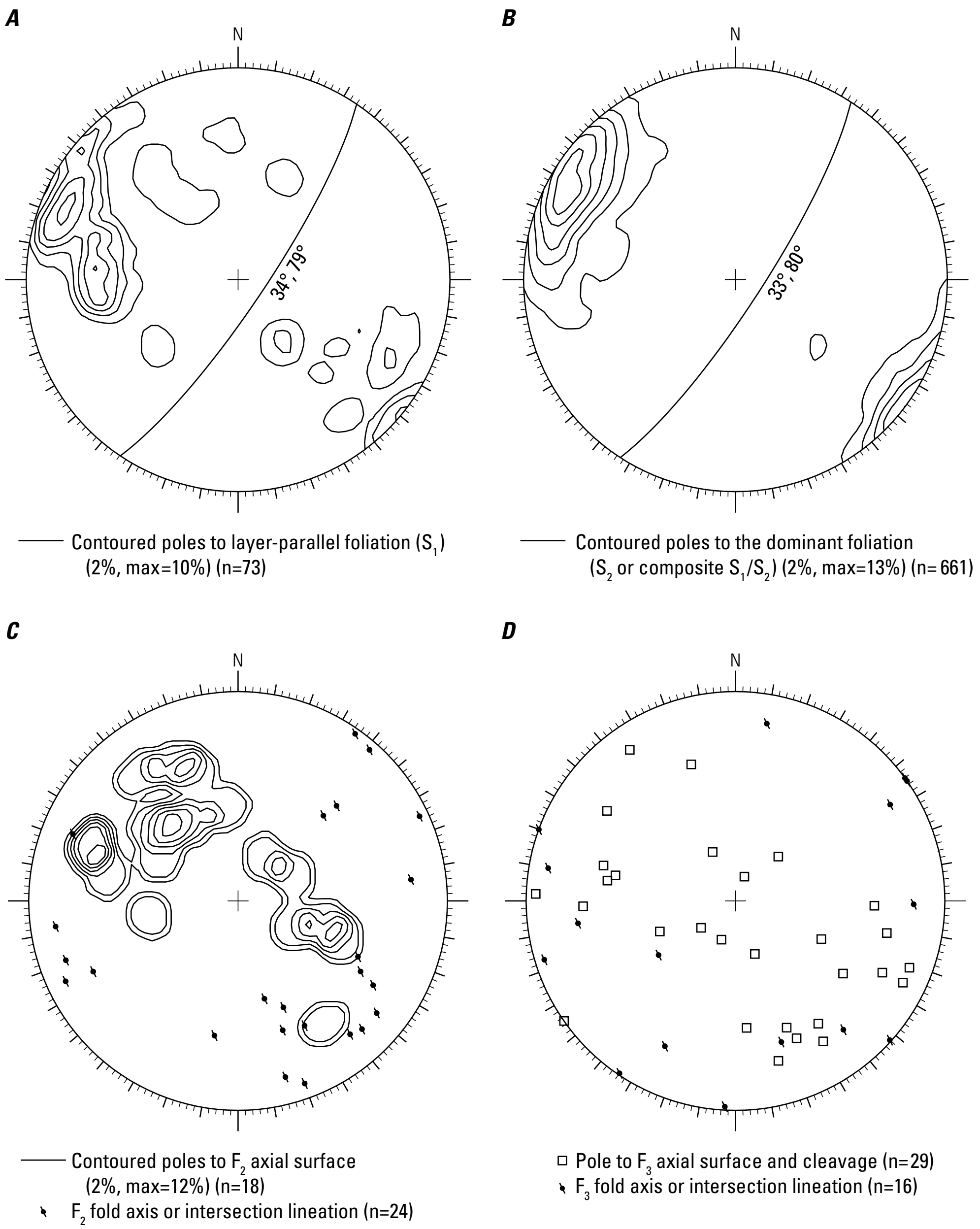
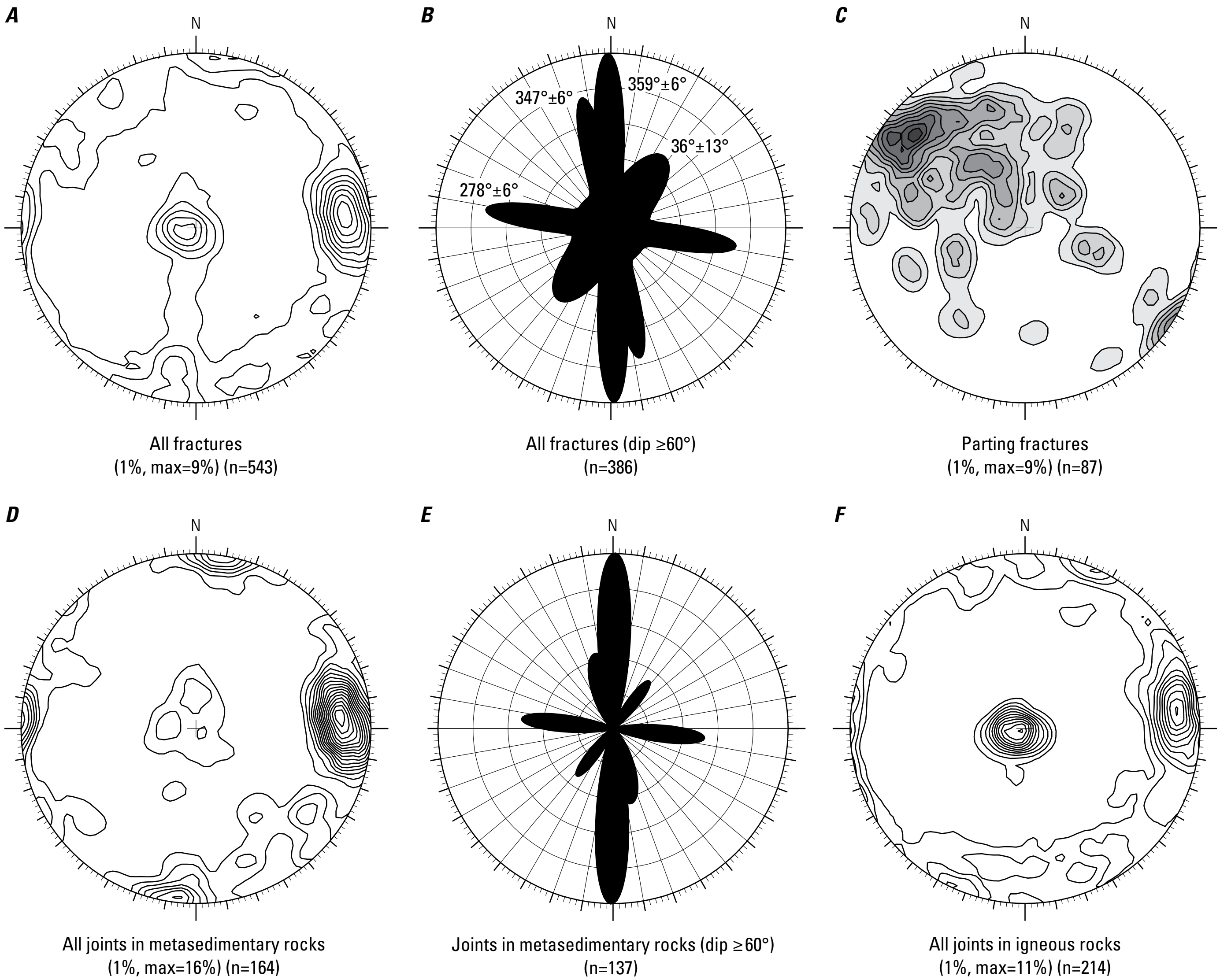


Figure 12. Lower hemisphere equal-area projections (stereonets) of ductile fabrics in the Nashua South quadrangle. For stereonets shown in *A*, *B*, and *C*, the contour interval (2 percent) and the maximum contoured value are indicated in parentheses. *A*, Contoured poles to S_1 layer-parallel foliation where it is the dominant foliation in the Berwick Formation. The orientation of the average plane is 34°, 79°. *B*, Contoured poles to the dominant foliation where it is either S_2 in the igneous rocks or a composite S_1/S_2 in the Berwick Formation. The orientation of the average plane is 33°, 80°. *C*, Contoured poles to F_2 axial surfaces and F_2 fold axes or intersection lineations. *D*, Poles to F_3 axial surfaces and cleavage (squares) and F_3 fold axes or intersection lineations. "N" indicates north, and "n" is the number of points in the dataset.

Figure 13. Photographs of major fracture types. *A*, Pegmatite sill in the Berwick Formation. North-south-striking, steeply dipping joints (parallel to red lines) are the most common crossing fractures in the area. Parting fractures (parallel to yellow lines) occur along the dominant foliation. *B*, Sheeting joints (parallel to orange line) in the Chelmsford Granite at Oak Hill Quarry. *C*, Granite sill (center) in the Berwick Formation showing foliation-parallel parting fractures (parallel to yellow line), sheeting fractures (parallel to orange line), north-south-trending joints (red arrow), and east-west-trending joints (parallel to white lines). Generally the same fractures occur in both rock types but to varying degrees.

Gaussian curve-fitting routine for determining peaks in directional data (Salvini and others, 1999) that was first described by Wise and others (1985). The rose diagrams include strike data for steeply dipping fractures (dip ≥60°, after Mabee and others, 1994).

Fracture data are summarized in figure 14, and the original data are located in the GIS database. The principal fracture trend is north striking and steeply west dipping, with a trend of 359° (fig. 14*A*, *B*). Parting fractures (fig. 14*C*) are a subset of all the fractures (fig. 14*A*) and are dominated by the steeply southeast-dipping, northeast-striking trend of the dominant foliation (figs. 12*A*, 14*B*, *C*). The variability in parting fracture orientations is evident in figure 14*C*, but is masked in figure 14*A*, where the data are dominated by more abundant joints. Joints are a subset of all the fractures and show the prominent north-striking, steeply west-dipping trend (fig. 14*D*–*G*). Joint data, separated by generalized rock type, show that the igneous rocks have a preferred subhorizontal fracture orientation related to sheeting (fig. 14*F*). Sheeting fractures are present in the metasedimentary rocks of the Berwick Formation but to a lesser degree than in the igneous rocks (fig. 14*D, F*). Fracture and rock mechanic studies of the Chelmsford Granite show that the sheeting fractures occur parallel to microscopic cracks in quartz and feldspar and represent the "rift" direction, or easiest splitting direction. Foliation-parallel fractures related to aligned mica are parallel to the "grain" direction, or second easiest splitting direction (Skehan, 1967; LeMasurier, 1967; Johnson, 1970; Peng, 1970, 1971; Peng and Johnson, 1972; Martin, 1973). Steeply dipping, northwest-striking joints are parallel to the third fracture direction, or "hard way" (Skehan, 1967; LeMasurier, 1967; Martin, 1973). Martin (1973) concluded that all three splitting



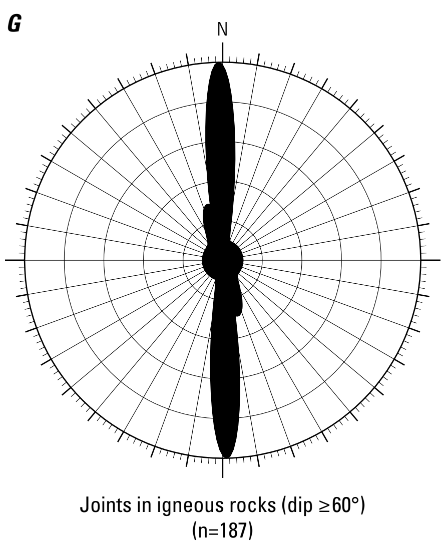


Figure 14. Lower hemisphere equal-area projections (stereonets) and azimuth-frequency (rose) diagrams of fractures. Poles contoured at 1 percent intervals, and the maximum contoured value is indicated in parentheses. *A*, Contoured poles to all fractures. *B*, Rose diagram showing steeply dipping fractures. *C*, Contoured poles to parting fractures. *D*, Contoured poles to joints in the Berwick Formation. *E*, Rose diagram showing steeply dipping data in *D*. *F*, Contoured poles to joints in the igneous rocks. *G*, Rose diagram showing steeply dipping data in *F*. "N" indicates north, and "n" is the number of points in the dataset.

directions in the Chelmsford Granite are related to muscovite and biotite cleavage planes, plagioclase twinning, and, to varying degrees, microcracks. Jahns' (1943) classic work on sheeting included detailed studies of the Chelmsford Granite at the Fletcher and Oak Hill Quarries and determined the following major findings:

- Sheeting occurs parallel to the surface of the bedrock topography.
- Sheets become thicker with depth (in other words, spacing increases with depth).
- Sheet structure occurs independently of rock type or rock fabric.
- Sheeting is developed best in rocks with the least well-developed joints.
- Sheet fractures occur at depths at least as deep as the deepest quarries in New England (~97 m).
- In quarries, new sheeting fractures develop in response to compressive stress and the removal of overburden.

Both the metasedimentary and igneous rocks contain joints that show the north-striking, steeply dipping trend (figs. 13*A*, *C*, 14*D*–*G*). Martin (1973) called the north-trending joints the "diagonal joints" because they diagonally intersected the trend of the dominant foliation and flow banding in the Chelmsford Granite. Joints within the metasedimentary rocks show a subordinate east-west trend that is not apparent in the igneous rock joint data (fig. 14*D*, *E*) but was observed at a few outcrops (fig. 13*C*). The principal north-striking fracture trend seen in the map area (fig. 14*B*, *E*, *G*) was not reported from the Windham quadrangle to the northeast (Walsh and Clark, 1999, 2000) and, conversely, the principal northwest-striking, steeply dipping fracture trend there is not apparent in the data from the Nashua South quadrangle. Steeply dipping, northwest-striking joints do occur in the Nashua South quadrangle, however, and are particularly apparent in the Chelmsford Granite at the Le Masurier and Fletcher Quarries in the south-central part of the map (individual joint data are in the database but are not plotted with symbols on the map). Martin (1973) called the northwest-trending joints the "cross joints" and noted their relation to quartz veins and pegmatite dikes in the Chelmsford Granite. The change in principal trend from north to northwest between the two adjacent quadrangles suggests a fundamental change in principal fracture trends across the two areas, despite the fact that the dominant foliation has the same overall trend.

Locally, joint and fault surfaces are coated with secondary minerals including quartz, sulfides, and zeolites. The locations of these mineralized zones are recorded in the database of this report. The zeolites occur exclusively as fracture-filling mats of white, radiating, acicular crystals in the Berwick Formation. Walsh and Clark (1999) reported the composition of the zeolites as a mixture of heulandite, stilbite, and barrerite.

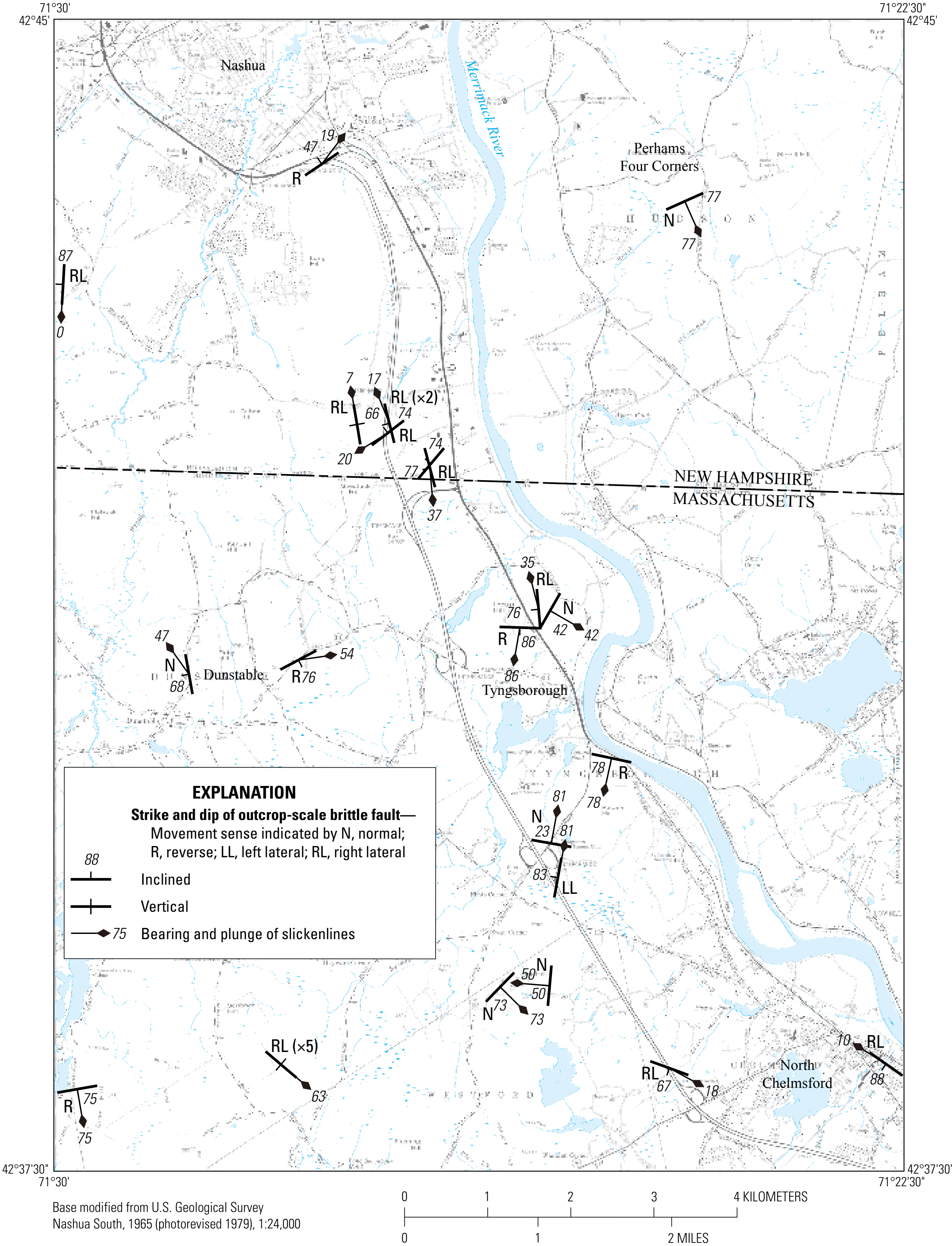
Twenty-seven outcrop-scale brittle faults were identified by slickensides or visible offsets (fig. 15). Eight normal, six reverse, three left-lateral, and ten right-lateral faults were observed. Generally, the faults show preferred steeply dipping, north-northwest-striking (348°) and northwest-striking (309°) trends (fig. 16*A*, *B*). The north-northwest trend is similar to a principal joint trend in the area (347°, compare figs. 14*B* and 16*A*). The northwest trend (347°–348°) also occurs as a principal joint trend in the adjacent Windham quadrangle (Walsh and Clark, 1999, 2000).

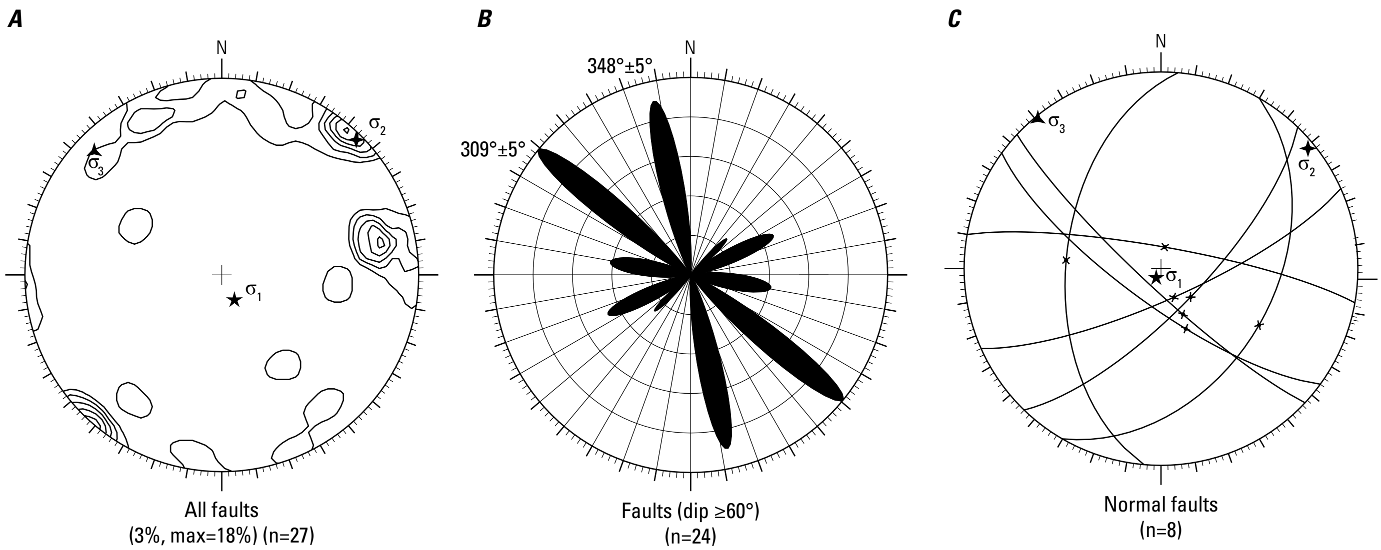
The faults are probably not coeval. A calculation of the mean P and T axes (fig. 16*A*) for all faults, and especially for the normal faults (fig. 16*C*), shows a calculated average stress field that is consistent with Late Triassic to Early Jurassic northwest-southeast extension associated with rifting of the New England crust during the initial opening of the Atlantic basin (Foland and Faul, 1977; McHone, 1978; Kaye, 1983; McHone and Butler, 1984; de Boer and Clifford, 1988; Manning and de Boer, 1989; Goldsmith, 1991). The northeast-striking Jurassic diabase dikes intruded at this time. The extension may have started during the late Paleozoic (Goldstein, 1994; Goldstein and Hepburn, 1999). Calculated paleostress tensors for the reverse and strike-slip faults (fig. 16*D*, *E*) show a shift to generally northeast-southwest compression. This change in the principal stress direction took place during younger phases of Mesozoic brittle deformation (McHone, 1978; McHone and Butler, 1984; Hardcastle, 1989; Manning and de Boer, 1989; de Boer, 1992). It was likely that the principal north-south joint trend also developed during this shift in the stress field, perhaps during north-south compression in the Jurassic (Manning and de Boer, 1989). The current stress field is east-west compression (Manning and de Boer, 1989). In situ stress measurements and study of sheeting in the Chelmsford Granite confirm that the rocks are currently under compressive stress (Jahns, 1943; Hooker and Johnson, 1969; Jahns and Holzhausen, 1976).

Glacial Features

Glacial striations and grooves were recorded during the course of mapping although they are not structures in the rocks. Their analysis is included here because it is often useful to understand the glacial trends when conducting fracture analysis in glaciated crystalline bedrock using remotely sensed data (Mabee and others, 1994). An average of nine measurements indicates a glacial trend of 167° (fig. 17). Coincident with this trend are a number of thick-till-cored drumlins with the long axis parallel to this orientation, especially Gilboa, Flushing, and Kendall Hills (Stone and Stone, 2007).

Figure 15 (facing page). Map of brittle faults in the Nashua South quadrangle. In two places, the symbols represent more than one fault where five (x5) or two (x2) faults had the same orientation.


71°30'
42°45'
71°22'30"
42°45'
Nashua
Merrimack River
Perhams
Four Corners
NEW HAMPSHIRE
MASSACHUSETTS
Dunstable
Tyngsborough
North
Chelmsford
RL (×2)
RL (×5)
EXPLANATION
Strike and dip of outcrop-scale brittle fault—
Movement sense indicated by N, normal;
R, reverse; LL, left lateral; RL, right lateral
88
Inclined
Vertical
75 Bearing and plunge of slickenlines
42°37'30"
71°30'
42°37'30"
71°22'30"
Base modified from U.S. Geological Survey
Nashua South, 1965 (photorevised 1979), 1:24,000
0 1 2 3 4 KILOMETERS
0 1 2 MILES



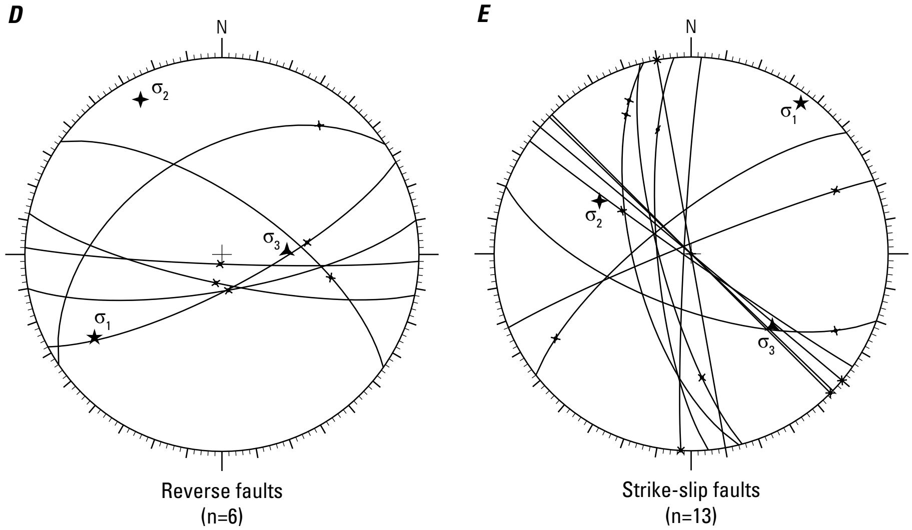


Figure 16. Lower hemisphere equal-area projections (stereonets) azimuth-frequency (rose) diagram of brittle faults. *A*, Poles to all faults contoured at 3 percent intervals, maximum contoured value is 18 percent. *B*, Rose diagram of steeply dipping faults. *C–E*, Stereonets showing fault planes, slickenlines, and calculated mean P and T axes for normal faults, reverse faults, and strike-slip faults, respectively. σ_1, shortening (P) axis; σ_3, extension (T) axis; ×, slickenlines. "N" indicates north, and "n" is the number of points in the dataset.

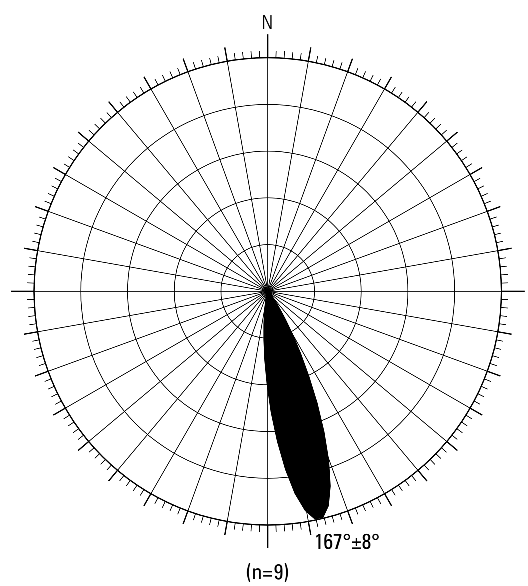


Figure 17 (facing column). Rose diagram of nine glacial striations in the Nashua South quadrangle. Single petal shows the average trend and 1-sigma error. "N" indicates north, and "n" shows the number of points in the dataset.

Metamorphism

Paleozoic metamorphic grade within the Nashua South quadrangle reached the garnet zone. Biotite is widespread in the Berwick Formation and in the Paleozoic intrusive rocks, but garnet (probably almandine) is common only in the intrusive rocks. In the Berwick Formation, metamorphic index minerals include actinolite, epidote, clinozoisite, sphene, grossular garnet, and diopside. Grossular garnet and diopside occur in the calc-silicate rocks in the Berwick Formation. Only rarely does the Berwick Formation contain almandine garnet in the more pelitic layers. Hornblende occurs in the Dad unit of the Ayer Granodiorite and in the diorite-gabbro suite. The growth of peak metamorphic minerals, such as garnet, diopside, and hornblende, is largely syn- to post-D_2 fabrics. Rare L_2 mineral lineations of biotite and hornblende imply peak metamorphic conditions during the D_2 event. Metamorphic zircon rims, although highly radiogenic and difficult to analyze, suggest growth at ~377 Ma.

Late-D_2 or post-D_2 faulting and retrograde metamorphic fabrics truncate the peak metamorphic isograds in the western part of the Rockingham anticlinorium (Robinson, 1978, 1981; Lyons and others, 1997). The isograds also are truncated along the Clinton-Newbury fault (Zen and others, 1983; Goldsmith, 1991). We show two post-peak metamorphic faults along the western border of the Nashua South quadrangle on the basis of the extension of faults mapped by Robinson (1978); these faults are not exposed in the Nashua South quadrangle.

Regionally, the peak metamorphism is attributed to the Devonian Acadian orogeny (Zen and others, 1983; Lyons and others, 1997). In the Merrimack trough, Attenouken and others (2004) report $^{40}Ar/^{39}Ar$ data that show peak metamorphism in the Devonian as part of the Acadian orogeny followed by overprinting in the Permian during the Alleghanian orogeny. The D_3 fabrics mapped in this quadrangle are probably a result of Alleghanian deformation.

Discussion

The metasedimentary rocks of the Berwick Formation form a homogeneous sequence of metapsammitic and metapelitic rocks that were deposited as limey sand and mud at ~425 Ma (Wintsch and others, 2007). The Berwick Formation varies only slightly in composition and bedding characteristics. Due to limited sedimentary topping criteria, it is not possible to tell the orientation of the stratigraphy within the Berwick Formation as a whole. Sriramadas' (1966) original interpretation that the rocks formed the southeastern limb of a major syncline could not be validated during this study because the rocks are significantly folded twice, and topping criteria are limited. The stratigraphy in the Merrimack trough shown on the cross sections of the map by Lyons and others (1997) appears to be deformed by only a single generation of upright folds, yet our mapping shows at least two significant folding events. Robinson (1978), Sundeen (1971), Fargo and Bothner (1995), and Walsh and Clark (1999) also note the presence of multiple deformation events, supporting the idea that the Berwick Formation has been multiply folded even though determining internal stratigraphy and finding topping criteria is difficult. The period of D_1 deformation recorded by the F_1 folds predates all intrusive igneous activity in the quadrangle. Our data for the Ayer Granodiorite suggest that the D_1 event occurred prior to ~407 Ma, probably during the earliest phase of the Acadian orogeny (for example, Bradley and others, 2000; Bradley and Tucker, 2002).

The period of D_2 deformation appears to be largely post-407 Ma. All of the rocks of the Ayer Granodiorite intrude the Berwick Formation after D_1 but prior to or at the onset of D_2. The Ayer Granodiorite generally contains a well-developed S_2 foliation, yet cuts the S_1 foliation in the Berwick Formation. Granitic rocks of the New Hampshire Plutonic Suite, including the Chelmsford Granite, trend subparallel to the D_2 fabric and are subsequently foliated by the D_2 schistosity. The Chelmsford Granite contains flow banding that is deformed by F_2 folds. These relations suggest that much of the New Hampshire Plutonic Suite is syntectonic with respect to D_2. The syntectonic nature of these rocks was noted regionally by Page (1968). Gore (1976, p. 120) also noted that the Chelmsford "…intruded into the axial regions of developing folds." The 375 Ma age of the Chelmsford Granite reported here, combined with a 381±2 Ma age from a foliated biotite granite dike in the New Milford quadrangle (Lyons and others, 1997; Walsh and Clark, 1999), support the D_2 deformation and intrusion as Acadian in age. Metamorphic rims on zircons from the Ayer Granodiorite and Chelmsford Granite, although not well constrained, suggest that the thermal peak of metamorphism was attained at ~377 Ma. $^{40}Ar/^{39}Ar$ data support peak metamorphism in the Devonian as part of the Acadian orogeny followed by overprinting in the Permian during the Alleghanian orogeny (Attenoukon and others, 2004).

Although tabular pegmatite and granite dikes crosscut the Ayer Granodiorite, Chelmsford Granite, and D_2 fabrics, they are generally deformed by D_3 cleavage, shear bands, and boudinage. It is possible that these relatively young dikes are Late Devonian to Permian in age, similar to other late- to posttectonic granitic rocks in the Milford area of southern New Hampshire (Aleinikoff and others, 1995; Lyons and others, 1997). If these observations are accurate, it is possible that the D_3 fabrics may be attributable to the Alleghanian orogeny. In support of this interpretation, Armstrong and others (1999) reported Alleghanian aged migmatites (~275 Ma) in the Massabesic Gneiss Complex and suggested that migmatization occurred during D_3 deformation in the Pinardville, N.H., quadrangle.

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