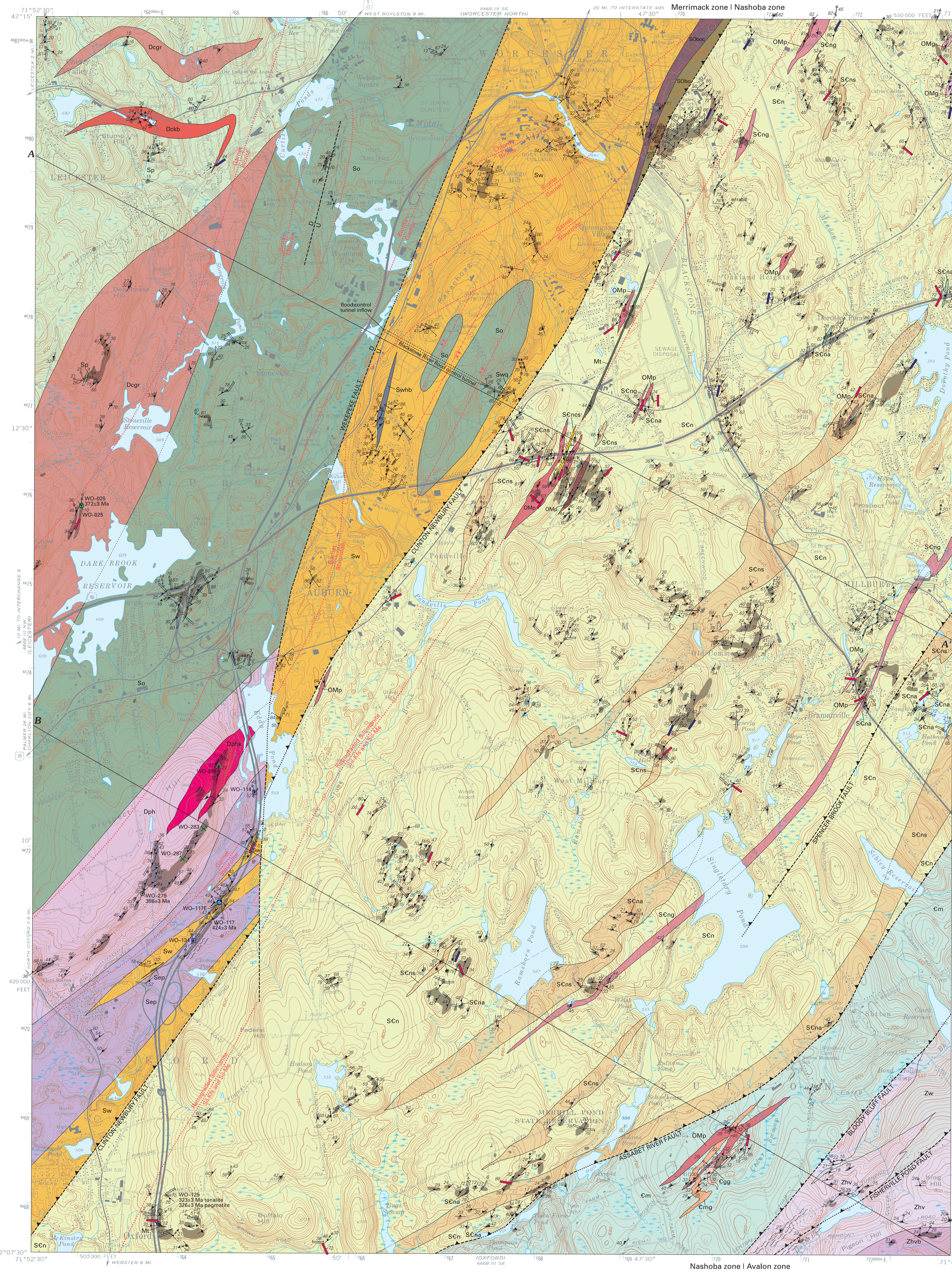
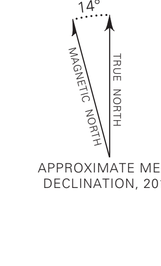
Prepared in cooperation with the
COMMONWEALTH OF MASSACHUSETTS
MASSACHUSETTS GEOLOGICAL SURVEY



Base from U.S. Geological Survey, 1973
Polyconic projection. 1927 North American Datum
1,000-meter Universal Transverse Mercator grid ticks, zone 19, shown in blue
Reprojected to Massachusetts Stateplane coordinate system, 1983 North American Datum
Interstate Route 395 south of US Route 20 added from photorevision of 2012

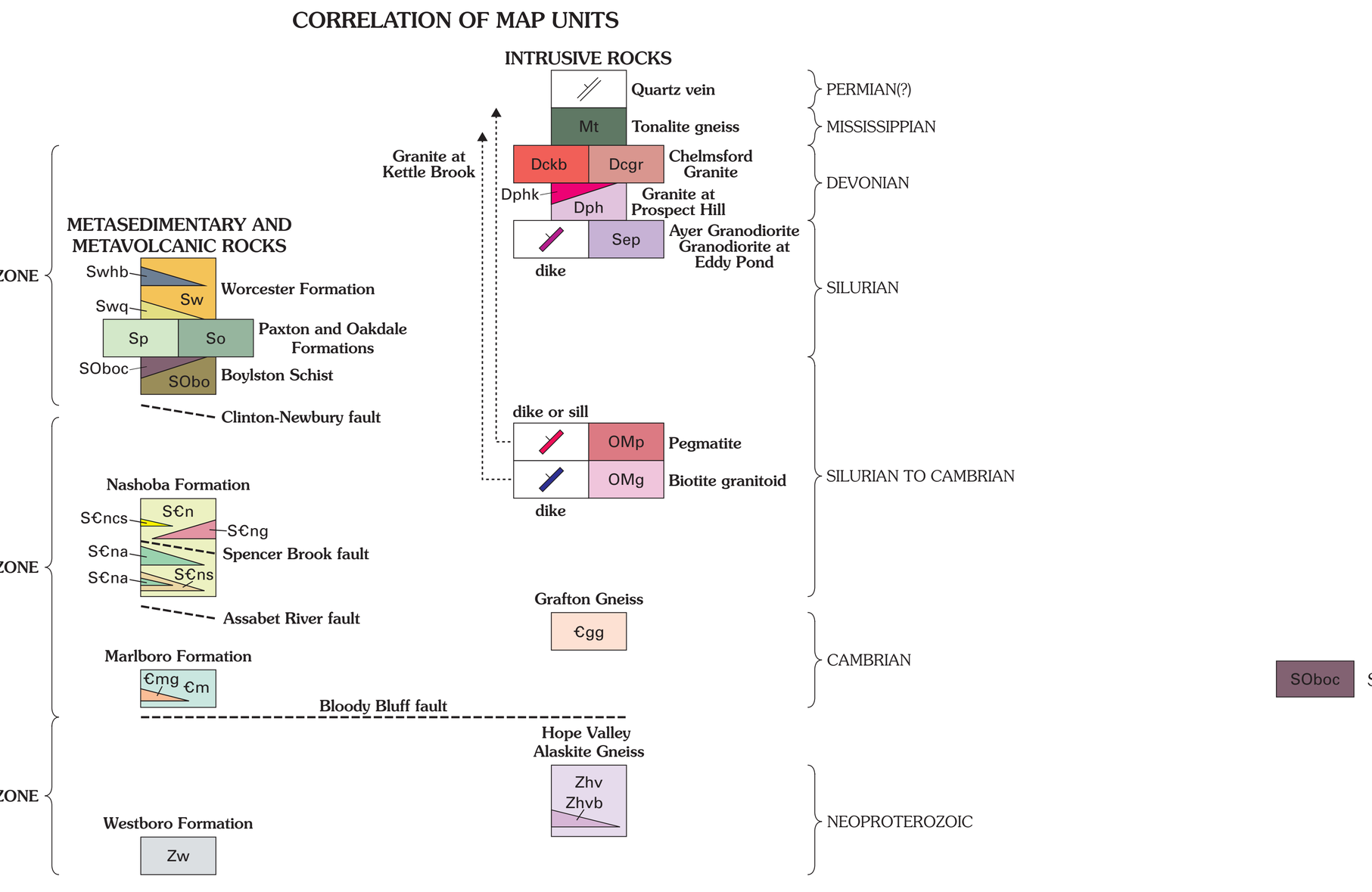


SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Geology mapped by Walsh (2008–2010), and Merschat (2010). Assisted by Jamie Kendall
Digital compilation by Walsh

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

[Station locations referenced on the map are included in the accompanying GIS database.]

INTRUSIVE ROCKS

Quartz vein (Permian?)—Quartz veins locally contain variable amounts of chlorite, ankerite, graphite, muscovite, magnetite, epidote, hematite, biotite, calcite, tourmaline, dolomite, sulfides, plagioclase, and alkali feldspar. Milky to smoky quartz veins are generally tabular and locally irregularly shaped, show sharp boundaries with the host rock, and locally contain blocky to elongate quartz crystals with euhedral terminations in vugs as much as several centimeters (cm) across along the median line. Strike and dip symbols show the location and orientation of 43 veins. Measured veins are as much as 0.3 meters (m) thick, dip steeply, and show variable strikes

ROCKS OF THE MERRIMACK ZONE

Intrusive Rocks

Dcgr **Chelmsford Granite (Late Devonian)**—Light-gray to white, rusty tan- to white-weathering, medium- to coarse-grained, foliated biotite-muscovite-quartz-plagioclase-microcline monzogranite and granitic pegmatite. Contains trace amounts of chlorite, opaques, apatite, garnet, titanite, epidote/clinozoisite, saussurite, and zircon. Occurs as outcrop- and map-scale dikes that range from several centimeters thick to kilometer-scale intrusions. Contacts with the adjacent Paxton and Oakdale formations are not exposed, but xenoliths of the Paxton Formation granofels were observed on the southern ridge of Deadhorse Hill. Good exposures occur in Auburn at cuts along the Penn Central Railroad northwest of Dark Brook Reservoir and on the southern ridge of Deadhorse Hill. Previously mapped as "mqm" ("muscovite-biotite quartz monzonite") by Barosh and others (1977) or as "Sagr" ("granite to tonalite") of the Ayer Granite on the State map (Zen and others, 1983). Barosh (unpub. data, 1996) correlates the rock with the Eastford Gneiss of Pease (1972), and Barosh (2009) uses the informal name Eastford granite for this unit. Walsh and others (2013b) report a Late Devonian SHRIMP uranium-lead (U-Pb) zircon age of 375±3 Ma (mega-annum) from the Chelmsford Granite in northeastern Massachusetts, and Wintsch and others (2007) report a SHRIMP U-Pb zircon age of 379±4 Ma from the Eastford Gneiss in northeastern Connecticut. Walsh and others (2013a) report a preliminary SHRIMP U-Pb zircon age of 372±3 Ma from sample number WO–025 collected north of Dark Brook Reservoir

Dckg **Granite at Kettle Brook (Devonian)**—White to very light gray, tan- to white-weathering, medium- to coarse-grained, foliated garnet-tourmaline-quartz-plagioclase-microcline monzogranite and granitic pegmatite. Contains conspicuous black tourmaline crystals up to 2 cm long and small (≤3 millimeters (mm)) garnet porphyroblasts. Contains minor to trace amounts of muscovite and biotite, plus trace amounts of chlorite and apatite. Well exposed in Kettle Brook north of Stump Hill in Worcester where it contains xenoliths of the Paxton Formation. Also occurs as a foliation-parallel sill within the Paxton Formation at a cut on the Penn Central Railroad near the junction of Grand View Avenue in Worcester; there it is shown by a purple strike and dip symbol. Previously included within "Sagr" of the Ayer Granite on the State map by Zen and others (1983)

Dph, **Dphk** **Granite at Prospect Hill (Devonian)**—Light-gray, gray to locally tan and rusty weathering, medium- to coarse-grained, equigranular, moderately to weakly foliated quartz-plagioclase-microcline monzogranite with a few percent muscovite and biotite in approximately equal proportion. The rock is generally less foliated and more massive towards the northwest, farther from the Clinton-Newbury fault. Contains trace amounts of chlorite, opaques, apatite, and zircon. Exposed on the southern and eastern slopes of Prospect Hill in Auburn and Oxford. It is well exposed along the power line in the vicinity of the Oxford–Auburn town line. The rock is similar to, but less micaceous than, the Chelmsford Granite. Contacts with the adjacent Oakdale Formation to the northwest and the Granodiorite at Eddy Pond to the southeast are not exposed. On the northeastern slopes of Prospect Hill, the unit contains a gray, inequigranular biotite-quartz-plagioclase-microcline monzogranite (mapped as **Dphk**) with distinctive microcline megacrysts up to 3 cm long. The feldspar crystals are locally euhedral, but in most places are deformed into augen generally 1 to 2 cm long. **Dphk** contains about 13 percent biotite and trace amounts of muscovite and chlorite. The contact between **Dph** and **Dphk** is not exposed, though nearby outcrops are within a few meters. Previously mapped as "Sagr" of the "Ayer Granite" on the State map by Zen and others (1983), informally as the Late Proterozoic Oxford quartz monzonite facies of the "Ayer Granite" by Barosh (unpub. data, 1996), or as "mqm" ("muscovite-biotite quartz monzonite") by Barosh and others (1977). Walsh and others (2013a) report a preliminary SHRIMP U-Pb zircon age of 386±3 Ma from sample number WO–279 collected on the south side of Prospect Hill

Sep **Ayer Granodiorite (Silurian) (name revised by Walsh and others, 2013b)**—Light- to medium-gray, generally equigranular, fine- to medium-grained, well-foliated to mylonitic, biotite-K-feldspar-quartz-plagioclase granodiorite to monzogranite. Plagioclase is altered to saussurite, K-feldspar is altered to sericite, and biotite is altered to chlorite. Contains minor to trace amounts of fabric-forming muscovite. Contains trace amounts of chlorite, hornblende, epidote/clinozoisite, allanite, opaques, titanite, tourmaline, garnet, zircon, calcite and apatite. Kinematic analysis of mylonitic fabric (see mylonitic pattern on map and station 1034 in GIS database) north of Chimney Pond shows down-dip normal motion at garnet grade, above chlorite stability. Mylonitic foliation is defined mostly by syn-tectonic muscovite-biotite and quartz ribbons. Asymmetric fabrics include mica fish, feldspar porphyroclasts, oblique foliation, and C′-type shear bands. Locally contains distinctive dark-gray biotite schist (**Sw** xenoliths) and biotite tonalite to quartz diorite enclaves that occur as 1 to 30 cm long patches and lenses that are flattened in the plane of the foliation and elongated into down-dip rods parallel to the lineation. Contains small (≤1 cm) feldspar megacrysts at exposures on Interstate 395 (I-395) northbound, north of Chimney Pond. Well exposed on I-395 between Exits 5 and 6, near Eddy Pond and Chimney Pond. Exposures in the median of I-395, approximately 400 m south of Cedar Street in Auburn, show that the granodiorite intruded the Worcester Formation (**Sw**) in a zone of abundant foliation-parallel dikes or sills, each of which is 10 to 20 cm thick; the location is shown on the map by a purple strike and dip symbol. Gore (1976) reports that the Clinton facies of the Ayer also intrudes the Worcester Formation. Previously mapped as "ape" ("early porphyritic quartz monzonite of the Ayer") by Barosh and others (1977) or as "Sacgr" ("Clinton facies") of the "Ayer Granite" on the State map by Zen and others (1983). The mapped rock is largely equigranular, however, it does not contain the large feldspar megacrysts that characterize the Clinton facies. Barosh (unpub. data, 1996) described the rock as the "Eddy Quartz Diorite Facies" for exposures near Eddy Pond. The unit is similar to the biotite granodiorite of the Devens-Long Pond facies of the Ayer Granodiorite in the Nashua South quadrangle (Walsh and others, 2013b). Walsh and others (2013a) report a preliminary SHRIMP U-Pb zircon age of 424±3 Ma from sample number WO–117 collected on I-395

Metasedimentary Rocks

Worcester Formation (Silurian)

Sw Phyllite and schist—Dark-gray to silvery gray, locally rusty weathering, carbonaceous quartz-muscovite phyllite or schist. Bedding that is locally graded is difficult to discern, but is characterized by light-gray, locally tan weathering, cm-scale sandy laminations and metasiltstone or metasandstone beds as much as 5 cm thick. Limited topping data from graded beds suggest that the Worcester Formation is stratigraphically above the Oakdale Formation. The unit varies northwest to southeast from chlorite grade in the northwest to staurolite grade in the southeast. The contact with the Boylston Schist is not exposed. The contact with the Oakdale Formation is exposed at one place in the outflow channel of the Blackstone River flood control tunnel; there it is sharp and marked by a quartzite (**Swq**). In the chlorite zone, the metapelite is a chlorite-muscovite-quartz phyllite with trace amounts of tourmaline, graphite, ilmenite, sulfides, plagioclase, epidote/clinozoisite, and apatite. In the biotite zone, the metapelite is a biotite-chlorite-quartz-muscovite phyllite with trace amounts of tourmaline, graphite, ilmenite, sulfides, plagioclase, epidote/clinozoisite, and apatite. In the garnet zone, the metapelite is a garnet-chlorite-biotite-quartz-muscovite phyllite to schist with trace amounts of tourmaline, graphite, ilmenite, sulfides, plagioclase, epidote/clinozoisite, and apatite. In the staurolite zone, the metapelite is a plagioclase-staurolite-garnet-biotite-quartz-muscovite schist with trace amounts of chlorite, tourmaline, graphite, ilmenite, hematite, sulfides, epidote/clinozoisite, zircon, and apatite. The unit contains calc-silicate rock mapped as **Swhb**

Swhb Calc-silicate granofels—Gray to light-gray, zoisite-clinozoisite/epidote-diopside-plagioclase-hornblende/tremolite-quartz granofels with distinctive light- to dark-green amphibole porphyroblasts. Exposed in Auburn along the west side of Pakachoag Street near the intersection of Burnap Street and Bancroft Street. Contacts with the surrounding schist are not exposed. Mapped as a hornblende quartz diorite gneiss by Grew (1970)

Swq Quartzite—Light-gray to white, tan-weathering, massive vitreous quartzite interlayered with gray plagioclase-staurolite-garnet-biotite-quartz-muscovite schist. This unit is approximately 8 m thick. Contact with the underlying Oakdale Formation is sharp where exposed in the outflow channel of the Blackstone River flood control tunnel. May be correlative with the Tower Hill Quartzite (Grew, 1970; Goldsmith and others, 1982; Markwort, 2007)

So **Oakdale Formation (Silurian)**—Interbedded gray, very light gray, purplish-gray, and purplish-green, locally rusty weathering, biotite-plagioclase-quartz granofels and lesser (≤25 percent) gray to dark-gray and purplish-gray plagioclase-chlorite-biotite-muscovite-quartz schist to phyllite. Rocks are locally calcareous, carbonaceous, or sulfidic. Granofels contains minor amounts of muscovite, chlorite, and carbonate, and trace amounts of actinolite/tremolite, epidote/clinozoisite, apatite, opaques (including sulfides and graphite), ilmenite, titanite, tourmaline, and zircon. Locally contains light-gray to purplish-gray or very pale green calc-silicate rock consisting of epidote/clinozoisite-actinolite/tremolite-biotite-plagioclase-quartz granofels containing mostly (>90 percent) plagioclase and quartz. Actinolite/tremolite crystals occur as tiny (>0.3 mm) grains generally aligned in the plane of the dominant foliation. Calc-silicate rock contains trace amounts of sphene, carbonates, zircon, opaques including sulfides, and apatite. Pelitic rocks contain abundant quartz veins with ankerite, dolomite, calcite, chlorite, lesser sulfides, tourmaline, and plagioclase. The contact with the Worcester Formation is exposed at one place in the outflow channel of the Blackstone River flood control tunnel (see description of units **Sw** and **Swq** above). In general the unit is poorly exposed, but roadcuts in Auburn at the following three locations provide excellent exposure: (1) the junction of I-290, I-395, and U.S. Route 20, (2) the I-90 exit 10 interchange, and (3) Water Street between I-290 and Route 12

Sp **Paxton Formation (Silurian)**—Gray, locally rusty weathering, slabby, biotite-quartz-plagioclase granofels with trace amounts of epidote/clinozoisite, actinolite, tourmaline, opaques (including sulfides and graphite), apatite, sphene, and zircon. Locally a calc-silicate granofels, consisting largely of biotite, quartz, and plagioclase with a few percent actinolite and epidote/clinozoisite, and trace amounts of apatite, sphene, and zoisite. The Paxton Formation contains dikes and sills of granite and pegmatite estimated to be about 10 to 20 percent of the unit (Barosh and Moore, 1988). The unit is lithologically similar to the Oakdale Formation, but lacks appreciable metapelite. The presence of granitoid rocks and the lack of carbonate indicate that it experienced a somewhat higher grade of metamorphism. This belt of rocks is considered the Paxton Group by Barosh and others (1977) or the Dudley Formation in the lower part of the Paxton Group by Barosh and Moore (1988) and Pease (1989). Here we use the name "Paxton Formation" for continuity with the statewide map (Zen and others, 1983; Robinson and Goldsmith, 1991). Robinson and Goldsmith (1991) noted a similarity between the Paxton Formation and the lower-grade Oakdale Formation. Grew (1970) mapped the Oakdale and the Paxton together as the Oakdale Formation, and showed higher grade rocks in the western part of the Worcester North quadrangle that we could not confirm in the Worcester South quadrangle because rocks with the appropriate bulk composition were not found. All thin sections from the two formations yielded essentially the same assemblage (±actinolite-biotite-quartz-plagioclase). The contact between the Paxton and Oakdale formations is either not exposed or is occupied by the Chelmsford Granite. The Paxton Formation is not well exposed, but representative outcrops occur in Kettle Brook between the elevations of 550–570 feet and in Lynde Brook between the elevations of 730–760 feet

Boylston Schist—(Silurian to Ordovician?)

SObo Schist and granofels—Gray, medium-grained, rusty weathering, staurolite-biotite-garnet-chlorite-plagioclase-quartz-muscovite schist and granofels with undifferentiated boudins and layers of gray to light-gray, equigranular muscovite-biotite-chlorite-quartz-plagioclase granodiorite to tonalitic granofels to gneiss. The unit is interpreted as a metasedimentary rock consisting of interlayered metapelite (schist) and metapsammite (granofels) with intrusive layers, sills, and boudins of metamorphosed igneous rock. Igneous rock layers and boudins range in thickness from about 10 cm to 2 m. Metasedimentary rocks contain trace amounts of opaques (includes sulfides), epidote/clinozoisite, and zircon. Metaigneous rock contains trace amounts of chlorite, sulfides, epidote, alkali feldspar, muscovite, and zircon. Retrograded staurolite, identified only in thin sections of schist, occurs as granular aggregates in sericite clots. Schist contains conspicuous garnet porphyroblasts, as much as 5 mm across. Biotite and garnet are retrograded to chlorite. Plagioclase occurs as deformed and recrystallized porphyroblasts in the metasedimentary rocks. The metamorphosed igneous rock exhibits a holocrystalline texture of quartz, feldspar, and biotite that experienced grain-size reduction and recrystallization during metamorphism. Rare small quartz and feldspar porphyroclasts, as much as 5 mm across, may be relict phenocrysts in the igneous rock. The unit contains rare small dark-gray to black pods, as much as 10 cm across, of quartz-plagioclase-biotite-chlorite granofels that may be altered xenoliths. The unit occurs between the Nashoba Formation (**S€n**) and the coticule-bearing Boylston Schist (**SOboc**) in the northeastern part of the map, and is exposed only along the power line northeast of the junction of Providence Street (Route 122A) and Route 146 in Worcester. The unit may be correlative with the Tadmuck Brook Schist (Barosh, 1976; Goldsmith and others, 1982), and the informally named "Science Park unit" (Hepburn, 1976). The metamorphic assemblage in the schist and the presence of similar igneous rocks resembles the schist mapped as Worcester Formation (**Sw**) west of the Wekepeke fault in the southwest part of the map. Our belt of Boylston Schist may also be correlative with the staurolite-grade rocks of the Worcester Formation. Grew (1970) considered both this belt of rock (**SObo** and **SOboc**) and the entire belt mapped by us (as the Worcester Formation (**Sw**)), as parts of the Boylston Schist, but we restrict the usage of the name "Boylston Schist" to the limited occurrence of this belt of rocks east of Providence Street based on usage shown on the State map by Zen and others (1983). Additional work is needed to more accurately characterize this belt of rocks to the northeast, and to determine the validity of the name "Boylston Schist." Robinson and Goldsmith (1991) and Goldsmith (1991) suggested that the higher grade (sillimanite) of the Boylston Schist at its type locality (Emerson, 1917) supported a correlation with the Nashoba Formation. In Boylston, Hepburn (1978) and Markwort (2007) mapped the Boylston Schist as a sillimanite-grade fault-bounded slice on the east side of the Merrimack terrane

SOboc Schist and coticule—Silvery gray to dark-gray, medium-grained, rusty weathering, biotite-garnet-chlorite-plagioclase-quartz-muscovite schist and granofels with distinctive boudins and layers of pink coticule to garnetiferous feldspathic quartzite. Coticule occurs as very fine grained, disarticulated, discontinuous, contorted, ribbony magnetite-quartz-garnet rock. Schist contains trace amounts of graphite, hematite, tourmaline, opaques (includes sulfides), epidote/clinozoisite, and zircon. Schist contains conspicuous garnet porphyroblasts, as much as 5 mm across. Biotite and garnet are retrograded to chlorite. The unit occurs between the Boylston Schist (**SObo**) and the Worcester Formation (**Sw**) in the northeastern part of the map, and is correlative with the informally named "Science Park unit" of Hepburn (1976) in the Worcester North quadrangle or the "Sts" phyllite member of the Tower Hill Quartzite (Hepburn, 1978). The unit is exposed only along the power line northeast of the junction of Providence Street (Route 122A) and Route 146 in Worcester

ROCKS OF THE NASHOBA ZONE

Intrusive Rocks

Mt **Tonalite gneiss (Mississippian)**—Gray, light-gray-weathering, weakly foliated, homogeneous, equigranular muscovite-biotite-quartz-plagioclase tonalitic granofels to gneiss within the Nashoba Formation. Contains trace amounts of alkali feldspar, chlorite, epidote/clinozoisite, opaques (including magnetite), garnet, sphene, apatite, and chlorite. Alkali feldspar is altered to sericite. The unit is characterized by a lack of leucosomes or alkali feldspar porphyroblasts typically found in the adjacent metasedimentary rocks. It occurs as thin sill-like bodies aligned in the plane of the dominant S_2 foliation. Mapped in the Nashoba Formation where it occurs as approximately 1- to 2-m-thick layers in the vicinity of Greenwood Street, south-southeast of Quinsigamond Village (stations 1602 and 1596), and on I-395 (station 1125) in Worcester; the thickness of the unit is exaggerated on the map to show the locations. Other smaller unmapped bodies occur within the Nashoba Formation at stations 1082, 1110, and 1392. Walsh and others (2013a) report a preliminary SHRIMP U-Pb zircon age of 323±3 Ma from a 1.2-m-thick tonalite (sample number WO–125) on I-395, about 400 m south of Dana Road in Oxford

OMp **Pegmatite dike (Permian?) or sill (Mississippian to Ordovician)**—Pink and white to white, white-weathering, coarse-grained, unfoliated, steeply dipping, tabular, muscovite granitic pegmatite dikes and foliated to weakly foliated syntectonic granitic pegmatite sills in the Nashoba and Marlboro Formations. Red strike and dip symbols on the map show the location and orientation of pegmatite dikes and sills. Symbols represent 15 measured dikes as much as 0.25 m thick or 22 sills as much as several meters thick. Fifteen measured tabular dikes postdate the foliation and show a preferred strike to the northwest. Pegmatite sills in the Nashoba Formation occur in the plane of the foliation. Other smaller syntectonic pegmatite sills occur throughout the Nashoba Formation but were not mapped separately. Large pegmatite bodies are mapped as **OMp**. A Permian age for the pegmatite dikes is inferred from regional correlations with similar dikes in Connecticut and Rhode Island in the Avalon zone (Zartman and Hermes, 1987; Wintsch and Aleinikoff, 1987; Zartman and others, 1988; Walsh and others, 2007). An age range of Ordovician to Mississippian is reported for the sills in the Nashoba Formation (Zartman and Naylor, 1984; Hepburn and others, 1995; Hepburn and Bailey, 1998; Acaster and Bickford, 1999). Walsh and others (2013a) report a preliminary SHRIMP U-Pb zircon age of 326±3 Ma from sample number WO–125 on I-395, about 400 m south of Dana Road in Oxford

OMg **Biotite granitoid (Mississippian to Ordovician)**—Pinkish-gray to light-gray, white-weathering, medium-grained, well-foliated, garnet-muscovite-chlorite-biotite-quartz-feldspar granitic to tonalitic sills and lesser dikes in the Nashoba Formation. Garnet is retrograded largely to chlorite and quartz. Feldspar consists mainly of recrystallized plagioclase and lesser sericitized alkali feldspar. Locally the unit contains muscovite porphyroblasts up to 2 cm across and also contains trace amounts of epidote and opaque minerals. Purple strike and dip symbols show the location and orientation of 3 dikes and 8 sills; includes one symbol in **Sp** which is correlated with a dike of **Dckb**. Symbols represent measured sills or dikes as much as 3 m thick. Sills occur in the plane of the foliation. Other smaller syntectonic granitic rocks occur throughout the Nashoba Formation but were not mapped separately; large granitic bodies are mapped as **Omg** in the northeastern part of the map. An Ordovician to Mississippian age range has been reported for the sills in the Nashoba Formation (Zartman and Naylor, 1984; Hepburn and others, 1995; Hepburn and Bailey, 1998; Acaster and Bickford, 1999)

Nashoba Formation (Silurian to Cambrian)

S€n Migmatitic gray schist to gneiss—Gray, medium- to coarse-grained, well-foliated, migmatitic, biotite-plagioclase-quartz-muscovite gneiss to muscovite-alkali-feldspar-plagioclase-quartz-biotite schist with distinctive foliation-parallel leucosomes and alkali feldspar porphyroblasts. Leucosomes locally contain muscovite porphyroblasts up to 2 cm across. May contain accessory chlorite, monazite, epidote/clinozoisite, apatite, hematite, and opaques including magnetite. Locally contains garnet and sillimanite visible in hand sample and staurolite or kyanite identified in thin section. Sericite, chlorite, and epidote/clinozoisite are retrograde products of biotite, garnet, sillimanite, staurolite, kyanite, plagioclase, and alkali feldspar. Locally the unit also contains unmapped boudins of dark-gray quartz-muscovite-biotite schist, amphibolite, and calc-silicate rock. Additionally the unit contains: (1) unmapped layers of gray epidote/clinozoisite-muscovite-biotite-feldspar-quartz gneiss, which may either be paragneiss or orthogneiss similar to tonalite gneiss unit (**Mt**); (2) amphibolite mapped as **S€na**; (3) calc-silicate rock mapped as **S€ncs**; (4) local garnetiferous schist that was mapped separately as **S€ng** where possible; and (5) migmatitic sulfidic schist (**S€ns**) mapped separately. The dominant foliation is locally mylonitic and characterized by extensive quartz ribbons, sericite-biotite-sillimanite±magnetite layers, and quartz-feldspar leucosomes. Sillimanite and K-feldspar assemblages show retrogression as sericite alteration of K-feldspar and minor alteration of sillimanite in sillimanite-magnetite bands surrounded by sericite. Distinctive porphyroblasts of plagioclase and lesser alkali feldspar are pre- to syntectonic, and as much as several centimeters across. Retrograde greenschist facies assemblages with abundant muscovite, biotite, and minor chlorite overprint amphibolite facies assemblages along the west side of the Nashoba Formation along the Clinton-Newbury fault. Contacts with the amphibolite unit (**S€na**) are sharp, but gradational with the sulfidic schist (**S€ns**) by intercalation over a few meters. Good exposures occur in roadcuts along the Massachusetts Turnpike, Route 146, and Route 20. The age of the Nashoba Formation is interpreted as Cambrian to Silurian (Hepburn and others, 1995; Hepburn, 2004; Wintsch and others, 2007; Loan and others, 2011)

S€ns Migmatitic sulfidic schist—Dark-gray, medium-grained, rusty weathering, well-foliated, sillimanite-alkali feldspar-muscovite-plagioclase-biotite-quartz schist and staurolite-garnet-quartz-biotite-muscovite schist. Contains accessory graphite, sulfides, ilmenite and hematite. Sericite and larger flakes of muscovite occur around alkali feldspar. The larger flakes of muscovite also occur both along and across the foliation. Sillimanite and alkali feldspar show retrogression to sericite. Biotite locally shows retrogression to chlorite. Contains amphibolite mapped as **S€na**. Plagioclase and lesser alkali feldspar porphyroblasts are pre- to syntectonic, and as much as 1 cm across. Staurolite occurs as microscopic unaltered, euhedral porphyroblasts. Typical exposures occur along the powerline west of Dorothy Road in Millbury and north of Town Farm Pond in Sutton

S€na Undifferentiated amphibolite and calc-silicate—Dark-green to black, rusty weathering, well-foliated, fine- to medium-grained, plagioclase-hornblende amphibolite gneiss and lesser well-layered calc-silicate gneiss. Amphibolite contains accessory sphene and quartz, and trace pyrite, chalcopyrite, magnetite, epidote/clinozoisite, and apatite. Calc-silicate gneiss is dark- to light-gray or dark-green, well-foliated, locally sulfidic, fine- to medium-grained, diopside-sphene-biotite-chlorite-actinolite-quartz-hornblende-plagioclase rock. Occurs as boudins and disarticulated layers less than a few meters across and is locally coarse-grained. Weakly foliated to non-foliated varieties may be intrusive metagabbroic dikes or sills. The size of the unit is exaggerated on the map to show outcrop locations. Good exposures occur in roadcuts in Millbury along the Massachusetts Turnpike (stations 1383 and 1386) and north of Dorothy Pond (station 1194). The biotite-plagioclase-quartz-hornblende calc-silicate observed on I-90 northwest of Dorothy Pond contains abundant disarticulated quartz veins (station 1386)

S€ncs Calc-silicate rock—Light-gray to gray, white- to tan-weathering, poorly foliated calc-silicate rock consisting largely of plagioclase-biotite-hornblende-quartz granofels. Contains minor amounts of diopside, epidote/clinozoisite, apatite, sphene, tremolite, chlorite, and opaques. Occurs in Millbury as a single layer a few meters across in a roadcut on the Massachusetts Turnpike (station 2078). Thickness is exaggerated on the map to show outcrop locations

S€ng Garnetiferous schist—Dark-gray, medium- to coarse-grained, locally rusty weathering, migmatitic, moderately foliated, kyanite-sillimanite-garnet-quartz-muscovite-biotite schist (eastern belt) or plagioclase-quartz-magnetite±staurolite±kyanite-garnet-biotite schist (western belt) with distinctive abundant garnet porphyroblasts. Locally a gneiss or a granofels. Contains minor amounts of plagioclase, K-feldspar, and magnetite and trace amounts of monazite, sericite, ilmenite, and apatite. Biotite defines the foliation and occurs as post-tectonic porphyroblasts across the foliation. Sillimanite, if present, occurs as fibrolite in the plane of the foliation. Microscopic kyanite (<1 mm), and mesoscopic garnet (<1 cm) and K-feldspar (<1 cm) occur as retrograded porphyroblasts. The foliation is defined largely by muscovite, biotite, quartz, and minor fibrolite. The three discontinuous along-strike units in the western belt in Worcester (in the northeastern part of the quadrangle) are retrograded; sillimanite or K-feldspar was not observed, but rather samples contain the lower-grade assemblages staurolite-kyanite-garnet (station 1225) or garnet-muscovite-chlorite (station 1044). Contacts with the surrounding map unit (**S€n**) are sharp. The unit is well exposed in Millbury on Route 146, east of Bramanville (station 1195, eastern belt), and on Route 20 near the Millbury-Worcester town line (station 1225, western belt)

Cambrian Intrusive Rocks

€gg **Grafton Gneiss (Cambrian)**—Light-gray to light-pink, medium-grained, well-foliated, chlorite-biotite-quartz-plagioclase-alkali feldspar granite gneiss. Contains secondary accessory sericite, epidote/clinozoisite, sphene, apatite, and magnetite. Relict allotriomorphic texture of intergrown quartz and 1.5 mm feldspar grains shows grain-size reduction along crystal boundaries. The foliation is defined by recrystallized quartz and feldspar and aligned biotite. Plagioclase shows relict polysynthetic twinning, local myrmekitic texture, and significant saussuritization and sericitization in a microcrystalline sieve texture. Alkali feldspar shows relict braided albite exsolution lamellae and mesoperthitic texture, and sericitization. Biotite, 2 to 5 percent of the rock, shows static retrogression to chlorite. Locally a dark- to medium-gray variety of gneiss contains 5 to 10 percent biotite. The interior of the rock body contains a somewhat heterogeneous distribution of biotite- and alkali feldspar-rich layers, but is relatively more homogeneous than the margins, which appear migmatitic and are characterized by abundant foliation-parallel granitic layers injected into the Marlboro Formation. The unit locally contains amphibolite xenoliths derived from Marlboro Formation. The unit is exposed only on the slopes east of Freeland Hill and west of Cedar Swamp in Sutton and correlated with similar rocks in the adjacent Grafton quadrangle where it yielded a Cambrian SHRIMP U-Pb zircon age of 515±4 Ma (Walsh and others, 2011a)

Lower Paleozoic Metasedimentary and Metavolcanic Rocks

Marlboro Formation (Cambrian)

€m Amphibolite gneiss and layered gneiss—Dark-green to black, rusty weathering, well-foliated, fine- to medium-grained, plagioclase-hornblende amphibolite gneiss containing banded dark-gray and light-gray well-layered felsic gneiss and lesser calc-silicate gneiss. Amphibolite gneiss contains accessory sphene and quartz and trace pyrite, chalcopyrite, magnetite, epidote/clinozoisite, and apatite. The layered gneiss consists of alternating bands of dark amphibolite gneiss and lighter amphibolite gneiss with lighter biotite granite gneiss, foliated pegmatite, and minor dioritic gneiss and calc-silicate gneiss. The layered gneiss (with injected granitic material) is migmatitic along the contact with the Grafton Gneiss (**€gg**) and younger pegmatite (**OMp**). The dioritic gneiss is dark-gray, medium- to coarse-grained, weakly to moderately foliated. The calc-silicate gneiss is gray to light-gray, well-foliated, locally sulfidic, fine- to medium-grained, biotite-chlorite-actinolite-quartz-hornblende-plagioclase rock. The age is Cambrian or older on the basis of the age of the Grafton Gneiss which intrudes it and the age of the interlayered Cambrian granofels (**€mg**). The unit is poorly exposed throughout the quadrangle, but locally well-exposed at the outfall of Town Farm Pond and west of Cedar Swamp on Freeland Hill in Sutton

€mg Granofels—Gray, fine- to medium-grained, massive to poorly layered, slabby and blocky weathering, biotite-quartz-feldspar granofels with light-colored quartz and feldspar porphyroclasts up to 0.5 cm. Individual granofels layers, interpreted as beds, are 10 to 50 cm thick. Contains thin layers of amphibolite that resemble rocks elsewhere in the Marlboro Formation. The unit is approximately 20 to 40 m thick. Granofels consists of approximately 40 to 50 percent feldspar (most of which is plagioclase), 40 to 45 percent quartz, 3 to 10 percent biotite, 1 to 3 percent epidote/clinozoisite, and trace to 1 percent magnetite, sphene, hematite, apatite, and tourmaline. The unit is correlated with a similar granofels in the adjacent Grafton quadrangle (Walsh and others, 2011a) and interpreted as a metawacke, perhaps of volcaniclastic origin. Contacts with the enclosing amphibolite gneiss and layered gneiss (**€m**) are not exposed, but contacts with cross-cutting pegmatite (**OMp**) are sharp. Occurs as a single map unit, structurally above the Grafton Gneiss (**€gg**), on Freeland Hill west of Cedar Swamp in Sutton. From a sample in the adjacent Grafton quadrangle, Walsh and others (2011b) report a preliminary SHRIMP U-Pb zircon age of 501±3 Ma from oscillatory zoned cores in complex zircons; suggesting that part of the Marlboro Formation is younger than the Grafton Gneiss

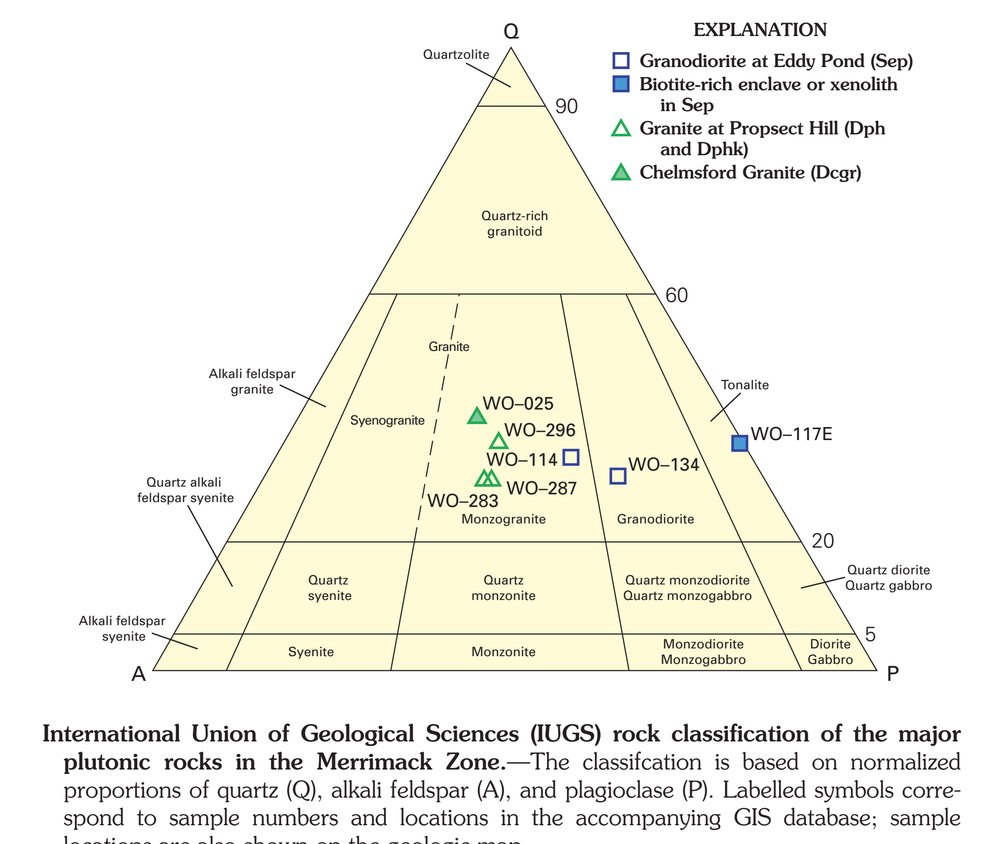
ROCKS OF THE AVALON ZONE

Intrusive Rocks

Zhv, **Zhvb** **Hope Valley Alaskite Gneiss (Neoproterozoic)**—Light-pink, tan to rusty or light-gray- to white-weathering, fine- to medium-grained, equigranular, well-foliated, plagioclase-quartz-alkali feldspar alkali granite to monzogranite gneiss. Contains approximately up to 25 percent plagioclase, 30 to 40 percent quartz, 30 to 40 percent alkali feldspar, and either trace to no biotite (**Zhv**) or trace to 3 percent biotite (**Zhvb**). **Zhvb** contains up to 3 percent chlorite from retrograded biotite. Contains up to 5 percent fabric-forming muscovite, up to 1 percent magnetite, and accessory garnet, apatite, and epidote-clinozoisite. Recrystallized quartz and feldspar define a faintly visible mineral aggregate lineation. Contacts were not observed in the map area, but the rock occurs both structurally above and below the Westboro Formation and probably intruded it. Walsh and others (2011a) report a Neoproterozoic SHRIMP U-Pb zircon age of 606±5 Ma from the adjacent Grafton quadrangle. Good exposures occur along Hartford Turnpike (**Zhv**) and south of Mendon Road (**Zhvb**)

Metasedimentary Rocks

Zw **Westboro Formation (Neoproterozoic)**—Silvery gray to pale-green or gray, quartz-rich chlorite-muscovite-quartz phyllite, and pale-green to very light gray or white, tan to rusty weathering quartzite. The unit is very poorly exposed and was observed at only one location east of Putnam Hill Road in Sutton



International Union of Geological Sciences (IUGS) rock classification of the major plutonic rocks in the Merrimack Zone.—The classifcation is based on normalized proportions of quartz (Q), alkali feldspar (A), and plagioclase (P). Labelled symbols correspond to sample numbers and locations in the accompanying GIS database; sample locations are also shown on the geologic map.

EXPLANATION OF MAP SYMBOLS

Contact—Approximately located; dotted where concealed by water. In cross section dotted where projected above the ground surface

Outcrops—Areas of exposed bedrock or closely spaced contiguous bedrock exposures examined in this study

Tunnel—Trace of the Worcester Diversion flood control tunnel on the Blackstone River (U.S. Army, 1956); not examined in this study. Geology extrapolated to the surface by Grew (1971)

FAULTS

Inferred mylonitic thrust fault—Parallel to metamorphic foliation; sawteeth on upper plate show dip direction. Possible early thrust motion on the Clinton-Newbury fault is overprinted by garnet-grade normal motion. Some faults are locally reactivated as normal brittle faults, especially along the Bloody Bluff fault. Dotted where concealed by water. In cross section dotted where projected above the ground surface

Inferred brittle fault—Relative motion indicated where known; U, upthrown side; D, downthrown side. Dotted where concealed by water. In cross section dotted where projected above the ground surface

FOLDS

[Showing trace of axial surface and direction of dip of limbs]

Inferred trace of F_2 folds in the Merrimack terrane (Acadian)

Overturned antiform

Overturned synform

PLANAR FEATURES

[Symbols may be combined; point of intersection shows location of measurement]

Strike and dip of graded bedding in the Worcester Formation

Inclined, overturned

Strike and dip of quartz vein (Permian?)

Inclined

Vertical

Strike and dip of OMp pegmatite dike (Permian) or sill (Ordovician to Mississippian)

Inclined

Vertical

Strike and dip of OMg granitic dike (Permian) or sill (Ordovician to Mississippian)

Inclined

Vertical

Strike and dip of Sep granodioritic dike (Silurian)

Strike and dip of deformed relict foliation (S_1)—Symbols show average strike and dip of highly deformed foliation

Strike and dip of deformed relict foliation (S_1)—Parallel to bedding or compositional layering

Strike and dip of dominant foliation (S_n)—Not age specific but largely S_2 or a composite S_1-S_2 foliation expressed as a schistosity in the sub-sillimanite-grade metasedimentary rocks and a schistosity to gneissosity in the intrusive and migmatitic rocks

Strike and dip of dominant foliation (S_2)—A schistosity to gneissosity in the metasedimentary and metavolcanic rocks, and a gneissosity in the intrusive rocks

Inclined

Vertical

Strike and dip of mylonitic or phyllonitic S_2 foliation—Observed locally near the Bloody Bluff and Clinton-Newbury faults

Strike and dip of axial surface of F_2 minor fold parallel to S_2 foliation—Tight to isoclinal, locally rootless folds

Strike and dip of crenulation cleavage (S_3)—Probably Alleghanian and correlative across the map

Inclined

Vertical

Strike and dip of axial surface of F_3 minor fold—Open to tight, late fold; probably Alleghanian and correlative across map

Inclined

Vertical

Strike and dip of F_3 or younger minor kink bands or shear bands—Late kink bands or shear bands locally associated with extensional veins or pegmatites; Alleghanian or younger and correlative across the map

Inclined

Vertical

LINEAR FEATURES

[Symbols may be combined; point of intersection shows location of measurement]

Bearing and plunge of L_2 intersection lineation—Intersection between the dominant foliation (S_2) and an older foliation that is parallel to compositional layering (S_1)

Bearing and plunge of L_3 intersection lineation—Intersection between a younger cleavage (S_3) and an older foliation (S_1 or S_2)

Bearing and plunge of L_2 mineral lineation—Aggregate lineation or grain lineation associated with the dominant foliation (S_2); consists of quartz, biotite, or K-feldspar in the Avalon zone; quartz, biotite, amphibole, sillimanite, or K-feldspar in the Nashoba zone; and quartz, biotite, or K-feldspar in the Merrimack zone

Bearing and plunge of F_2 minor fold axis—Fold axis of tight, isoclinal, or rootless fold associated with the dominant foliation (S_2)

Bearing and plunge of F_3 minor fold axis—Fold axis of late open to tight fold or crenulation lineation

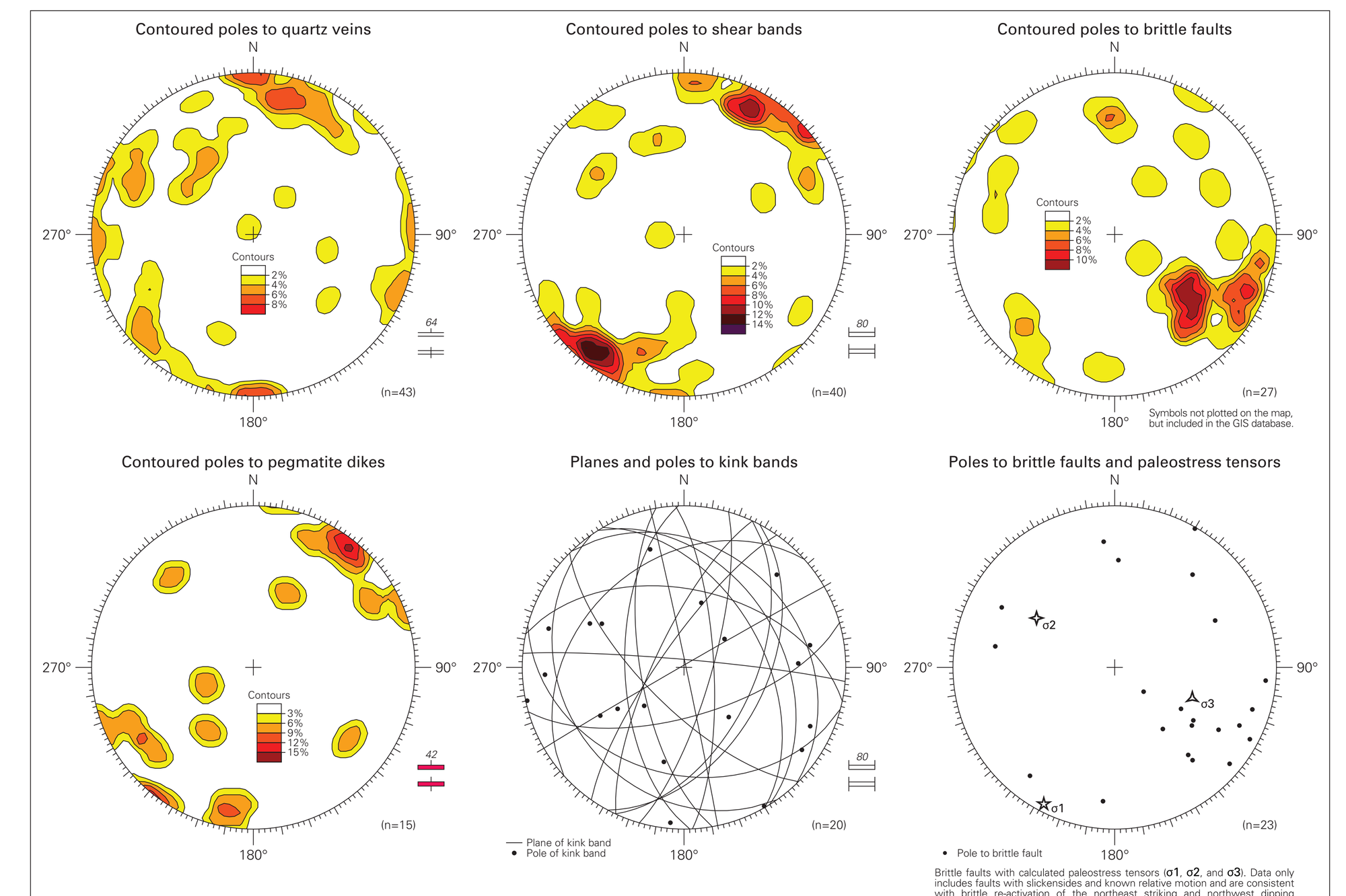
OTHER FEATURES

Garnet / Staurolite **Metamorphic isograd**—Approximate boundary between metamorphic zones. Poorly constrained in the Paxton Group and Oakdale Formation due to bulk composition; there rocks labelled in the garnet zone contain actinolite. Well constrained in the Worcester Formation northeast of the Wekepeke fault, but less well constrained southwest of the fault where the formation is entirely within the staurolite zone. Upper amphibolite facies rocks in the Nashoba Formation are overprinted by biotite-grade greenschist facies assemblages in a belt east of the Clinton-Newbury fault; the limit of this belt is schematic and poorly constrained. Metamorphic grade in the Avalon zone is extrapolated from the adjacent Grafton quadrangle (Walsh and others, 2011) due to the very limited occurrence of the Westboro Formation in the Worcester South quadrangle

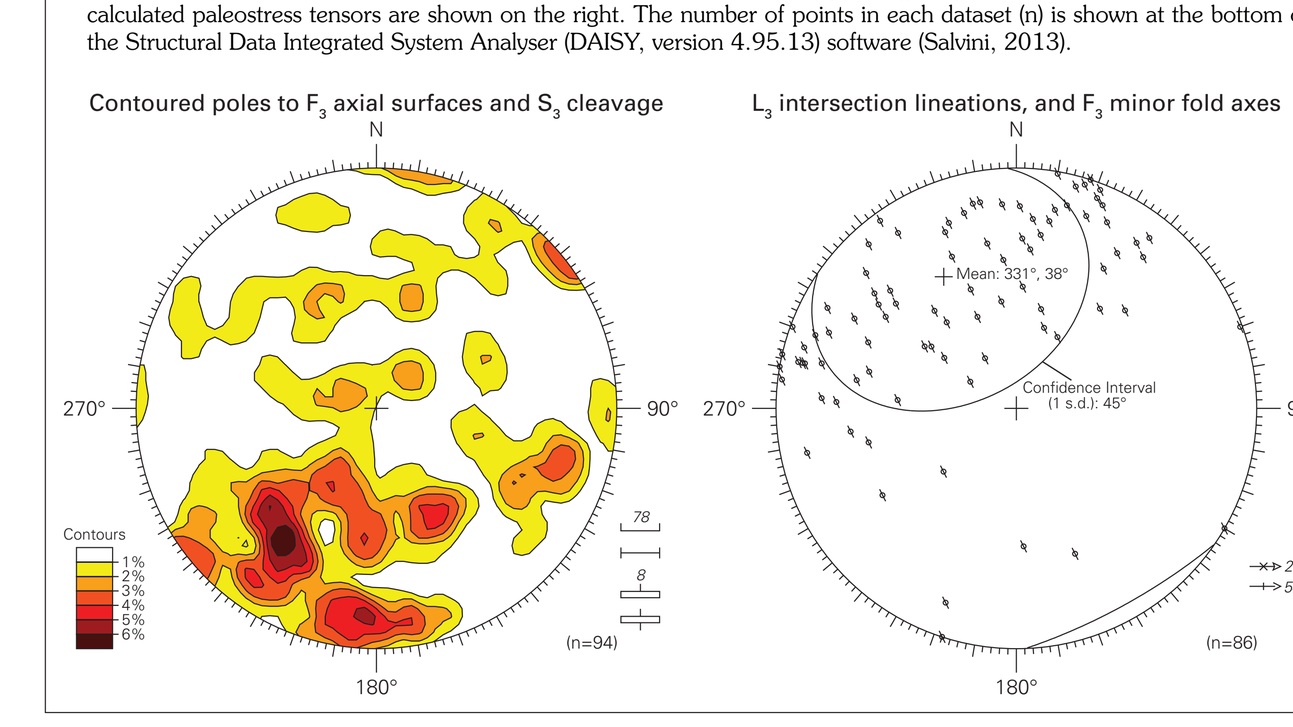
Abandoned quarry—Includes one quarried pegmatite erratic north of Oakland Heights

Spring

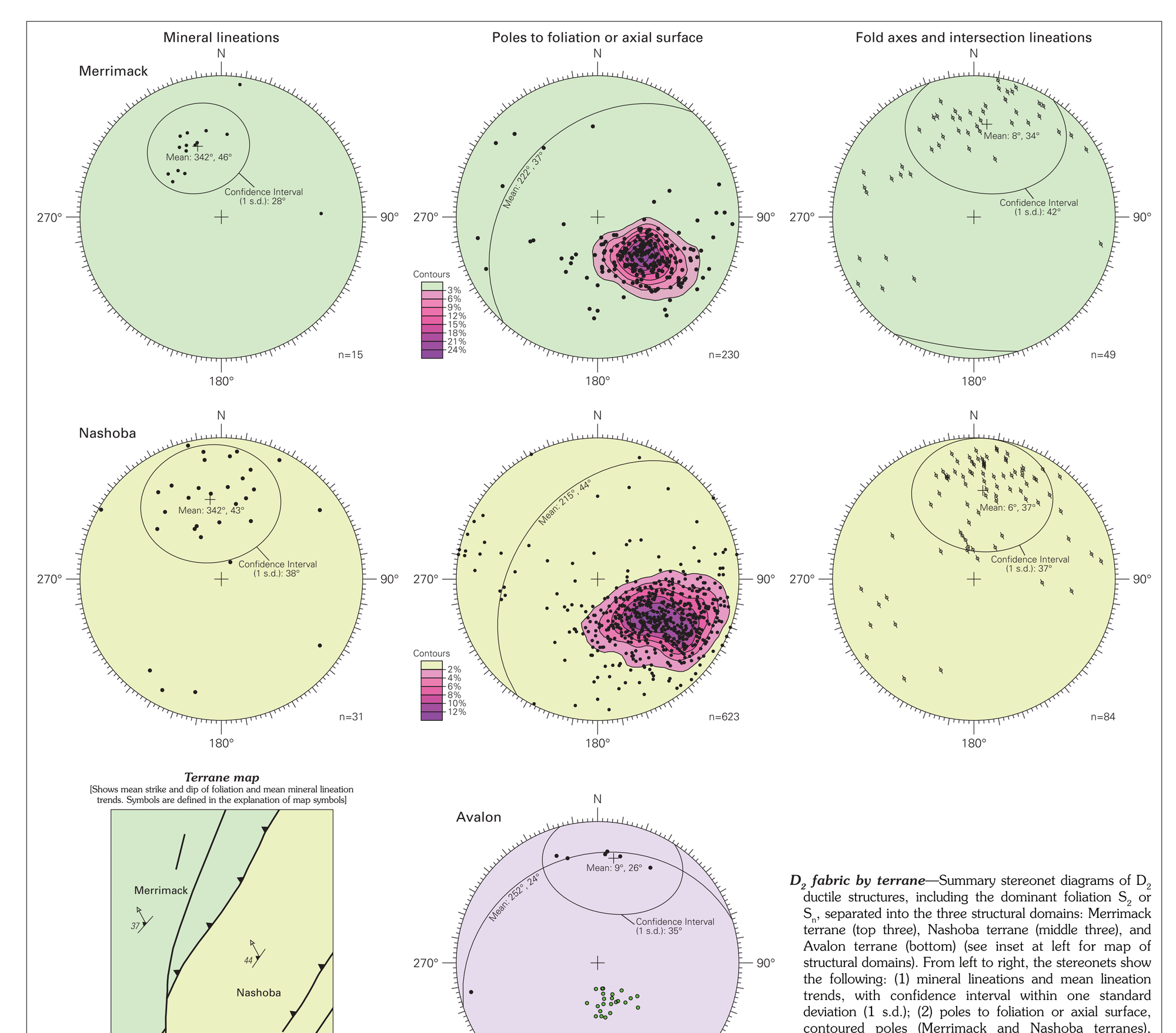
WO–117 424±3 Ma **Geochronology sample location showing age**—Preliminary SHRIMP U-Pb zircon age from Walsh and others (2013). Map locations of geochronology samples **WO–117** and **WO–025** are coincident with map locations of IUGS rock classification samples **WO–117E** and **WO–025**, respectively

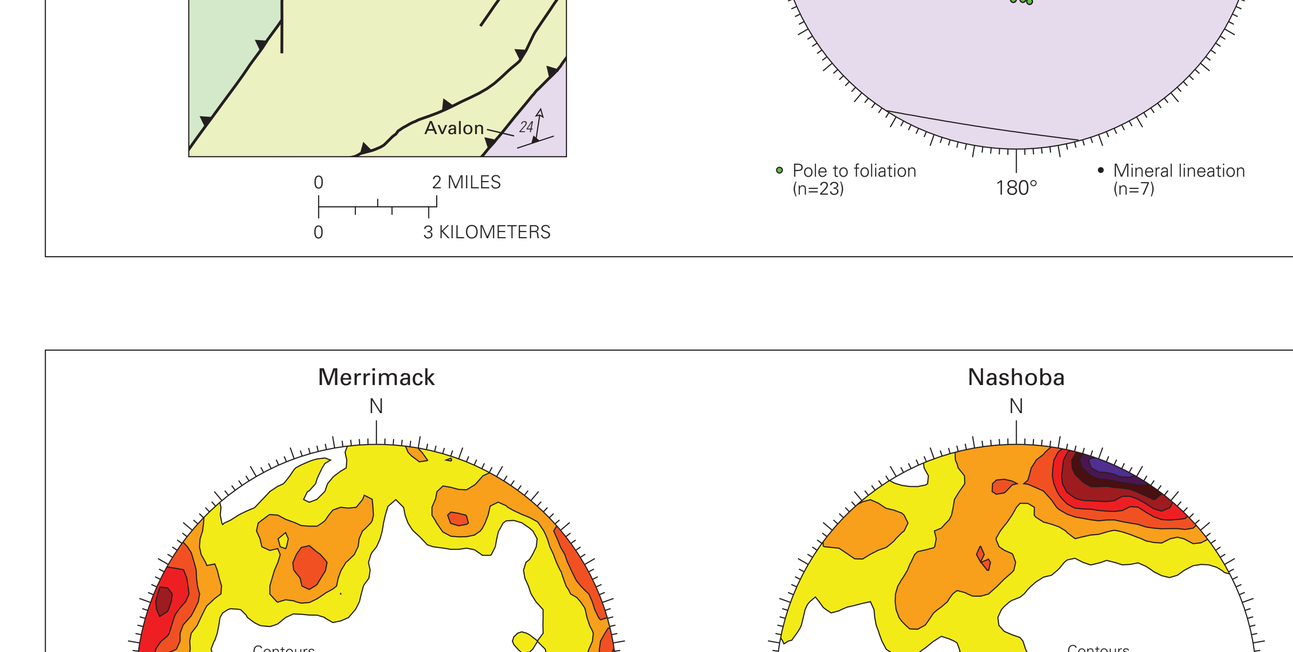


D_3 to D_4 fabric—Summary stereonet diagrams of D_3 ductile to D_4 or younger brittle structures for the map area. The poles to veins, pegmatite dikes, and shear bands are contoured. Planes and poles to kink bands are random and not contoured. Corresponding map symbols are shown on the lower right of each stereonet. Contoured poles to brittle faults and calculated paleostress tensors are shown on the right. The number of points in each dataset (n) is shown at the bottom of each diagram. Stereonets and rose diagrams were plotted using the Structural Data Integrated System Analyser (DAISY, version 4.95.13) software (Salvini, 2013).

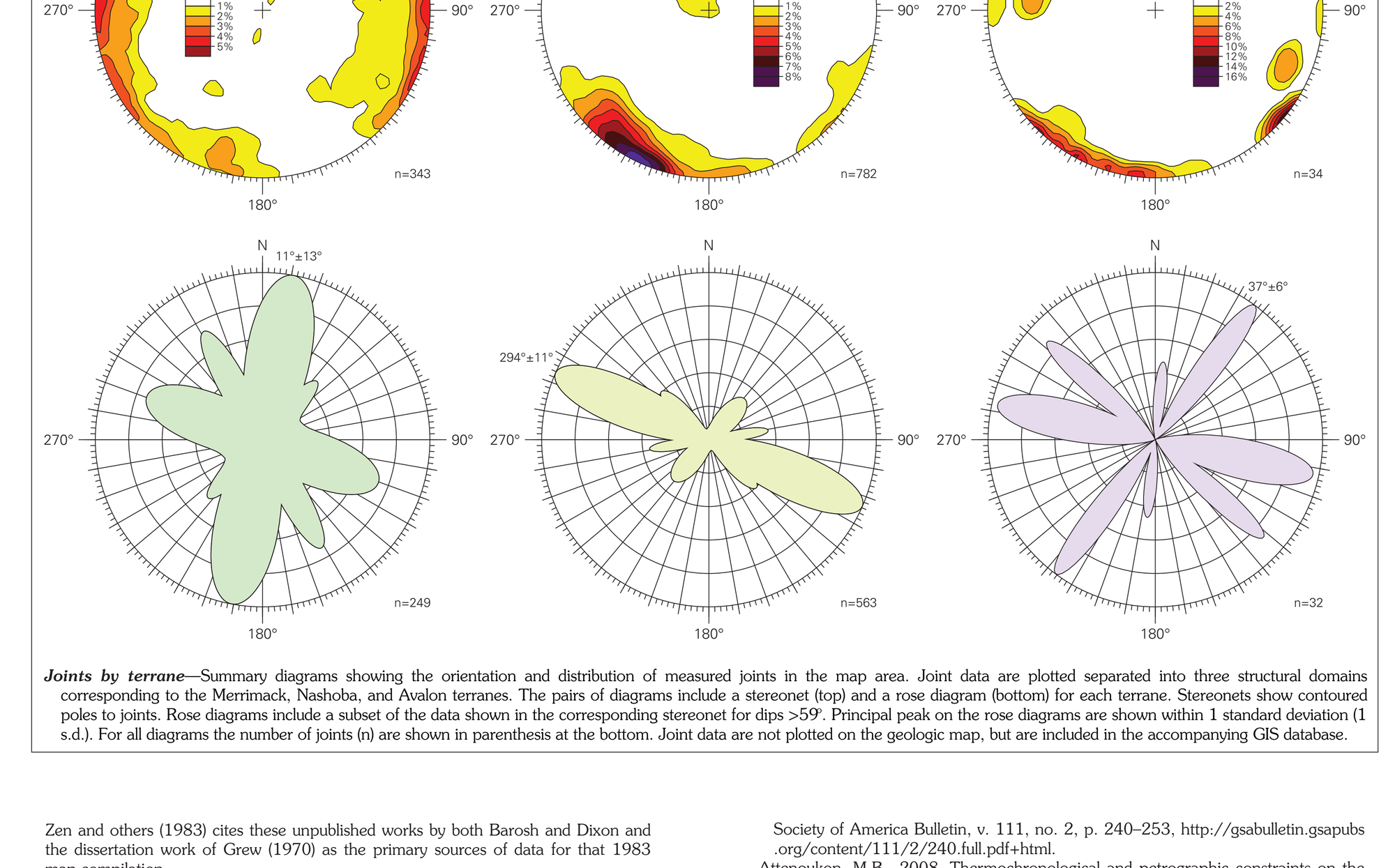


D_3 fabric—Summary stereonet diagrams of D_3 ductile structures for the map area. The left stereonet shows contoured poles to F_3 axial surfaces and S_3 cleavage. The right stereonet shows L_3 intersection lineations, L_3 crenulations, F_3 minor fold axes, and the mean lineation trend with confidence interval within one standard deviation (1 s.d.). Corresponding map symbols are shown on the lower right of each stereonet. Regionally this fabric, and the generally northwest-trending veins, shear bands, and pegmatite dikes are largely related to the alternately named Douglas Woods anticline of Goldstein (1982) or the Oxford anticline of Barosh (2005).

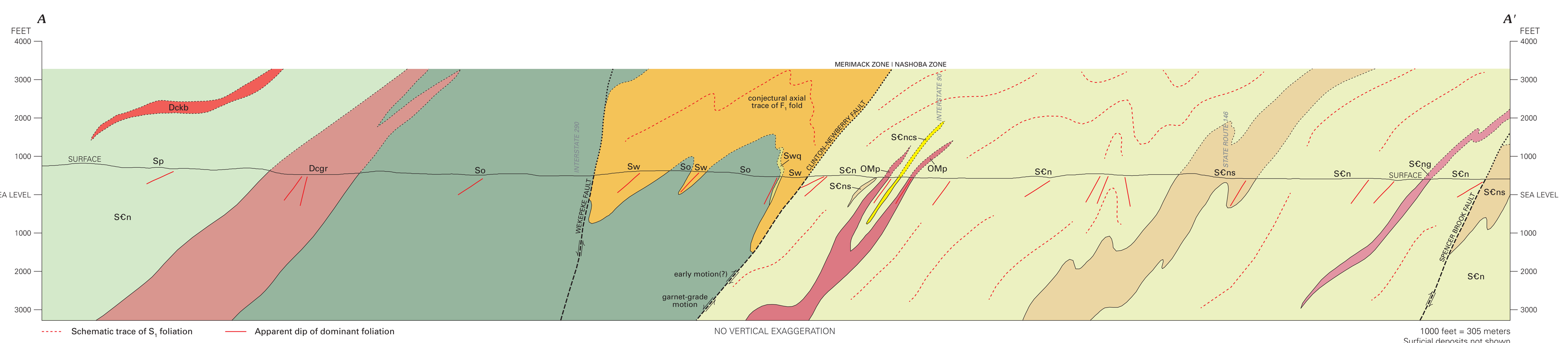




D_2 fabric by terrane—Summary stereonet diagrams of D_2 ductile structures, including the dominant foliation S_2 or S_n, separated into the three structural domains: Merrimack terrane (top three), Nashoba terrane (middle three), and Avalon terrane (bottom) (see inset at left for map of structural domains). From left to right, the stereonets show the following: (1) mineral lineations and mean lineation trends, with confidence interval within one standard deviation (1 s.d.); (2) poles to foliation or axial surface, contoured poles (Merrimack and Nashoba terranes), best-fit great circle to poles, and confidence interval within 1 s.d. (Avalon terrane); and (3) fold axes and intersection lineations with confidence interval within 1 s.d. Due to a limited dataset, the poles to foliation and the mineral lineations for the Avalon terrane are combined into a single stereonet.



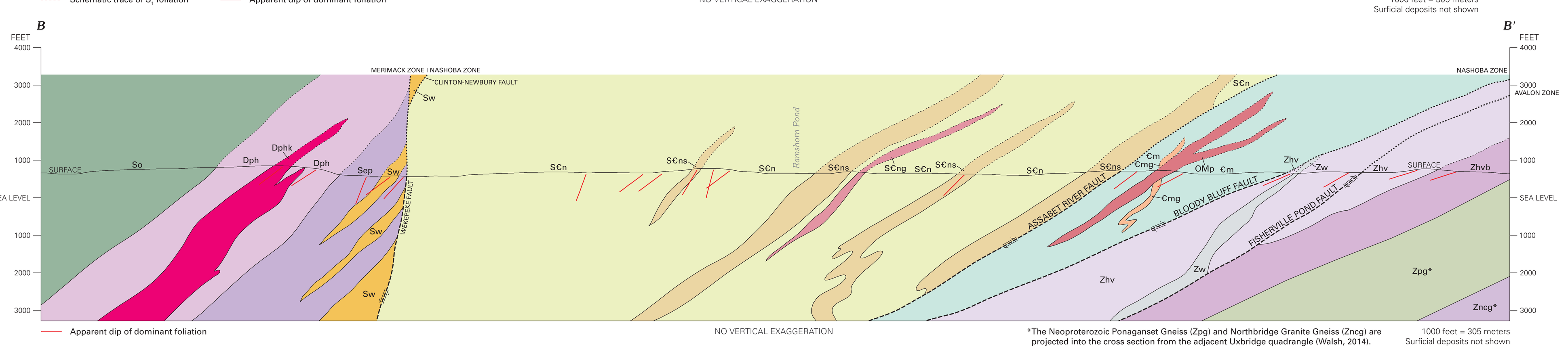
Joints by terrane—Summary diagrams showing the orientation and distribution of measured joints in the map area. Joint data are plotted separated into three structural domains corresponding to the Merrimack, Nashoba, and Avalon terranes. The pairs of diagrams include a stereonet (top) and a rose diagram (bottom) for each terrane. Stereonets show contoured poles to joints. Rose diagrams include a subset of the data shown in the corresponding stereonet for dips >59°. Principal peak on the rose diagrams are shown within 1 standard deviation (1 s.d.). For all diagrams the number of joints (n) are shown in parenthesis at the bottom. Joint data are not plotted on the geologic map, but are included in the accompanying GIS database.



Schematic trace of S_1 foliation — Apparent dip of dominant foliation

NO VERTICAL EXAGGERATION

1000 feet = 305 meters
Surficial deposits not shown

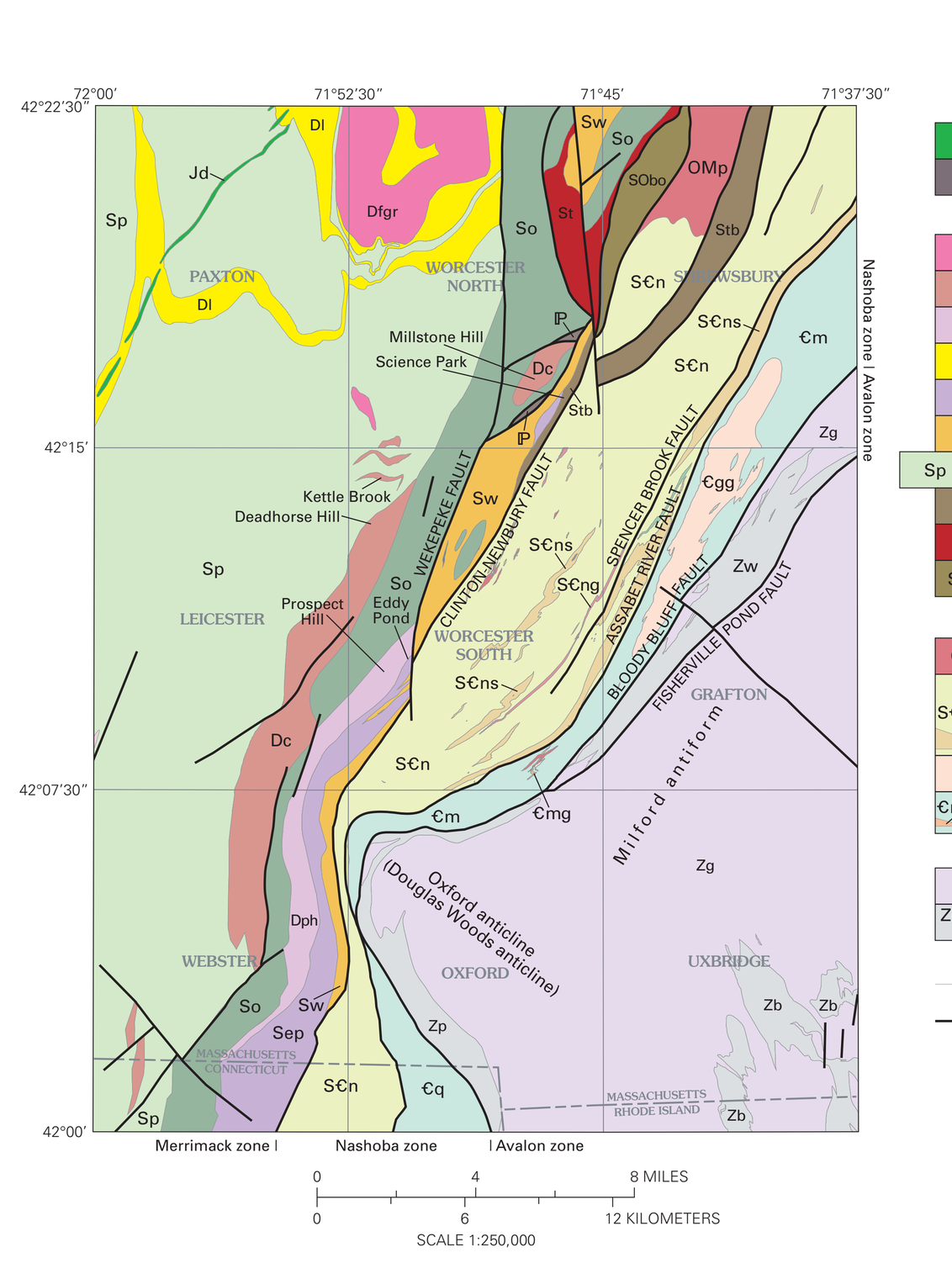


Apparent dip of dominant foliation

NO VERTICAL EXAGGERATION

*The Neoproterozoic Ponaganset Gneiss (Zpg) and Northbridge Granite Gneiss (Zncg) are projected into the cross section from the adjacent Uxbridge quadrangle (Walsh, 2014).

1000 feet = 305 meters
Surficial deposits not shown



EXPLANATION

- **Jd** Diabase dike or sill (Jurassic)
- **IP** Worcester basin (Pennsylvanian)

Merrimack zone and Central Maine Belts

- **Dfgr** Fitchberg Complex (Devonian)
- **Dc** Chelmsford Granite and related granite (Devonian)
- **Dph** Granite at Prospect Hill (Devonian)
- **Dl** Littleton Formation (Devonian)
- **Sep** Ayer Granodiorite at Eddy Pond (Silurian)
- **Sw** Worcester Formation (Silurian)
- **Sp**, **So** Paxton Formation and Oakdale Formation (Silurian)
- **Stb** Tadmuck Brook Schist (Silurian)
- **St** Tower Hill Quartzite (Silurian)
- **SObo** Boylston Schist (Silurian to Ordovician?)

Nashoba zone

- **OMp** Granite and pegmatite (Mississippian to Ordovician)
- **S€ng**, **S€n**, **S€ns** Nashoba Formation (Silurian and Cambrian)
- **€gg** Grafton Gneiss (Cambrian)
- **€mg**, **€m**, **€q** Marlboro and Quinebaug Formations (Cambrian)

Avalon zone

- **Zg** Granitoids of the Rhode Island batholith (Neoproterozoic)
- **Zb**, **Zp**, **Zw** Metasedimentary Blackstone Group (Zb), Westboro Formation (Zw), and Plainfield Formation (Zp) (Neoproterozoic)

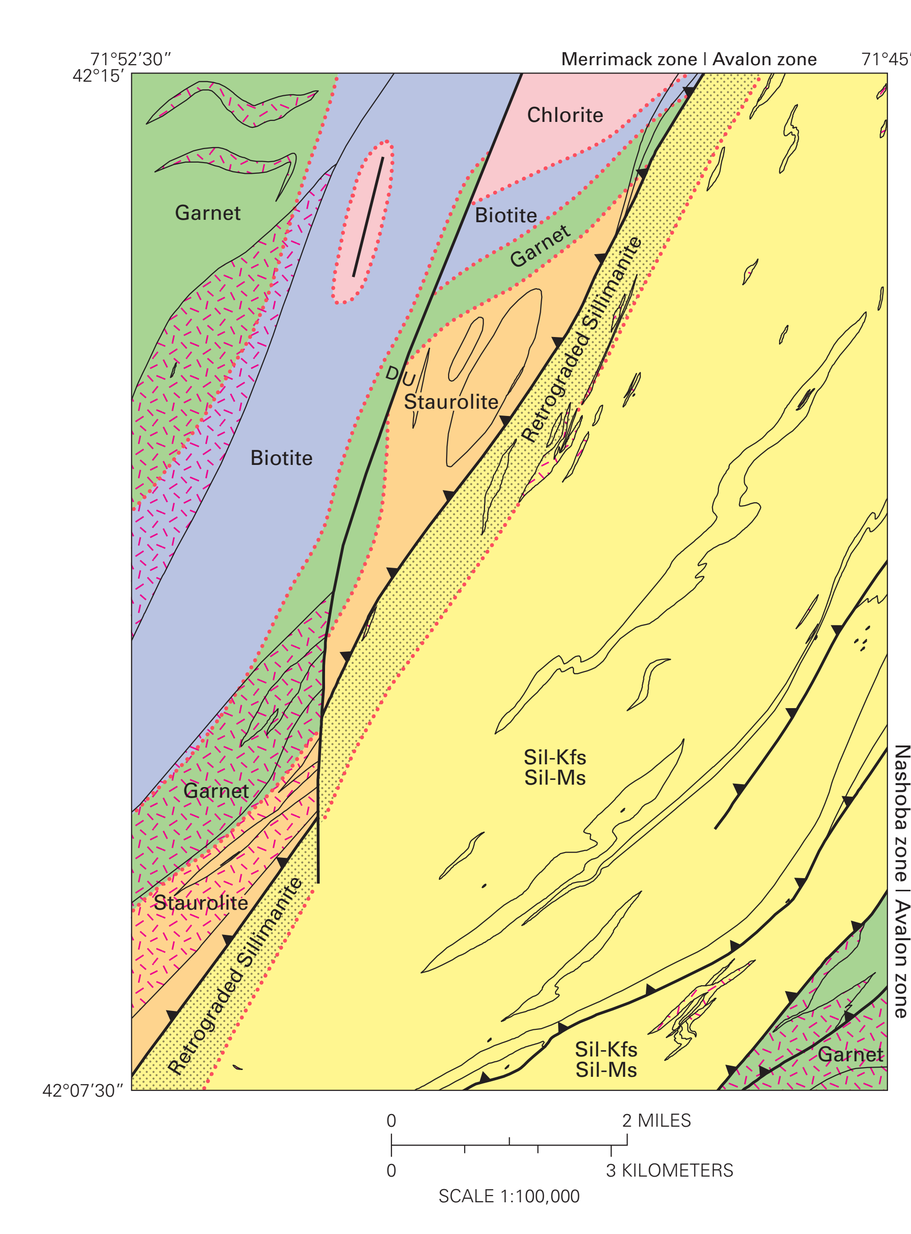
Contact

Fault

Index to mapping in adjacent 7.5-minute quadrangles

Paxton (Zen and others, 1983)
Leicester (Barosh and Johnson, 1976)
Webster (Barosh, 2009)
Oxford (Barosh, 2005)
Uxbridge (Walsh, 2014)
Grafton (Walsh and others, 2011a)
Shrewsbury (Hepburn, 1978; Markwort, 2007)
Worcester North (Hepburn, 1976)

Simplified tectonic map.—Modified after Zen and others (1983) and mapping in adjacent quadrangles.



EXPLANATION

Metamorphic grade

- Chlorite
- Biotite
- Garnet—Garnet grade rocks, locally constrained by the presence of actinolite in calc-silicate rocks. Poorly constrained in the Paxton Group, Oakdale Formation, and the Avalon zone
- Staurolite
- Approximate limit of retrograded sillimanite grade rocks in the footwall of the Clinton-Newbury fault—Retrograded to greenschist and lower amphibolite facies. Other retrograded areas not shown though retrograde greenschist facies assemblages of sericite after staurolite, and chlorite after garnet and biotite, occur in the hanging wall of the Clinton-Newbury fault
- Undifferentiated Sillimanite-K-feldspar (Sil-Kfs) and Sillimanite-Muscovite (Sil-Ms)—Locally retrograded to greenschist facies, but not shown
- Plutonic rocks

Contact

Fault—U, upthrown side; D, downthrown side

Thrust fault—Saw teeth on upper plate show dip direction

Approximate metamorphic isograd

Metamorphic map of the Worcester South quadrangle

DISCUSSION

INTRODUCTION

The bedrock geology of the 7.5-minute Worcester South quadrangle, Massachusetts, consists of deformed Neoproterozoic to Paleozoic crystalline metamorphic and intrusive igneous rocks in three fault-bounded terranes (zones), including the Avalon, Nashoba, and Merrimack zones (Zen and others, 1983). This quadrangle spans the easternmost occurrence of Ganderian margin arc-related rocks (Nashoba zone) in the southern New England part of the northern Appalachians, and coincides with the trailing edge of Ganderia (Merrimack and Nashoba zones) where it structurally overlies Avalonia (Hibbard and others, 2006; Pollock and others, 2012; van Staal and others, 2009, 2012).

Neoproterozoic intrusive rocks and minor metasedimentary rocks crop out in the Avalon zone and structurally underlie the rocks of the Nashoba zone along the Bloddy Bluff fault. Due to poor exposure, the position of the Bloody Bluff fault is not well-constrained and its location is partly extrapolated from mapping in adjacent areas (Barosh, 2005; Walsh and others, 2011a). Cambrian intrusive rocks and Cambrian to Silurian metasedimentary and metavolcanic rocks crop out in the Nashoba zone, and are overlain by largely Silurian metasedimentary rocks of the Merrimack zone along the Clinton-Newbury fault. Ordovician to Permian(?) plutonic rocks intrude the Merrimack and Nashoba zone rocks. Paleozoic metamorphism in the Merrimack and Nashoba zones peaked during Salinic, Acadian, and Neoacadian orogenesis from the Silurian to Mississippian (Wintsch and others, 2007; Stroud and others, 2009; Walsh and others, 2011a; Hepburn and others, 2014). Metamorphism in the Avalon zone peaked during Alleghanian orogenesis in the Mississippian to Permian (Wintsch and others, 1992, 1993, 2001; Attenoukon, 2008). Evidence for garnet-grade extensional Alleghanian mylonitization showing normal motion along the Clinton-Newbury fault occurred after presumed original terrane juxtaposition by left-lateral Acadian thrusting (Goldstein, 1994). Subsequent post-peak metamorphic deformation produced outcrop-scale open folds and weak cleavage, local faults, veins, shear bands, and pegmatite dikes. Locally, along re-activated ductile faults such as the Bloody Bluff fault and along the Wekepeke fault, late Paleozoic to Mesozoic mainly brittle normal fault motion led to the current configuration of fault-bounded lithotectonic terranes (Goldstein, 1982, 1994, 1998; Goldstein and Hepburn, 1999; Goldsmith, 1991; Attenoukon, 2008; Wintsch and others, 2012). The youngest deformation includes kink bands, brittle faults, and joints.

The bedrock geology was mapped to study the tectonic history of the area and to provide a framework for ongoing hydrogeologic characterization of the fractured bedrock of Massachusetts. This report presents mapping by Gregory J. Walsh and Arthur J. Merschat from 2008 to 2010. The report consists of a map and GIS database, both of which are available for download at http://dx.doi.org/10.3133/sim3345. The database includes contacts of bedrock geologic units, faults, outcrop locations, structural information, and photographs.

PREVIOUS WORK

Early geologic mapping more than a century ago covered the northern part of the Worcester South quadrangle (Perry and Emerson, 1903) and was compiled into a regional synthesis by Emerson (1917). Prior to new mapping from 2008 to 2010 for this report, 1:24,000-scale published mapping in the Worcester South quadrangle was limited, although Grew (1970) mapped the northeastern corner of the Worcester South quadrangle and a preliminary map was completed by Barosh (1977). In addition, a provisional unpublished bedrock geologic map of the Worcester South quadrangle at 1:24,000 scale was completed by Patrick J. Barosh in 1996 and a copy was archived by the Massachusetts Geological Survey. [In the rest of the text this unpublished map is cited as Barosh (unpub. data, 1996).] Barosh published the results of some his work in the Worcester South quadrangle in fieldtrip guidebook articles (Barosh, 1976, 1982) and in small-scale compilations (Barosh, 1977; Barosh and others, 1977). Unpublished reconnaissance geologic map data of the Worcester South quadrangle by H. Roberta Dixon (1977–78) was acquired from the U.S. Geological Survey Field Records Collection Library in Denver, Colo. The state geologic map by Zen and others (1983) cites these unpublished works by both Barosh and Dixon and the dissertation work of Grew (1970) as the primary sources of data for that 1983 map compilation.

ACKNOWLEDGMENTS

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REFERENCES CITED

Acaster, Martin, and Bickford, M.E., 1999, Geochronology and geochemistry of Putnam-Nashoba terrane metavolcanic and plutonic rocks, eastern Massachusetts; Constraints on the early Paleozoic evolution of eastern North America: Geological Society of America Bulletin, v. 111, no. 2, p. 240–253, http://gsabulletin.gsapubs.org/content/111/2/240.full.pdf+html.
Attenoukon, M.B., 2008, Thermochronological and petrographic constraints on the timing of terrane assembly in eastern New England: Bloomington, Indiana University, Ph.D. dissertation, 300 p.
Barosh, P.J., 1976, Stratigraphy of the Webster-Worcester region, Massachusetts, *in* New England Intercollegiate Geological Conference, 68th Annual Meeting, Boston, Mass., Oct. 8–10, 1976, Geology of southeastern New England; A guidebook for field trips to the Boston area and vicinity: Princeton, N.J., Science Press, p. 352–365. [Edited by B. Cameron.]
Barosh, P.J., 1977, Preliminary map showing bedrock geology superposed on an aeromagnetic base map of the Worcester region, Massachusetts, Connecticut, and Rhode Island: U.S. Geological Survey Open-File Report 77–131, 38 p., 2 pls., scale 1:125,000. [Also available at http://pubs.er.usgs.gov/publication/ofr77131.]
Barosh, P.J., 1982, Structural relations at the junction of the Merrimack province, Nashoba thrust belt and the southeast New England platform in the Webster-Oxford area, Massachusetts, Connecticut, and Rhode Island, in New England Intercollegiate Geological Conference, 74th Annual Meeting, Storrs, Conn., Oct. 2–3, 1982, Guidebook for fieldtrips in Connecticut and south-central Massachusetts: Connecticut Geological and Natural History Survey Guidebook 5, p. 395–418. [Edited by R. Joesten and S.S. Quarrier.]
Barosh, P.J., 2005, Bedrock geologic map of the Oxford quadrangle, Worcester County, Massachusetts, Providence County, Rhode Island, and Windam County, Connecticut: Amherst, Mass., Office of the Massachusetts State Geologist, unnumbered Open-File Report, scale 1:24,000, http://mgs.geo.umass.edu/biblio/draft-preliminary-bedrock-geologic-map-oxford-quadrangle-worcester-county-massachusetts.
Barosh, P.J., 2009, Bedrock geologic map of the Webster quadrangle, Worcester County, Massachusetts and Windham County, Connecticut: Office of the Massachusetts State Geologist Open-File Report 09–02, scale 1:24,000, http://mgs.geo.umass.edu/biblio/preliminary-bedrock-geologic-map-webster-quadrangle-massachusetts.
Barosh, P.J., Fahey, R.J., and Pease, M.H., Jr., 1977, Preliminary compilation of the bedrock geology of the land area of the Boston 2° sheet, Massachusetts, Connecticut, Rhode Island, and New Hampshire: U.S. Geological Survey Open-File Report OF–77–285, scale 1:125,000. [Also available at http://pubs.er.usgs.gov/publication/ofr77285.]
Barosh, P.J., and Johnson, C.K., 1976, Reconnaissance bedrock geologic map of the Leicester quadrangle, Massachusetts: U.S. Geological Survey Open-File Report 76–814, 9 p., scale 1:24,000. [Also available at http://pubs.er.usgs.gov/publication/ofr76814.]
Barosh, P.J., and Moore, G.E., Jr., 1988, The Paxton Group of southeastern New England: U.S. Geological Survey Bulletin 1814, 18 p. [Also available at http://pubs.er.usgs.gov/publication/b1814.]
Emerson, B.K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geological Survey Bulletin 597, 289 p., 1 pl. in pocket, scale 1:250,000. [Also available at http://pubs.er.usgs.gov/publication/b597.]
Goldsmith, Richard, 1991, Structural and metamorphic history of eastern Massachusetts, chap. H *of* Hatch, N.L., Jr., ed., The bedrock geology of Massachusetts: U.S. Geological Survey Professional Paper 1366, p. H1–H63. [Also available at http://pubs.er.usgs.gov/publication/pp1366EJ.]
Goldsmith, Richard, Wones, D.R., and Shride, A.F., 1982, Stratigraphic names in eastern Massachusetts and adjacent states, *in* Stratigraphic notes, 1980–1982: U.S. Geological Survey Bulletin 1529–H, p. H57–H72. [Also available at http://pubs.er.usgs.gov/publication/b1529H.]
Goldstein, A.G., 1982, Geometry and kinematics of ductile faulting in a portion of the Lake Char mylonite zone, Massachusetts and Connecticut: American Journal of Science, v. 282, no. 9, p. 1378–1405, http://www.ajsonline.org/content/282/9.toc.
Goldstein, A.G., 1994, A shear zone origin for Alleghanian (Permian) multiple deformation in eastern Massachusetts: Tectonics, v. 13, no. 1, p. 62–72, http://onlinelibrary.wiley.com/doi/10.1002/tect.v13.1/issuetoc.
Goldstein, A.G., 1998, Lake Char-Honey Hill-Clinton Newbury fault system from southern Massachusetts to southern Connecticut; Low-angle normal faults in the northern Appalachians and their tectonic significance, *in* New England Intercollegiate Geological Conference, 90th Annual Meeting, Kingston, R.I., Oct. 9–11, 1998, Guidebook to field trips in Rhode Island and adjacent regions of Connecticut and Massachusetts: Kingston, R.I., University of Rhode Island, p. A1–1 to A1–20. [Edited by D.P. Murray.]
Goldstein, A.G., and Hepburn, J.C., 1999, Possible correlations of the Norumbega fault system with faults in southeastern New England, *in* Ludman, Allan, and West, D.P., Jr., eds., Norumbega fault system of the northern Appalachians: Geological Society of America Special Paper 331, p. 73–83, http://specialpapers.gsapubs.org/content/331/73.full.pdf+html?sid=095f56f7-f071-4c01-9026-58145a92d616.
Gore, R.Z., 1976, Ayer crystalline complex at Ayer, Harvard, and Clinton, Massachusetts, *in* Lyons, P.C., and Brownlow, A.H., eds., Studies in New England geology, eastern Massachusetts: Geological Society of America Memoir 146, p. 103–124, http://memoirs.gsapubs.org/content/146/103.full.pdf+html?sid=87b58c49-0226-4cfa-be99-0308a66a1cc9.
Grew, E.S., 1970, The geology of Pennsylvanian and pre-Pennsylvanian rocks of the Worcester area, Massachusetts: Cambridge, Mass., Harvard University, Ph.D. thesis, 263 p.
Hepburn, J.C., 1976, Lower Paleozoic rocks west of the Clinton-Newbury fault zone, Worcester area, Massachusetts, Geology of southeastern New England, *in* New England Intercollegiate Geological Conference, 68th Annual Meeting, Boston, Mass., Oct. 8–10, 1976, A guidebook for field trips to the Boston area and vicinity: Princeton, N.J., Science Press, p. 366–382. [Edited by B. Cameron.]
Hepburn, J.C., 1978, Preliminary reconnaissance bedrock geologic map of the Shrewsbury quadrangle, Worcester County, Massachusetts: U.S. Geological Survey Open-File Report 78–951, 14 p., 1 sheet, scale 1:24,000. [Also available at http://pubs.er.usgs.gov/publication/ofr78951.]
Hepburn, J.C., 2004, The peri-Gondwanan Nashoba terrane of eastern Massachusetts; An early Paleozoic arc-related complex and its accretionary history, *in* New England Intercollegiate Geological Conference, 96th Annual Meeting, Salem, Mass., Oct. 8–10, 2004, Guidebook to field trips from Boston, MA to Saco Bay, ME: Salem, Mass., Salem State College, p. 17–38. [Edited by L.S. Hanson.]
Hepburn, J.C., and Bailey, R.H., 1998, The Avalon and Nashoba terranes in eastern Massachusetts, *in* New England Intercollegiate Geological Conference, 90th Annual Meeting, Kingston, R.I., Oct. 9–11, 1998, Guidebook to field trips in Rhode Island and adjacent regions of Connecticut and Massachusetts: Kingston, R.I., University of Rhode Island, p. C3–1 to C3–24. [Edited by D.P. Murray.]
Hepburn, J.C., Dunning, G.R., and Hon, R., 1995, Geochronology and regional tectonic implications of Silurian deformation in the Nashoba terrane, southeastern New England, U.S.A., *in* Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., Current perspectives in the Appalachian-Caledonian orogen: Geological Association of Canada Special Paper 41, p. 349–366.
Hepburn, J.C., Kuiper, Y.D., Buchanan, J.W., Kay, Andrew, and Dabrowski, D.R., 2014, Evolution of the Nashoba terrane, an early Paleozoic Ganderian arc remnant in eastern Massachusetts, *in* New England Intercollegiate Geological Conference, 106th Annual Meeting, Wellesley, Mass., Oct. 10–12, 2014, Guidebook to field trips in southeastern New England (MA-NH-RI): p. B3–1 to B3–19. [Edited by M.D. Thompson.]
Hibbard, J.P., van Staal, C.R., Rankin, D.W., and Williams, H., 2006, Lithotectonic map of the Appalachian orogen, Canada-United States of America: Geological Survey of Canada Map 2096A, 2 sheets, scale 1:1,500,000, http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=221912.
Loan, M.L., Hepburn, J.C., Kuiper, Yvette, and Tubrett, M.N., 2011, Age constraints on the deposition and provenance of the meta-sedimentary units of the Nashoba terrane [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 1, p. 160.
Markwort, R.J., 2007, Geology of the Shrewsbury quadrangle, east-central Massachusetts: Chestnut Hill, Mass., Boston College, M.S. thesis, 193 p., 2 pls., scale 1:24,000.
Pease, M.H., Jr., 1972, Geologic map of the Eastford quadrangle, Windham and Tolland Counties, Connecticut: U.S. Geological Survey Geological Quadrangle Map GQ–1023, 3-p. text, 1 sheet, scale 1:24,000. [Also available at http://pubs.er.usgs.gov/publication/gq1023.]
Pease, M.H., Jr., 1989, Correlation of the Oakdale Formation and Paxton Group of central Massachusetts with strata in northeastern Connecticut: U.S. Geological Survey Bulletin 1796, 26 p., 1 sheet, scale 1:250,000. [Also available at http://pubs.er.usgs.gov/publication/b1796.]
Perry, J.H., and Emerson, B.K., 1903, Geology of Worcester, Massachusetts: Worcester, Mass., Worcester Natural History Society, 166 p., https://archive.org/details/geologyworcester00perriala.
Pollock, J.C., Hibbard, J.P., and van Staal, C.R., 2012, A paleogeographical review of the peri-Gondwanan realm of the Appalachian orogen: Canadian Journal of Earth Sciences, v. 49, no. 1, p. 259–288, http://www.nrcresearchpress.com/doi/pdf/10.1139/e11-049.
Robinson, Peter, and Goldsmith, Richard, 1991, Stratigraphy of the Merrimack belt, central Massachusetts, *in* Hatch, N.L., Jr., ed., The bedrock geology of Massachusetts: U.S. Geological Survey Professional Paper 1366 E–J, p. G1–G37. [Also available at http://pubs.er.usgs.gov/publication/pp1366EJ.]
Salvini, Francesco, 2013, DAISY 3; The Structural Data Integrated System Analyser (version 4.95.13): Rome, Italy, Università degli Studi di "Roma Tre," Dipartimento di Scienze Geologiche, software available at http://host.uniroma3.it/progetti/fralab/Downloads/Programs/.
Stroud, M.M., Markwort, R.J., and Hepburn, J.C., 2009, Refining temporal constraints on metamorphism in the Nashoba terrane, southeastern New England, through monazite dating: Lithosphere, v. 1, no. 6, p. 337–342, http://lithosphere.gsapubs.org/content/1/6/337.full.pdf+html.
U.S. Army Corps of Engineers, New England Division, 1956, Worcester diversion, Blackstone River, Massachusetts, Blackstone River flood control; Design memorandum no. 5, geology and soils: [Concord, Mass.,] U.S. Army Corps of Engineers, New England Division, 16 p., 14 pls.
van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., Ancient orogens and modern analogues: Geological Society, London, Special Publications, v. 327, London, p. 271–316, http://sp.lyellcollection.org/content/327/1/271.
van Staal, C.R., Barr, S.M., and Murphy, J.B., 2012, Provenance and tectonic evolution of Ganderia; Constraints on the evolution of the Iapetus and Rheic oceans: Geology, v. 40, no. 11, p. 987–990, http://geology.geoscienceworld.org/content/40/11/987.full.pdf+html?sid=fed01ef1-d231-4f7d-a97e-5e0bb2ef5b75.
Walsh, G.J., 2014, Bedrock geologic map of the Uxbridge quadrangle, Worcester County, Massachusetts, and Providence County, Rhode Island: U.S. Geological Survey Scientific Investigations Map 3295, 1 sheet, scale 1:24,000, 36-p. pamphlet, http://dx.doi.org/10.3133/sim3295.
Walsh, G.J., Aleinikoff, J.N., and Dorais, M.J., 2011a, Bedrock geologic map of the Grafton quadrangle, Worcester County, Massachusetts: U.S. Geological Survey Scientific Investigations Map 3171, 1 sheet, scale 1:24,000, 39-p. pamphlet. [Also available at http://pubs.usgs.gov/sim/3171/.]
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, http://www.ajsonline.org/content/307/1.toc.
Walsh, G.J., Aleinikoff, J.N., Wintsch, R.P., and Ayuso, R.A., 2011b, Origin of the Quinebaug-Marlboro belt in southeastern New England [abs.]: Geological Society of America Abstracts with Programs, v. 43, no. 1, p. 158.
Walsh, G.J., Aleinikoff, J.N., Wintsch, R.P., Ayuso, R.A., 2013a, Integrated bedrock mapping and geochronology in the terranes of southeastern New England [abs.]: Geological Society of America Abstracts with Programs, v. 45, no. 1, p. 64.
Walsh, G.J., Jahns, R.H., and Aleinikoff, J.N., 2013b, Bedrock geologic map of the Nashua South quadrangle, Hillsborough County, New Hampshire and Middlesex County, Massachusetts: U.S. Geological Survey Scientific Investigations Map 3200, scale 1:24,000, 31-p. pamphlet. [Also available at http://pubs.usgs.gov/sim/3200/.]
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, southcentral Connecticut: American Journal of Science, v. 287, no. 2, p. 107–126, http://www.ajsonline.org/content/287/2.toc.
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, http://www.ajsonline.org/content/307/1.toc.
Wintsch, R.P., Kelsheimer, K.L., Kunk, M.J., and Aleinikoff, J.N., 2001, A new look at the Alleghanian overprint of Acadian metamorphic rocks in southern New England; Evidence from structure, petrology and thermochronology, *in* West, D.P., Jr., and Bailey, R.H., eds., Guidebook for geological field trips in New England; 2001 Annual Meeting of the Geological Society of America: Boston, Mass., Nov. 5–8, p. V1–V26.
Wintsch, R.P., Kunk, M.J., Aleinikoff, J.N., Roden-Tice, Mary, Stokes, M.R., Stewart, E.M., and Steinen, R.P., 2012, Temperature-time paths tie the tales of two forelands; The Narragansett and Hartford basins, *in* Thomas, M.A., ed., Guidebook for fieldtrips in Connecticut and Massachusetts: Geological Society of America Northeast Section 47th Annual Meeting, March 17–20, 2012, Hartford, Conn., Connecticut Geological and Natural History Survey Guidebook 9, p. C1–C32.
Wintsch, R.P., Sutter, J.F., Kunk, M.J., Aleinikoff, J.N., and Boyd, J.L., 1993, Alleghanian assembly of Proterozoic and Paleozoic lithotectonic terranes in south-central New England; New constraints from geochronology and petrology, *in* Cheney, J.T., and Hepburn, T.C., eds., Field trip guidebook for the northeastern United States: University of Massachusetts, Department of Geosciences, Geosciences Contribution 67, v. 1, p. H–1 to H–30. (Guidebook for the 1993 meeting in Boston of the Geological Society of America and the New England Intercollegiate Geological Conference.)
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, http://onlinelibrary.wiley.com/doi/10.1029/91TC02904/abstract.
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, http://www.sciencedirect.com/science/article/pii/0012821X87902044.
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, http://www.ajsonline.org/content/288/4.toc.
Zartman, R.E., and Naylor, R.S., 1984, Structural implications of some radiometric ages of igneous rocks in southeastern New England: Geological Society of America Bulletin, v. 95, no. 5, p. 522–539, http://gsabulletin.gsapubs.org/content/95/5/522.full.pdf+html?sid=10c1b665-591a-4b5d-9682-ece73b20484e.
Zen, E-an, ed., and Goldsmith, Richard, Ratcliffe, N.M., Robinson, Peter, and Stanley, R.S., comps., 1983, Bedrock geologic map of Massachusetts: U.S. Geological Survey Open-File Report 81–1327, 3 sheets, scale 1:250,000.

BEDROCK GEOLOGIC MAP OF THE WORCESTER SOUTH QUADRANGLE, WORCESTER COUNTY, MASSACHUSETTS

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