Preliminary Bedrock Geologic Map
of the Hudson 7.5' Quadrangle
Worcester and Middlesex Counties, Massachusetts
(Report to accompany 1:24000 scale geologic map)
Version 1.0

MGS Open File Report 14-01

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View looking east from Wataquadock Hill into Hudson quadrangle. Rattlesnake Hill at left and Pine Hill at center-right, middle distance.
Photo by J. Kopera, July, 2014

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GEOLOGIC SETTING

The Hudson quadrangle straddles the Clinton-Newbury Fault Zone (CNFZ), which separates low metamorphic grade Silurian turbiditic metasediments and Devonian plutons of the Nashua sub-belt (Robinson and Goldsmith, 1991) of the Merrimack Terrane to the northwest from the high-grade, migmatitic Cambro-Ordovician arc-complex of the Nashoba Terrane (Walsh et al., 2011; Loan 2011). This general area comprises the suture between the Gander and Avalon composite terranes of the Northern Appalachians (cf. Hibbard et al., 2006).

Metasedimentary rocks of the Merrimack Terrane are generally poorly exposed, with intrusives (Day, Dayp, SDgdt) and the Clinton-Newbury Fault zone and associated rocks (Ot) forming a prominent northeast trending ridge (Oak Hill in the town of Harvard) marking the eastern bordering slope of the Worcester Plateau (Emerson, 1917, p. 16). Elevation and local topographic relief gradually decreases and glacial cover increases to the east-southeast across the strike of the Nashoba Formation, which, locally, forms low-relief NE-trending strike-parallel ridges. These are cut by dramatic cross-strike cliffs and glacial spillway gorges developed along cross-strike joints and brittle faults, most notably on the western slopes of Rattlesnake Hill, southern slope of Powder House Hill and in Camp Resolute in Bolton in the west-central portion of the quadrangle, and the southern slope of the hill along the west side of Codman Hill Road in Harvard in the north-central portion of the quadrangle. The migmatitic ortho- and paragneisses, schists and associated metavolcanic rocks of the Nashoba Formation (€Sn) form a northeast striking belt underlying the southern two-thirds of the quadrangle. These are intruded by a variety of presumed Ordovician to Silurian intermediate intrusives (OSd, OSaqd) and Devonian or younger tonalites to granites (Dan, Danp, Dac).

DESCRIPTION OF ROCK UNITS

(Note: descriptions are based on hand-sample observation and predate petrographic analysis)

Merrimack Terrane

Tectonites

PDm – Felsic Mylonite and Phyllonite (latest Devonian to Permian)
Well laminated quartzofeldspathic mylonites, ultramylonites, and chlorite-rich phyllonites. Presumably derived from Day and DSgdt along their contact with Ot. These mylonites define the trace of the Rattlesnake Hill Fault in the Hudson quadrangle. See "Faults and Shear Zones" below for discussion of kinematics.

Intrusive Rocks

Dayc – Ayer Granite, Clinton facies (early Devonian)
Light-gray coarse-grained ± chlorite ± muscovite, biotite-plagioclase-microcline-quartz granite to granodiorite. A porphyritic facies (Daycp) contains abundant microcline megacrysts averaging 5 cm in length.

Age: 420.13±0.5 Ma for non-porphyritic phase (U-Pb CA-TIMS; Charnock et al., 2014).

DSgdt – Granodiorite and Tonalite (late Silurian to early Devonian)
Predominantly medium-grained gray or greenish-gray ± muscovite ± biotite ± hornblende ± microcline, plagioclase-orthoclase-quartz granodiorite and tonalite. Alteration to chlorite and cataclasis of feldspars is pervasive. Increasingly sheared towards contacts, with microcline forming white augen. Altered xenoliths of chlorite schist are common near contacts. Similar in composition and structural position to tonalitic phase of Devens-Long Pond facies of Ayer granodiorite (Walsh, et al. 2013a).

Metastratified Rocks

So – Oakdale Formation (Upper Silurian)
Fine-grained dark gray-green finely-laminated ankeritic quartz-metasiltstone and phyllite with minor calcareous beds. Weathering of ankerite to limonite gives outcrops distinctive brown spots along cleavage in natural outcrops, which also show distinctive alternation between brown to buff metasiltstone and greenish-gray to black phyllite.

Age: 431 ± 12 Ma (U-Pb CA-TIMS; Sorota, 2013). Equivalent to Unit 2 of Peck (1976) and DSsp (Peck, 1975; Kopera and Peck, 2012) in the adjoining Clinton 7.5'quadrangle to the west.

Sq – Quartzite (Silurian or older)
Very fine-grained buff- to light-gray laminated quartzite locally interbedded with thin layers of phyllite and schist. Generally forms poor outcrop. Equivalent to DSq of Peck (1975; Kopera and Peck, 2012). Hansen (1956) mapped this unit as a lateral extension of ℙOvh.

ℙOvh – Vaughn Hills Formation (Ordovician to Pennsylvanian?)
Alternating layers of fine-grained white to buff-colored laminated quartzite and dark gray chlorite-sericite-quartz schist and phyllite. Bedding is turbiditic and typically 1 to 4 cm in thickness. Thick (0.5 to 1 m) interbeds of polymict pebble conglomerate (ℙOvhc) appear and increase in abundance to the northeast. Clasts are distinctly dominated by rounded pebbles of white bull quartz but are locally angular, up to cobble-size, and comprised of fine-grained light gray to red quartzite and other rock types in a medium- to coarse-grained

polymict matrix. Nature of contacts with other units is ambiguous due to poor exposure and extensive shearing. May be correlative with the Pennsylvanian(?) Harvard Conglomerate exposed at Pin Hill to the north in the town of Harvard (Ayer 7.5' quadrangle; Kopera, 2006) which unconformably overlies DSgdt and Dayc. Hansen (1956) and Peck (1975, 1976) interpret Ot to grade upward into PPOvh, however this relationship is ambiguous given shearing along the Clinton-Newbury Fault Zone.

Nashoba Terrane

Intrusive Rocks

Dac – Acton Granite (Devonian or younger?)
Fine- to medium-grained gray ± muscovite, biotite-microcline-plagioclase tonalite to granite. Dikes, sills, and masses occur in majority of outcrops of Nashoba Formation but mappable masses are rare. Several generations of tonalite are present and likely to be of different age and provenance than type Acton in the Westford 7.5' quadrangle to the northeast (Kopera et al., 2009; e.g. Walsh et al., 2013b; in review), but can not be distinguished at map scale based on field observation alone. Where the tonalites occur as mappable bodies they are included within Dac.

Danp – Andover Granite, pegmatitic phase (early Devonian)
Buff weathering ± beryl, biotite-microcline-quartz pegmatite and associated fine-grained granite of same composition. Typically intrudes Nashoba Formation as large layer-parallel sills and strike-parallel dikes that form prominent outcrops. In southeastern corner of quadrangle it delineates a regional-scale strike-parallel lobe extending southwest from the main pluton in Andover. Accessory minerals (± garnet ± muscovite ± magnetite) typically match those of the country rock.

Age: 412 ± 2 Ma (U-Pb; Hepburn et al., 1995)

Dan – Andover Granite, biotite-granite (early Devonian)
Foliated coarse-grained ± garnet ± muscovite, biotite-plagioclase-microcline-quartz granite.

Age: 419.65 ± 0.51 Ma (CA-TIMS U-Pb; Dabrowski, 2014).

SOaqd – Assabet Quartz Diorite (Ordovician to Silurian?)
Medium-grained, locally porphyritic, poorly foliated dark-gray to dark-gray-green biotite-hornblende-quartz diorite to tonalite. Accessory minerals (± garnet ± muscovite ± magnetite) reflect composition of country rock, with pyrite occurring locally. Contains xenoliths of rusty-weathering ± garnet, silliminite-muscovite-biotite-schist. Other units are locally migmatized, with conspicuous melt-pillow textures, near their contacts with SOaqd. The diorite may be equivalent to the approximately 430 Ma Sharpners Pond Diorite (Zartman and Naylor, 1984) to the northeast.

SOd – Diorite at Pine Hill (Ordovician to Silurian?)
Medium- to coarse-grained dark-gray biotite-microcline-plagioclase-hornblende diorite. Commonly well foliated, locally folded, and predates D_2. Accessory minerals (± garnet ± muscovite ± magnetite) reflect composition of country rock. Locally occurs as foliation-parallel sills. Common rusty-weathering zones interpreted to be incorporated xenoliths of SЄng. Contains abundant fine- to coarse-grained xenoliths of layered amphibolite near contacts.

Metastratified rocks

(Note: Mappable units in the Nashoba terrane represent a tectonostratigraphy with highly transposed compositional layering. Sedimentary structures are generally absent, and, in the extremely rare cases where preserved, topping indicators are ambiguous due to multiple generations of folding in outcrop. The units are listed in order of structural position, highest to lowest).

Ot – Tadmuck Brook schist (Ordovician?)

Rusty weathering sulfidic ± biotite, muscovite-quartz schist and phyllonite with interbedded quartzite and amphibolite (a). Metamorphic grade decreases southwest to northwest across-strike from silliminite-biotite, to staurolite, to andalusite, to chlorite (Otc). Sulfide-oxide mineralization along cross-fractures is ubiquitous, with pyrite being common in the rock mass. Otc is characterized by a coarse (2-3 cm spacing) anastomosing crenulation cleavage displaying northwest-side down motion (S_{4b}-S_5, discussed below). Otc is in sharp contact along its northwestern margin with felsic-to-intermediate mylonites, ultramylonites, and phyllonites (PDm). Ot and its subunits delineate the boundary between the Nashoba and Merrimack terranes.

S€n – Nashoba Formation (Upper Cambrian to lower Silurian?)

Migmatitic ± calc-silicate ± garnet ± muscovite, microcline-silliminite-biotite-plagioclase-quartz gneisses with interlayered amphibolite (a), sulfidic schist, calc-silicate rocks (cs), and marble (m).

Age: Approximately 465 Ma (U-Pb, LA-ICPMS; Loan, 2011) for gneisses north of the Assabet River Fault Zone.

Tectonites within the Nashoba Formation

S€ngsp – Sulfidic calcarous schist and phyllonite

Crumbly, rusty- to black-weathering sulfidic calcareous muscovite-biotite-silliminite schist and phyllonite with thin interlayers of quartzite and impure marble. Distinct sulfurous odor from fresh-broken surfaces. Presumed to be phyllonite associated with pre-to syn-D_2 thrust faults. Typically occurs as subunit of S€ng, developed along margins of S€nga and in contact with S€ncs.

Metastratified rocks within the Nashoba Formation

S€ncs – Calc-silicate gneiss

Flaggy weathering fine-grained greenish-gray to purple-gray ± garnet ± diopside ± actinolite ± hornblende, biotite-plagioclase-quartz gneiss. Compositional layering is distinctly laminar to tabular. Hornblende and other calc-silicate minerals are most conspicuous as aggregates in selvages along foliation-parallel quartz ribbons. Radial masses of scapolite and/or tremolite commonly occur on cross-joints. Locally contains interlayers of massive amphibolite (a) and associated pods of coarse-grained greenish-brown to megacrystic ± diopside ± epidote ± ankerite-actinolite-hornblende calc-silicate rock (cs). Neosomes of migmatitic melt generally rare to absent.

S€nrsg – Rusty schist and granofels

South of Spencer Brook Fault

Interlayered rusty- to- black-weathering, locally sulfidic, ±garnet-silliminite-muscovite-biotite-schist and ±hornblende plagioclase-quartz granofels locally interbedded with amphibolite. Garnet locally occurs as coticule in the granofels and porphyroblasts up to 3 cm in diameter. Presumed to be laterally equivalent to S€ng.

S€nga – Amphibolite gneiss

Coarse-grained, massive, porphyroblastic hornblende-plagioclase amphibolite-gneiss and laminated amphibolites interlayered with garnet-silliminite-biotite schists and migmatitic gneiss. Locally garnetiferous with individual porphyroblasts up to 2 cm in diameter, forming conspicuously "bumpy" foliation surfaces. Amphibolite generally occurs as meter-scale boudins in other lithologies of this unit. Laterally equivalent to portions of S€ng and/or S€ncs. Rusty weathering with abundant oxide and sulfide mineralization in proximity to Ball Hill Shear Zone. Presumed to be laterally equivalent to rocks mapped as Boxford Member of Nashoba Formation of Bell and Alvord (1976) northwest of Assabet River Fault based on similarity of lithology and structural position. Not equivalent to "type" Boxford Member (Boxford Formation of Castle et al., 2005) southeast of Assabet River Fault zone near Boxford.

S€ng – Garnet bearing biotite gneiss

Rusty weathering, commonly garnetiferous and/or sulfidic, ± muscovite-silliminite-biotite-quartz-plagioclase stromatic gneiss, schist and granofels with interlayered amphibolite (a) and hornblende-bearing stromatic gneisses. Compositional layering is commonly contorted. Where garnet is absent, distinguishable from S€ns by lack of magnetite and muscovite. Interlayers of fine- to medium-grained layered ± magnetite-biotite-amphibolite (a) are common. Exposures of this unit on the southwest facing slope of Rattlesnake Hill contain up to 50% amphibolite interlayers. Buff-weathering neosomes of biotite-microcline-quartz pegmatite are abundant. Local interlayers of pure calcite marble (m) are ubiquitously quarried out, notably on the south slope of Rattlesnake Hill (see Economic Geology). Calc-silicate minerals are abundant along the margins of the marble layers in distinct mineralogical zones related to evolution and migration of fluids during intrusion of pegmatites nearby (described in detail in Hansen, 1956, and Cook, 1974), with individual scapolite crystals up to several meters in length. Contact with S€ns is locally gradational or interfolded. Layered amphibolite (a) locally occurs along their contact.

S€ns – Magnetite bearing muscovite-silliminite gneiss

Strongly to moderately magnetic magnetite-muscovite-silliminite-biotite-quartz-plagioclase stromatic gneiss with rare interlayered laminated ± magnetite amphibolite (a). Compositional layering is commonly contorted by multiple fold generations. Megascopic muscovite and silliminite conspicuously occur in schistose laminae interlayered with granofelsic material. Large flakes of retrograde muscovite are locally abundant. Bright pink to buff-weathering ± magnetite ± muscovite-biotite-microcline-quarts migmatitic leucosomes are also abundant. Garnet coticule (gc) locally occurs along the contact with S€ng in roadcuts on I-495 SB, immediately south of the Rt. 111 interchange. This unit corresponds with distinctive positive anomalies on regional aeromagnetic maps (e.g., Daniels and Snyder, 2004)

S€nf – Felsic biotite gneiss

Moderately magnetic, fine- to medium-grained, buff weathering magnetite-biotite-microcline ± plagioclase-quartz banded felsic to tonalitic gneiss. Pegmatites of Danp and associated fine-grained biotite granite are abundant in this unit. S€nf can be distinguished from these by the presence of magnetite and gneissic banding. Layered amphibolite (a) is locally present along or near contacts with S€ns. Contact with S€ns gradational and locally marked by a transition through massive gray magnetite-bearing biotite-gneiss.

O€m – Marlborough Formation (Upper Cambrian to Ordovician)

A heterogeneous package of metavolcanics and volcanogenic metasediments characterized by abundant amphibolite in surface exposures and containing interlayered schists, greenish-white marble, quartzite, and felsic to intermediate granofels.

Age: Structurally lower, amphibolite-rich, portion of formation older than 515 ± 4 Ma Grafton Gneiss which intrudes it (U-Pb SHRIMP; Walsh et al., 2011)

OCms – Muscovite schist

Locally rusty-weathering to sulfidic, fine-grained ± garnet, muscovite-silliminite-biotite-plagioclase-quartz schist.

METAMORPHISM AND STRUCTURE

Several phases of peak metamorphism occurred in the late Silurian to early Devonian during latest Salinic to Acadian through Neoacadian orogenesis (Hepburn et al., 1995; Stroud et al., 2009; Attenoukon, 2009). A sharp decrease in M_1 (see below) peak metamorphic grade occurs northwest across-strike in the Tadmuck Brook schist, from upper-amphibolite facies K-feldspar-silliminite grade migmatites of the Nashoba terrane to greenschist to lower-amphibolite facies chlorite- to biotite-grade assemblages in the eastern Merrimack terrane. Overprinting greenschist-facies retrograde metamorphism associated with the Mississippian through Permian Alleghenian orogeny is pervasive in the Nashua sub-belt of the eastern Merrimack terrane (Attenoukon, 2009), but only locally developed in the Nashoba terrane adjacent to the CNFZ. Post-Acadian sinistral-normal motion along the CNFZ is thought to be responsible for the juxtaposition of different facies of peak metamorphism along the boundary between the two terranes (e.g., Goldstein, 1994).

In the Nashoba terrane silliminite-grade peak metamorphism (M_1) occurred circa. 425 Ma (Hepburn et al., 2005) and possibly represents late Salinic to early Acadian orogenesis (e.g. van Staal et al., 2009). Second-silliminite-K-feldspar grade metamorphism (M_2) later occurred ca. 395 Ma with subsequent peaks at ca. 376-305 Ma (Hepburn, et al., 1995; Jerden, 1997; Stroud et al., 2009; Buchanan et al., 2014). Migmatization likely occurred diachronously with deformation during several pulses after ca. 395 Ma (e.g., Buchanan et al., 2014) with leucomes in the Nashoba Formation to the southwest of Worcester occurring as late as ca. 320 Ma (Walsh et al., 2013b).

Metastratified rocks of the Merrimack terrane underwent early isoclinal folding and nappe-style thrusting (D_1) during the Acadian orogeny followed by several phases of northeast and east-directed folding and thrusting during the Alleghenian (D_2 and D_3; cf. Robinson, 1981; cf. Kopera and Walsh, 2014, and references therein) followed by late extension (D_4). Poor exposure of these rocks in the Hudson quadrangle, combined with ongoing structural study of the Vaughn Hills Formation (Charnock et al., 2014), and ongoing mapping of these rocks by the author, precludes a more detailed discussion of the structure of the Merrimack terrane here.

Deformational fabrics in the Nashoba Formation represent a presumed Acadian-age high-grade fold-thrust belt (e.g., Barosh, 1984) with present-day southeastward vergence progressively transitioning to bulk sinistral shearing and then northwest-side-down oblique extension during the Alleghenian orogeny and into the Mesozoic (e.g., Goldstein, 1994; Stroud et al., 2009). Six distinct phases of deformation can be delineated in the Nashoba formation in the Hudson quadrangle at map and outcrop scale (Figures 1, 2, and 3). These are in large part similar to those observed in the Nashoba and equivalent Tatnic Hill Formation south of Worcester (Goldstein, 1982; Walsh and Merschat, in review):

D_1 – Layer-parallel gneissosity (S_1) axial planar to rare isoclinal folds (F_1; Figure 1) and thrust faults.

D_2 – A pervasive layer-parallel foliation (S_2) that is axial planar to outcrop-to-map-scale shallow-plunging tight-to-isoclinal, locally asymmetric, folds (F_2) and associated thrust faults (Figure 1). Migmatitic neosomes developed along S_1 are folded by F_2, but are also developed along F_2 axial planes (S_2; cf. Massey and Alvord, 2011) and may represent migmatitc anetectic "melt channels" described by Weinberg and Mark (2008). Leucosome development is not restricted to D_1 and D_2 and is likely diachronous with fabric development across the Nashoba terrane (Buchanan et al., 2014; e.g., Walsh and Mershat, in review). Subhorizontal to moderately dipping silliminite-quartz lineations and intersection lineations (L_1 - L_2) are nearly ubiquitous on S_1 - S_2 composite foliations in most outcrops. Strain along S_1-S_2 shows no asymmetry and abundant evidence for a regime dominated by pure shear with extension parallel to L_1 - L_2, with symmetric chocolate-tablet style boudinage of pegmatites and leucosomes being prominent.

D_3 – Upright subhorizontal antiforms and synforms (F_3) with parasitic outcrop-scale open gentle warps to sharp folds developed in their hinge zones (Figure 1). F_3 is likely partially responsible for the steepening of S_1-S_2 fabrics into their present day orientation.

D_4 – Defined by a progressive transition between end-members representing earlier sinistral strike-slip (D_{4a}) to later sinistral-normal (D_{4b}) oblique-extensional bulk asymmetry. D_{4a} is predominantly manifested by outcrop-scale, steep to subvertical north-plunging tight to open sinistral asymmetric folds (F_{4a}) with layer-subparallel axial planes. These transition to moderate to shallow north plunging gentle asymmetric folds with shallow to moderately northwest dipping axial planes displaying NW-side-down asymmetry (Figure 2; F_{4b}). S_{4a} sinistral fabrics are locally developed along and cutting S_1-S_2 compositional foliation, and consist of C and C' planes, asymmetric tails on leucosomes and porphyroblasts (commonly garnet and hornblende), and asymmetric rootless intrafolial folds. In schistose units, a subhorizontal S_{4b} crenulation cleavage is commonly developed. In **Ot** and **Otc** a strongly-developed steep SW dipping S_4 coarse crenulation cleavage with NW-side down asymmetry is commonly observed cutting S_1-S_2 schistosity (e.g. Dougherty and Kuiper, 2013; Kuiper et al., 2014). S_1-S_2-parallel, syn- to post-D_4, normal faults are common in the Nashoba terrane (e.g., Goldstein, 1982; Walsh and Mershat, in review) but were not observed in the Hudson quadrangle. Leucosomes are generally folded by F_4 but are locally cut by dikes which may represent migmatitic melt (Buchanan et al., 2014).

D_5 – Subvertical, north- to northeast-striking amphibolite- to chlorite-grade ductile normal faults containing ultracataclastite (S_5) displaying NW-side down displacement (Figure 3). Recrystalized quartz beards on microcline porphyroclasts, chlorite, and laminated quartz ribbons are common. Numerous presumed syn- to post-D_5 chlorite-grade to semi-brittle shear zones and faults of varying orientations and kinematics can also be observed in many outcrops.

D_6 – Numerous brittle faults of varying orientation and offset with abundant oxide mineralization. A suite of cross-strike en-echelon, NW striking, presumably subvertical to steep NE dipping brittle faults offset contacts in the Hudson quadrangle and are consistent with east-west directed extension during the Jurassic and Cretacious (McHone, 1978; McHone et al., 1987; Wise, 2005). Sets of slickenlines on the only exposure of one of these faults, north of the Horse Meadows in Harvard, have steep to down-dip plunges. Brittle structures within the Hudson quadrangle are thoroughly described by Mabee (2005).

Due to the relatively poor quality and small size of most natural outcrops in the Nashoba Formation, the relative age of the dominant foliation (S_n) is ambiguous and generally presumed to represent a composite S_1-S_2 layer-parallel fabric, especially in **S€ncs**. The relative ages of lineations on Sn are also ambiguous and have been designated L_n and are presumed to represent a composite L_1 – L_2 intersection lineation (Figure 4). Complete suites of the deformation sequences listed above are best preserved in **S€ns**, and D_1-D_4 can be seen in roadcuts at the Rt 111 / I-495 interchange in Boxborough and the adjacent office park to the southwest on Codman Hill Road. S_5 shear zones are best observed in and near the hinge zones of F_3 map-scale folds where S_1-S_2 is shallowly dipping. Excellent examples are exposed in roadcuts at the Rt 62 / I-495 interchange.

Kilometer-scale subhorizontal F_2 and F_3 antiforms and synforms are largely responsible for the first-order map pattern of subunits in the Nashoba Formation. Structural elements between D_1 – D_2 and D_3 are subparallel and co-linear (Figure 4) suggesting that these events occurred under the same stress regime and may overlap in age, if not representing progressive deformation during a protracted tectonic event. It is possible that later components of strain rotated all D_1-D_3 elements into parallel. Axes of F_3 folds are defined by zones of subhorizontal S_1-S_2 displaying outcrop-scale F_3 open folds. Good exposures of F_3 hinge zones can be found on the southwestern slopes of Rattlesnake Hill in Bolton, in the Horse Meadows conservation land and Great Elms conservation land immediately southeast of Murrays Lane in Harvard. F_1-F_2 and F_4 map-scale folds are less common and mostly defined by outcrop-scale structure and repetition of tectonostratigraphy in the subunits of the Nashoba Formation on the limbs and in hinges of F_3 folds.

Outcrop evidence for the relative timing between D_3 and D_4 structures is ambiguous. Outcrop scale F_3 folds commonly deform tight asymmetric open similar folds with NW-side down asymmetry (Figure 1). It is unclear, however, whether or not these are F_2 or F_4 folds based on fold style alone. Relations between D_3 and D_4 structures in outcrop are generally absent and ambiguous where exposed. Locally, many F_4 folds display box-hinges and noncylindrical hinge lines (Figure 2) implying that they may be refolded folds (possibly F_2). The kinematics of D_3 progressing into D_4, however, are consistent with the general regional progression of deformation (e.g., Goldsmith, 1994; Stroud et al., 2009).

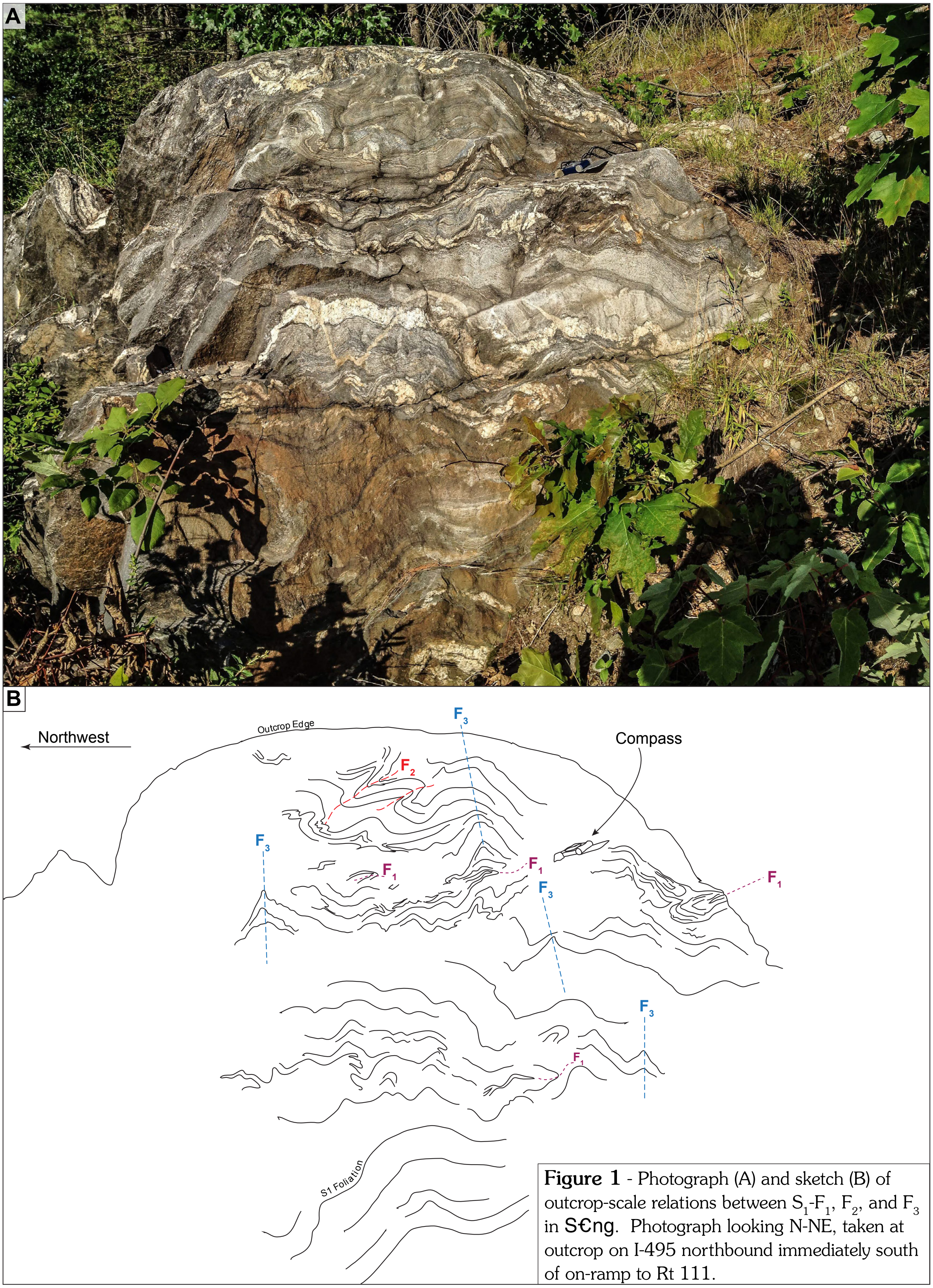

Figure 1 - Photograph (A) and sketch (B) of outcrop-scale relations between S_1-F_1, F_2, and F_3 in SЄng. Photograph looking N-NE, taken at outcrop on I-495 northbound immediately south of on-ramp to Rt 111.

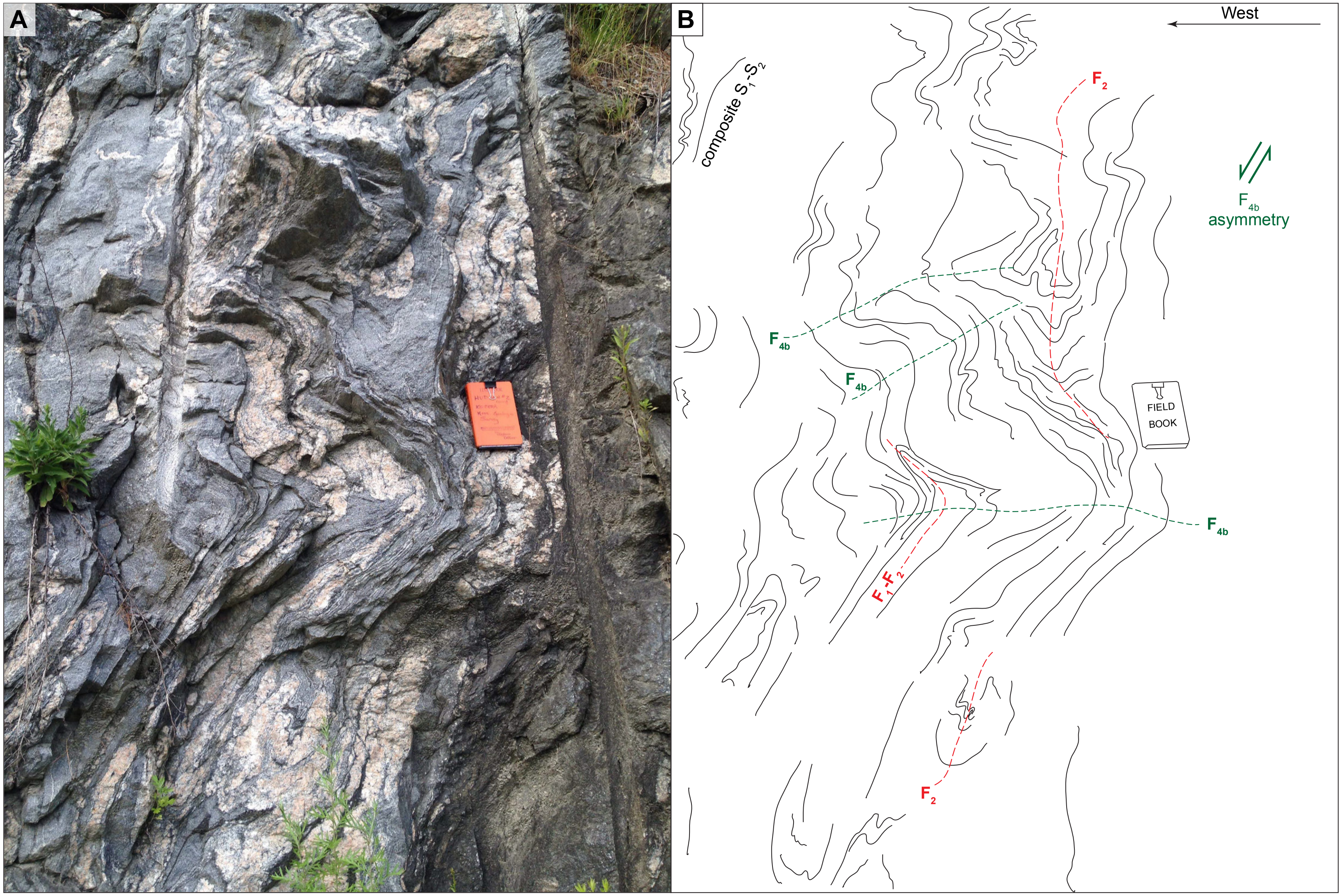

Figure 2 - Photograph (A) and sketch (B) of outcrop-scale relations between F_1-F_2 and F_{4b} in S€ns. Photograph looking north at roadcut on north side of Rt 111 at I-495 and Rt 111 interchange in Boxborough.

Figure 3 - Photograph of outcrop-scale relations between S_1-S_2, F_{4b}, and S_5 shear zones. Drag folding of fabrics along S_5 displays NW-side down motion.

Figure 4
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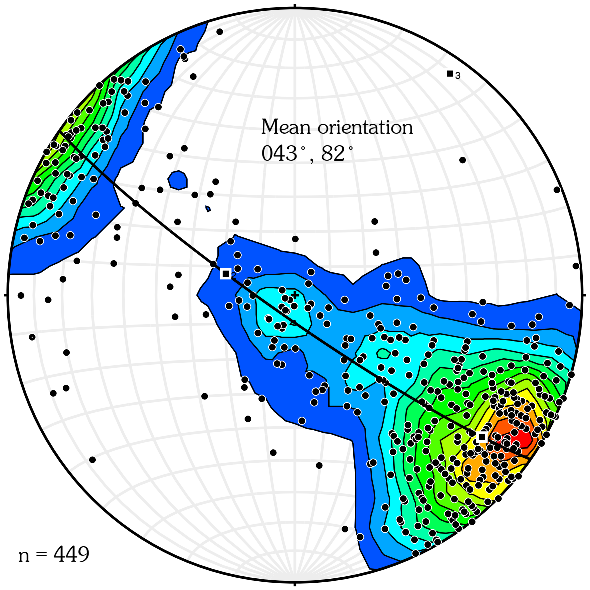
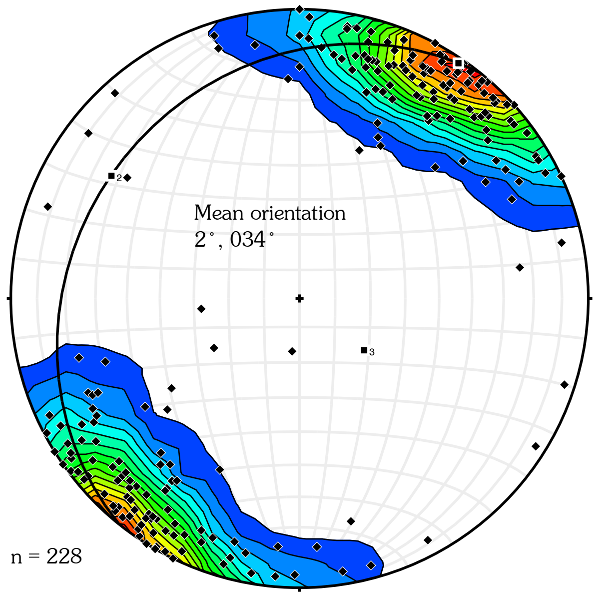
Poles to Sn (Composite S_1-S_2)



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.7062	127.2,	19.6	2.0	4.0
2.	0.2275	287.4,	69.3		
3.	0.0663	034.9,	06.5	2.0	4.5

Best fit great circle (strike, dip RHR) = 124.9, 83.5

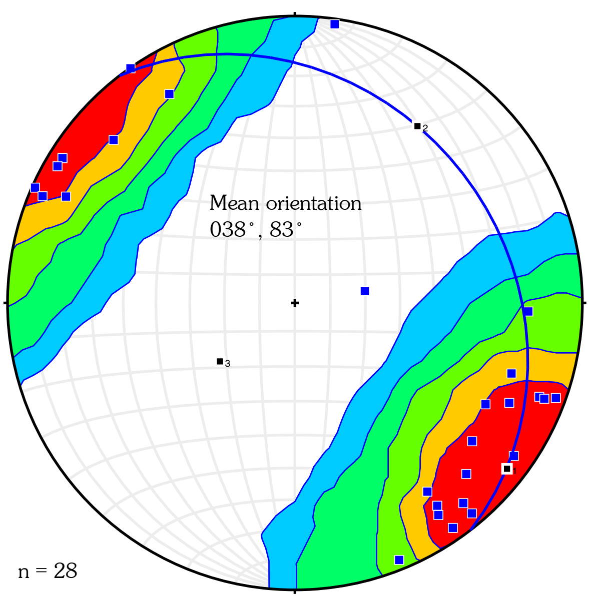
Ln lineations (Composite L_1-L_2)



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.8147	034.0,	02.0	2.4	3.4
2.	0.1209	303.1,	23.1		
3.	0.0644	128.6,	66.8	2.4	17.2

Best fit great circle (strike, dip RHR) = 218.6, 23.2

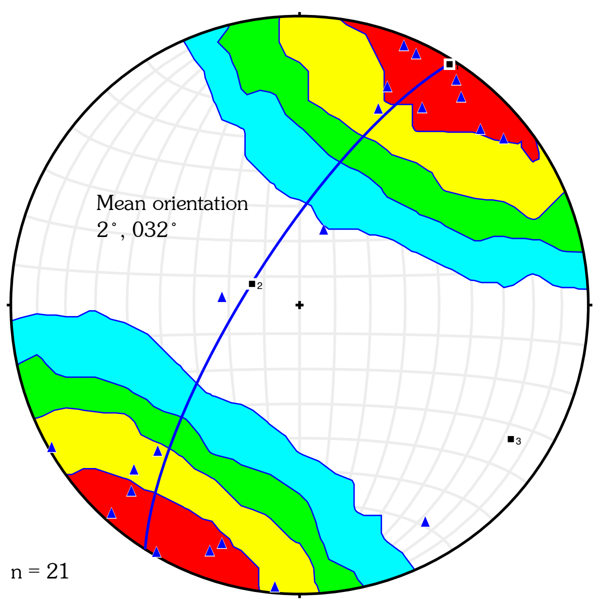
Poles to axial planes of F_3 (S_3)



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.8361	128.1,	07.2	6.6	9.0
2.	0.1029	034.5,	26.0		
3.	0.0610	232.4,	62.9	N/A	N/A

Best fit great circle (strike, dip RHR) = 322.4, 27.1

F_3 Fold Axes

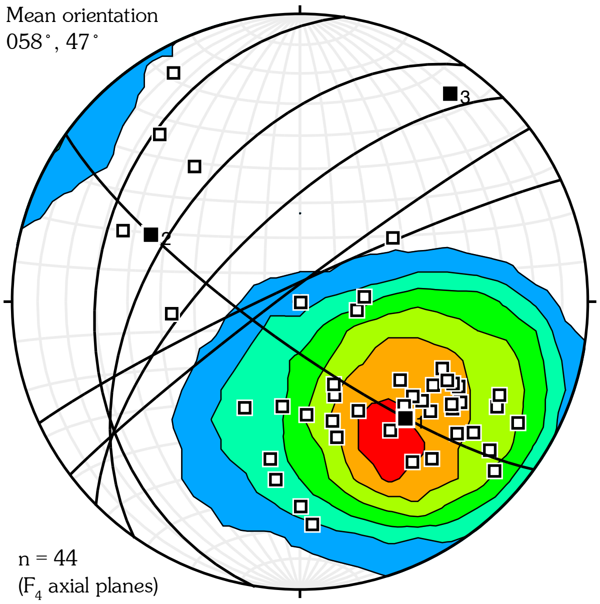


Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.7777	031.8,	02.0	N/A	N/A
2.	0.1414	294.2,	75.2		
3.	0.0809	122.3,	14.6	N/A	N/A

Best fit great circle (strike, dip RHR) = 212.3, 75.4

Figure 4
Page 2 of 2

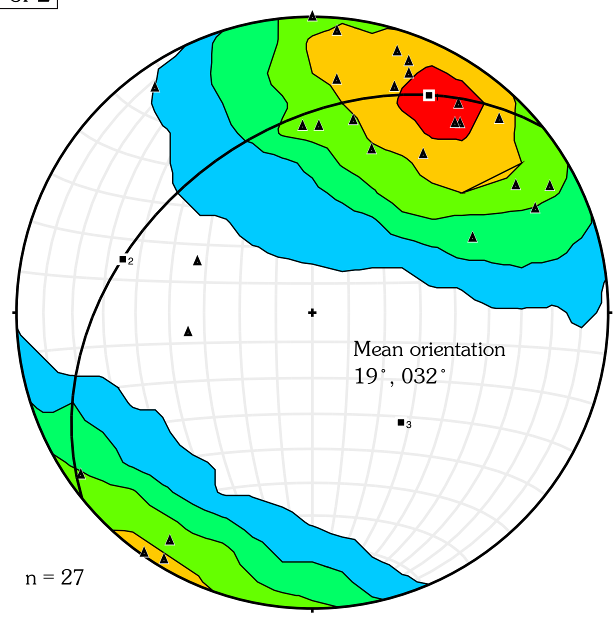
Poles to F_4 Axial Planes and S4 (great circles)



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.7411	137.9,	45.0	6.7	10.3
2.	0.1810	294.3,	42.5		
3.	0.0779	035.6,	12.0	6.6	25.2

Best fit great circle (strike, dip RHR) = 125.6, 78.0

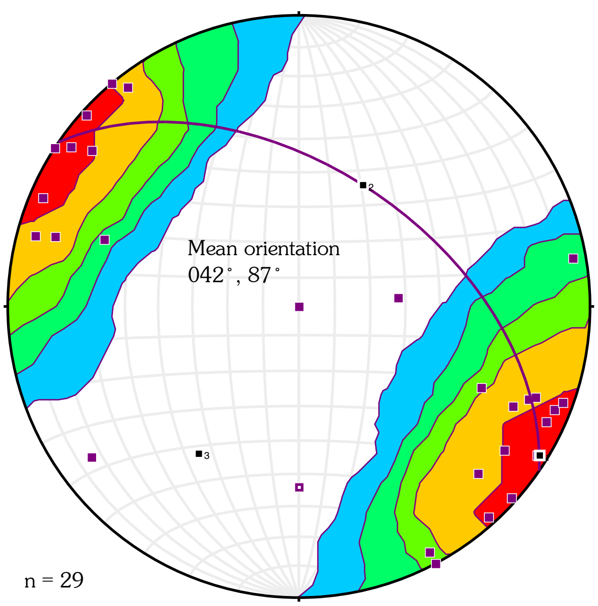
F_4 Fold Axes



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.7544	028.1,	17.7	8.6	12.3
2.	0.1636	285.8,	33.7		
3.	0.0821	141.1,	50.8	8.8	51.6

Best fit great circle (strike, dip RHR) = 231.1, 39.2

Poles to S_5 shear zones



Axis	Eigenvalue	Trend	Plunge	±min	±max
1.	0.7811	121.7,	03.3	7.3	9.0
2.	0.1260	027.7,	51.0		
3.	0.0930	214.4,	38.8	N/A	N/A

Best fit great circle (strike, dip RHR) = 304.4, 51.2

Figure 4 - Equal area projection lower hemisphere stereoplots of deformation fabric elements in the Hudson 7.5' quadrangle produced with Stereonet v 9.2.0 (Allmendinger et al., 2013; available from http://www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet.html).

North is up.

Kamb contoured with 2 sigma intervals. Red area shows mean orientation of structures with 2 sigma confidence. Great circle shown on plot is best fit great circle.

Results from Bingham axial analysis listed below each plot. For plots of poles to planar structures, Axis 1 roughly corresponds to pole of the mean orientation of the planes, with Axis 3 corresponding to the pole of the best fit great circle (e.g., Beta axis). For linear data Axis 1 corresponds to the mean orientation, with Axis 3 also corresponding to the pole of the best fit great circle.

Mean orientation taken from center of red 2 sigma confidence zone on Kamb contour plots.

THRUST FAULTS AND SHEAR ZONES

The Clinton-Newbury Fault Zone (CNFZ) passes under the northeastern portion of the quadrangle forming the boundary between the Merrimack terrane to the northwest and the Nashoba terrane to the southeast. In the Hudson quadrangle the CNFZ is defined by the Clinton-Newbury Fault, and Rattlesnake Hill and Ball Hill Faults of Stroud et al. (2009). All of these faults are presumed to have originated as pre-to-syn metamorphic D_1-D_2 southeast-vergent thrust faults (e.g., Goldsmith, 1991 and references therein), if not earlier, and are nearly completely overprinted by sinistral (D_{4a}) and oblique sinistral-normal (D_{4b} and D_5) motion during the Neoacadian orogeny and Allegehnian orogeny (Goldstein, 1994; Stroud et al., 2009; Kuiper et al., 2014). The Tadmuck Brook Schist (Ot and Otc), as a unit, displays the same sequence of sinistral-normal kinematic fabrics as its bounding faults (Dougherty and Kuiper, 2013) and is considered in large part to be a phyllonite separating the Merrimack terrane and Nashoba terranes (e.g. Jerden, 1987). These are all delineated on the map as early thrust faults, with the exception of the Ball Hill Fault as it only displays outcrop evidence for sinistral and oblique-normal motion (Stroud et al., 2009) while earlier S_1-S_2 presumed thrust-related fabrics can be observed in the other faults (this study; Dougherty and Kuiper, 2013; Kuiper et al., 2014; Goldstein, 1994). The similarity in metamorphic grade of the southeastern portion of the Tadmuck Brook Schist (Ot) to the Nashoba Formation precludes major displacement along the Ball Hill Fault Zone during M_1-M_2, and presumably D_1-D_2. The change in grade across it suggests that the unit itself acted as a fault zone across its entire thickness, accommodating later D_4 and D_5 deformation that juxtaposes the present-day Merrimack and Nashoba terranes.

The Spencer Brook and Assabet River faults are internal to the Nashoba Formation. They are presumed to have initiated as early pre-to-syn D_1-D_2 thrusts. Both are poorly exposed in the Nashoba terrane except in the southern portion of the Hudson quadrangle and in the Marlborough quadrangle at the I-290 / I-495 interchange. Both are characterized by rusty weathering sulfidic schists, phyllonites, and protomylonites to felsic ultramylonites. A deeply weathered and sulfidic amphibolite-grade garnet-silliminite-biotite phyllonite was observed along the trace of the Spencer Brook Fault Zone in a temporary outcrop (autumn, 2004) on the southeastern side of Judith Road in Hudson (road post-dates topographic base for geologic map). The Spencer Brook fault historically has marked the boundary between the gneisses of the Nashoba Formation to the northwest and the schist and amphibolite of the Boxford Member of the Nashoba Formation (presumed equivalent to S€nga), with the Assabet River Fault serving as the boundary between the Nashoba Formation as a whole with the Marlborough Formation, Fish Brook Gneiss, and Shawsheen Gneiss (presumed equivalent to S€ns) to the southeast (Bell and Alvord, 1976). The Spoon Hill Fault (named here) separates the Nashoba Formation and main body of Danp from the Marlborough Formation in the immediate area (Kopera et al., 2006). Kinematic indicators along all three faults in the Hudson quadrangle are ambiguous, although Massey and Alvord (2011) observed sinistral motion near the Spencer Brook Fault to the northeast in the Billerica quadrangle. Both faults cut Dan and Danp, and thus have syn-to-post Devonian components of motion along them. A lobe of Danp extends southwest along both fault zones from the main Andover pluton to the northeast, and has led various workers to hypothesize that Danp utilized the faults as pathway for intrusion (e.g., Barosh, 1984) and was subsequently cut by them.

ECONOMIC GEOLOGY

Marbles within the Nashoba Formation (S€ng) were extensively quarried in the 18th and 19th centuries (Cook, 1964; Hansen, 1956). Quarries at the Bolton Lime Kiln on the southeastern slope of Rattlesnake Hill west of the village of Brockway Corner in Bolton have been documented as being the second lime quarry discovered in New England and having been in operation as early as 1733 (Whitcomb, 1938, page 214). The marble was processed to lime on site and was used primarily for plaster and later, in the 20th century, for agricultural use.

Several small quarries and pits of very flaggy calc-silicate gneiss (S€ncs) exist west of Hudson Road in Bolton. The quarries were presumably used in the 19th century for field and foundation stone on account of the planarity of S_n-parallel fractures. Stones from this quarry may have been used in the construction of the Bolton Library in 1901, where S€ncs is common in the exterior facing stone of the building ("Bolton field stone" in Whitcomb, 1938; page 141).

The Tadmuck Brook Schist on Oak Hill (locally called "Bear Hill") has historically been a target for mineral collectors due to its sulfidic character. Considerable quantities of scheelite have been found in a thin section from the Tadmuck Brook schist in the general vicinity (J.C. Hepburn, personal communication, 2012). As Peter Whitney (*History of Worcester County*, 1793; quoted in Whitcomb, 1938, page 7) comments, however:

> "By some this is called Bear Hill and by others Oak Hill. This hill is thought to contain mines and minerals and has, consequently, for a number of years engaged the attention of a respectable society of mineseekers; but their expectations have exceeded their gains; for though its bowels have been explored with much painful labor and sanguine hope, yet the mountain has not even to this day brought forth a mouse."

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