Text to accompany Massachusetts Geological Survey Geologic Map GM-17-01

BEDROCK GEOLOGIC MAP OF THE NEWTON 7.5' QUADARANGLE, MIDDLESEX, NORFOLK AND SUFFOLK COUNTIES, MASSACHUSETTS[*]

By
Margaret D. Thompson, Wellesley College, Wellesley, MA

INTRODUCTION

The Newton quadrangle, located west of Boston, Massachusetts, is mainly underlain by clastic sedimentary and minor igneous rocks occupying the topographic Boston Basin (Crosby, 1880; Emerson, 1917; LaForge, 1932; Billings, 1976 and references therein). Fault blocks dominated by older plutonic and volcanic rocks truncate the Basin sequence on the west and south. Although fossiliferous Cambrian strata overlying plutonic basement had been reported some 30 miles away in North Attleboro, MA (Billings, 1929), the first quadrangle map including the Newton area (1:62,500 Plate I of LaForge, 1932) portrayed the plutonic units as "Early Paleozoic" and assigned all the others to the Devonian or Carboniferous periods. By the time the Newton quadrangle appeared at 1:24,000 scale (Kaye, 1980), emerging U-Pb zircon geochronology had revealed Neoproterozoic (Ediacaran in timescale of Gradstein et al., 2012) crystallization ages both for the Mattapan Volcanic Complex and the Dedham Granite on the south side of the map area (Kaye and Zartman, 1980; written communication of Zartman and Naylor, 1980 not published until 1984). The Boston Basin sequence in this map was inferred to be Neoproterozoic in the absence of a break with overlying Cambrian strata (Kaye and Zartman, 1980), an interpretation confirmed shortly thereafter by the discovery of Ediacaran microfossils in the top portion of the sedimentary section ("Vendian" in Lenk et al., 1982). In the map presented here, U-Pb zircon dates obtained by the author over twenty years with colleagues at MIT's Radiogenic Isotope Lab constrain all map units except mafic dikes. During this interval, U-Pb analyses have become more precise and accurate, leading also to significant refinements to the dates used by Kaye in 1980, as discussed further in the section on Stratigraphy.

A few comments regarding reliance on previous mapping in the Newton quadrangle are also in order. Not surprisingly during more than a century of investigation, exposure has steadily declined as this suburban area has become increasingly developed. Clifford Kaye found less outcrop during his field mapping (1975-1979) than was available to earlier workers cited above, but he included locations described in their works (Kaye, 1980, Sheet 2). Field work leading to the current map took place mainly between 1981 and 1984 with extensive field checking in 2014-2015. The latter phase has turned up many instances where exposures remain, but are off limits because they lie on private

---

property. Continuing Kaye's practice, I have included outcrops from his 1980 map in areas I was unable to visit completely. Also included are outcrops from earlier writings and/or maps of Crosby (1880), Burr (1901) and LaForge (1903, 1932). Sub-surface data from the City Tunnel Extension and City Tunnel (Billings and Tierney, 1964; Tierney et al., 1968), as well as core borings archived by the Massachusetts Water Resources Authority provide additional control.

Some geologic data has also been incorporated from previous maps where poor or inaccessible exposure precluded making additional observations. Contacts between plutonic units (though not names) in the southwest corner of the quadrangle are those of LaForge (1932), and the Northern Boundary Fault and diabase pod in the northwest corner are from Kaye (1980). Bedding orientations in argillites immediately north of the Mount Hope Fault include several measurements taken by Kaye from LaForge (1903, 1932). Importing conglomerate bedding from previous mapping, however, is problematic. Kaye's Newton quadrangle map (1980, Sheet 1), in particular, contains numerous locations showing bedding where only cleavage was observed during my mapping (further discussion in section on Cleavage). The decision to omit these measurements means that some areas in the present map show no structural control, but assures that all indicated orientations have been obtained from sandstone interbeds or other compositional layering in the conglomerate. This approach leads to some simplifications in the fold pattern in the central part of the quadrangle. Other simplified interpretations where Kaye's distinctions could not be verified are also elaborated in later sections. The Dedham Island Fault (proposed name), for example, is treated as a single strand rather than closely spaced fracture zones, and undifferentiated Westwood Granite is shown west of this fault rather than Dedham Granite with a chilled margin. Such modifications do not affect the regional stratigraphic and structural interpretations detailed below.

STRATIGRAPHY

The sequence within and surrounding the Boston Basin is discussed below, starting with the oldest rock formation. U-Pb zircon dates supporting this chronology appear at the top of the map legend in the chart entitled Correlation of Rock Units, and dates obtained from samples in the Newton quadrangle are summarized in the table at the bottom of the legend.

Dedham Granite (Zdgr following usage of Zen et al., 1983) underlying most of the southeast corner of map area appears in previous maps as Dedham Granodiorite (Emerson, 1917; Billings, 1929; LaForge, 1932). Both labels are oversimplifications because modal compositions ranging from alkali feldspar-rich granite to plagioclase-rich granodiorite and tonalite, as well as quartz-poor monzonite and diorite have long been reported across southeastern Massachusetts (summary in Wones and Goldsmith, 1991). Textural variants of the Dedham suite include pegmatite, aplite, and porphyry with quartz phenocrysts in a micrographic matrix. The latter variety in and adjoining the Stony Brook Reservation has previously been mapped as rhyolite (Bascom, 1900), assigned to the Mattapan Volcanic Complex (LaForge, 1932) and confused with the

Westwood Granite (Thompson, 1985 and 1993). The interpretation adopted here follows Kaye (1980) in treating the quartz porphyry as a chilled border phase of the Dedham Granite.

A coarse-grained granite sample from the West Roxbury Crushed Stone Quarry (Hyde Park section of Boston in the southeast corner of the quadrangle) yielded a weighted mean $^{206}Pb/^{238}U$ CA-TIMS zircon date of 609.1 ± 1.1 Ma. Methods used to obtain this date and reasons why it is not only more precise but also younger than the previously reported 630 ± 15 Ma upper concordia intercept date (Zartman and Naylor, 1984) can be found in Thompson et al. (2010). While the previous date broke new ground in clarifying that the Dedham Granite is older than Early Paleozoic as suggested by LaForge (1932), it significantly overestimates the age of Dedham magmatism.

Coarse-grained Dedham Granite extends west and south across the Charles River towards Dedham, MA in the south-central portion of the Newton quadrangle as shown by LaForge (1932) and confirmed by recent visits to the area. Kaye (1980) mapped fine-grained granite in this area as part of the Dedham Granite in this area, but this is re-assigned here to the Westwood Granite discussed below.

Westwood Granite (Zwgr) was originally defined in the northwest corner of the Norwood quadrangle that adjoins the Newton quadrangle on the south. Distinguished from Dedham Granite by its generally finer grain size, it occurs typically as light pinkish-gray massive, quartz-rich granite with only minor mafic minerals (Chute, 1966). A sample of this rock from the interchange between Route 128S and Route109W in the Norwood quadrangle yielded a U-Pb zircon upper concordia intercept date of 599 ± 1 Ma based on four multi-grain zircon fractions (Thompson et al., 1996). The same granite continues northward into the Newton quadrangle as a narrow band in contact with the Dedham Granite on the west side of the Charles River. The exact position of the contact cannot be traced because of sparse or inaccessible outcrop in marshes lining the river, but Chute (1966, p. B19) reports Dedham inclusions within the Westwood Granite consistent with the geochronology.

Fine-grained granite exposed farther north in the vicinity of Needham, MA appears both as Mattapan Volcanic Complex in the map of LaForge (1932) and as Dedham granite and its chilled border according to Kaye (1980). Because fine-grained granite is not limited to the center of the body, however, Kaye's zoning is not shown in the current map. The undifferentiated granite is also re-assigned to the Westwood Granite based on the presence of hematite patches that link the rock with the pink variety of the latter described by Chute (1966). Chute also included "hybrid" mixtures of granitic and mafic phases as part of the Westwood Granite, but that was before any of these rocks could be isotopically dated. Currently available geochronology contradicts Chute's interpretation as explained in the next section.

Wilson Mountain Quartz Diorite (Zwqd) is proposed here for the complex plutonic assemblage equated in previous quadrangle maps with Newburyport Quartz Diorite defined originally in coastal occurrences in the northeastern-most corner of

Massachusetts (Emerson, 1917). The variability of this unit is best described by Chute (1966) around Westwood, MA in the northwestern Norwood quadrangle. His account emphasizes medium- to coarse-grained diorite with minor interstitial quartz, K-feldspar and equi-dimensional poikilitic hornblende crystals as the most typical rock type. The typical diorite grades into medium-grained and pegmatitic varieties containing long slender hornblende crystals. In road-cuts lining the Route 128S/Route 109W off-ramp, the author has additionally documented gradations between quartz diorite and darker gabbro, as well as co-mingling textures between quartz diorite and a lighter colored granitic phase distinguishable from Westwood Granite by its greater abundance of mafic minerals. Many of these varieties can also be found on nearby Wilson Mountain in the Newton quadrangle which is proposed here as the type locality.

Medium-grained quartz diorite in the Route 128 road-cut described above was sampled for U-Pb geochronology (Thompson et al., 1996). Analyses obtained from five multi-grain zircon fractions, including three that are essentially concordant, yield an upper concordia intercept date of 589 ± 2 Ma interpreted as the crystallization age.

Previous quadrangle maps erroneously show intrusives assigned here to the 599 ± 1 Ma Westwood Granite as younger than the quartz diorite now demonstrated to be ten million years younger. The relationship between the two is further obscured by descriptions of contact zones in which granitic Westwood magma reportedly incorporates blocks of or hybridizes with phases assigned to the Newburyport Quartz Diorite and Salem Gabbro-Diorite (Chute, 1966), both now constrained by U-Pb dates indicative of mid-Paleozoic age (upper concordia intercept date of Zartman and Naylor, 1984; weighted mean ^{206}Pb-^{238}U LA-ICPMS dates of Hanson and McFadden, 2014). Reducing Chute's outcrop descriptions to purely lithologic terms, the hybrid and breccia zones are here interpreted as textural variants observed in 589 ± 2 Ma quartz diorite of the Route128 road-cuts, and thus to represent mixtures of coexisting liquids of slightly different compositions formed during post-Westwood Granite magmatism. Blocks of the typical pale-colored variety of the latter found within Wilson Mountain Quartz Diorite during field checking in the Wilson Mountain area provide field evidence consistent with the geochronology.

Lynn-Mattapan Volcanic Complex is jointly applied to asssemblages originally defined separately as the Mattapan Volcanic Complex south and west of Boston (LaForge, 1932), and the Lynn Volcanic Complex to the north (Clapp, 1921). LaForge (1932, p. 35) suspected that they were the same age, and this was finally demonstrated about ten years ago by a 596 ± 3 Ma lower concordia intercept date from Lynn rhyolite in Saugus, MA (Hepburn et al, 1993) and a 596 ± 2 Ma upper concordia intercept date from Mattapan ash-flow tuff in Westwood, MA (Thompson et al., 1996). Other samples of Lynn-Mattapan volcanic rocks (Zlmv) have since been dated to establish a range of crystallization ages from 597.4 ± 1.5 Ma in the central part of the Newton quadrangle (weighted mean ^{207}Pb/^{206}Pb date of Thompson et al., 2007) to 593.19 ± 0.72 Ma in the adjoining Boston South quadrangle to the east (weighted mean ^{206}Pb/^{238}U date of M. Thompson et al., 2014). One of the five analyzed zircons from the Boston South sample was considerably older (607.88 ± 0.55 Ma), indicating a xenocrystic component

possibly from a source like the Dedham Granite. The 602 ± 3 Ma upper concordia intercept date of Kaye and Zartman (1980) is probably not a reliable Lynn-Mattapan crystallization age because there would have been many such xenocrystic grains in the large multi-zircon samples required in such early U-Pb geochronological studies.

LaForge (1932) also correctly interpreted other aspects of the Lynn-Mattapan Volcanic Complex that are born out by investigations leading to the present map. His account of the Lynn resting on a deeply weathered granite surface (p. 31), first of all, is consistent with the ten-million-year gap now demonstrated between the Dedham Granite and the Lynn-Mattapan Volcanic Complex, not only in the Newton quadrangle but also farther east in Hingham, MA (discussion in Thompson et al., 2010). LaForge also reports (p. 34) "much confusion in the interpretation of the stratigraphy and structure of the Boston Basin arising from the failure to recognize that well stratified conglomerate, sandstone and slate near the top of the volcanic complex south of Boston are not the base of the Roxbury Conglomerate." This sequence has been distinguished as the Neponset Gorge member (Zlmn) of the Lynn-Mattapan Volcanic Complex chiefly because its clast assemblage contains only igneous lithotypes and lacks quartz arenite ubiquitous in the Roxbury proper (further discussion in M. Thompson et al., 2014).

Roxbury Conglomerate, Brighton Igneous Suite and Cambridge Formation are adopted here for units that LaForge (1932) combined as the **Boston Bay Group**. These formation names are slightly modified from LaForge's original "Roxbury conglomerate," "Brighton melaphyre" and "Cambridge slate" (Cambridge Argillite of Billings, 1929 and thereafter), and some new internal divisions are also introduced. The most significant stratigraphic revision is that the Roxbury-Brighton assemblage traditionally shown as inter-fingering- northward across the Boston Basin into Cambridge strata (Billings and Tierney, 1964; Billings, 1976) is ruled out by U-Pb geochronological constraints detailed by M. Thompson et al. (2014) and summarized in the following paragraphs.

The Roxbury Conglomerate, beginning with LaForge's summary *in* Emerson (1917) has long been divided, in ascending order, into the conglomeratic Brookline Member, the red and purple slate-dominated Dorchester Member and the Squantum Member with its still-debated "tillite". Subsequent investigation convinced LaForge (1932, p. 39-40) that "this three-fold division does not persist throughout the area occupied by the formation with sufficient definiteness to warrant the mapping of the members separately." This author follows LaForge in not differentiating the Dorchester and Squantum members that have previously been delineated only in the subsurface (Billings and Tierney, 1964; Tierney et al., 1968; Richardson, 1977). The conglomerate, however, is subdivided in this map into two members based on lithological differences (clast size, clast assemblages, abundance of sandstone and finer interbeds) and especially distinctions in detrital zircon age spectra (complete discussion in M. Thompson et al., 2014). Older conglomerate in the south-central portion of the map, including southwestern-most Brookline, MA, is named the Franklin Park member (Zrf) for deposits originally described by Crosby (1880) in what is now the Boston South quadrangle. Sandstone near the top of this sequence yielded the youngest of several

hundred analyzed detrital zircons from three samples at various stratigraphic levels of the conglomerate across the Boston Basin. The ^{206}Pb/^{238}U date of 595.14 ± 0.90 Ma from this zircon establishes a maximum depositional age for all of the Roxbury Conglomerate (M. Thompson et al., 2014). Brookline member (Zrb) is retained as the name for younger conglomerate in the north-central portion of the map that includes most of Brookline, MA. Sandstone and siltstone horizons are more common in this belt, as are members of the Brighton Igneous Suite discussed in the following paragraphs.

The Brighton assemblage, ranging in composition from ~ 48 to 68 weight % SiO_2 (Cardoza et al., 1990; M. Thompson et al., 2014), was called melaphyr(e) before routine geochemical characterization became possible (Crosby, 1880; Burr, 1901; Emerson, 1917; LaForge, 1932; Billings, 1929 and 1976). More recent literature (Bailey, 1987; Hepburn and Bailey, 1998; Thompson and Grunow, 2004 for example) refers to the Brighton "Volcanics," but Brighton Igneous Suite (M. Thompson et al., 2014) is adopted here because intrusives are also common.

Brighton intrusives (Zbi) are most widely exposed in Brookline, MA, extending southward from Dane Park along the fairways of the Robert T. Lynch Golf Course and westward across Hammond Street. On the west, porphyry with chilled margins shows steep contacts protruding at high angles across northwesterly strikes of a stratified section including lava flows, volcanic breccia and a few conglomerate interbeds. At the northeast-dipping upper contact on the east side of the golf course, the porphyry appears to have invaded overlying conglomerate and sandstone that was not entirely consolidated, thereby forming confused mixtures in which each type of rock can be found in places to intrude the other. Quartz-filled vesicles at the top of the porphyry are flattened parallel to the contact, rather than rounded as might be expected in a surface flow. Brighton intrusions have likewise been described in the northwest corner of the map (Burr, 1901) and in the City Tunnel Extension (Billings and Tierney, 1964), as illustrated in cross sections AA' and BB', respectively. Brighton intrusives have yielded crystallization ages of 584.19 ± 0.70 Ma (near Dane Park) and 585.37 ± 0.72 Ma (northwest corner of the map) that provide a minimum age of ~ 585 Ma for the entire Roxbury Conglomerate section (M. Thompson et al., 2014). Brighton lava flows and pyroclastic deposits of basaltic composition in the Webster Conservation Area of Newton, MA and Ringer Park in Allston, MA (Zbv) yielded insufficient zircon for U-Pb geochronology. The 595 Ma to 585 Ma constraints on the Roxbury Conglomerate apply to these (and any other) volcanic horizons as well.

Brighton occurrences for which intrusive versus extrusive origin has not or cannot be resolved appear on the map as undifferentiated (Zbu). One uncertainty that can be settled is whether the Brighton Igneous Suite is best viewed as the final stage of Lynn-Mattapan activity or as an entirely distinct later magmatic episode (LaForge, 1932, p. 43). Rocks comprising the two suites overlap substantially in composition and jointly define a calc-alkaline trend indicative of arc-related Avalonian magmatism (analyses in M. Thompson et al., 2014). The 8 million-year gap between the youngest Mattapan eruption and the 585 Ma Brighton intrusions, however, justifies maintaining them as separate map units.

Thinly bedded, monotonously gray deposits overlying the Roxbury Conglomerate on the north and south margins of the Boston Basin appear in early investigations as Cambridge slate (Shaler, 1869; Dodge, 1875; Crosby, 1880, Emerson, 1917). LaForge (1932) followed this long-established convention in his map, while at the same time noting that the rock is too poorly cleaved in most places to warrant the name. Billings (1929) modified the formation name to Cambridge Argillite to be more consistent with the usually massive character of mudstone and siltstone comprising this sequence. This name has been further modified here to Cambridge Formation as used in passing by Tierney et al. (1968) to permit the two-fold division shown in the present map.

The majority of Cambridge strata are assigned to the Argillite member (Zca) in the northern part of the map. LaForge (*in* Emerson, 1917) reports beds of re-worked tuff in the sequence, and major element geochemistry of these rocks is consistent with a significant component of volcanic ash (Thompson and Bowring, 2000). Outside the quadrangle in Somerville, MA, the Cambridge Argillite member contains volcanic ash with a mixed population of zircon that yielded a range of discordant $^{207}Pb/^{206}Pb$ dates, as well as one concordant analysis at ~570 Ma judged to be a good estimate of the age (Thompson and Bowring, 2000). Because the possibility of still younger zircons cannot be ruled out, however, this is listed as a maximum age in the correlation chart.

Siltstone and fine-grained sandstone occupying a thin belt on the south side of the map differ from the Argillite member in containing small amounts of detrital muscovite. Mudstone with similar petrographic (and geochemical) characteristics encountered in the Braintree Weymouth Tunnel (Green, 2002) passes upward into muscovite-bearing quartz arenite and interbedded multi-colored siltstone that is overlain in turn by fossiliferous strata of the Weymouth Formation. The detrital muscovite-bearing beds record the transition from Ediacaran to Lower Cambrian sedimentation and are thus distinguished on the map as the Transition member of the Cambridge Formation (Zct).

Diabase dikes (Cambrian to Jurassic?) cut all bedrock formations of the Newton quadrangle, but only two of these can be shown at the scale of this map. One trends NNW through Dedham Granite west of the Stony Brook Reservation (southeast corner of map) and the other trends NE within the Brighton intrusion northwest of Newton, MA. Both dikes are approximately 30 m thick. A broader view of dike frequency, size and orientation across the quadrangle can be gleaned from relationships in the City Tunnel Extension. Here Roxbury Conglomerate and Cambridge Formation are intruded both by Brighton intrusives and by diabase showing various degrees of alteration (melaphyre and mafic rocks, respectively, in Billing and Tierney, 1964). Between Shaft 7 (west of the Chestnut Hill Reservoir) and Shaft 8 (just outside the eastern boundary of the Newton quadrangle), the tunnel transects 43 diabase dikes averaging approximately 3 m thick, only two of which are thick enough to appear in the cross section BB' constructed from the strip maps of Billings and Tierney (1964; scale approximately 1 inch to 200'). Five diabase sills with thicknesses averaging approximately 4.5 m were also reported, but not shown in the strip maps. Most of the dikes in the tunnel trend northeast like the Newton example, but a second generally north-trending group

resembles the Stony Brook occurrence. Dikes of this orientation may be related to the alkaline Medford Dike that cuts the northern border fault of the Boston Basin in the Boston North quadrangle (discussion in Wones and Goldsmith, 1991), but corroborating geochemical data are not available in the Newton quadrangle.

None of the dikes in the Newton quadrangle has been isotopically dated, and none of the isotopic dates reported for comparable dikes in areas extending northward to Cape Ann, MA (Ross, 1990) were obtained via U-Pb geochronology. Available dates are based on K-Ar isotopic analyses of whole rock samples or individual minerals, (Krueger, 1964; Zartman et al., 1970; Weston Geophysical Research, Inc., 1977) as well as $^{40}Ar/^{30}Ar$ whole rock isotopic analyses (Ross and Bailey, 2001). All of these analyses are likely to have been affected by alterations like those documented in the Newton quadrangle, leading to probable inaccuracies in reported crystallization ages ranging from lowest Cambrian through Jurassic.

STRUCTURAL GEOLOGY

Structural features of the Newton quadrangle are best summarized in the two cross sections accompanying the map. Section AA' trending diagonally from northwest to southeast shows the Mount Hope Fault bounding the Boston Basin on the south as well as the generally anticlinal structure within the Basin and local areas of short-wavelength folds. All of these structures are cut by high angle faults. Section BB', based on relationships mapped in the City Tunnel Extension by Billings and Tierney (1964), reveals structural complexity that is probably representative of the entire map area but is obscured at the surface by widespread surficial deposits (not shown in the map). Details of the regional structure are elaborated below.

Faults cutting rock formations in and around the Boston Basin are inferred at the surface where lithologic units are truncated, bedding attitudes change abruptly or rock is brecciated and/or veined by quartz. Other discontinuities shown on the map coincide with lineations in aeromagnetic map patterns. Zones identified by either means comprise NNE-trending, NW-trending and EW-trending groups. The NNE-trending Stony Brook Fault in the southeastern corner of the quadrangle (Billings, 1929) exemplifies the first and youngest of the three groups. This fault cuts the EW-trending Mount Hope Fault on the north, and it continues southward into the Norwood quadrangle where it cuts Pennsylvanian deposits of the Norfolk Basin (Chute, 1966). The Hammond Pond Fault (proposed name) in the center of the quadrangle is another member of this group. The most conspicuous example of the NW-trending group is the fault that lifts Lynn-Mattapan volcanic rocks intruded by Westwood Granite in the southwest corner of the quadrangle against the Franklin Park member of the Roxbury Conglomerate to the east. The southern segment of this fault passes east of Dedham Island and is named here for that location. The Dedham Island Fault is younger than the Mount Hope Fault which it also cuts, but it is more difficult to be certain of its age relative to the NNE-trending group. While the Hammond Pond Fault truncates a NW-trending fault north of the Chestnut Hill Reservoir, this relationship cannot be confirmed elsewhere in the quadrangle. Dips likewise cannot be established at the surface for

either NNE-trending or NW-trending faults. Billings and Tierney (1964), however, report that most common faults in the City Tunnel Extension have an average strike of N60W, an average dip of 60NE and normal displacement measuring typically inches or feet.

The EW-trending group includes the Mount Hope Fault originally named by Billings (1929) in the southeast corner of the quadrangle and shown by Billings (and LaForge, 1932) as a south dipping thrust bringing Dedham Granite over Roxbury Conglomerate to the north.   Subsurface mapping in the Dorchester Tunnel east of the Newton quadrangle (Richardson, 1977) subsequently demonstrated a north dip for this fault, thus requiring normal displacement. Paralleling the Mount Hope Fault on the north is a fault shown by LaForge (1932) as a north-dipping thrust. Here named for its easternmost exposure in LaForge's map at Savin Hill, this fault is likewise considered here to be a normal fault. Both of these have been interpreted as Ediacaran structures that localized Roxbury Conglomerate deposition into sub-basins from source areas that contributed differing clast assemblages and detrital zircon suites (full discussion in M. Thompson et al., 2014).

Folds. Sedimentary strata arch broadly across the Boston Basin as recognized by earliest workers in the area (Crosby, 1880; Billings, 1929; LaForge, 1932). This so-called "central anticline" (Billings, 1929 and thereafter) is best expressed in the Argillite member of the Cambridge Formation in Boston Harbor where the Inter-Island Tunnel transects the hinge beneath Thompsons Island (sketch map of P. Thompson et al., 2014). This hinge can be traced westward into the Boston South quadrangle (sketch map of M. M. Thompson et al., 2014 and in preparation at 1:24,000). Here the anticline appears in units topping the Brookline member of the Roxbury Conglomerate. In the middle of that quadrangle, these units (Dorchester and Squantum members of earlier workers) are down-faulted along NNW-trending faults that expose the Franklin Park member of the Roxbury in the core of the fold.

In the Newton quadrangle, the anticlinal structure, as foreseen by Crosby (1880, p. 232), is not as simple as described above or shown in earlier maps drawn at a variety of smaller scales (LaForge *in* Emerson, 1917, LaForge, 1932, Billings 1929 and 1976; Zen et al., 1983; Goldsmith, 1991). Arching is apparent in the central portion of the quadrangle in moderately north dipping bedding in the Brookline member of the Roxbury Conglomerate and more steeply south dipping bedding in the Franklin Park member. The south limb of the fold, however, is cut off by the Savin Hill Fault which likewise truncates the Lynn-Mattapan Volcanic Complex and Brighton Igneous Suite, previously shown as straddling the hinge in the core of the anticline. The present map also shows that the latter units dip uniformly northeast, so that the anticlinal hinge (Brookline anticline in map) can only roughly be traced through the Brookline member of the Roxbury which itself is disrupted along its faulted contact with Brighton units on the west. The Brookline anticline may be the westward continuation of the central anticline in the neighboring Boston South quadrangle and Boston Harbor, but in those areas the hinge zone lies at least two kilometers farther south.

Figure 1 shows stereographic representations of folds affecting the Brookline member of the Roxbury Conglomerate north of the Savin Hill Fault. In the sector between the Savin Hill Fault and the Hammond Pond Fault, the strike of bedding sweeps from NNW to WNW, thus establishing a N62E/17NE fold axis for the Brookline anticline (Fig. 1A). This direction is also used to orient the hinge in the map itself. Anticlines and synclines with wavelengths measuring only few hundred feet in the areas west of Hammond Pond and the northwest corner of the quadrangle yield a comparable fold axis (N59E/14NE in Fig. 1B). Similarly oriented folds can be found west of the Chestnut Hill Reservoir and southeast of Newton Highlands.

Other aspects of fold geometry in the Newton quadrangle are less straightforward. Combining bedding poles in Figure 1 with poles from bedding south of the Savin Hill Fault (Fig. 2) yields a quadrangle-wide fold axis oriented approximately 10-15° clockwise of the direction in Figure 1. The stereographically determined N74E/10NE orientation more closely resembles the N84E/19NE axis reported for the Charles River
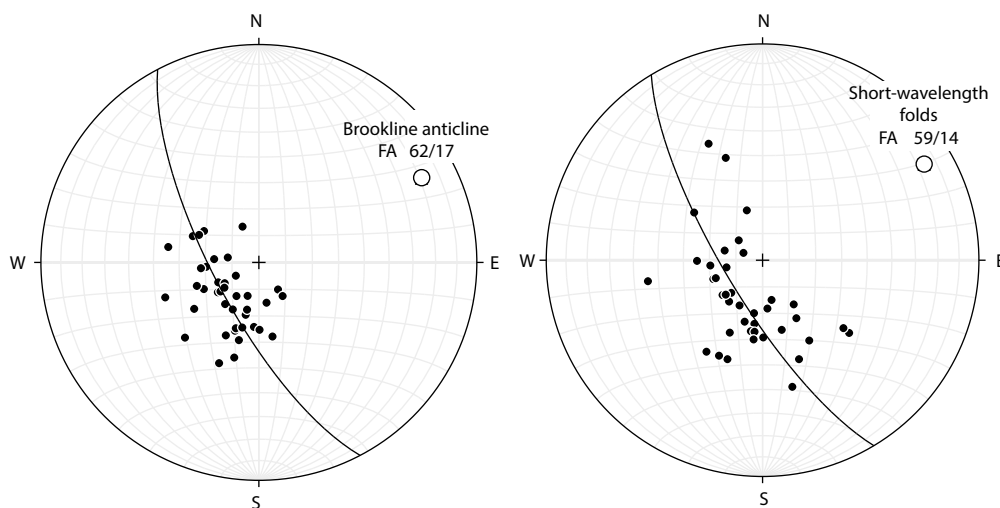
Figure 1. Stereographic representation of folding in north of the Savin Hill Fault in the Newton quadrangle based on poles to bedding of the Brookline member of the Roxbury Conglomerate. A. Brookline anticline with fold axis (FA) oriented 62/17 (n = 39). B. Short wavelength folds in Webster Conservation Area and NW corner of the map yield comparable fold axis of 59/14 (n = 40).

syncline (Billings and Tierney, 1964; Billings 1976) that lies outside the Newton quadrangle to the north. These directions furthermore nearly lie within steep north-dipping cleavage (also shown in Fig. 2) reported by Billings (1976) as axial planar to folds in argillaceous rocks transected by the City Tunnel Extension. Yet similarly oriented cleavage in both the Brookline and Franklin Park members of the Roxbury Conglomerate (discussion in following section; mean S_1 in Fig. 2) strikes diagonally across fold hinges north of the Savin Hill Fault, implying that these folds represent a phase of deformation pre-dating cleavage formation throughout the Boston Basin. Brightonintrusives cut closely spaced folds in both cross section AA' and BB', further implying that the early folding is older than approximately 585 Ma. The scale and regional regularity of the short-wavelength folds argues against origin by soft-sediment

slumping, and the conglomerate is too young to have been affected by early tectonism reported in meta-sedimentary units intruded by the Dedham Granite (Bailey et al., 1989; Goldsmith, 1991).

Figure 2. Poles to bedding throughout the Newton quadrangle define a fold axis (FA) oriented N74E/10 NE that lies within steep N-dipping cleavage shown by great circles (red—reported in City Tunnel Extension by Billings and Tierney, 1964: blue—mean S_1 cleavage attitude discussed in next section). Other fold axes: ○ —directions shown in Figure 1; ▲—Charles River Syncline (Billings, 1976).
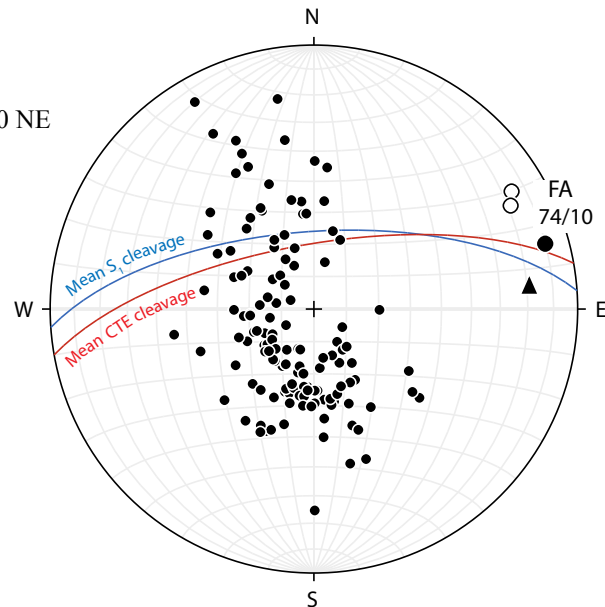
A possible explanation for the relationships described above may be that fold geometries in the quadrangle reflect interactions with the same fault-blocks proposed to have controlled Roxbury Conglomerate deposition (M. Thompson et al., 2014). ENE-trending hinges of short-wavelength folds north of the Savin Hill Fault run parallel to the trace of the fault, suggesting that the footwall block of the fault may have acted as a buttress against which conglomerate of the Brookline member was shortened. Subsequent reactivation of the Savin Hill and Mount Hope faults may have lifted the Franklin Park member of the Roxbury in the intervening block, thereby arching the overlying Brookline member and Cambridge Formation to produce the broad central anticline. It is also possible that these two sets of folds represent phases of a single compressive event, so they are not differentiated as F_1 and F_2. Further support for this interpretation is the presence of steep cleavage in all sedimentary units except the Transitional member of the Cambridge Formation overlying Roxbury Conglomerate on the south side of the quadrangle. If the inferred Cambrian age for the latter is correct, the central anticline would also be an Ediacaran structure.

Cleavage throughout the Roxbury Conglomerate in the Newton quadrangle is a composite of early structures crenulated by or deflecting into later surfaces. The early direction (blue symbols in Figure 3) is the steep S_1 structure mentioned above. The stereographically determined mean attitude of S_1 is N84W/66NE based on 38 poles to cleavages mapped in conglomerate across the map area (Fig. 4). The cleavage is expressed in outcrop as aligned or flattened clasts and by a fabric of aligned white mica in thin section. This cleavage has been mistaken for steep north-dipping bedding in earlier maps of conglomerate on the south side of quadrangle (LaForge, 1932; Kaye, 1980; Fig. 5). S_1 symbols accompanied by "K" in Figure 3 and the quadrangle map mark locations where the author has detected this problem. Gently dipping cleavage discussed

below has likewise been reported as bedding in various places, and symbols for these are similarly annotated.
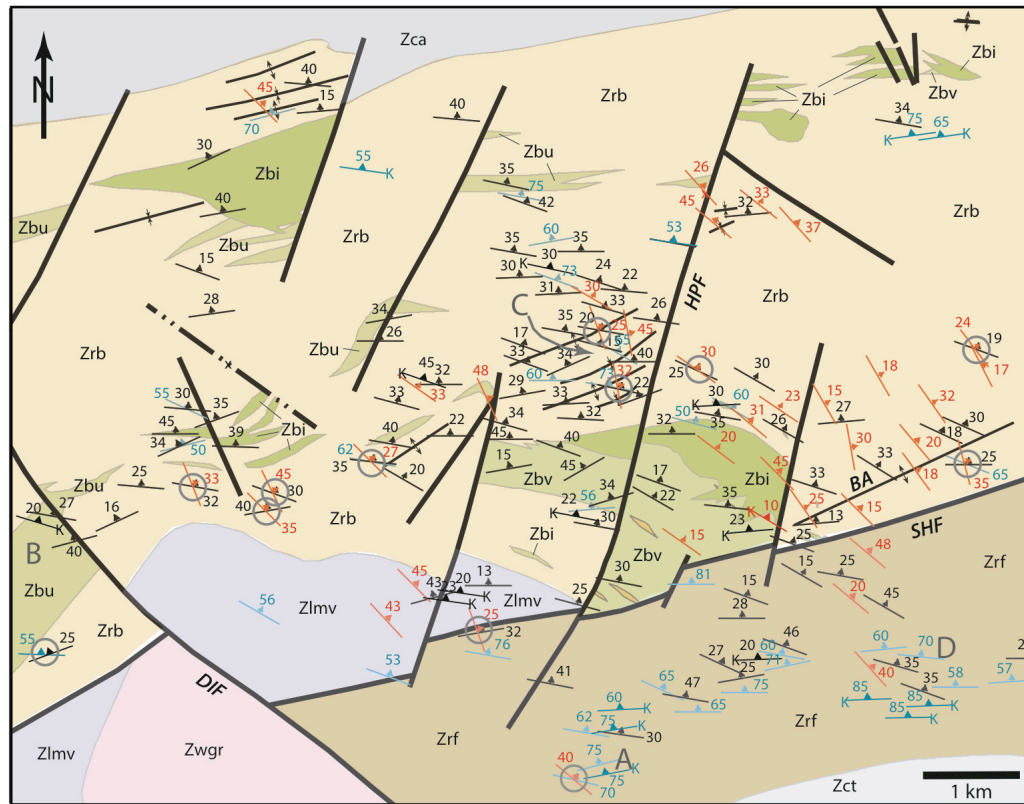

Figure 3. Simplified map (scale 1:100,000) showing only cleavages in central portion of Newton quadrangle. Blue symbols—S_1; black symbols—S_2; red symbols—S_3. Symbols with " K" show locations where structure was previously mapped as bedding (Kaye, 1980). Circles mark locations where more than one cleavage was mapped in a single outcrop. *BA—Brookline anticline; DIF—Dedham Island Fault; HPF—Hammond Pond Fault; SHF—Savin Hill Fault.* A, B, C, D denote locations illustrated in Figures 7, 8 and 9.   Abbreviated formation names defined in legend of 1:24,000 map.
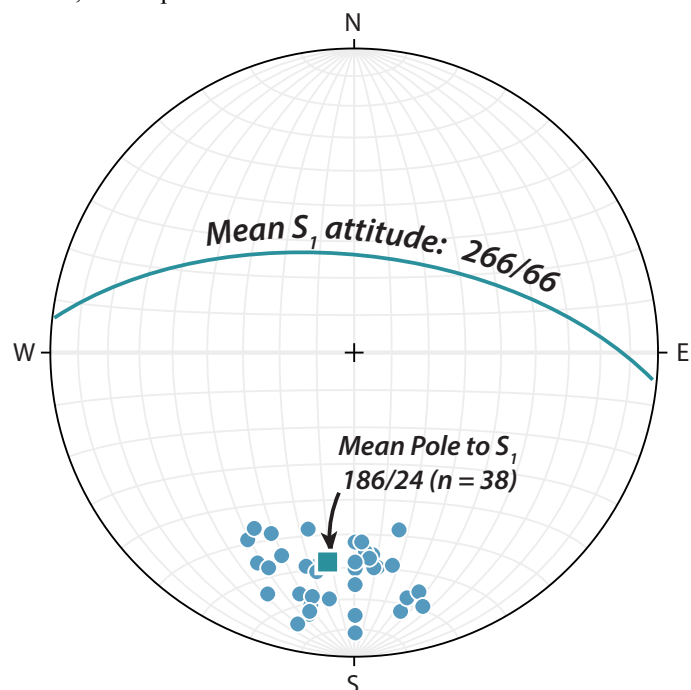
Figure 4. Poles to S_1 cleavage in Newton quadrangle and mean attitude based on 38 measurements.
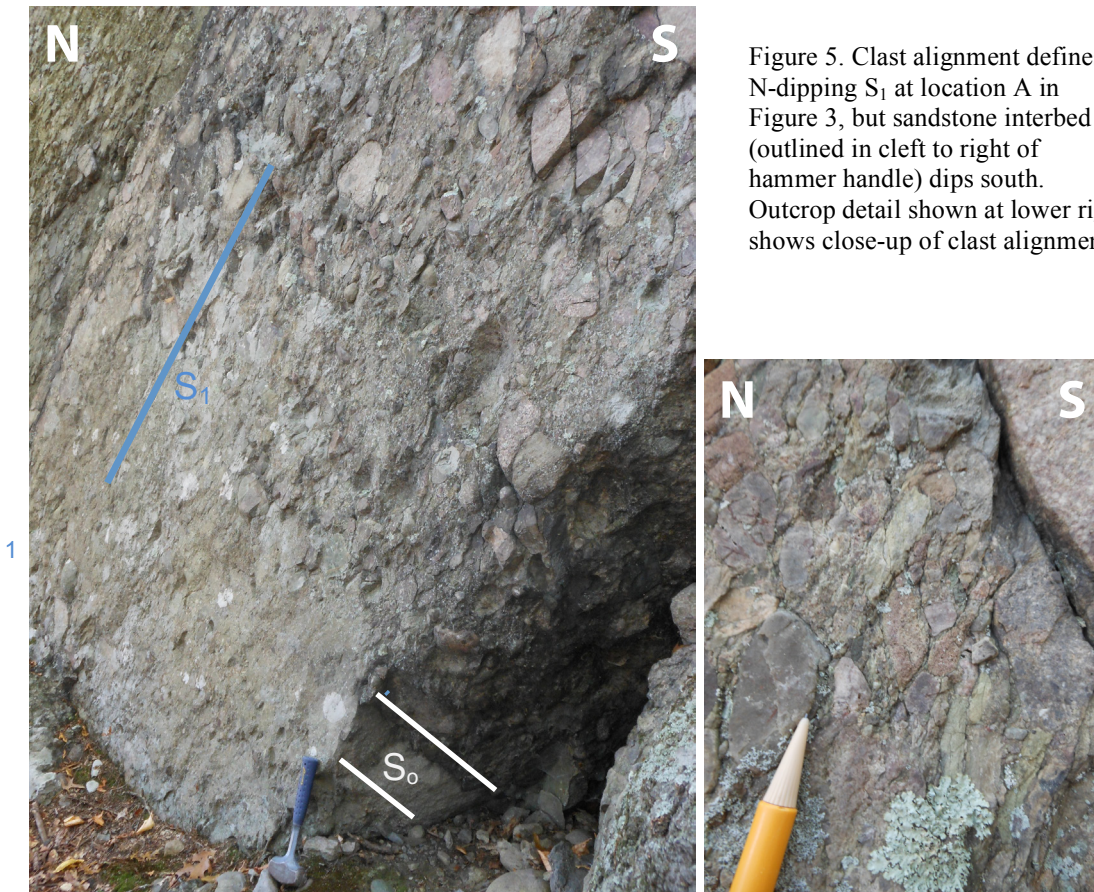
Figure 5. Clast alignment defines N-dipping S_1 at location A in Figure 3, but sandstone interbed (outlined in cleft to right of hammer handle) dips south. Outcrop detail shown at lower right shows close-up of clast alignment.

Steep S_1 directions are pervasively overprinted by irregular partings that dip north at an average of about 30 degrees (Fig. 6). Circled locations in Figure 3 represent outcrops containing two such gently dipping structures, the younger S_3 (in red) typically striking 40-50 degrees clockwise of the older S_2 (in black). The mesoscopic partings correlate with both normal and extensional microscopic crenulations of S_1 micas arising from intra-clast rotation and initial differences in S_1 orientation with respect to the later fabrics (Thompson and Burks, 1992; Figs. 7, 8, 9). Penetrative S_2 fabric in some quartz arenite clasts and mica locally parallel to S_3 reflect persistent low-grade metamorphic conditions throughout low-angle cleavage formation.
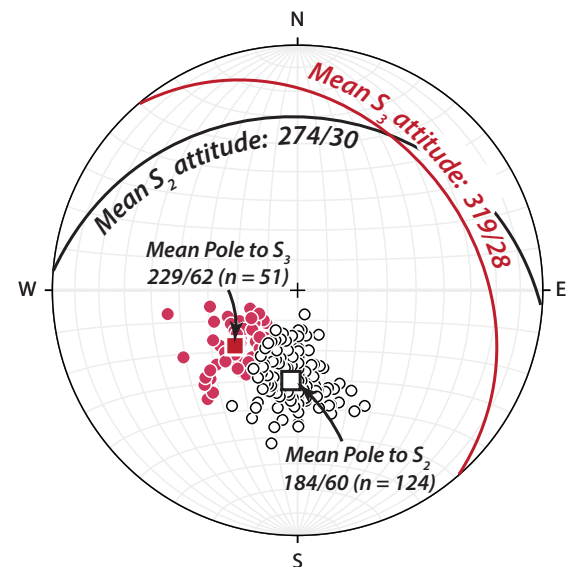
Figure 6. Poles to S_2 and S_3 cleavages in the Newton quadrangle and mean attitudes based on 124 measurements of S_2 and 51 measurements of S_3.
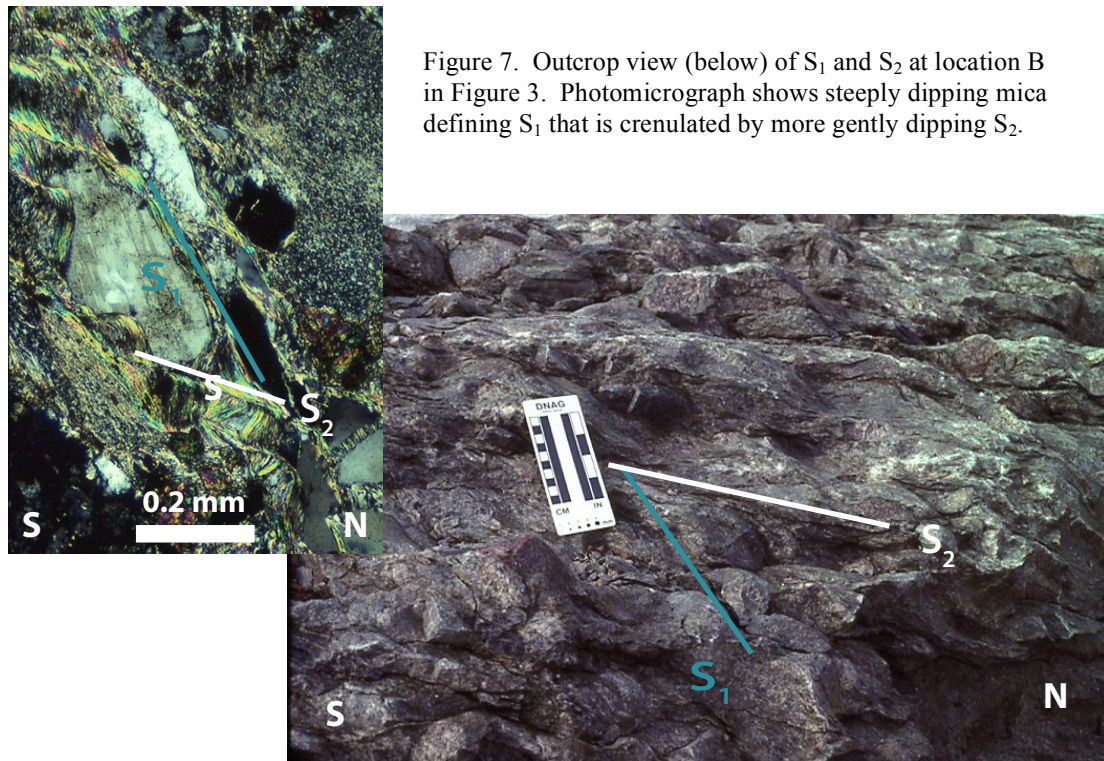
Figure 7. Outcrop view (below) of S_1 and S_2 at location B in Figure 3. Photomicrograph shows steeply dipping mica defining S_1 that is crenulated by more gently dipping S_2.
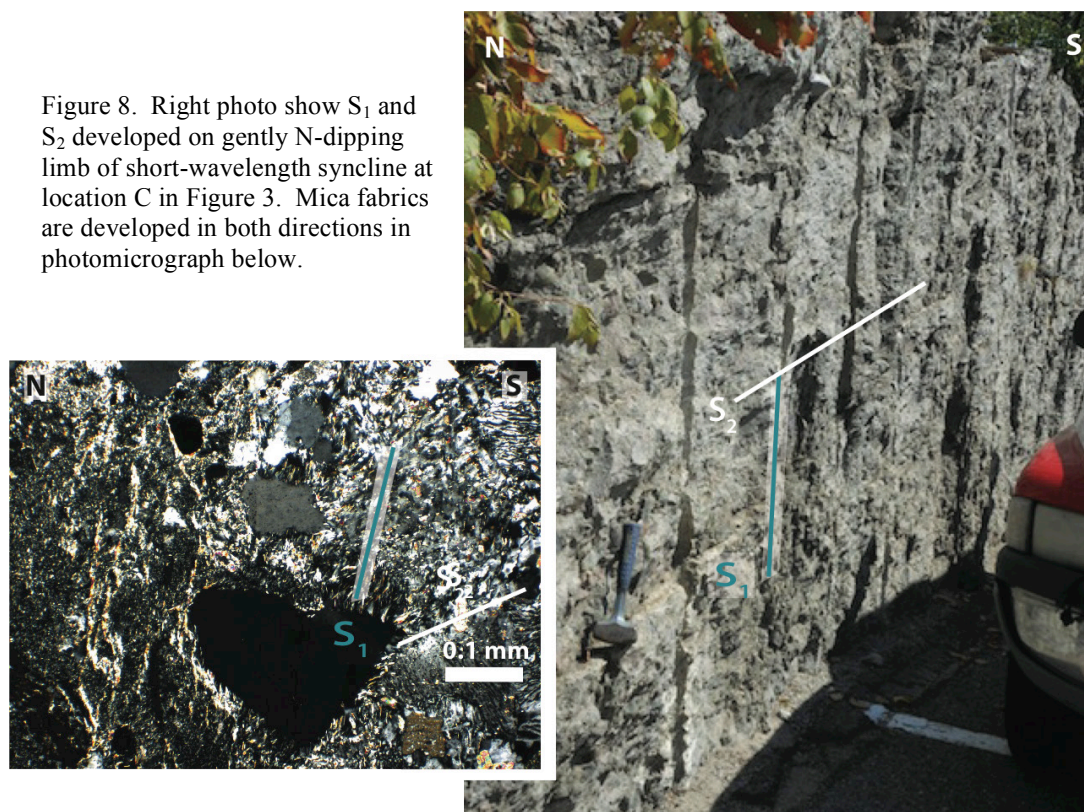
Figure 8. Right photo show S_1 and S_2 developed on gently N-dipping limb of short-wavelength syncline at location C in Figure 3. Mica fabrics are developed in both directions in photomicrograph below.
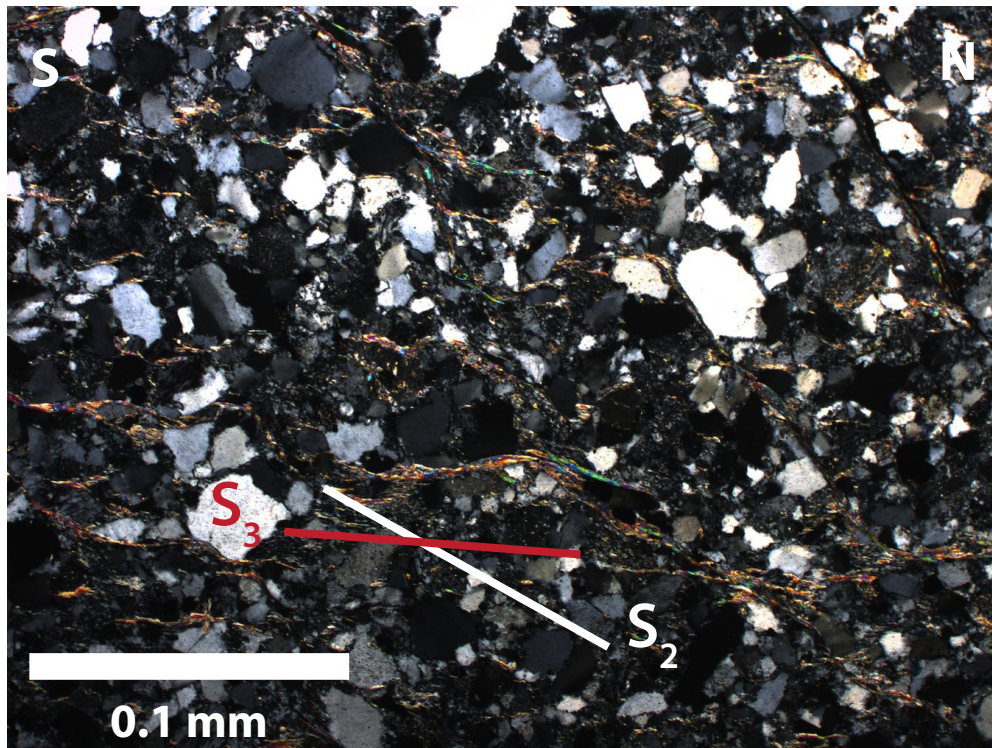
Figure 9. Photomicrograph of sample from location D in Figure 3 showing S_2 micas deflecting into horizontal trace S_3 in thin section cut parallel to strike of the latter. S_3 is not macroscopically visible in this location, so there is no S_3 symbol in Figure 3.

Typical outcrops contain only a single low-angle cleavage that has been assigned to S_2 in cases where strikes vary around EW or to S_3 if strikes are NW-to-NNW. However, examples with intermediate orientations are also common in the map area, suggesting that the collective range of directions might record a single progressive episode of deformation. In the absence of $^{40}Ar/^{39}Ar$ geochronology on the fabric micas, the age of S_2 and S_3 remain unclear. Thompson and Burks suggested links with either Avalonian or Alleghanian events, but subsequent documentation of dextral movements accompanying Late Devonian rifting in southeastern New England (Thompson and Hermes, 2003) raises another possibility.

ACKNOWLEDGEMENTS

REFERENCES CITED

Bailey, R.H., 1987, Stratigraphy of the Boston Bay Group, Boston area, Massachusetts *in* Roy, D.C., ed., Geological Society of America Centennial Field Guide— Northeastern Section: Boulder, CO, Decade of North American Geology Centennial Field Guide no. 5, p. 209-212.

Bailey, R.H., Skehan, J.W., Dreier, R.B., and Webster, M.J., 1989, Olistostromes of the Avalonian terrane of southeastern New England, *in* Horton, J.W., Jr. , and Rast, N., eds., Mélanges and olistostromes of the U.S. Appalachians: Geological Society of America Special Paper 228, p. 93-112.

Bascom, F., 1900,Volcanics of Neponset Valley, Mass: Geological Society of America Bulletin, v. 11, p.115-126.

Billings, M. P., 1929, Structural geology of the eastern part of the Boston Basin: American Journal of Science, series 5, v.18, p. 99-137.

Billings, M. P., 1976, Geology of the Boston Basin, *in* Lyons, P. C. and Brownlow, A. H., editors, Studies in New England Geology: Geological Society of America Memoir 146, p. 5-28.

Billings, M. P., and Tierney, F. L., 1964, Geology of the City Tunnel Extension: Journal of the Boston Society of Civil Engineers, v. 51, p. 111-154.

Burr, H. T., 1901, The structural relations of the amygdaloidal melaphyr in Brookline, Newton and Brighton, Mass.: Bulletin of the Museum of Comparative Zoology at Harvard College, v. 38, p. 53-69.

Cardoza, K. D., Hepburn, J. C., and Hon, R., 1990, Geochemical constraints on the paleotectonic settings of two late Proterozoic mafic volcanic suites, Boston-Avalon zone, eastern Massachusetts, *in* Socci, A. D., Skehan, J. W., and Smith G. W., editors, Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper 245, p. 113-131.

Chute, N.E., 1966, Geology of the Norwood quadrangle, Norfolk and Suffolk Counties, Massachusetts: U.S. Geological Survey Bulletin 1163-B, 78 p.

Clapp, C.H., 1921, Geology of the igneous rocks of Essex County, Massachusetts: U.S. Geological Survey Bulletin 704, 132 p.

Crosby, W. O., 1880, Contributions to the geology of eastern Massachusetts: Boston, MA, Boston Society of Natural History, 286 p. (accompanying 1:62,500 scale map dated 1877).

Dodge, W.W., 1875, Notes on the Geology of Eastern Massachusetts: Proceedings of the Boston Society of Natural History, v. 15, p. 388-419.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geological Survey Bulletin 597, 289 p. (accompanying 1:250,000 scale map dated 1916).

Goldsmith, R., 1991, Structural and Metamorphic History of eastern Massachusetts: U.S. Geological Survey Professional Paper 1366—H, p. H1-H63.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., 2012, The geologic time scale 2012: Oxford, U,K., Elsevier, 2 volumes, 1176 p.

Green, T.A., 2002, South Shore Stratigraphy of the Boston Basin, Insights from the Braintree-Weymouth Tunnel [unpublished honors thesis]: Wellesley, Massachusetts, Wellesley College, 68 p.

Hanson, L., and McFadden, R., 2014, Rocks and landforms of the Lynn Woods and Breakheart Reservation: What do they reveal and what still needs to be explored *in* Thompson, M.D., ed., Guidebook to field trips in southeastern New England (MA-NH-RI): Wellesley, MA, New England Intercollegiate Geologic Conference Annual Meeting 10th Guidebook, p. C2-1 to C2-24.

Hepburn, J.C., and Bailey, R.H., 1998, The Avalon and Nashoba terranes of eastern Massachusetts, *in* Murray, D.P., ed., Guidebook to field trips in Rhode island and adjacent regions of Connecticut and Massachusetts: Kingston, RI, New England Intercollegiate Geologic Conference Annual Meeting 90th Guidebook, p. C3-1-C3-24.

Hepburn, J. C., Hon, R., Dunning, G. R., Bailey, R. H., and Galli, K., 1993, The Avalon and Nashoba terranes (eastern margin of the Appalachian orogen in southeastern New England), *in* Cheney, J. T., and Hepburn, J. C., editors, Field Trip Guidebook for the Northeastern United States: Geological Society of America, Annual Meeting, Boston, v. 2, p. X1-X31.

Kaye, C. A., 1980, Bedrock geologic map of the Boston North, Boston South and Newton quadrangles: U.S. Geological Survey Map MF1241, scale 1:24,000.

Kaye, C. A., and Zartman, R. E., 1980, A Late Proterozoic Z to Cambrian age for the stratified rocks of the Boston Basin, Massachusetts, *in* Wones, D. R., editor, The Caledonides in the USA: Virginia Polytechnic Institute and State University Memoir 2, p. 257-261.

Krueger, H.W., 1964, The age of the diabase dike, Massachusetts: Cambridge, Massachusetts, Geochron Laboratories, Inc.: Geochronicle no. 3.

LaForge, L., 1903, Geology of Somerville, Massachusetts [Ph.D thesis]: Cambridge, Massachusetts, Harvard University, 2 vol., 121 p.

LaForge, L., 1932, Geology of the Boston area, Massachusetts: U.S Geological Survey Bulletin 839, 105 p.

Lenk, C., Strother, P. K., Kaye, C. A., and Barghoorn, E. S., 1982, Precambrian age of the Boston Basin: New evidence from microfossils: Science, v. 216, p. 619-620.

Richardson, S. M., 1977, Geology of the Dorchester Tunnel, Boston, Massachusetts: Journal of the Boston Society of Civil Engineers, v. 63, p. 247-269.

Ross, M.E., 1990, Mafic dikes of the Avalon Boston terrane, Massachusetts *in* Socci, A.D., Skehan, J.W., and Smth, G.W., eds., Geology of the composite Avalon terrane of southern New England: GSA Special Paper 245, p. 133-153.

Ross, M.E. and Bailey, R.H., 2001, Igneous and sedimentary petrology of East Point, Nahant, Massachusetts *in* West, D.P., and Bailley, R.H., eds., Guidebook for Geological Field Trips in New England: Geological Society of America, Annual Meeting, Boston, p. O1-O29.

Shaler, N.S., 1869, Relations of the rocks in the vicinity of Boston, Massachusetts: Proceedings of the Boston Society of Natural History, v. XIII, p. 172-177.

Thompson, M.D., 1985, Evidence for a late Precambrian caldera in Boston, Massachusetts: Geology, v. 13, p. 641-643.

Thompson, M. D., 1993, Late Proterozoic stratigraphy and structure in the Avalonian magmatic arc southwest of Boston, Massachusetts: American Journal of Science, v. 293, p. 725-743.

Thompson, M. D. and Bowring, S. A., 2000, Age of the Squantum "Tillite," Boston Basin, Massachusetts: U-Pb zircon constraints on terminal Neoproterozoic glaciation: American Journal of Science, v. 300, p. 630-655.

Thompson, M.D. and Burks, R.J., 1992, Shear band fabric in Late Proterozoic Roxbury Conglomerate, Boston, MA: Geological Society of America Abstracts with Programs, v. 24, no. 3, p. 81.

Thompson, M.D. and Hermes, O.D., 2003, Early rifting in the Narragansett Basin, Massachusetts—Rhode Island: Evidence from Late Devonian bimodal volcanic rocks: Journal of Geology, v. 111, p. 597-604.

Thompson, M. D., and Grunow, A. M., 2004, A Roxbury review: Conglomerates of greater Boston, Massachusetts, *in* Hanson, L. S., editor, Guidebook to field trips in Rhode Island and Massachusetts: Salem, MA, New England Intercollegiate Geologic Conference Annual Meeting 96th Guidebook, p. C2-1 - C2-21.

Thompson, M. D., Hermes, O. D., Bowring, S. A., Isachsen, C. E., Besancon, J. B., and Kelly, K. L., 1996, Tectonostratigraphic implications of Late Proterozoic U-Pb zircon ages in the Avalon Zone of southeastern New England, *in* Nance, R. D., and Thompson, M. D., editors, Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic: Geological Society of America Special Paper 304, p. 179-191.

Thompson, M. D., Grunow, A. M., and Ramezani, J., 2007, Late Neoproterozoic paleogeography of the Southeastern New England Avalon Zone: Insights from U-Pb geochronology and paleomagnetism: Geological Society of America Bulletin, v. 119, p. 681-696.

Thompson, M. D., Ramezani, J., Barr, S. M., and Hermes, O. D., 2010, High-precision U-Pb zircon dates for Ediacaran granitoid rocks in SE New England: Revised magmatic chronology and correlation with other Avalonian terranes, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodinia to Pangea: The lithotectonic record of the Appalachian Region: Geological Society of America Memoir 206, p. 231-250.

Thompson, M.D., Ramezani, J., and Crowley, J.R., 2014, U-Pb zircon geochronology of Roxbury Conglomerate, Boston Basin, Massachusetts: Tectono-stratigraphic

implications for Avalonia in and beyond New England: American Journal of Science, v. 314, p. 1009-1040.

Thompson, P., Kopera, J., Ross, M., Bailey, R., and Thompson, M.D., Bedrock Geology of Boston Harbor: Cambridge Argillite and associated diabase sills and debris flows *in* Thompson, M.D., editor, Guidebookk to field trips in Southeastern New England (MA-NH-RI): Wellesley, MA, New England Intercollegiate Geologic Conference Annual Meeting 106th Guidebook, p. C1-1 – C1-32.

Tierney, F. L., Billings, M. P., and Cassidy, M. M., 1968, Geology of the City Tunnel, greater Boston, and Massachusetts: Journal of the Boston Society of Civil Engineers, v. 55, p. 60-96.

Weston Geophysical Research, 1977 (Revision 1), Boston Edison Company, Pilgrim Unit 2, Geologic Investigations: Docket No. 50-471, Report BE-SG 7603, Appendix G-b, Radiometric Dating, p. 1-7.

Wones, D.R., and Goldsmith, R., 1991, Intrusive rocks of eastern Massachusetts: U.S. Geological Survey Professional Paper 1, p. I1-I61.

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, p. 522-539.

Zartman, R.E., Hurley, P.M., Krueger, H.W., and Giletti, B.J., 1970, A Permian disturbance of K-Ar radiometric ages in New England: Its occurrences, and causes: Geological Society of America Bulletin, v. 81, p. 3359-3374.

Zen, E-an, 1983, Bedrock geologic map of Massachusetts: United States Geological Survey, 3 sheets, scale 1:250,000.