The Bedrock Geology of the Middlesex Fells Reservation and Adjoining Northern Boston North 7.5-minute Quadrangle in Middlesex County, Massachusetts, USA

(see also http://sites.tufts.edu/fellsgeology)

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(This explanation is intended for poster display with the map. A more detailed explanation with hand sample and thin section images is given at the web address.)

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SCHOOL OF ARTS AND SCIENCES
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Base Map Information

The bedrock geology was mapped and compiled in GIS format since 2012 with continuing updates. Field data recorded with UTM coordinates (zone 19T) using the 1927 North American Datum. Base map is a hill-shaded relief map from 2015 MassGIS LiDAR raster data with 1-meter resolution produced with ESRI's Multi-Directional Hillshade Raster Function in ARCMAP 10.4 and then projected to 1927 NAD UTM zone 19T. Field mapping was done at 1.0-meter resolution. Transportation infrastructure outside the Middlesex Fells is from the MassGIS MassDOT shape file with roads and rail lines (1983 NAD; last updated 2013). Trails and roads in the Middlesex Fells are from the MassGIS DCR Roads and Trails shape file (1983 NAD; last updated 2014). Small corrections were made to roads and trails in the Fells to better correspond to the hillshade base where there was a clear mismatch. Water bodies and wetlands were traced as geologic units using the LiDAR generated hill shaded base map as a guide and 1927 NAD UTM zone 19T GPS coordinates measured in the field. The map area is within the 1956, 1971, and 2015 editions of the 7.5-minute Boston North, MA Quadrangle (1:24,000), 1985 Boston North, MA 7.5 x 15-minute Quadrangle (1:25,000 metric), and the 1909 Boston, MA 15-minute Quadrangle. The western edge of the map area includes a small portion of the 1956, 1971, and 2015 editions of the Lexington, MA 7.5-minute Quadrangle (1:24,000).

DESCRIPTION OF MAP UNITS

Igneous rock terminology follows the IUGS classification (Le Bas and Streckeisen, 1991). A separate document at http://sites.tufts.edu/fellsgeology gives a picture catalogue of volcanic rock features and textures in the Middlesex Fells, both in thin sections and hand samples, as well as definitions to show how volcanic rocks were interpreted and classified. The word "hornfels" is used in this document as a term for hard, brittle, generally fine-grained rock that breaks irregularly or with conchoidal fractures and is produced by contact metamorphism, loosely following the definition of Winter (2010). Here, hornfels includes fine-grained rocks produced by the contact metamorphism of fine quartzite, metasiltstone, mudstone, argillite, and basalt, which can be difficult to distinguish in the field. New formal rock names are used on this map to indicate a subdivision of previously named units and to reinterpret rock units and their correlations. Nomenclature for color of rock units is according to the Geological Society of America's Munsell Rock Color Chart as revised in 2009 and the Munsell Soil Color Chart, 1975 edition. Color is given only for fine-grained rocks or for individual mineral types. Unit symbols for Neoproterozoic rocks use the "Z" designation adopted by the U.S. Geological Survey. Full unit descriptions, point count data and plots, and a tabulation of radiometric ages are in the detailed map explanation at: http://sites.tufts.edu/fellsgeology

Quaternary and Artificial Deposits and Water Bodies

af **Artificial fill -** Land formed by artificial filling or construction by humans. Only shown where it prevents interpretation of the bedrock geology.

w **Water bodies –** ponds, lakes, and rivers. Water bodies were traced as units using the LiDAR generated hill-shaded base map as a guide and 1927 NAD UTM zone 19T GPS coordinates measured in the field. In some places the map shows shoreline topography in areas mapped as open water because the LiDAR data were obtained when reservoirs had generally low levels.

sw **Swamps and other wetlands** – areas covered by wetlands including permanent swamps and large vernal pools.

q **Quaternary deposits** – glacial, stream, mass movement, and other surficial deposits, where they are thick enough to prevent interpretation of the bedrock geology. Includes areas of till cover and end moraines near South Reservoir, at Wrights Pond, and south of Ravine Road.

▤ **Areas of bedrock exposure** – Screen overlay pattern shown only outside the Middlesex Fells.

Intrusive Igneous Rock Units Occurring as Dikes (Unnamed)

d **Dolerite and basalt dikes (Neoproterozoic through Mesozoic?)** – Grayish-black to dark gray (N 2-3) and greenish-black to greenish-gray (5G 2-6/1), aphanitic to fine-grained phaneritic, mafic dikes weathering to a rusty brown to gray color. Includes lamprophyric dikes. Some dikes have vesicles or amygdules with epidote, calcite, quartz, and prehnite mineralization. Dikes that could not be fully traced have terminations marked with (?). Rare dikes known to terminate with blunt ends are marked with (e). Chemistry, field relationships, and ages of the dikes are discussed by Ross (1981, 1984, 1990, 1992, 2010, 2020, 2021). The Medford Dike cuts across all dolerite dikes that it comes in contact making the likely age of dolerite dikes pre-Mesozoic. Dolerite dikes are cut by major E-W and N-S trending faults. Crosscutting of dikes shows that an E-W trending set of dolerite dikes that intruded a major E-W trending fault set is the youngest major dike set. Mapped where dikes exceed a width of 1.0 m. Thinner dikes that are not as traceable are shown with a separate line symbol. Radiometric ages for dolerite dikes are: 573 ± 5 Ma (^{40}Ar/^{39}Ar, whole rock), 353 ± 4 Ma (^{40}Ar/^{39}Ar, whole rock), 290 ± 15 Ma (K/Ar whole rock), 226 ± 3 Ma (^{40}Ar/^{39}Ar, whole rock) from Ross (2001) and Zartman et al. (1970). Ages are of limited accuracy because of later thermal events.

dp **Porphyritic dolerite and basalt dikes (Neoproterozoic through Paleozoic?) –** Grayish-black to dark gray (N 2-3) and greenish-black (5G 2/1), aphanitic to fine-grained phaneritic, porphyritic dolerite and basalt dikes. Weather to a rusty brown or gray color. Plagioclase phenocrysts are up to10 cm long and can occur as single tabular crystals or cumulophyric clusters. Includes occasional lamprophyric dikes with altered hornblende and biotite phenocrysts. Porphyritic dolerite dikes may be related to the non-porphyritic dolerite dikes and likely have similar ages. Plagioclase in the porphyritic dikes tends to be more altered. Some porphyritic dolerite dikes on the west shore of Middle Reservoir also have large black, basalt xenoliths with densely packed coarse plagioclase phenocrysts. Amygdules are common. Mapped only where dikes exceed a width of 1.0 m. Thinner dikes that are not as traceable are shown with a separate line symbol.

gb **Gabbro dikes (Neoproterozoic through Paleozoic?)** – Dark greenish-gray (5G 4/1), medium to coarse-grained, phaneritic, equigranular gabbro dikes. Composition like dolerite dikes (d) but coarser. Heavily altered with plagioclase replaced by sericite and pyroxene (augite) altered to amphibole (actinolite) and chlorite. Crosscut by dikes trending NW-SE that pre-date the Medford Dike (TRm). A whole rock ^{40}Ar/^{39}Ar age by Ross (2001) is 403 ± 3 Ma.

ad **Highly altered mafic dikes (Neoproterozoic through early Paleozoic?)** – Green (5G 4-2/4-6) heavily veined dikes of altered gabbro, dolerite, and basalt. Included in this unit are highly altered (oxidized), dark reddish-gray (5R 2/2 to 4-2/1), hematite-rich dolerite dikes. All dolerite dikes are altered to some degree, but this unit identifies extreme cases. Alteration includes almost complete replacement of feldspar by very fine sericite and epidote and replacement of pyroxene by amphibole (uralite or actinolite) and chlorite. Older than dolerite dikes (d) in the same area because they are crosscut by the less altered dikes (d). They may show the same deformation (fractures and foliation) as the rock units they intrude and can have a highly irregular trace.

ap **Gray Porphyritic andesite to dacite dikes (Neoproterozoic?) –** Greenish-gray (5GY 5/1) to light to medium gray (N 5-7/0) weathering and dark to medium gray (N 2-3/0) when non-weathered, porphyritic, sometimes cumulophyric, aphanitic andesite to dacite dikes. Phenocrysts are plagioclase and much lesser euhedral hornblende. Dikes can have abundant quartzite, argillite, basalt, and volcanic xenoliths and very fine quartz xenocrysts as well as possible andesitic autoliths from dike margins. Coarse quartz and feldspar xenocrysts are absent. On east side of Spot Pond near the Stone Zoo dikes may be offshoots of the Stoneham Granodiorite (Zst) underlying the northern end of the pond. May have more than one age. Mapped only where dikes exceed a width of 1.0 m. Thinner dikes that are not as traceable are shown with a separate line symbol.

fp **Pink porphyritic dacite to rhyolite dikes (Neoproterozoic?) –** Reddish- to orangish-gray (5R 3/2 to 2.5YR 4/2) weathering, pinkish- to tannish-gray and light gray (7.5YR 7/2 to 5Y 7/1) non-weathered, dacite and rhyolite dikes that are generally heavily fractured. Phenocrysts are plagioclase that are usually cumulophyric. Possibly more than one age. West of Rt. 93 at Wenepoykin Hill a reddish variety crosscuts the Spot Pond Granodiorite (Zsg) and is truncated by the Rams Head Porphyry (Zrhp). Mostly north-south trending lenticular reddish-gray rhyolitic dikes also occur in the Winchester Granite (Zwg). Mapped with this unit are elongate lenticular rhyolite dikes in the Nanepashemet Formation that appear to be associated with the intruding Winchester Granite. Mapped only where dikes exceed a width of 1.0 m. Thinner dikes are shown with a separate symbol.

fq **Dacite to rhyolite dikes with coarse quartz and feldspar xenocrysts (Neoproterozoic to early Paleozoic?)** – White (10YR 8/1) weathering, light gray (10YR 7/1) rhyolite to dacite dikes with medium to coarse (up to 1.5 cm), rounded and embayed feldspar and quartz xenocrysts and multi-grain granitic xenoliths. The xenocrysts are derived from coarse granitic units. Color can vary from dark to light gray or tan (N 2-3/0 and 7.5YR 7/2 to 5Y 8/1) within one dike due to differences in grain size and assimilation of host units. Unit can weather to a chalky surface with protruding xenocrysts. Only found on Whip Hill, in the MWRA excavation south of Ravine Road, at the east shore of the peninsula in the Fells Reservoir and extending to east of the Fellsway East (same as MWRA site), and in the Winchester Granite (Zwg) near South Border Road. On Whip Hill, the dike has pinched and necked ends and contains cubic fluorite phenocrysts coated with hematite.

Named Rock Units North of the Walden Pond Fault of Kaye (1980) – All descriptions modified from Castle and others (2005)

Dp **Peabody Granite (Late and Middle Devonian) –** Medium to coarse-grained, orange syenogranite composed chiefly of microperthite, quartz, hornblende and plagioclase. In the Boston North Quadrangle occurs as a large intrusion and as small, roughly north to northeast oriented pods intruding the Diorite at Lake Quannapowitt and vicinity (Castle and others, 2005) described below. Biotite occurs in peripheral rocks. Included with "alkalic" intrusive series of Toulmin (1964). Age about 360 ± 24 (Rb-Sr) to 395 ± 20 (U-Pb).

Diorite at Lake Quannapowitt and vicinity (Silurian or Ordovician) – Age about 444 ± 3 (U-Pb). Two facies from Castle and others (2005) occur in the Boston North Quadrangle.

SOqd **Hornblende diorite facies** - Chiefly massive, medium grained, gray to black, alkali-rich diorite. Composed mainly of plagioclase and hornblende along with variable but generally small amounts of quartz and biotite. Alkali feldspar occurs in small bands and pods. Accessory minerals are chiefly magnetite and sphene.

SOqt **Biotite-hornblende tonalite facies** - Chiefly massive, medium-grained gray, alkali-rich tonalite. Composed largely of plagioclase, hornblende, quartz and biotite. Contains abundant epidote.

Waltham Tectonic Melange (Late Proterozoic to Silurian?) – Description modified from Castle and others (2005) as modified from LaForge (1932).

Zwba **Amphibolite facies of B member** - Chiefly fine-grained, distinctly foliated and locally thinly layered, gray to black amphibolite and plagioclase amphibolite. Composed mainly of hornblende and plagioclase with lesser amounts of magnetite, chlorite and calcite. Occasional bands of sheared quartzite. Epidote conspicuous locally. Mapped only where amphibolite or plagioclase amphibolite is the predominant rock type.

Named Rock Units South of the Walden Pond Fault of Kaye (1980)

TRm **Medford Dike (middle Triassic) –** Brownish- to olive-black (5YR-Y 2/1), medium to coarse-grained gabbro. This is the Medford Diabase or Medford Dike of Wilson (1901) and LaForge (1932). Mostly composed of plagioclase, augite partly altered to actinolite, biotite, and accessory magnetite and possibly ilmenite. Unit contains abundant fine apatite needles and sparse interstitial calcite. Dike margins have olivine, and the west margin has kaersutite (Ross, 2020). Deeply weathered along fractures to depths of more than 10 m in quarry walls and reduced to grus and corestones that show spheroidal weathering in surface exposures. The dike extends north-northeast across Rt. 93 where it pinches out just west of Wrights Pond with a smaller branch of the dike further north along the east side of Rt. 93. A small branch also occurs on the west side of Lawrence Memorial Hospital. The unit crosscuts all known adjacent dolerite dikes except a north-south trending dike reported by Wilson (1901) in Medford. Chemistry and field relationships to other dikes are discussed by Ross (1990, 1992, 2020, 2021). The Medford Dike has a new CA-ID-TIMS U-Pb zircon age (6 zircons) on the west side of Pine Hill of 238.07 ± 0.09 Ma, which places it in the Central New England Magmatic Province.

Zca **Cambridge Argillite (Neoproterozoic)** – Dark to medium gray argillite and fine sandstone. Unit can be sulfidic and often has iron oxide precipitation along fractures. Baked in many places adjacent to diorite dikes, especially around Tufts University where surface exposures are most abundant. At Tufts University contains lens of coarse sandstone and reddish-purple argillite, the so-called Tufts Quartzite. No exposures are known north of the Northern Border Fault.

Zrx **Roxbury Conglomerate? (Neoproterozoic)** – Gray to purplish-gray, moderately well-sorted, polymictic, mostly clast-supported conglomerate; also known as puddingstone in Boston) and light tannish-gray to faintly reddish-gray fine to coarse sandstone. Sandstone appears to dominate and is well cemented. Pebbles in the conglomerate are various volcanic lithologies from the Wakefield Formation of the Lynn Volcanic Complex, granodiorite, basalt, and quartzite likely from the Westboro Fm. Unit appears to unconformably overlie fine volcanic units (vitric tuff) of the Wakefield Formation of the Lynn Volcanic Complex (Zlvv) and the Lawrence Woods Granophyre (Zlwg). In places the conglomerate beds have a poorly developed cleavage and pebbles are fractured because of local faulting. Units in Medford were first recognized by Kaye (1980) and appear to be an outlier of the Roxbury Conglomerate at the northern edge of the Boston Basin like Roxbury units in the Hammond Pond Park area of Newton.

Subvolcanic Plutonic Rock Units Associated with the Lynn Volcanic Complex

Zst **Stoneham Granodiorite (Neoproterozoic)** – Greenish-gray (5B-GB 5-6/1) mostly granodiorite to tonalite in the northern Fells and further north and northwest. Has appearance in the field of quartz diorite or diorite because quartz and alkali feldspar are often fine-grained and inconspicuous, and the rock can have a high mafic content. Usually porphyritic in chill zones, but less so away from these areas, and has tabular euhedral plagioclase with varying alteration of interiors to sericite and epidote. Plagioclase is sometimes enclosed in fresher more alkaline rims forming zonation. Typically, felsic minerals are 15-30% quartz grains, which are smaller than plagioclase and interstitial, and mostly less than 15% alkali feldspar that may be heavily altered and difficult to distinguish from altered plagioclase without potassium staining. Mafic minerals are 15-25% of the whole rock and are biotite and hornblende that are mostly to partly altered to chlorite, epidote, and opaque oxides. Contains abundant inclusions of quartzite and argillite from the Westboro Formation (Zvwq) and basalt from the Nanepashemet Formation (Znpm), and to the north, basalt and basaltic tuff from the Wakefield Formation of the Lynn Volcanic Complex (Zlbf). A chill zone contact with the rhyolite flow facies of the Wakefield Formation (Zlvf) occurs at the north end of Spot Pond and a chill zone with crystal tuff in the Wakefield (Zlvx) occurs at the northeast corner of Spot Pond. The Wanapanaquin Porphyry (Zwap) may be an extension of this unit into the Nanepashemet Formation (Znpm). Interpreted by Kaye (1980) and LaForge (1932) to be correlative to the Paleozoic Newburyport Quartz Diorite of Emerson (1917). Bell (1948) classified this unit as the "Newburyport Quartz Diorite" phase of the Dedham Granodiorite. This unit was also lumped with the Dedham Granodiorite (Spot Pond Granodiorite and Winchester Granite of this map) as a dioritic phase (Smith and Hon, 1984, Smith, 1985) but it is texturally distinct from these units. A U-Pb age (CA-ID-TIMS, 6 zircons) from along Pond Street northwest of Spot Pond is 595.14 +/- 0.17 Ma that separates it from the Dedham by about 14 Myr and eliminates Paleozoic correlations.

Zwap **Wanapanaquin Hill Porphyry (Neoproterozoic)** – Pinkish-tan to gray aphanitic porphyry at the south end of Wanapanaquin Hill and along the east shore of Middle Reservoir in Winchester. Phenocrysts of well-formed tabular plagioclase in a much finer matrix of quartz, altered mafic minerals, and very minor alkali feldspar. The unit is no more than 100 m across and occurs entirely within the Nanepashemet Formation (Znpm). The relationship of this unit to surrounding plutonic bodies remains uncertain, but it is like the porphyritic chill zone of the Stoneham Granodiorite (Zst) with a similar mineralogy, and it appears to be a branch of this unit. First recognized by Hampton (2017).

Zdg **Diorite-Gabbro (Neoproterozoic)** – Previously unrecognized greenish-gray (5G 4/1) diorite/gabbro in the southwestern Fells. About 40-50% zoned euhedral plagioclase with the remainder of the rock hornblende that is partly altered to chlorite and opaque mineral grains. Plagioclase is partly altered to sericite. Skeletal titanomagnetite and possibly ilmenite, and sparse sphene (titanite) occur as accessory minerals. Has a single occurrence as a lenticular outcrop (150 x 30 m) intruding the Westboro Formation (Zvwq) on its north side and bounded to the south by an east-west trending fault west of South Reservoir. The unit contains Westboro xenoliths. Except for rare isolated grains of interstitial quartz that may be recrystallized xenocrysts, quartz and alkali feldspar are absent, making the unit difficult to associate with any other intrusive body in the Fells. A new U-Pb zircon age for the unit is 596.02 ± 0.32 Ma (5 zircons, CA-ID-TIMS).

Zlwg **Lawrence Woods Granophyre (Neoproterozoic)** – Porphyritic granophyre in the southern Fells and extending eastward. Pale red to pale reddish-purple (5R 6/2 to 5RP 6/2) and pale brown (10YR 6/3) to faintly brownish- to reddish-gray (5-10YR 4-6/1) syenogranite to monzogranite granophyre with phenocrysts of plagioclase and needle-like hornblende. Its granophyric and micrographic alkali matrix gives the unit its reddish to pinkish color and the unit heavily stains for potassium. Chill zones are very fine-grained, porphyritic, and distinctly reddish-orange to pink along contacts with the Lynn Volcanic Complex (Zlvc and Zlvx), Spot Pond Granodiorite (Zsg), and Rams Head Porphyry (Zrhp). Unit gets progressively coarser to the south away from contacts with other units. Contains xenoliths from the Wakefield Formation (Zlvx) of the Lynn Volcanic Complex on the west side of Middle Hill and from the Rams Head Porphyry in northeast Lawrence Woods. The granophyre is clearly plutonic in thin section and is a subvolcanic body related to the Lynn Volcanic Complex. Mapped as part of the Dedham Granodiorite by LaForge (1932) and Kaye (1980) with the finer chilled margin of the unit lumped by Kaye (1980) with the Boojum Rock Tuff (Zbrc) of the Lynn Volcanic Complex of this map. Bell (1948) classified this unit as the "porphyritic micrographic granodiorite" and "micrographic granodiorite" phases of the Dedham Granodiorite. This unit was also lumped with the Dedham Granodiorite as a granophyric marginal phase (Smith and Hon, 1984; Hepburn and others, 1993). However, the contact with the gradational chilled margin is sharp and coarsens away from the Spot Pond Granodiorite and Lynn Volcanic Complex. U-Pb zircon ages (CA-ID-TIMS) reveal a range of ages from about 596.3-598.3 Ma and there are inherited grains and also possible prolonged crystallization. The youngest zircon ages (3 zircons) at Elm Street in Medford give a mean of 596.77 ± 0.54 Ma, while three older zircons from this site average 598.13 ± 0.27 Ma. Along Rt. 93 at Pine Hill the 3 youngest zircons are 596.50 ± 0.53 Ma while other zircons are outliers at 610 Ma or greater. The mean values suggest the unit is older than the Rams Head Porphyry contrary to field relationships but interpretation of the age of the Lawrence Woods is complicated by possible prolonged crystallization.

Zrhp **Rams Head Porphyry (Neoproterozoic)** – Greenish-gray to gray (5G 4-5/1) porphyritic tonalite to quartz diorite in the southern Fells. Looks like diorite in the field because: 1) quartz and alkali feldspar form fine interstitial pockets lying inconspicuously between much larger euhedral zoned plagioclase phenocrysts that dominate the rock, and 2) mafic mineral content is relatively high. Typically, the felsic minerals are about 10-25% quartz and <10% alkali feldspar. Mafic mineral content is typically 15-25% of the whole rock but can be higher and is mostly hornblende with lesser biotite that are usually altered to chlorite, calcite, epidote and opaque oxides. Accessory minerals are interstitial sphene (titanite) and occasional rutile. Southeast of South Reservoir and near Medford High School are dismembered rafts of the Spot Pond Granodiorite (Zsg) that may form a roof pendant. In contact with the Spot Pond Granodiorite the porphyry has chilled margins and contacts that show assimilation and inclusions of granodiorite. This unit intrudes the Westboro Formation (Zvwq) near Rams Head Hill in northern Lawrence Woods and on Silver Mine Hill. The Lawrence Woods Granophyre (Zlwg) has a chill zone along its contact with the Rams Head at the entrance to Medford High School and a Rams Head inclusion in Lawrence Woods. The Rams Head crosscuts and terminates reddish-colored rhyolite dikes (fp) that pass through the Spot Pond Granodiorite at Wenepoykin Hill. Southeast of South Reservoir LaForge (1932) did not distinguish the porphyry from the much coarser and quartz-rich Spot Pond Granodiorite of this study. Kaye (1980) distinguished the porphyry from the Spot Pond and classifies the unit as "tonalite-granodiorite", but the unit generally has too little alkali feldspar to be granodiorite. Kaye includes the unit with the Stoneham (cont.) Granodiorite (Zst) of this map in the northern Middlesex Fells but the Stoneham intrudes volcanic units younger than the Rams Head and has a younger radiometric age. The Stoneham and Rams Head are not physically connected at the surface and the Stoneham is only faintly porphyritic except in its contact areas. Kaye (1980) correlates the Rams Head with the Newburyport Quartz Diorite of Emerson (1917) and LaForge (1932), now the Paleozoic Newburyport Complex (Zen and others, 1983; Wones and Goldsmith, 1991). A U-Pb zircon age (6 crystals, CA-ID-TIMS) for the Rams Head on Sheep Pasture Hill is 596.14 ± 0.21 Ma which disproves the Newburyport correlation and eliminates the Rams Head as part of the Dedham Complex.

The Lynn Volcanic Complex – The Lynn Volcanic Complex, originally called the "Lynn volcanics" by Clapp (1921), is here given group status and is subdivided into two formations that are then classified into facies. The two formations are the older Boojum Rock Tuff and the younger Wakefield Formation, which are separated by an unconformity. Future mapping may allow the separation of the Wakefield into separately named formations or members, but a subdivision at this point is premature before new areas are mapped in Melrose, Wakefield, and Saugus. For an explanation of the subdivision of volcanic rocks in the area see the full explanation on the Fells Geology web site http://sites.tufts.edu/fellsgeology/. This includes the details of the distinction between the basaltic units of the Nanepashemet and Wakefield Formations as well as details of the separation of the Lynn Volcanic Complex into the formations discussed here.

Wakefield Formation (Neoproterozoic) – The Wakefield Formation is subdivided into two groups of facies based on composition and volcanic rock types as listed below. The Wakefield has not yet been further divided into lithostratigraphic units of formation or member status. It has become clear that there are multiple areas of the same facies and some repeated sequences. Therefore, it is anticipated that the Wakefield might eventually be further subdivided when a complete mapping of the unit continues further east in Saugus and Lynn and the continuity of units can be demonstrated between fault blocks.

Zlbf **Basaltic flow/breccia/tuff facies** – Dark greenish-gray (5BG-5G 3-4/1) to dark reddish-gray (10R 3/1) altered aphanitic to very fine phaneritic and occasionally amygdaloidal basalt and basaltic breccia and tuff in the northern Fells and northward into Stoneham and Wakefield. Breccias may be autobrecciated flows or a part of tuff units with monomictic clast types. Quartz, calcite, epidote, and iron oxide mineral precipitates occur in amygdules and veins. The basalt units are sometimes interlayered with laminated to thin bedded, dark bluish- to greenish-gray (5BG-5G 3-4/1) highly altered basaltic argillite to fine sandstone. The sedimentary units are often faulted, contorted and heavily altered with epidote and chlorite. At least one argillaceous unit at the base of a basalt flow is calcareous and displays alveolar weathering that mimics vesicles. So far, pillows have been identified in this unit at Stoneham High School (Smith and Hon, 1984) and on High Rock in Wakefield. All the basaltic units described here are mapped as a single facies because they are co-mingled, and because of alteration and very fine grain sizes they cannot be consistently distinguished in field exposures without thin section analysis.

Zlbc **Basaltic volcaniclastic facies** – Greenish- to bluish-gray (5GY 6/1-5B 5/1), gray weathering (5Y 6/1), polymictic conglomerate and breccia dominated by clasts of mafic volcanic rocks including very fine basaltic lava, porphyritic basalt, diabase and gabbro, amygdaloidal basalt, basaltic breccia, and basaltic tuff with granule size angular black basalt fragments. Also includes rare clasts of felsic volcanic rock types and rarer quartzite. Clasts are very rounded to subangular and matrix- to clast-supported. The matrix ranges from muddy sand to mudstone. The conglomerate has subtle bedding. Only one outcrop is known which extends from the Greenwood School northward east of Main Street in Wakefield.

Zlvc **Felsic volcaniclastic facies** - Felsic volcaniclastic conglomerate to breccia in several different places across the Middlesex Fells and further north. Felsic volcaniclastic rocks are distinguished from other clastic facies by having: 1) many felsic volcanic as well as other clast types (polymictic), 2) a range of particle shapes from well rounded to angular, and 3) matrices that are reworked sand, muddy sand and mudstone that is not dominated by devitrified glass particles and crystals as in lithic tuff units. A green, rusty weathering, poorly sorted sandstone is a common matrix sediment. This facies resembles sections of the Vinegar Hill Member of the Lynn Volcanic Complex identified further east by Smith and Hon (1984) and Smith (1985). Volcaniclastic conglomerate and breccia units usually form the base of the Wakefield Formation but can occur higher in the Wakefield.

Zbjp **Rhyolite porphyry facies** – Rhyolite porphyry, up to 100 m wide and trending north-northeast to south-southwest, that cuts across the Boojum Rock Tuff (Zbrc). Traced from the Boojum Rock area northward to the northeast peninsula of the Fells Reservoir where it terminates at a fault. On Boojum Rock it could not be found south of a dolerite dike that intruded an east-west trending fault. The unit has a distinct reddish- to pinkish-gray color (2.5YR6/6 to 5YR 7/2) when weathered and is medium to dark reddish-gray (2.5YR 4-5/2) when non-weathered. It has euhedral cumulophyric plagioclase phenocrysts and rounded and embayed quartz crystals. This unit is distinct from the Boojum Rock Tuff because it has: 1) large almost completely euhedral, cumulophyric plagioclase that is fresher and larger than in the Boojum Rock, where crystals are mostly broken and never cumulophyric; 2) areas of flow layering along its contact with the same color characteristics and plagioclase crystals as in the dominant more massive porphyry at the center of the unit; and 3) abundant rounded and embayed quartz crystals that do not occur in the Boojum Rock Tuff. Along the unit's contact is occasional pinkish-gray to light gray (7.5YR 7/0-8/2) weathering and gray to faintly greenish-gray (7.5YR 5/0 to 5BG 6/1), volcaniclastic sandstone or lithic tuff that has red to pink and gray rounded volcanic lithic fragments. Based on its map geometry and composition, this unit is tentatively interpreted to be a fissure or vent invaded by the porphyry. Similarities with the Lawrence Woods Granophyre (Zlwg) suggest that it is an offshoot of the granophyre, but no physical connection has been found.

Zlvv **Vitric tuff facies** - Light bluish- to pinkish-gray (5B 7/1 to5 YR 8/1), fine vitric tuff with occasional faint layering and a chert-like appearance in outcrops. Weathers to a white to light gray color. This unit grades between almost pure fine ash tuff and fine ash tuff with sparse crystals and lithic fragments. In the Pine Hill area, rocks of this lithology are very small zones within crystal tuff. Along faults this unit deforms with a peculiar wavy, lenticular foliation. Glacial erratics of this facies are found south of Crystal Lake in Wakefield and are from vitric tuff beneath the lake.

Zlvx **Crystal tuff facies** – The dominant facies of the Wakefield Formation. Dusky blue to grayish-purple (5PB 4/2-6/2 to 5P 2-4/2) and dark bluish-gray (5B 4/1) to gray (N4/1) welded rhyolitic crystal tuff with varying banding and sizes and abundances of crystals in the southern Fells where it is sometimes inter-layered with thin vitric and lithic tuff layers. Crystal tuff across the northern Fells from Straw Point to Melrose varies from west to east from light gray to gray (10YR 5-7/1), welded to non-welded, crystal tuff with scattered lithic fragments to dark gray (7.5YR 4/0) and pinkish-gray (7.5YR 6/2) to gray (7.5YR 6/0), welded to non-welded crystal tuff. A wide area of crystal tuff also covers much of Wakefield and Saugus and is relatively uniform being welded and very crystal-rich with a dusky red 10R 2.5-3/1-3 to medium to dark gray (N4-5) matrix color that weathers to a lighter pale red (10R 6-5/1-2) to gray (N6). In all these areas outlines of collapsed glass shards and flattened pumice, and deeply embayed quartz crystals are common. Plagioclase dominates the crystals with minor alkali feldspar and altered biotite and hornblende. Crystal tuff in the Wakefield Formation was not accurately separated by LaForge (1932) and Kaye (1980) from the Boojum Rock Tuff (Zbrc) or the Lawrence Woods Granophyre (Zlwg) in the southern Fells. Scattered lithic fragments are mostly volcanic but include quartzite, multi-grain granitic fragments, and scarcer basalt.

Zlvl **Lithic tuff facies** - The lithic tuff facies occurs near Boojum Rock, at Wrights Pond in Medford, in Pine Banks Park in Malden, and in what so far appears to be a single continuous lithic tuff layer in Wakefield and Saugus. Lithic tuff layers near Boojum Rock are too thin to map separately and are mapped as part of the felsic clastic (Zlvc), crystal tuff (Zlvx) and vitric tuff (Zlvv) facies within which they occur as discontinuous layers. The lithic tuff facies in Wakefield is a thick layer within a very thick crystal tuff (Zlvx) sequence and is bounded to the south by a basalt flow (Zlbf). This lithic tuff unit is medium to dark gray (N5-4) to weak red (10R 4/1), easily weathers to light gray (N7) to red colors (10R 5/3) and has a crystal tuff matrix. Matrix crystals are mostly plagioclase with secondary quartz. Fragments are dominantly felsic tuff and flow fragments that are mostly dark gray to black (Zlvl1-2 and 5) and can weather to a red color. Lithic tuff is distinguished from felsic volcaniclastic units by having more angular and fewer fragment types that are almost entirely felsic volcanic fragments. Lithic tuff units have a matrix of crystal tuff with no evidence of sorting. Included with lithic tuff may be rocks formed as debris flows or lahars, i.e., reworking of volcanic materials and therefore technically volcaniclastic, that are rich in angular fragments but with a few subangular to subrounded accidental clasts. Units with large clasts appear to form the base of lithic tuff units mapped here. Accidental quartzite, basalt, and granite fragments are not uncommon. Flattened and oriented pumice fragments are common, and they are well aligned in some samples but hard to see in outcrops.

Zlvf **Rhyolite flow facies** – At Straw Point on Spot Pond, Middle Reservoir and Wamoset Hill the base of the Wakefield Formation is banded rhyolite flows. At Straw Point these units are light gray (10YR 7/1) to gray (10YR 6/1), recrystallized, faintly-banded rhyolite with scattered lithic inclusions and at Middle Reservoir is very dark grayish-brown to reddish-brown (5YR 5-4/4-6) banded rhyolite both interpreted to be flows with euhedral cumulophyric plagioclase. Faint layering on the east side of Straw Point defines the unit's gentle dip, which parallels overlying basaltic units (Zlbf). At Straw Point the unit has a micropoikilitic ("snowflake") texture due to devitrification and recrystallization, possibly related to contact metamorphism adjacent to the Stoneham Granodiorite (Zst). This texture gives hand samples and weathered surfaces on outcrops a spotted appearance. A U-Pb zircon age at Middle Reservoir is: 594.70 ± 0.32 Ma (zircon CA-ID-TIMS, ± 2σ F. MacDonald, pers. comm.). A rhyolite flow at the north end of Spot Pond has an age of 595.27 ± 0.34 Ma (4 zircons, CA-ID-TIMS).

On Wamoset Hill and extending eastward through Whip Hill Park and into Melrose are very dark gray (7.5R 3/0), banded, rhyolitic lava flows with cumulophyric feldspar. The top of a banded flow unit in Whip Hill Park has macro-spheroidal texture (relict lythophysae). The basal contact of a flow on Wamoset Hill is an unconformity that truncates metamorphic foliation in the Westboro Formation (Zvwq). The flow unit lacks the Westboro's deformation and metamorphism. Above the flow unit is crystal tuff with flattened pumice and flow fragments. A U-Pb zircon age in the flow unit at Wamoset Hill is 595.82 ± 0.23 Ma (5 zircons, CA-ID-TIMS, ± 2σ; F. MacDonald, pers. comm.). East of Whip Hill in Sewall Woods there are at least two similar flow units with abundant outcrops of banded flows with cumulophyric plagioclase. The flow units are separated by crystal tuff units (Zlvx).

Boojum Rock Tuff of the Lynn Volcanic Complex (Neoproterozoic) – Massive, dacitic to andesitic, very crystal-rich, tuff in the southeastern Fells and extending eastward into Malden and Melrose where it is redder and coarser (Pine Banks Park and Waitts Mount). Three facies of the unit are recognized in the Fells that form an eastward-dipping regional structure with younger parts of the unit to the east. The unit is dominated by crystal tuff but contains many volcanic lithic fragments as well as quartzite and argillite lithic fragments from the Westboro Formation (Zvwq and Zwp). This unit, unlike younger volcanic units in the Wakefield Formation, has only very sparse fine, broken quartz fragments that are xenocrysts derived from quartzite in the Westboro Formation. They are not first-generation crystals, or the embayed and rounded quartz xenocrysts derived from coarse granitic rocks as are found in the younger parts of the Lynn Volcanic Complex. The Boojum Rock may be co-magmatic with the Rams Head Porphyry (Zrhp). The tuff unconformably overlies the Spot Pond Granodiorite near Hemlock Pool and the Westboro Formation at Pine Banks Park. The Boojum Rock is heavily fractured with well-oriented joint sets and, in places, has a closely-spaced wavy cleavage with slickensides that are mineralized by hematite. Correlated by Kaye (1980) to the Lynn Volcanic Complex of Clapp (1921) and LaForge (1932) but was not separated from other parts of the Lynn.

Zbrv **Vitric (fine-crystal) tuff facies –** Light bluish- to pinkish-gray (5B 7/11 to5 YR 8/1), vitric to very fine crystal tuff. Weathers to very pale orange to very light gray to almost white (10 YR 8/2 – N8) and in places has faint steeply eastward-dipping layers. Can have a chert-like appearance and crystals greater than 1 mm are sparse. This unit also has more fine broken quartz fragments than the other facies. The unit occurs in a small area at the southeastern border of the Fells in Malden and Melrose where it is truncated by a fault zone on its eastern side.

Zone with flattened glass (pumice?) fragments – Recrystallized flattened glass/pumice fragments at the top (east side) of the lithic crystal tuff facies (Zbrl). Fragments are up to 10 cm long, but usually 2-4 cm, weather to a dark color, and are recessed from the rock surface due to weathering. The mineralized pockets parallel the overall layering depicted by the lithic tuff facies and infrequent banding measured throughout the Boojum Rock Tuff. Measurements of the strike and dip of the foliation defined by the pockets are indicated with a separate symbol.

Zbrl **Lithic crystal tuff facies** – A traceable N-S striking, east-dipping layer within the crystal tuff facies (Zbrc). Like the crystal tuff facies but with the addition of up to 20% mostly volcanic lithic fragments more than 0.5 cm in diameter. Rounded to angular lithic fragments range up to 8 cm and include abundant reddish-brown and medium to dark gray crystal tuff with white plagioclase crystals, medium to dark gray aphanitic devitrified volcanic rock, sparse amygdaloidal rocks, highly foliated very fine-grained banded felsite, lithic fragments with flattened glass or pumice, devitrified flattened porphyritic felsic lava fragments (originally glass), and occasional quartzite and argillite. Important is this unit's lack of accidental material derived from coarse felsic plutonic rocks. The unit has a sharp western contact and grades to the east to crystal tuff with smaller and sparser lithic fragments that occur in discontinuous patches where the rock transitions back to the crystal tuff facies. This suggests that the unit is upright and younger to the east. Layering defined by the unit matches the layering trend occasionally seen in the adjacent crystal tuff facies and internal to the unit. LaForge (1932) recognized this unit as a breccia with a dacitic matrix in the Melrose Highlands and Oak Grove areas of Malden (Black and Melrose Rocks).

Zbrc
Zbrr
Crystal tuff facies – The dominant facies of the Boojum Rock Tuff. Light to dark gray (N3-6 with slight greenish or reddish tones) welded crystal tuff that weathers by flaking. Surface of unit weathers to a very pale orange (10YR 8/2) to yellowish-gray (5Y 8/1) color. A separate symbol is used to identify dark reddish-gray to purplish-gray (10R 2/1) areas of the crystal tuff (Zbrr). Up to 55% of the rock is crystals of white plagioclase sitting in a very hard, dark, aphanitic ground mass of finely intergrown quartz and feldspar formed from devitrified glass. Matrix areas stain weakly for potassium and geochemical analyses (Smith, 1985; Hamilton, 2017) indicate a dacitic to andesitic rather than rhyolitic composition. Crystals are 0.5-3 mm, tabular to blocky, and euhedral to broken plagioclase with less abundant broken and euhedral amphibole (hornblende) crystals that are usually altered to pseudomorphic chlorite and epidote. The matrix occasionally shows bands, faint microscopic layering warped around crystals and lithic fragments, and faint layering defined by flattened and pinched black to reddish-black porphyritic lenses that stain heavily for potassium, especially at Black Rock. These elongate masses are rarely observable in outcrop and have a spherulitic and axiolitic microscopic texture indicating devitrified flattened glass or pumice fragments. Scattered lithic fragments of volcanic lithologies and argillaceous quartzite are generally 0.2-1.0 cm. The unit has a very high crystal density throughout except in a narrow band at the contact with the Spot Pond Granodiorite north of Hemlock Pool. The massive homogeneous character of the unit across its entire outcrop area supports well-organized joint patterns. It also has mineralized (specular hematite), closely-spaced, wavy slickensided surfaces not related to the joints that form a crude cleavage that doesn't appear in the Wakefield Formation. A new CA-ID-TIMS U-Pb zircon age near Pinnacle Rock (site 725BN) is 596.35 ± 0.21 Ma (6 zircons).

The Dedham Complex (Neoproterozoic) – ***Plutonic igneous rock units in the 609-610 Ma age range that pre-date the Lynn Volcanic Complex***

Zsg **Spot Pond Granodiorite (Neoproterozoic) –** Coarse-grained, partly leucocratic, equigranular granodiorite with some areas of tonalite and granite. Plagioclase is creamy white or light greenish-gray (5GY 8/1) euhedral to subhedral with greenish appearance when altered to epidote and sericite. Subordinate pale red (10R 5-6/2), perthitic, interstitial alkali feldspar (microcline; see also Zsgk below) that is occasionally a poikilitic host to euhedral plagioclase. Feldspar colors determine the overall color of the rock. Quartz occurs as abundant (up to 50%), coarse, strained polycrystalline grains with undulatory extinction. Mafic minerals (usually <15%), are chlorite, epidote and opaque minerals formed by alteration of biotite with a few scattered primary opaque grains that are titanomagnetite or ilmenite. Hornblende also occurs in the unit but is less abundant than biotite and is usually altered to chlorite and epidote. Local variations occur with: 1) alkali feldspar concentration, 2) minor grain size changes, and 3) mafic mineral concentration. Areas of higher alkali feldspar have fewer mafic minerals. Accessory minerals are sphene (titanite), which occurs in almost every non-deformed sample, and apatite, which occurs as small elongate crystals mostly in areas of biotite alteration. Occurs at the southern end and southeastern corner of Spot Pond and extends west of Rt. 93 through the northern Pine and Gerry Hill areas to Lawrence Woods as rounded glacially streamlined outcrops. Heavily baked quartzite and argillite xenoliths of all sizes (up to 150 m in length) from the Westboro Formation (Zvwq), sometimes partly assimilated, may form a roof pendant. Displays a strong foliation with polycrystalline quartz and aligned plagioclase and mafic minerals within a kilometer of its contact with the Westboro Formation on Gerry Hill. The Spot Pond is the ideal "Dedham" lithology of previous studies and Bell's (1948) "normal" variety of the Dedham Granodiorite. It is the main part of the Dedham Granodiorite of Emerson (1917) and LaForge (1932), who lumped several plutonic bodies with it. Smith and Hon (1984) and Smith (1985) mapped this unit east of the Fells as the Dedham North Granodiorite. Mapped as trondhjemite by Kaye (1980) but it is too rich in potassium feldspar for this to be the case. Kaye's map groups several younger plutonic bodies with the Spot Pond and because of this makes the claim that it intrudes surrounding volcanic rocks. No evidence for this intrusive relationship has been found for the Spot Pond with volcanic rocks of the Lynn Volcanic Complex, which have embayed and rounded quartz grains (xenocrysts) thought to be derived from the Spot Pond. Volcaniclastic conglomerate of the Lynn (Zlvc) also contains coarse granitic debris from the Spot Pond. The Boojum Rock Tuff of the Lynn (Zbrc) is also younger based on U-Pb ages. The Spot Pond has rare felsic volcanic xenoliths of unknown origin (see Zfi below). A U-Pb zircon age near Red Cross Path is 609.45 ± 0.25 Ma (CA-ID-TIMS; F. MacDonald, pers. com.). New U-Pb CA-ID-TIMS ages are south of Spot Pond (site 11368;, 5 zircons) 609.11 ± 0.22 Ma and near Doleful Pond (site 10409, 5 zircons) 609.08 ± 0.24 Ma.

Zsgk **Spot Pond Granodiorite, leucocratic alkali feldspar granite zones (Neoproterozoic) –** Leucocratic and alkali-rich areas within the Spot Pond Granodiorite that have alkali feldspar dominant over plagioclase, almost no mafic minerals, and generally a bright orangish-red color (2.5YR 6/6-5/8). Two types of areas have been mapped. One type is more abundant and is alkali granite as coarse as the host granodiorite with abundant light red (2.5YR 6/8) coarse alkali feldspar crystals (up to 50%) and less than 15% plagioclase. This syenogranite may be a local variation of the granodiorite (enclave) or large xenoliths of a unit not exposed at the surface in the Fells. These zones occur along the east side of Rt. 28 northwest of Wrights Pond, south of Gerry Hill, and in Lawrence Woods near Medford High School. An area of the first type has also been mapped in the Winchester Granite (Zwg, see description) west of Bear Hill and is identical to what is described here. This lends support for these areas being xenoliths. The alkali areas resemble the Ball Quarry Granite to the east described by Smith and Hon (1984) and Smith (1985). A second type of syenogranite occurs at only one place on a hilltop northwest of Wrights Pond and is a distinctly finer-grained zone than the host granodiorite with a granular outcrop appearance. It has sharp contacts and may be a xenolith from a unit not exposed at the surface in the Fells area.

Zwg **Winchester Granite (Neoproterozoic)** – Reddish- to pinkish-tan, medium-grained, equigranular monzogranite to tonalite in the northwestern Fells west of South, Middle, and North Reservoirs. The reddish color is derived from moderate reddish-orange (10R 6/6) to moderate reddish-brown (10R 4/6) alkali feldspar that is up to 35% of the rock. The red color can be misleading in some areas and results from hematite staining. Mafic minerals can be up to 25% and up to 50% along contacts with the Nanepashemet Formation (Znpm). Quartz is 25-35% and plagioclase 40-60% of felsic minerals. The unit displays rapid changes in grain size and mafic mineral content suggesting local assimilation of mafic-rich quartz diorite, altered basalt, and coarse alkali granite. It is distinct from the Stoneham Granodiorite (Zst) in being equigranular (non-porphyritic) and having larger quartz grains and more abundant alkali feldspar. Two areas with atypical lithologies have been mapped as xenoliths on Money Hill (Zwgd) and west of Bear Hill (Zsgk). Assimilated mafic rock, possibly Zwgd, occurs at the north to northeast end of Middle Reservoir. The Winchester Granite is heavily sheared in some places near faults. In the northwest Fells along Wyman Path and along Middle Reservoir this unit has occasional basalt xenoliths from the Nanepashemet Formation. Bell (1948) classified this rock as the "Stoneham red granite stock" and identified it as different than the more tonalitic rocks at Bear Hill and further east in Stoneham, the Stoneham Granodiorite (Zst) here. Kaye (1980) classified it as tonalite-granodiorite and lumped it with the Stoneham Granodiorite (Zst) of this study. Kaye, like Emerson (1917) and LaForge (1932) correlated it with the Paleozoic Newburyport Quartz Diorite. A U-Pb zircon age near Long Pond is 609.7 ± 0.24 Ma (CA-ID-TIMS; F. MacDonald, pers. com.), giving it an age like the Spot Pond Granodiorite and much older than the Newburyport.

Pre-Dedham Xenoliths in the Dedham Complex - (Neoproterozoic?)

Zfi **Baked xenoliths of Sialic Volcanic Rock in the Spot Pond Granodiorite (Neoproterozoic?) –** Small (up to 10 m) dark gray (N 5/0), greenish-gray (5G-5GB 5/1), and brown (10YR 5/1) very fine rhyolitic to dacitic volcanic xenoliths that are sparsely porphyritic. Except for minor color differences and alteration by contact metamorphism, all occurrences have the same overall appearance. Occur at three places: 1) east side of Woodland Avenue across from Quarter Mile Pond, 2) the southwest side of the swamp along Rt. 28 west of Wrights Pond, and 3) west of Red Cross Path and the northern extension of Middle Hill. The sources (or source) of the sialic xenoliths is not known.

Zwgd **Quartz Diorite Xenolith in Winchester Granite (Neoproterozoic?)** – Gray, medium-grained, equigranular to faintly porphyritic quartz diorite xenolith on the east side of Money Hill in the northwestern Fells. This xenolith has a higher mafic content than other sialic plutonic bodies and plagioclase is heavily altered. On the north shore of North Reservoir this rock type may be assimilated in the granite. The source of the xenolith is not known.

Znpm **Nanepashemet Formation (Neoproterozoic)** – Dark gray to almost black (N 1-4) and dark olive to greenish- and bluish-gray (5Y-5G 3-4/1), altered basalt, basalt breccias and conglomerates, basaltic tuff, dark argillite and basal red mudstone to sandstone and breccia. The basalt breccia/conglomerate beds and tuff are hydrothermally altered and may have had a matrix of palagonite. They are often difficult to recognize in the field and are likely more widespread than where identified so far. The overall dark greenish-gray color of the formation, results from various combinations of chlorite, actinolite, hornblende, and epidote. This formation has mostly been altered to hornfels near its contacts with the Winchester Granite (Zwg) and Stoneham Granodiorite (Zst) and in places appears to form a thin roof over these plutonic bodies. Later sialic intrusions have created plutonic breccias and numerous irregular felsic dikes in the basaltic units. Contact metamorphism causes the alteration of large phenocrysts/xenocrysts of pyroxene and alteration of tuff that causes the rock to weather with a honeycomb (alveolar) texture in some places that mimics lava with coarse vesicles. The recrystallized dark hornfels makes mapping younger dolerite and basalt dikes intruding the unit challenging, especially where they have diffuse contacts due to melting of the hornfels. Although the unit has altered basalt, no lava flow or pillow structures have been recognized in the Fells. Amygdaloidal basalt pebbles occur in the conglomerates. Recognition of primary structures is limited because: 1) the unit can be sheared along faults imparting a wavy chlorite/actinolite foliation with epidote veins; 2) original bedding may have been obscured by mass flow in volcaniclastic units; 3) the unit is hydrothermally altered by fluids that created epidote, oxides, quartz, and opal veins; and 4) the unit occurs near plutons and dikes that have transformed the unit to actinolite-hornblende hornfels, especially from Sheepfold northward to Taylor Mountain. In addition to basalt/argillite hornfels, the unit has three unique lithologies among rocks in the Fells including: 1) a basal matrix-supported breccia and conglomerate with quartzite clasts in a black to red mudstone to well-bedded reddish-gray to light gray sandy matrix; 2) scattered clast-supported conglomerate and breccia beds with fine to coarse mafic pebbles. A notable location is at the northeast corner of Middle Reservoir beneath an unconformity with younger volcanic units where baked conglomerate beds contain pebbles of basalt, vesicular basalt, dolerite, gabbro and sparse red felsic volcanic lithologies; and 3) marble (skarn) at the north end of Middle Reservoir that is interlayered with greenish-black hornfels adjacent to a contact with the Winchester Granite (Zwg). Bounding time relationships have been difficult to discern because of major east-west trending faults and large intrusions that baked and interrupted the formation. In outcrops west of South and Middle Reservoirs and on the north side of a fault along Molly's Spring Road the Nanepashemet Formation rests unconformably on the Westboro Formation (Zvwq) and truncates the Westboro's regional metamorphic foliation. The base of the Nanepashemet has a sandy breccia/conglomerate with angular chunks of the Westboro in a sandy matrix. Nearby are also partly melted and recrystallized inclusions of quartzite with opal veins in basalt. Along Molly's Spring Road are also well bedded red mudstone to reddish fine sandstone layers in float boulders associated with the quartzite-bearing breccia and conglomerate beds. Exposures of the top of the formation are equally elusive because the unit is mostly terminated at faults or interrupted by intrusions (Stoneham Granodiorite and Winchester Granite). At the north end of Middle Reservoir, steeply foliated hornfels and bedding in conglomerate beds in the Nanepashemet are truncated by gently dipping, banded rhyolite in the Lynn Volcanic Complex (Wakefield Fm.) at an angular unconformity. Local float boulders of bedded siliceous mudstone hornfels are associated with the conglomerate. The Nanepashemet Formation was correlated to the Marlboro Formation of Emerson (1917) by LaForge (1932) based on its mafic composition, but the Nanepashemet displays none of the regional metamorphic structures of the Marlboro. Later the rocks were defined as part of the Middlesex Fells Volcanic Complex (Bell and Alvord, 1976), which is here split into different formations (Nanepashemet and Wakefield) that have an unconformable contact. See the Lynn Volcanic Complex for a more detailed discussion of this separation. The Nanepashemet is intruded by the Winchester Granite (~610 Ma) and therefore older than the Dedham Complex in the Fells while the Wakefield units are much younger (~595 Ma).

The Westboro Formation (Neoproterozoic) – ***The Westboro Formation occurs in two approximately east-west fault blocks cut by several north-south trending faults. In the southern Fells (Virginia Wood area) the unit has low-grade regional metamorphism and deformation with a prominent layer-parallel foliation and Ca/Mg silicate units. In the northwest Fells (Whip Hill) the Westboro is not regionally metamorphosed and is purely sedimentary with olistostromes, and it has no Ca/Mg silicate units.***

Zwp **Non-metamorphosed Westboro at Whip Hill (Neoproterozoic)** – Dark gray (7.5YR 3/0), well cemented, laminated to thinly bedded, sandy mudstone and 10 cm to 20 m thick, massive, muddy mass flow units with very fine to medium sandstone olistoliths and mudstone breccias. Sandstone olistoliths are dismembered and contorted with cusped edges from soft sediment deformation. Mudstone units exhibit rusty yellowish-brown weathering (10YR 5/6). The unit has flat, laminated and graded bedding with crosscutting beds in mudstone units and ripple crossbeds (see Bailey, 1984 and Bailey and others, 1989). Bedding dips very steeply north to west (up to N and W) and may be slightly overturned in some places. Unconformably overlain by the Lynn Volcanic Complex (Zlvx) at the north end of Whip Hill. At the southern end of Whip Hill, the unit is in fault contact with the Lynn Volcanic Complex in another fault block to the south that houses the Westboro Formation at Virginia Wood. The Whip Hill Westboro units were mapped with the Westboro at Virginia Wood to the south on previous maps without the intervening Lynn Volcanic units (LaForge, 1932; Bell and Alvord, 1976; Kaye, 1980; Bailey, 1984; Bailey and others, 1989) which were not recognized to their full extent. U-Pb ages (LA-ICPMS) were determined for 210 zircon grains from a quartz sandstone olistolith on Whip Hill (site 11355). The zircon age distribution and youngest zircon age of about 910 Ma (maximum age for the unit) agree with other zircon distributions from north of Boston measured in the Westboro (Thompson and others, 2012; Francis MacDonald, pers. comm.).

Zvwq **Westboro Formation in Virginia Wood (Neoproterozoic)** – Alternating layers of dark gray (7.5YR 4-5/0), rusty weathering, siliceous argillite, metasiltstone, and white to light gray (7.5 YR 8-7/0), layered to massive, fine to medium quartzite. These units have zones with calcium/magnesium silicate minerals (tremolite, diopside, calcite, and zoisite) with minor calcite along an east-west band on Pond Street, in Virginia Wood, and west of the southern end of South Reservoir. Quartzite seems to dominate outcrops, but argillaceous units are not as well exposed and make up a considerable part of the unit. At the north side of the entrance to the southern parking lot at Sheepfold the upper surface of the unit is a thick (2-3 m) quartzite layer truncated unconformably beneath the Nanepashemet Formation (Znpm). East of Middle Reservoir and west of Sheepfold the unit is truncated along a fault bounded to the north by bluish-green (5G-BG 4/1-2), chloritic, altered basalt and argillite of the Nanepashemet Formation (Znpm). West of South Reservoir along Molly's Spring Road the unit is unconformably truncated by basal sedimentary units of the Nanepashemet Formation (see Nanepashemet description above). The Westboro is unconformably overlain by the Boojum Rock Tuff in eastern Pine Banks Park in Melrose and the Wakefield Formation on Wamoset Hill in the Fells. The lowest part of the Westboro in the Fells is in fault contact with or unconformably overlain by younger volcanic units (Boojum Rock Tuff, Zbrc) south of Ravine Road, but glacial sediment conceals this contact. From Spot Pond to the area east of Medford High School the Westboro is truncated below by intrusive igneous rocks. In other places the unit is truncated above by faults and intrusions. Slab-like quartzite/argillite hornfels xenoliths of the Westboro up to 150 m long are mapped in the Spot Pond Granodiorite. Argillite in the unit is baked to hornfels in inclusions or where it is intruded by the Spot Pond Granodiorite (Zsg), Rams Head Porphyry (Zrhp), Winchester Granite (Zwg), and Stoneham Granodiorite (Zst). The hornfels generally has biotite or chlorite and/or hornblende crystals. The Stoneham Granodiorite has abundant small xenoliths from the Westboro. The Westboro has low-grade regional metamorphism not seen in any other unit in the Fells. Foliation is generally parallel to original bedding which is preserved to varying degrees depending on local shear and contact metamorphism. Usually, thick quartzite layers are massive and may be brittley dismembered or are stretched within argillaceous units to form boudin-like lenses or folds. Quartzite units have flattened and heavily sutured and serrated quartz grains with muscovite tails and shadows. The unit can be mylonitic in southern Virginia Wood and near faults, which gives the rock a banded or streaked appearance. These deformed units usually have abundant tremolite. There is a consistent W to SW striking foliation that dips to the N to NW except where this trend is reoriented near faults, or the foliation is slightly overturned. The unit has a well developed magnetic (AMS) foliation with a weak lineation indicating only minor stretching. Localized small drag folds occur west and south of South Reservoir, along Pond Street in Virginia Wood, and in large quartzite xenoliths, and are likely in other areas but are hard to see in the field. The sense of shear indicated by folds on the NW dipping plane of foliation at Pond Street is for SE translation of layers upward on the foliation plane over layers below and in agreement with the weak magnetic lineation. The Westboro was previously mapped with the Westboro units at Whip Hill as the Westboro Quartzite by LaForge (1932) as originally defined by Emerson (1917) without recognition of the intervening Lynn Volcanic Complex at Wamoset Hill. Kaye (1980) also did not recognize the intervening volcanic rocks. The Westboro in the Fells is not physically connected to the type area of the Westboro Formation (Bell and Alvord, 1976) and in the Fells it has a somewhat different lithology with more abundant calcium-magnesium silicate zones and a lower metamorphic grade than described by Bell and Alvord (1976). Metamorphic grade is still higher than for any other unit in the Fells. Minimum zircon ages from Pond Street (909 ± 24 Ma; F. Macdonald, pers. com.) indicate the formation is younger than ~910 Ma and likely from the Tonian Period like the Westboro at Whip Hill. This matches the Westboro Formation further east (F. Macdonald, pers. com.; Thompson et al., 2012).

EXPLANATION OF MAP SYMBOLS

ORIENTATION DATA

Strike and dip of planar features in sedimentary and foliated fine-grained metamorphic rocks including altered basalt

70 Orientation of bedding for which top is known. At these locations bedding has not been significantly altered by structural deformation.

70 Orientation of overturned bedding for which top is known. At these locations bedding has not been significantly altered by structural deformation.

70 Orientation of bedding/layering for which a top is not known from field information. At these locations bedding has not been significantly altered by structural deformation.

70 Orientation of foliation. Represents orientation of compositional layering and in most cases is a strong foliation parallel to significantly deformed bedding.

45 Bearing and plunge of lineation on bedding or foliation plane.

Strike and dip of planar features in volcanic rocks

60 Orientation of foliation represented by banding in felsite or flow structure in basalt.

60 Foliation of flattened and stretched glass or pumice fragments (fiammé).

Strike and dip of planar foliation in deformed plutonic igneous rocks

75 Foliation in coarse-grained igneous rocks expressed as elongated quartz grains and the orientation of other minerals. Only found in the Spot Pond Granodiorite (Zsg) near its intrusive contact with quartzite west of Rt. 93.

Orientation of magnetic susceptibility measurement

65 58 Anisotropy of magnetic susceptibility (AMS): strike and dip of magnetic foliation - plane of maximum (K1) and intermediate (K2) susceptibility axes (strike and dip symbol and large number) and plunge of lineation (K1) on foliation plane (arrow and small number).

Strike and dip of dikes

80 basalt   80 dolerite   80 porphyritic basalt/dolerite

Small dikes – trace of dikes less than 1.0 m in width that are traceable over at least 2 m.

b basalt   d dolerite   p porphyritic basalt/dolerite   f andesite, dacite or rhyolite

65e **Strike and dip of veins or mineralized minor fault surfaces sometimes with gouge -** labels indicate vein minerals and materials: q – quartz, e - epidote, g – fault gouge.

70 **Strike and dip of continuous planar fractures and joints -** only shown where fractures are flat and continuous over a distance of at least 5 m. Associated with these prominent joints are many other local fractures not indicated on the map. Density of measurements is dependent on rock units, some of which have a massive character that allows the development of long flat fractures while other units have fractures with many directions that are not traceable over more than a few meters.

50 66 **Slickensides –** strike and dip of surface on which slickensides occur (large number is dip of slickensided surface) with arrow indicating plunge direction and plunge (small number) of slickensides on the dipping slickensided surface.

50 63 **Tension gashes along shear or joint surfaces –** strike and dip of shear or major joint surface (black) and strike and dip of tension gash surfaces (red).

FAULTS

- - - - — **Minor faults and fracture zones (dashed where inferred) –** prominent fractures and minor faults with small lateral extent and displacement as determined by the offset of dikes, contacts between major rock units, and other continuous features in rock units including other fractures and faults. Usually expressed as low spots or slot-like valleys in rock surfaces where erosion has taken advantage of fractures. Minor fault zones have smaller displacement and less shearing of adjacent rock than major faults.

— — — **Major faults (dashed where inferred) -** major faults with large lateral extent (over 1 km) and displacement (>50 m) as determined by the offset of dikes, contacts between major rock units, and other continuous features such as other fractures and faults. These faults are generally associated with highly sheared rock that forms larger valleys or ravines than along minor faults or they have associated shear fabrics. Major faults are in two sets, an older generally E-W trending set and a younger generally N-S trending set. The E-W set was intruded by the youngest E-W set of dolerite dikes, as is suggested by the large displacement of rock units on opposite sides of the dikes, and later these dikes were displaced by the N-S trending set of major faults.

▬ ▬ ▬▬▬ **Major faults separating large sections of the Avalon terrane (dashed where inferred) –** major faults separating sections of the Avalon Terrane with different groups of rock formations not just the offset of similar rock formations. Sometimes associated with mylonitic shear zones. Most notable is the Walden Pond Fault of Kaye (1980) in the northern Boston North Quadrangle and extending down the Mystic Valley further west in the Lexington Quadrangle.

UNCONFORMITIES

- - - - Surfaces overlain by sedimentary, pyroclastic or volcaniclastic units, or lava flows that are interpreted to be unconformities, which either truncate bedding or foliation in the unit below, represent erosion of the unit below, or represent an abrupt change in metamorphism that requires erosion in the absence of a fault.

OTHER FEATURES

▲ 10573 Bedrock sample site with sample number. Sites are hyper-linked to digital images in the original GIS map. Sample sites are numbered in two sequences. Sites with three digits, beginning with site 001, are from an earlier surficial mapping project. Five-digit numbers beginning with site 10001 are from more recent bedrock mapping. Samples marked Pf, DG, X, and MR are approximate locations of sites of Zarrow (1978).

▲ 10226 Locations where bedrock displays noteworthy properties described in field notes. Sites are hyper-linked to digital images in the original GIS map.

⚒ Bedrock quarry, mine, or excavation for fill. Dashed line only used in areas of large excavations. Abbreviations for rock types: f - felsite, g - granite, G – gabbro, m – metasedimentary rock, d - dolerite.

⚒ Abandoned bedrock quarry, mine, or excavation for fill. Dashed line only used in areas of large excavations. Abbreviations for rock types: f - felsite, g - granite, G – gabbro, m – metasedimentary rock, d - dolerite.

◩ Abandoned mine shaft on Silver Mine Hill in the Middlesex Fells Reservation east of South Reservoir.

✱ Exposure of pre-glacially weathered rock or saprolite (up to 10 m exposed). The only unit of occurrence is the Medford Dike.

♦602 Site of radiometric age with age listed in millions of years before present (Ma).

REFERENCES (see detailed map explanation with images at: http://sites.tufts.edu/fellsgeology)

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