Bedrock Geology of the Middlesex Fells Reservation and Adjoining Parks and Preserves in Malden, Medford, Melrose, Stoneham, and Winchester in Middlesex County, Massachusetts (see also http://sites.tufts.edu/fellsgeology)

(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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Base Map Information

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 the 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. Point count data and plots can be found 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 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. 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 – shown o0nly in areas outside the Fells.

Intrusive Igneous Rock Units Occurring as Unnamed Thin Dikes

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 only 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: 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). Dolerite dikes have experienced 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. 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 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. Weather to a rusty brown or gray color. 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 determination by Ross (2001) is 403 ± 3 Ma.

ad — **Highly altered gabbro, dolerite, and basalt 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. 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 highly 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 dioritic 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-gray 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 sometimes cumulophyric. Possibly more than one age. West of Rt. 93 at Wenepoykin Hill a red 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. Mapped with this unit are elongate lenticular rhyolite dikes in the Nanepashemet Formation that appear to be associated with the intruding Winchester Granite (Zwg). 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 which may trigger variations in composition. Unit can weather to a chalky surface with protruding xenocrysts. Only found on Whip Hill, in the MWRA excavation south of Ravine Road, from the east shore of the peninsula in the Fells Reservoir extending to east of the Fellsway East (same as MWRA site), and in the Winchester Granite 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

TRm — **Medford Dike (late Pennsylvanian) –** Brownish- to olive-black (5YR-Y 2/1), medium to coarse-grained gabbro. The Medford Diabase or Medford Dike of Wilson (1901) and LaForge (1932). Mostly composed of plagioclase, partly altered augite (actinolite), biotite, and accessory magnetite and possibly ilmenite. Margins have olivine and west margin has kaersutite (Ross, 2020). Unit contains abundant fine apatite needles and sparse interstitial calcite. 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 (see detailed explanation document for more at: *http://sites.tufts.edu/fellsgeology*). Chemistry and field relationships to other dikes are discussed by Ross (1990, 1992, 2020, 2021). The unit has a K-Ar (biotite) age of 190 Ma (Ross, 1981, 1990, 2001) and an $^{40}Ar/^{39}Ar$ biotite age of 304.4 ± 0.6 Ma (Ross, 2020). A new CA-ID-TIMS U-Pb zircon age (6 zircons) on the west side of Pine Hill is 238.07 ± 0.09 Ma which appears to be the most reliable age.

Zst — **Stoneham Granodiorite (Neoproterozoic)** – Greenish-gray (5B-GB 5-6/1) mostly granodiorite to tonalite. 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, at least 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 mineral content of 15-25% that includes biotite and hornblende that are mostly to partly altered to chlorite, epidote, and opaque oxides. 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 and sedimentary rock from the Straw Point Volcanic Complex (Zspb). A chill zone contact with the rhyolite facies of the Straw Point Volcanic Complex (Zspr) and Straw Point inclusions, occur on the western of two small peninsulas at the north end 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 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 clearly separates it from the Dedham Complex by about 14 Myr and eliminates the Newburyport Quartz Diorite correlation.

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 red matrix color is due to hematite staining. 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).

<u>Volcanic Rock Units in the Northern Fells</u> **– T*wo volcanic units of similar age but different compositions: Straw Point and Lynn Volcanic Complexes. These units are mapped separately because they have different compositions and are separated by a major fault at the north end of Spot Pond.***

Straw Point Volcanic Complex (Neoproterozoic) –Distinct units of bimodal volcanic flows (basalt and rhyolite), felsic pyroclastic rocks, and dark bluish- and greenish-gray argillite and basaltic tuff at the northwest corner of Spot Pond and the northeast corner of Middle Reservoir. Mapped by Emerson (1917) and LaForge (1932) as the upper bimodal volcanic part of the Marlboro Formation but this is untenable given the Straw Point's lack of metamorphism. Bell and Alvord (1976) defined these units and dark units beneath them (mapped here as the Nanepashemet Formation) that lie on the Westboro Formation as the Middlesex Fells Volcanic Complex. Mapping in the Fells by Kaye (1980) misidentified large areas of chloritic and epidote-rich basalt hornfels and dark argillite as "quartz vitrophyre" that he included with the Middlesex Fells Volcanic Complex following the stratigraphy of Bell and Alvord (1976). The Nanepashemet Formation (Znpm) is interpreted here to have pervasive contact metamorphism, hydrothermal alteration, and an unconformable relationship with the overlying Straw Point Volcanic Complex at the north end of Middle Reservoir. The Straw Point is not exposed in contact with the Nanepashemet Fm. at the northwest corner of Spot Pond due to faults and intrusion of the Stoneham Granodiorite but contact of the Straw Point and Nanepashemet may occur beneath Spot Pond.

Zspb — **Basalt/argillite 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 tuff interlayered with laminated to thin bedded dark bluish- to greenish-gray (5BG-5G 3-4/1) argillite to fine sandstone, that has minor amounts of felsic volcaniclastic or pyroclastic rock. Basalt flows, tuff, and argillite are mapped as a single facies because they are interlayered, and it has not been possible because of alteration and very fine grain sizes to consistently separate them in the field without thin section analysis. Bedding in the argillite is often contorted. Basaltic and sedimentary units are often heavily altered with abundant chlorite, and quartz, calcite, epidote, and iron oxide mineral precipitates in amygdules and veins. At least one argillaceous unit at the base of a basalt flow is partly calcareous and displays alveolar weathering that mimics vesicles. This is the topmost unit of the Straw Point Volcanic Complex at Straw Point but exposures north and east of the Fells may have multiple basalt/felsite cycles. Most of Straw Point was mapped by Kaye (1980) as a dolerite intrusion. Pillow basalt occurs in this unit outside the Fells at Stoneham High School (Smith and Hon, 1984) and at High Rock in Wakefield.

Zspc — **Pyroclastic/volcaniclastic facies** – Light gray to gray (10YR 5-7/1), welded to non-welded, crystal tuff and volcaniclastic sandstone to conglomerate with abundant lithic fragments and broken plagioclase crystals. Deeply embayed quartz xenocrysts that are abundant in the Lynn Volcanic Complex at Wamoset Hill and in the southern Fells are present but sparse. The unit is dominantly felsic pyroclastic and volcaniclastic rock with lithic volcanic clasts and basalt and quartzite lithic fragments. Unit overlies the rhyolite facies and is beneath and interbedded with the basaltic facies (Zspb) at Straw Point. Not mapped by Kaye (1980) as a separate unit.

Zspr — **Rhyolite flow facies** – Lowest part of Straw Point Volcanic Complex that is light gray (10YR 7/1) to gray (10YR 6/1), banded, recrystallized rhyolite with sparse lithic fragments and very dark grayish-brown to reddish-brown (10YR 3/2 to 5YR 4/4), banded rhyolite both interpreted to be flows with sparse euhedral cumulophyric plagioclase crystals. Units on the east side of Straw Point display faint flow banding that dips gently and parallel to overlying basaltic units and indicates the unit's orientation. At Straw Point and on the north shore of Spot Pond the unit displays a micropoikilitic texture due to devitrification and possibly recrystallization during contact metamorphism adjacent to the Stoneham Granodiorite (Zst), which gives hand samples and weathered surfaces a spotted appearance resembling ooids. At Middle Reservoir there is a U-Pb zircon age of 594.7 ± 0.3 Ma (CA-ID-TIMS, 5 zircons, F. MacDonald, pers. comm.) and at Straw Point a U-Pb zircon age (CA-ID-TIMS, 4 zircons) of 595.27 ± 0.34 Ma.

Zwh — **Lynn Volcanic Complex at Wamoset Hill (Neoproterozoic)** – Steeply-dipping, sialic volcanic units from east of Whip Hill Park to the north end of Spot Pond that include very dark gray (7.5R 3/0) flow-banded rhyolitic lava with cumulophyric feldspar; dark gray (7.5YR 4/0) welded, vitric tuff with oriented fine plagioclase crystals; pinkish-gray (7.5YR 6/2) to gray (7.5YR 6/0), mildly to non-welded, crystal to lithic tuff; and volcaniclastic rock with broken plagioclase and quartz crystals, abundant volcanic lithic fragments, and coarse granitic debris. Displays macro-spheroidal texture (relict lythophysae?) and relict perlitic texture in Whip Hill Park at the top of a flow unit. The basal contact to the south is an unconformity crosscutting the Westboro Formation. It displays none of the Westboro's deformation or metamorphism south of Wamoset Hill (Zvwq). The unit is in fault contact above with another, non-metamorphosed section of the Westboro Formation (Zwp). Was included with the Westboro Formation on Wamoset Hill by LaForge (1932) and Kaye (1980). Kaye overextends the unit along Pond Street in Stoneham to Greenwood Park. East of the Fells the unit has a much larger outcrop area and has been subdivided into **Zwct** (crystal tuff) and **Zwbr** (banded rhyolite), where LaForge and Kaye show the Lynn Volcanic Complex Lynn (Volcanics of Clapp, 1921). The Lynn in the northern Fells is mapped separately from the Straw Point Volcanic Complex because the Lynn has no basaltic component, but these two units are close in age. Has not been correlated to a member of the Lynn (Smith and Hon, 1984; Smith, 1985). The unit has a U-Pb zircon age of 595.82 ± 0.23 Ma (CA-ID-TIMS, 5 zircons; F. MacDonald, pers. com.) and it appears to be slightly younger than the Lynn in the southern Fells which is intruded by units that are older than 596 Ma.

<u>Plutonic Rock Units in the Southern Fells Contemporary with the Lynn Volcanic Complex</u> ***–Porphyritic rock formations that are likely subvolcanic units to the Lynn Volcanic Complex.***

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 on its north side. Except for rare isolated grains of quartz that may be recrystallized xenoliths, 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 – 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, Spot Pond Granodiorite, and Rams Head Porphyry. Unit gets progressively coarser to the south away from contacts with other units. Contains xenoliths from 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 appears to be 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 Lynn Volcanic Complex. 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 in the Fells. U-Pb zircon ages (CA-ID-TIMS) reveal a range of ages from about 596.3-598.3 Ma related to inheritance and 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 the ages from these units are statistically indistinguishable.

Zrhp — **Rams Head Porphyry (Neoproterozoic)** – Greenish-gray (5G 4-5/1) porphyritic tonalite to quartz diorite. 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 about 10-25% quartz and typically <10% alkali feldspar in the non-mafic component. Mafic mineral content is typically 15-25% but can be higher and is mostly hornblende with lesser biotite that are usually altered to chlorite, calcite, epidote and opaque oxide minerals. 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 classified the unit as "tonalite-granodiorite", but the unit generally has too little alkali feldspar to be granodiorite. Kaye includes the unit with the Stoneham Granodiorite of this map in the northern Middlesex Fells. The Stoneham Granodiorite (Zst) 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 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 596.24 ± 0.21 Ma and disproves the Newburyport correlation.

<u>Lynn Volcanic Complex in the Southern Fells</u> **(Neoproterozoic)** ***– Volcaniclastic and pyroclastic felsic volcanic units unconformably overlying the Spot Pond Granodiorite (Zsg) in the Pine Hill to southeastern Fells areas. The Lynn is subdivided into three separate groups of units based on location and composition. Two areas of younger units that are likely correlative have been mapped in the Pine Hill to Wrights Pond area (Zpmh, Zpt) and from eastern Wrights Pond to the western Boojum Rock (Zbjc, Zbjp, Zbjv, Zbjb). These eastern units unconformably rest on a lower part of the Lynn covering the whole southeastern Fells, the massive, quartz-deficient Boojum Rock Tuff (Zbrc, Zbrl, Zbrv). The Lynn Volcanic Complex in the southern Fells currently lacks direct radiometric age control except from the Boojum Rock Tuff. There are no flow units in this area, which give better radiometric age results than pyroclastic units. However, ages are constrained by radiometric ages from units that intrude the Lynn (Lawrence Wood Granophyre, Zlwg) and units that appear as clasts in the Lynn (Spot Pond Granodiorite, Zsg and Westboro Formation, Zvwq and Zwp). The Lynn units in the southern Fells are thought to be loosely correlative to volcanic units in the northern Fells but very slightly older. Present mapping of the Lynn Volcanic Complex in the Pine Hill to western Boojum Rock areas does not match the volcanic units mapped by LaForge (1932) or Kaye (1980), who lumped units of the current map in the Pine Hill to western Boojum Rock areas with the Boojum Rock Tuff (Zbrc). In earlier studies of the Pine Hill area (Zarrow, 1978; Naylor, 1981, Smith and Hon, 1984; Smith, 1985) the Lynn units were thought to be intruded by the "Dedham Granodiorite" (the Spot Pond Granodiorite of this map). However, the volcaniclastic Middle Hill Member of the Lynn in the Pine Hill area of the current map has clasts of the Spot Pond Granodiorite (Zsg). The plutonic unit that intrudes the Lynn Volcanic Complex on Middle, Little Pine, and Pine Hills and in the Wrights Pond and Boojum Rock areas is the subvolcanic Lawrence Woods Granophyre (Zlwg) of this map. Previously, the Spot Pond and Lawrence Woods plutonic units in the southern Fells were lumped as the Dedham Granodiorite, but they are now known to have radiometric ages different by ~13 Myr with the Lawrence Woods being too young to be a part of the Dedham. Thus, the supposed intrusion of Lynn rocks by granitic rocks with a Dedham age, is incompatible with new mapping and radiometric ages. The supposed intrusion of the Lynn in the Pine Hill area by a Dedham unit led to mapping of the Lynn in this area as part of an older "Middlesex Fells Volcanic Complex" (Smith and Hon, 1984; Smith, 1985) and it was not correlated to the Lynn Volcanic Complex further east.***

The Lynn Volcanic Complex from Pine Hill to western Wrights Pond - From Pine Hill to western Wrights Pond, the Lynn is split into two members: mixed volcaniclastic sediment and pyroclastic units of a lower Middle Hill Member (Zpmh), and lithic crystal tuff of an upper Wrights Tower Tuff Member.

Zpt — **Wrights Tower Tuff Member ("Tower Member" of Zarrow, 1978)** – Dark bluish-gray (5B 4/1) to gray (N4/1) welded crystal tuff with varying sizes and abundances of crystals and lithic fragments. The unit is well exposed at Wrights Tower on Pine Hill and on the southern end of Middle Hill where it is intruded by the Lawrence Woods Granophyre (Zlwg). At Wrights Tower the unit contains irregular and pinched masses of vitric tuff . Crystals are both euhedral and broken and are primarily plagioclase but also include rounded and embayed quartz crystals that are xenocrysts from the Spot Pond Granodiorite and include rounded quartz dipyramids, and minor alkali feldspar. Lithic fragments include a wide variety of felsic volcanic rocks and quartzite that sometimes has heavily sutured, stretched, and recrystallized quartz grains indicating a Westboro Formation (Zvwq) source. Thin sections display layering and crystal fabrics that are deformed around lithic fragments but they are difficult to recognize in the field.

Zpmh — **Middle Hill Member** – Dark bluish-gray (5BG 3-4/1) to gray (N4/1) fine-grained volcaniclastic sandy mudstone to greenish-gray (5GY-G 5/1 matrix) polymictic conglomerate (diamictite) with a variety of lithic grains including pebbles to boulders of the Spot Pond Granodiorite (Zsg). Large Spot Pond Granodiorite (Zsg) clasts on Middle Hill were first recognized by Robert Reuss of Tufts University (samples and unpub. field notes, 1982-1985). The Lawrence Woods Granophyre intrudes this unit. On Pine and Middle Hills are deformed and pinched masses of light gray weathering, gray (N 5-6) vitric tuff that are sometimes banded and enclosed in a rusty weathering volcaniclastic sandstone to conglomerate containing abundant rounded and broken plagioclase and quartz crystals, sparse alkali feldspar, and granodiorite, volcanic, and quartzite sand to cobble size clasts. This appears to be an equivalent of the breccia/volcaniclastic conglomerate facies in the Boojum Rock area (Zbjc).

Lynn Volcanic Complex facies from eastern Wrights Pond to western Boojum Rock – From eastern Wrights Pond to the western Boojum Rock area, the Lynn Volcanic Complex is split into four facies not traceable as members because this area is so heavily faulted along the Quarter Mile Pond Fault.

Zbjb — **Banded and flattened pumice-bearing welded crystal tuff facies** – Dusky blue to grayish-purple (5PB 4/2 to 5P 2-4/2), welded, lithic and crystal tuff with well preserved volcanic structures including banding, flattened pumice fragments, and (auto-?) brecciated, reddish-purple to purple, crystal and banded tuff. Surface of unit weathers to a pale grayish-blue (5PB 5-6/2). On the northeast shore of Wrights Pond the unit is reddish-black (5R 2/1), welded and banded, vitric tuff with minor crystals and lithic fragments.

Zbjv — **Vitric tuff facies** - Light bluish- to pinkish-gray (5B 7/11 to 5 YR 8/1), fine vitric tuff with occasional faint layering and a chert-like appearance in outcrops. This unit grades between almost pure fine ash tuff and fine ash tuff with sparse fine crystals and lithic fragments. In the Pine Hill area, rocks of this lithology have only small aerial extent.

Zbjc — **Granule to boulder volcanic breccia and volcaniclastic conglomerate facies** – Medium light to dark gray (N3-6) to greenish-gray (5GY-G 5/1, matrix) volcanic breccia to volcaniclastic, clast-supported, round pebble conglomerate like the Middle Hill Member in the Pine Hill (Zpmh) area but with different clasts, especially dark red volcanic fragments and alkali granite. Lithologies are interbedded but generally grade upward from volcanic breccia with only volcanic clasts and a very poorly sorted matrix to better sorted, polymictic volcaniclastic conglomerate with round pebbles. In addition to volcanic lithologies, pebbles are also composed of white and gray to red, quartz sandstone, quartzite, laminated fine sandstone and siltstone, and granitic rocks including alkali granite that resembles the Ball Quarry Granite (Smith and Hon, 1984; Smith, 1985). This facies forms the base of the group of units in this area and rests on an angular unconformity cutting across the regional trend of layering in the Boojum Rock Tuff (Zbrc). It may be the same as the Vinegar Hill Member of the Lynn Volcanic Complex described by Smith and Hon (1984) and Smith (1985).

Zbjp — **Red 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 plagioclase phenocrysts and rounded and embayed quartz crystals. This unit is distinct from the Boojum Rock Tuff in that it has: 1) large almost completely euhedral plagioclase phenocrysts or cumulophyric clusters that are 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 connection has been found.

Boojum Rock Tuff Member 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 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, 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 that are found in all younger volcanic units. 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 it does not fit into any of the Lynn members defined by Smith and Hon (1984) and Smith (1985).

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 light colors (very pale orange to very light gray: 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 where it is truncated by a fault zone on its eastern side.

Zone with flattened glass (pumice?) fragments – At the top (east side) of the lithic crystal tuff facies (Zbrl), recrystallized flattened glass/pumice fragments. 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. This 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 dacitic matrix in the Melrose Highlands and Oak Grove area of Malden (Black and Melrose Rocks).

Zbrc — **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. Up to 50% 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 wrapped 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 appear to be a cleavage, possibly formed early in the rock's history. A new CA-ID-TIMS U-Pb zircon age near Pinnacle Rock (site 725BN) is 596.35 ± 0.21 Ma (6 zircons).

<u>The Dedham Complex</u> **(Neoproterozoic)** ***– Plutonic igneous rock units in the 609-610 Ma age range pre-dating the Lynn Volcanic Complex***

Zsg — **Spot Pond Granodiorite (Neoproterozoic)** – Coarse-grained, mostly 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 on 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 plutonic bodies with the unit mapped here 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 and Straw Point Volcanic Complexes, which have embayed and rounded quartz grains (xenocrysts) thought to be derived from the Spot Pond. The Lynn Volcanic Complex (Zpmh) 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 1136B;, 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 larger 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 east of 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). Normalized quartz is 25-35%, and plagioclase is 40-60%. 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. 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 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 indistinguishable from the Spot Pond Granodiorite and much older than the Newburyport rocks.

<u>Pre-Dedham Xenoliths in the Dedham Complex</u> - **(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 reddish-brown (10R 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 source or sources 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, altered 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 at places 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 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 flows 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 may 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 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, diorite, 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 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 Straw Point Volcanic Complex 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 basaltic 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 (Straw Point and Nanepashemet) that have an unconformable contact. See the Straw Point 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 Straw Point (~595 Ma) in the Fells while the Straw Point units are much younger (~595 Ma).

<u>The Westboro Formation</u> **(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) 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 northwest (up to N-NW) and may be slightly overturned in some places. Unconformably overlain by the Lynn Volcanic Complex (Zwh) north 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 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 along with the intervening Lynn Volcanic units (LaForge, 1932; Bell and Alvord, 1976; Kaye, 1980; Bailey, 1984; Bailey and others, 1989) that were not recognized. U-Pb ages (LA-ICPMS) were determined for 210 zircon grains from a quartz sandstone olistolith on Whip Hill (site 1135S). 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 at 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 rocks of the Nanepashemet Formation (see Nanepashemet description above). 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 argillaceous units are stretched 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 E to NE striking foliation that dips to the NNW 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

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

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

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.

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

Bearing and plunge of lineation on bedding or foliation plane.

Strike and dip of planar features in volcanic rocks

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

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

Strike and dip of planar foliation in deformed plutonic igneous rocks

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

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

basalt — dolerite — porphyritic basalt/dolerite

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

basalt — dolerite — porphyritic basalt/dolerite — andesite, dacite or rhyolite

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.

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.

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.

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.

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

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 sites of Zarrow (1978).

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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