Tabulation of Age Relationships of Bedrock Units in the Middlesex Fells Reservation and Boston North Quadrangle

Prepared by Jack Ridge
Dept. of Earth and Climate Sciences
Tufts University
Medford, MA 02155

Summary of Bedrock Stratigraphy

Last update: May 27, 2025

238 Ma — Trm — **Medford Dike** – NNE-SSW trending gabbro dike. **Age (Ma): 238.07 ± 0.09 (U-Pb zircon CA-TIMS)**

---- Time gap, Medford Dike crosscuts all dikes below, except possible rare Mesozoic dikes ----

d, dp — **Dolerite and basalt dikes (d), porphyritic dolerite and basalt dikes (dp)** – numerous ages from Neoproterozoic to possibly Mesozoic, offset by faults and crosscut each other, youngest set is relatively large dikes that are E-W trending. Crosscut by the Medford Dike.

gb — **Gabbro dikes** – altered, crosscuts some dolerite dikes, west side of Middle Hill and northern Pine Hill. Not related to Medford Dike. Neoproterozoic to Paleozoic (?).

Dike ages (Ma)*: d 226 ± 3 (^{40}Ar/^{39}Ar whole rock); d 290 ± 15, (K/Ar whole rock); d 353 ± 4, (^{40}Ar/^{39}Ar whole rock); gb 402.5 ± 3 (^{40}Ar/^{39}Ar whole rock); d 573 ± 4 (^{40}Ar/^{39}Ar whole rock)
*K/Ar and Ar/Ar ages not accurate due to later thermal events

ad — **Highly altered dolerite and basalt dikes** – chloritic with epidote and porphyroblasts of amphibole and chlorite. Often have diffuse contacts. Possibly several ages, Neoproterozoic to Paleozoic. In Nanepashemet Fm. may have fed basalt flows in hydrothermal environments.

---- Large time gap in major map units. Dikes above are Neoproterozoic to possibly Mesozoic ----

Boston Bay Group *(~590-565 Ma)*

Zca — **Cambridge Argillite** – argillite south of Northern Border Fault

Zrx — **Roxbury Conglomerate** – conglomerate and sandstone north of Northern Border Fault

fq — **Felsic dikes with medium to coarse embayed quartz and feldspar xenocrysts** – intrudes Zwp on Whip Hill, Zsg at MWRA facility, and Zbrc near Black Rock. Xenocrysts from coarse granite, has fluorite crystals. Neoproterozoic.

ap — **Gray porphyritic andesite to dacite dikes** – east side of Spot Pond, probably offshoot of Zst. Xenoliths and xenocrysts including embayed quartz. Hornblende phenocrysts. Neoproterozoic.

Subvolcanic rocks related to Lynn Volcanic Complex ~597-595 Ma

Zst — **Stoneham Granodiorite** – granodiorite to tonalite, high mafic content, porphyritic at contacts. **Age (Ma): 595.14 ± 0.17 (U-Pb CA-TIMS)**

Zwap — **Wanapanaquin Porphyry** – granodiorite porphyry. Branch of Stoneham Granodiorite. Neoproterozoic.

Zlwg — **Lawrence Woods Granophyre** – porphyritic granophyre with needle-like hornblende. **Age (Ma) - 2 zircon populations : inherited 598.13 ± 0.27 (U-Pb CA-TIMS); 596.77 ± 0.25 (U-Pb CA-TIMS)** - at Wrights Pond; **596.50 + 0.53 (U-Pb CA-TIMS)** - at Pine Hill.

Zdg — **Unnamed gabbro-diorite porphyry** - intrudes Zvwq, may be related to Zrhp. **Age (Ma): 596.02 + 0.32 (U-Pb CA-TIMS)**

Zrhp — **Rams Head Porphyry** – tonalite porphyry with minor quartz and alkali feldspar, intrudes Spot Pond Granodiorite. **Age (Ma): 596.24 ± 0.16 (U-Pb CA-TIMS)**

---- Stoneham Granodiorite intrudes Zlvf, Zlbf and Zlvx at Straw Point on Spot Pond and in Melrose, Stoneham and Wakefield ----
---- Lawrence Woods Granophyre intrudes base of Zlvc at Pine Hill and Boojum Rock, and Zlvx and Zlvv at Wrights Pond ----

Lynn Volcanic Complex (Neoproterozoic).

Lynn Volcanic Complex (597-594 Ma)

596-594 Ma — Zlbf, Zlbc, Zlvc, Zlvp

Wakefield Formation – interlayered volcanic facies (bimodal):
(Zlbf) – basaltic flows and associated breccia and tuff
(Zlbc) – basaltic volcaniclastic units, polymictic breccia and conglomerate
(Zlvc) – felsic volcaniclastic units, polymictic breccia and conglomerate
(Zlvp) – rhyolite porphyry, fissure intrusion

Zlvv, Zlvx, Zlvl, Zlvf

(Zlvv) – felsic vitric tuff
(Zlvx) – felsic crystal tuff
(Zlvl) – felsic lithic tuff
(Zlvf) – rhyolitic flows

Ages (Ma): 594.70 ± 0.32 (U-Pb CA-TIMS) Zlvf at Middle Res.; **595.27 + 0.34 (U-Pb CA-TIMS)** Zlvf at Spot Pd.; **595.82 ± 0.23 (U-Pb CA-TIMS)** Zlvf at Wamoset Hill

---- Zlvc rests unconformably on Boojum Rock Tuff and Zsg ----

---- Unconformity, start of abundant embayed quartz and coarse feldspar xenocrysts in Lynn and felsic dikes ---

597-596 Ma — Zbrv, Zbrl, Zbrc, Zbrr

Boojum Rock Tuff – dacitic tuff facies with rare quartz (xenocrysts derived from broken quartzite in Westboro Fm.)

Zbrv - vitric tuff
(- - - - -) fiammé zone, top of Zbrl, Melrose to Pinnacle Rocks, dips steeply east
Zbrl - lithic crystal tuff facies
Zbrc – dominant crystal tuff facies, coarsens to east in Malden and Melrose
Zbrr – red crystal tuff in Malden and Melrose

Age (Ma): 596.35 ± 0.21 (U-Pb CA-TIMS), high in Zbrc east of Boojum Rock

---- Zbrc rests unconformably on Zsg north of Boojum Rock and Zvwq at Pine Banks Park ----

Dedham Complex (Neoproterozoic).

Dedham Complex (609-610 Ma)

Zsg — **Spot Pond Granodiorite** – coarse granodiorite to granite with abundant Zvwq xenoliths. **Ages (Ma): 609.46 ± 0.18 (U-Pb CA-TIMS)** - Red Cross Path; **609.11 + 0.22 (U-Pb CA-TIMS)** - South of Spot Pond; **609.08 + 0.24 (U-Pb CA-TIMS)** - Doleful Pond

Zwg — **Winchester Granite** – equigranular medium granite with relatively high mafic content. Plagioclase subordinate or equal to alkali feldspar. **Age (Ma): 609.72 ± 0.24 (U-Pb CA-TIMS)**

Zsgk — **Alkali granite** - alkali granite zones/xenoliths in the Dedham Complex (in both Zsg and Zwg). Uncertain origin and age.

fp — **Dark red to tan porphyritic rhyolite dikes west of Spot Pond** – in Zsg, Zwg and Znpm, several Neoproterozoic ages possible. At Wenepoykin Hill red dikes crosscut Zsg and are crosscut by Zrhp.

Zwgd — **Quartz Diorite Xenoliths in Zwg** – medium-grained quartz diorite xenoliths (uncertain source and age).

Zfi – felsite xenoliths in Zsg, unknown source and age.

---- Units below intruded by Zsg and Zwg ----

Znpm — **Nanepashemet Formation** – mostly hydrothermally altered (baked) basalt and basaltic tuff with basaltic breccias and conglomerates. Basal red conglomerate and sandstone and dark argillite with Westboro Fm. clasts.

---- Angular Unconformity overlain by basal breccia/conglomerate of the Nanepashemet Formation along Molly's Spring Rd.) ----

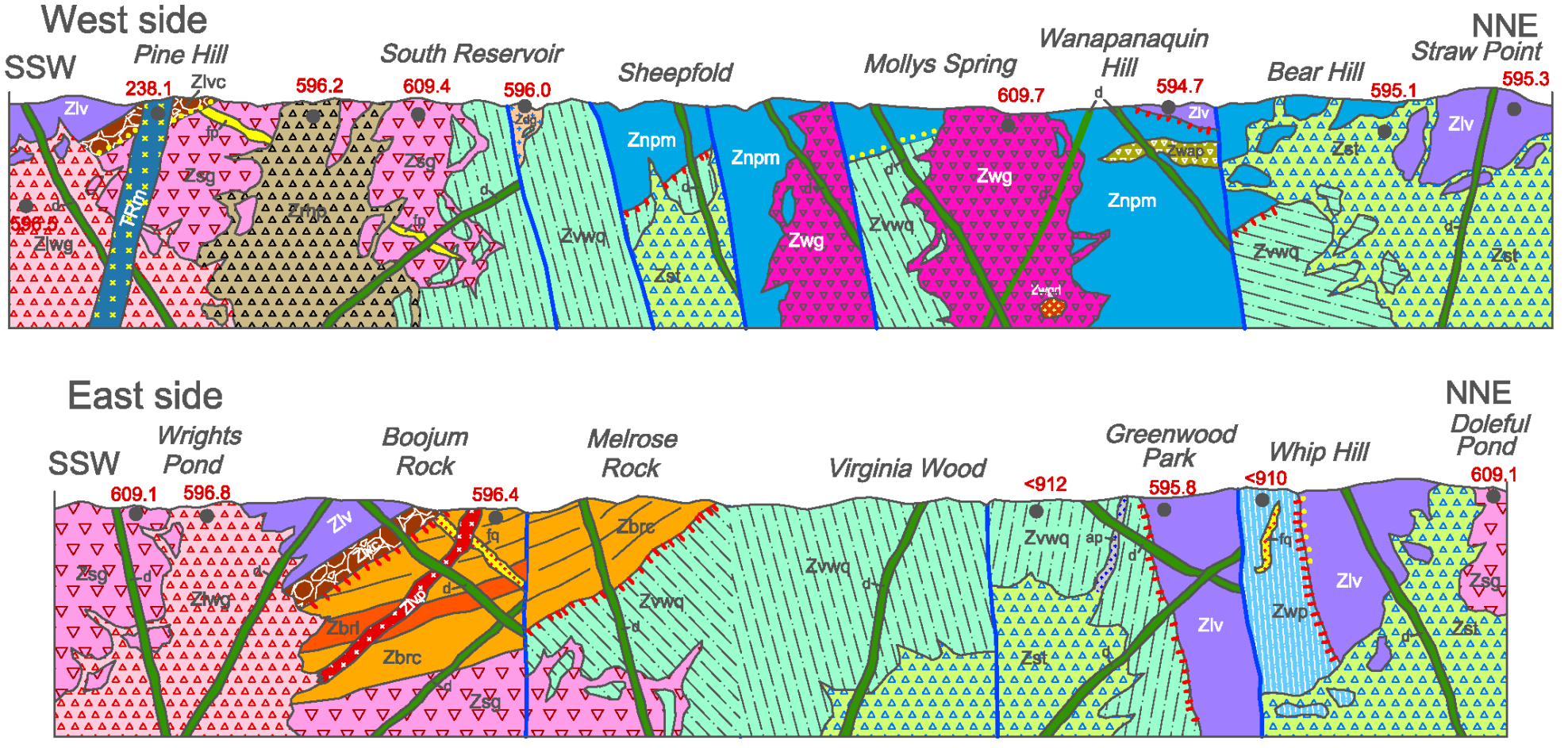
------ period of low-grade regional metamorphism ------

Westboro Fm. < 912 Ma

Zwp — **Westboro Formation in Whip Hill area** – non-metamorphosed laminated mudstone, fine sandstone, and mass flow units with quartz sandstone olistoliths. Not regionally metamorphosed. Isolated in a separate fault block. Intruded by ap and fq dikes. Neoproterozoic. **Max. Age: < 910 Ma (LA-ICPMS, 210 detrital zircon grains, quartz sandstone olistolith)**

Zwvq — **Westboro Formation in Virginia Wood and west of Spot Pond** – metamorphosed at a low grade and sheared, quartzite and argillite with calcium/magnesium silicate intervals. **Max. Age: < 912 ± 0.6 Ma (U-Pb CA-TIMS youngest detrital zircon)**

Diagrammatic cross sections showing relative age relationships of bedrock units in the Middlesex Fells.



Diagrammatic cross sections of the eastern and western sides of the Middlesex Fells Reservation intended to show the field and age relationships of the bedrock units. Geologic symbols are the same as those used on the bedrock map and in the explanation. Separate facies in the Upper Lynn Volcanic Complex (Zlv) are not shown here except for the felsic clastic units (Zlvc). Black dots with red numbers are radiometric ages. Except for the limiting zircon ages in the Westboro Formation, all ages are CA-ID-TIMS U-Pb zircon ages. Unconformities are shown as surfaces beneath areas where either a unit above the unconformity contains fragments of the unit below that document erosion of the lower unit (yellow dots above unconformity surface) or erosion is documented beneath the unconformity as crosscutting of foliation or layering below (red tic marks beneath the unconformity).

Medford Dike (TRm): gabbro dike, crosscuts all other units including all other dolerite dikes and faults except one small (~7 cm) dike on Governor's Avenue in Medford outside the Fells and a dike mapped by Wilson (1901). Most recently obtained radiometric age: 238.07 ± 0.09 Ma (CA-ID-TIMS U-Pb zircon). Argon method ages are no longer valid because of reheating events.

Unnamed gabbro, dolerite, and basalt dikes and their porphyritic and altered variants (gb, d, dp, ad): various ages (see below).

1. Compositional variations, degree of alteration, fault displacements, well-organized orientation sets (sets of parallel dikes of the same rock type) and crosscutting of different dike sets indicate several ages. Where exposure allows: LaForge's (1932) classification of major E-W dikes crosscutting N-S dolerite dikes is confirmed in almost all places, but there are other directions, and not all dike intersections have crosscutting relationships that can be determined in the field. The youngest (E-W) dike set seems to have intruded major E-W trending faults and are crosscut by N-S trending faults. These dikes tend to be relatively thick and on the order of at least 10 m.
2. Radiometric ages (in order) determined in previous works for basalt, dolerite, and gabbro dikes are:

   d (small) - 573 ± 5 Ma ($^{40}Ar/^{39}Ar$ whole rock),
   gb - 402.52 ± 3.22 ($^{40}Ar/^{39}Ar$ whole rock),
   d - 353 ± 4 Ma ($^{40}Ar/^{39}Ar$ whole rock),
   d - 290 ± 15 Ma (K/Ar whole rock),
   d - 226 ± 3 Ma ($^{40}Ar/^{39}Ar$ whole rock).

   The ages suggest a wide variety of ages from Neoproterozoic to Mesozoic. The accuracy and uncertainty of these ages is poor since these dikes experienced later thermal events and many are on whole rock analyses or obtained many years ago. The dike with a radiometric age at 226 Ma is crosscut by the Medford Dike and is inconsistent with the new Medford Dike U-Pb age. The other dike ages are internally consistent with field relationships and the youngest age for E-W trending dikes. The most recently determined age for the Medford Dike suggests that the dolerite dikes can be no younger than early Triassic and are probably Paleozoic.

BIG Q: Is there a systematic composition, age, or paleomagnetic direction with dike set orientation?

Porphyritic andesitic (ap) and red to tan dacitic to rhyolitic dikes (fp, fq): mixture of at least 3 ages intruding the Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc), Spot Pond Granodiorite (Zsg), Winchester Granite (Zwg), Nanepashemet Fm. (Znpm), Westboro Formation at Whip Hill (Zwp), and the Westboro Formation in Virginia Wood (Zvwq). These dikes have not yet been found in the Stoneham Granodiorite (Zst), Lawrence Woods Granophyre (Zlwg) and Rams Head Porphyry (Zrhp), and they are crosscut by basalt/dolerite dikes. The dikes all have conspicuous chill zones. There are three main compositions: 1) gray porphyritic andesite/dacite, 2) tan to red porphyritic dacite/rhyolite, and 3) rhyolite containing many course embayed and rounded xenocrysts of quartz and feldspar and rounded multi-grain xenoliths from coarse granitic rocks.

1. Gray porphyritic andesite/dacite dikes in the northeast Fells along shore of Spot Pond and in Pond Street area to Whip Hill may be associated with the Stoneham Granodiorite (Zst). They primarily occur in the Westboro Formation.
2. At Wenepoykin Hill, reddish-gray porphyritic rhyolitic dikes cut through the Spot Pond Granodiorite (Zsg) and Westboro Formation (Zvwq) but are crosscut by the Rams Head Porphyry (Zrhp) indicating an age from 609-595 Ma.
3. In the northern Fells and beyond, rhyolite/dacite dikes do not occur in the Stoneham Granodiorite (Zst).
4. Irregular reddish-brown porphyritic rhyolite dikes cut through the Winchester Granite (Zwg). These dikes are not aplite dikes, which have also been found in the Winchester Granite.
5. Several rhyolitic dikes with abundant coarse, embayed, and rounded and resorbed quartz, plagioclase, and alkali feldspar xenocrysts as well as similar multi-grain xenoliths post-date a coarse granitic plutonic body in the Fells (Stoneham Granodiorite, Spot Pond Granodiorite, or Winchester Granite). These dikes have been found in the Westboro Formation at Whip Hill (Zwp), Spot Pond Granodiorite (Zsg), and Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc).
6. All felsic dikes are cut by the basalt and dolerite dikes in the Fells indicating that the felsic dikes are older and likely associated with a Neoproterozoic plutonic body.

BIG Qs: How many ages and what are the ages, origins and sources relative to granitic plutons?

Wanapanaquin Porphyry (Zwap): Porphyritic tonalite to granodiorite, sometimes with orange color due to hematite or other iron oxide stain in its matrix. Only occurs on Wanapanaquin Hill. Same composition as Stoneham Granodiorite (Zst) but has rusty orange color. Has less alkali feldspar than the Winchester Granite (Zwg).

1) Appears to be a porphyritic branch of the Stoneham Granodiorite (Zst) west of a major fault that runs along the west flank of Bear Hill. Similar in texture to contact areas of the Stoneham east of the fault. This would be the only area of the Stoneham exposed west of the Bear Hill fault.

2) Intrudes the Nanepashemet Formation (Znpm).

3) Crosscut by dolerite dikes (d) and altered dolerite dikes (ad).

Stoneham Granodiorite (Zst): Mostly equigranular granodiorite to tonalite. Porphyritic in chill zones. Contains altered plagioclase with clean rims. Higher mafic content than other large granitic intrusive bodies in the Fells. Orangish color in places is due to iron oxide in matrix. Has less alkali feldspar than the Winchester Granite (Zwg).

1) Has abundant inclusions from: 1) the Westboro Fm. (Zvwq), both white quartzite and argillite hornfels and 2) basalt hornfels of the Nanepashemet Formation (Znpm) and Lynn Volcanic Complex (Zlbf), all of which it intrudes. Inclusions are very abundant on Deer Hill and its Rt. 93 roadcut, on islands in northwest Spot Pond, along Pond Street northwest of Spot Pond and north of Spot Pond in Stoneham.
2)) The chill zone contact where it intrudes the Lynn Volcanic Complex (Zlvf) at the small peninsula forming the east side of the northwest cove of Spot Pond has large rhyolite inclusions from the Lynn.
3) Unit appears to have a roof pendant of hornfels of the Westboro Fm. (Zvwq) on Deer Hill and at Sheepfold, and of the Nanepashemet Fm. (Znpm) at Sheepfold and further north on Winthrop and Bear Hills and on Taylor Mountain.
4) Probably feeds the Wanapanaquin Porphyry (Zwap).
5) Separated from Winchester Granite (Zwg) by a major fault on the west side of Bear Hill.
6) The only other plutonic body with which the Stoneham has a visible contact is the Spot Pond Granodiorite (Zsg) near Doleful Pond and Stoneham High School. Intrusion into the Westboro Fm. at Whip Hill (Zwp) seems likely, but no visible contact has been found, and this may be a fault contact concealed by wetlands north of Whip Hill.
7) This unit appears to underlie much of the northern half of Spot Pond and is likely the source of gray andesite to dacite dikes (ad) on Whip Hill and along Pond Street in Stoneham.
8) The Stoneham has a contact with much assimilation of the Westboro Formation along the shore of Spot Pond at the south end of the Stoneham Zoo parking lot and along nearby Pond Street.
9) U-Pb age: 595.08 $\pm$ 0.17 Ma (zircon, CA-ID-TIMS) from Pond Street northwest of Spot Pond. Slightly younger than the Lynn Volcanic Complex at Wamoset Hill and slightly older than the Lynn Volcanic Complex at Middle Reservoir. It intrudes the Lynn at the north end of Spot Pond. This unit is too young to be associated with the Dedham Complex (Spot Pond Granodiorite and Winchester Granite).

The Upper Lynn Volcanic Complex in the Northern Fells

(Zlbf, Zlvf, Zlvx): These units form a gently dipping (nearly horizontal) bimodal volcanic sequence at the northwest corner of Spot Pond (Straw Point) including sialic and basaltic units interbedded with contorted and coarse to fine basaltic sediment and tuff. A banded rhyolite flow at the north end of Middle Reservoir is mapped with this unit. Basaltic units (and its bimodal character) make it unique among volcanic units of similar age within the Lynn Volcanic Complex in the Fells, but the basaltic units are abundant to the north and northeast of the Fells (see Smith and Hon, 1984; Smith, 1985; Cardoza, 1987; and Cardoza et al., 1990.

1) At the northeast corner of Middle Reservoir low-angle banded felsic lava and layered pyroclastic units sit on an angular unconformity over steeply dipping beds in hornfels and conglomerate of the Nanepashemet Formation (Znpm).
2) Intruded by Stoneham Granodiorite (Zst) at Straw Point and the northeast corner of Dark Hollow Pond.
3) Tuff units contain embayed and rounded quartz xenocrysts from a medium to coarse granodiorite and granite (likely Zsg or Zwg).
4) Lynn Volcanic Complex rocks are entirely felsic at the north end of Middle Reservoir, but this is a small outcrop area and slightly younger than parts of the unit at Spot Pond. Pyroclastic units at Straw Point (Zlvx) have basaltic lithic fragments.
5) U-Pb age: Zlvf at Middle Reservoir is 594.70 $\pm$ 0.32 Ma (zircon, CA-ID-TIMS). This is slightly younger than ages for the Lynn Volcanic Complex (Wamoset Hill) and Stoneham Granodiorite in the Spot Pond area. The radiometric age at Middle Reservoir is statistically indistinguishable from the Stoneham Granodiorite that intrudes the units at Straw Point (northwest corner of Spot Pond).
6) U-Pb age: Zlvf at the north end of Spot Pond is 595.27 $\pm$ 0.34 Ma (zircon, CA-ID-TIMS).

The Upper Lynn Volcanic Complex in the Northern Fells (cont.)

Lynn Volcanic Complex from east of Whip Hill Park to north end of Spot Pond (Zlvf, Zlvx): Welded and non-welded crystal and lithic tuffs and banded rhyolite forming tuff and lava flows. Pyroclastic units contain embayed quartz crystals. No basaltic lithic fragments have been found in these areas.

1) The unit's upper surface is in fault contact with the Westboro Formation at southern Whip Hill (Zwp).
2) Contains quartzite and argillite lithic fragments from the Westboro Fm. (Zvwq and Zwp).
3) Contains embayed and rounded quartz xenocrysts from medium to coarse granite or granodiorite (Zwg, Zsg). (Too old for the Stoneham Granodiorite (Zst) to be included.
4) Unconformably overlies the Westboro Fm. of Virginia Wood (Zvwq) on Wamoset Hill and outside the Fells in Sewall Woods Park along the Lynn Fells Parkway. Unit does not have the metamorphic grade or fabric of the Westboro Fm. in Virginia Wood (Zvwq)
5) It has strictly felsic (rhyolitic) components unlike the Lynn Volcanic Complex at the north end of Spot Pond which has felsic and basaltic components.
6) U-Pb age at Wamoset Hill: 595.82 $\pm$ 0.23 Ma (zircon, CA-ID-TIMS). This age is younger than the Spot Pond Granodiorite and Winchester Granite by about 13 Myr but only slightly older than the Stoneham Granodiorite and Lynn Volcanic Complex at Middle Reservoir and northwest Spot Pond. This unit is younger than the Boojum Rock Tuff (Zbrc) of the Lynn Volcanic Complex in the southeastern Fells.

Q1: How are these units related to proposed members of the Lynn to the East (Smith, 1985; Smith and Hon, 1984)?

Lawrence Woods Granophyre (Zlwg): Pinkish-gray to gray granophyric porphyry with euhedral phenocrysts of plagioclase, embayed quartz, granophyric grains of fine alkali feldspar and quartz, and needle-like amphibole phenocrysts. Subvolcanic intrusive unit that is associated with the Lynn Volcanic Complex as is found further east (Smith and Hon, 1984; Smith, 1985). In current mapping outside the Fells other granophyric bodies that are subvolcanic units associated with the Lynn have a similar lithology and are lumped into this unit but might have a slightly different age.

1) Intrudes and has chill zone against Upper Lynn Volcanic Complex at Boojum Rock, Wrights Pond, and in the Pine and Middle Hill areas (Zlvv, Zlvx, Zlvc).

2) Intrudes and has chill zone against Spot Pond Granodiorite (Zsg) in Lawrence Woods, and on Pine, Little Pine, and Middle Hills, and near Boojum Rock.

3) Intrudes and has chill zone against the Rams Head Porphyry (Zrhp) at the entrance to Medford High School. This is contrary to U-Pb zircon ages for the Lawrence Woods and Rams Head, but just barely and this difference is not statistically distinct (see #7 below).

4) Contains xenolith of Zlvx in valley along west side of fault west of Middle Hill.

5) Has a peculiar contact zone with the Lynn Volcanic Complex (Zlvx) on Pine Hill that makes the Lynn look porphyritic along the contact. The volcanic rock appears to be recrystallized along the contact.

6) Has an inclusion of the Rams Head Porphyry (Zrhp) south of South Border Road near Lawrence Memorial Hospital in Lawrence Woods. This is contrary to U-Pb zircon ages for the Lawrence Woods and Rams Head, but just barely and this difference is not statistically distinct (see #7 below).

7) U-Pb (zircon, CA-ID-TIMS) ages (2 populations, 3 crystals each, both possibly inherited): 598.13 $\pm$ 0.27 Ma; 596.77 $\pm$ 0.25 Ma from Elm Street in North Medford. U-Pb (zircon, CA-ID-TIMS) age (population of 3 crystals plus several much older crystals): 596.50 $\pm$ 0.53 Ma at Pine Hill on west side of Rt. 93. Unit shows field evidence of being younger than the Rams Head Porphyry (see #5 and #6 above). Ages could be too old due to prolonged crystal growth and some inherited grains.

8) Since ages of Zlwg and Zrhp are close they may be separate but closely related magma pulses. These units are too young to be part of the Dedham Granodiorite (Spot Pond Granodiorite and Winchester Granite) by about 13 Myr.

Rams Head Porphyry (Zrhp): Porphyritic, highly plagioclase-dominated tonalite to quartz diorite porphyry with very low alkali feldspar content.

1) Unit has a chill zone and partly assimilated inclusions in contact with the Spot Pond Granodiorite (Zsg) just west of Rt. 93 near Wenepoykin Hill and at the southern end of South Reservoir. Inclusions are well exposed at the point on the west side of the small eastern embayment at the south end of South Reservoir.
2) Has an inclusion in the Lawrence Woods Granophyre (Zlwg) in Lawrence Woods but this is contrary to U-Pb zircon ages, but just barely and this difference is not statistically distinct (see item #7 of the Lawrence Woods Granophyre above.)
3) Crosscuts reddish-colored rhyolite dikes that cut through the Spot Pond Granodiorite on Wenepoykin Hill.
4) U-Pb zircon (CA-ID-TIMS) age: 596.24 $\pm$ 0.16 Ma. Age close to (slightly younger than) Lawrence Woods (Zlwg). Field relationships indicate an age older than the Lawrence Woods. This age, the more dioritic composition of the unit, and the abundant plagioclase and hornblende crystals in the Boojum Rock Tuff (Zbrc) suggest that the Rams Head may be co-magmatic with the Boojum Rock which has a similar age.

Zdg: A sliver of diorite-hornblende gabbro in the southwestern Fells. This unit has not been recognized previously. The unit has <2% quartz (possibly melted inclusions from the locally intruded Westboro Fm.) and no alkali feldspar with 45% plagioclase and 55% amphibole (hornblende). It does not closely resemble any granitic plutonic unit in the Fells.

1) The north side of the diorite-gabbro exposure is an intrusive contact with the Westboro Formation (Zvwq).
2) The south side of the body is truncated along a major E-W trending fault.
3) U-Pb age: 596.02 $\pm$ 0.32 Ma (zircon, CA-ID-TIMS).

Upper Lynn Volcanic Complex in the Southern Fells

Pine Hill area (Zlvx, Zlvc):

Welded to non-welded crystal and lithic tuffs of Pine and Middle Hills and at eastern Wrights Pond. Rests on basal volcaniclastic rocks with quartz and alkali feldspar crystals, clasts derived from Spot Pond Granodiorite (Zsg), and volcanic and quartzite/argillite hornfels lithic fragments from the Westboro Formation. Includes greenish-gray diamictite basal units on Middle Hill that do not appear to be glacial. A similar pattern is recognized for the Lynn Volcanic Complex in the Boojum Rock area.

1. Zlvc inclusion in Lawrence Woods Granophyre (Zlwg) west of fault on west side of Middle Hill.
2. Zlvx and Zlvc intruded by Lawrence Woods Granophyre (Zlwg) on southern Pine, Little Pine and Middle Hills, and at Wrights Pond with chill zone in Zlwg. The age difference is likely very small, and the two units are likely related.
3. Zlvc has granite debris from the Spot Pond Granodiorite (Zsg) in volcaniclastic conglomerates on Middle, Little Pine, and Pine Hills and west of Middle Hill.
4. Quartzite lithic fragments and clasts (some with flattened and sutured, but also some with intact, round grains) from the Westboro Formation like in both the Virginia Wood (Zvwq) and Whip Hill (Zwp) areas, and abundant volcanic lithic fragments of a variety of types.
5. Sampling for a U-Pb age was not attempted because of abundant lithic fragments from older units and no flows were found.

BIG Q1: How is this unit related to the Upper Lynn Volcanic Complex in the northern Fells? Similar lithologies as Lynn Volcanic Complex at Wamoset Hill except for the banded rhyolitic flows at Wamoset Hill.

BIG Q2: What are its equivalent units further east in the Lynn Volcanic Complex (see members of Smith and Hon, 1984 and Smith, 1985)?

Lynn Volcanic Complex in Boojum Rock area (Zlvv, Zlvx, Zlvc, Zlvp): occurs at northeast corner of Wrights Pond and on Boojum Rock as far east as the MIT Observatory. Above the basal clastic unit (Zbjc) these volcanic units tend to have a pale reddish to purplish color.

Zlvv - ultra fine-grained chert-like vitric tuff with very small crystals that are hard to detect in outcrops.

Zlvx - mixture of pyroclastic banded and welded crystal to lithic tuffs with a dark purplish-gray color and in some places very well preserved primary volcanic structures such as pyroclastic banding and fiammé. Includes areas that look like coarse dark gray porphyry but are a highly welded crystal tuff. Also has patches of reddish volcanic breccia like in unit below. At northeast corner of Wrights Pond includes dark reddish-black welded and banded tuff with varying crystal and lithic fragment concentrations.

Zlvc – The base of this unit is a poorly sorted green sandstone that gives way upward to a polymictic volcaniclastic breccia. The volcanic breccia has highly angular red volcanic clasts and grades into better sorted rounded-pebble, clast-supported, polymictic conglomerate. The matrix of this unit is a poorly sorted greenish-gray sandstone. Clasts are volcanic, quartzite, alkali granite (possibly Ball Quarry Granite of Smith and Hon, 1984 and Smith, 1985), red sandstone, and interbedded argillite and fine sandstone.

Zlvp –traceable dike-like zone of reddish- to pinkish-gray porphyritic rhyolite with non-broken, euhedral and cumulophyric plagioclase crystals and sparse lithic fragments. Has flow-banded zones and thinner volcaniclastic zones with rounded volcanic clasts along its contacts with the Boojum Rock Tuff (Zbrc). Has not been found south of a large E-W trending dolerite dike on Boojum Rock. It appears to be an intruded fissure associated with the Lynn.

Contacts and continuity of the facies are hard to trace because of intense shearing and dismemberment of rock units east of the Quarter Mile Pond Fault along Woodland Road.

1) Breccia and conglomerate of Zlvc rest on an unconformity on the Boojum Rock Tuff (Zbrc) near the MIT Observatory and the Spot Pond Granodiorite (Zsg) near Woodland Road.
2) Basal unit contains granite pebbles and boulders including red alkali granite, possibly from the Ball Quarry Granite to east (Smith and Hon, 1984; Smith 1985), and abundant quartz grains, which are much smaller and rare in the underlying Boojum Rock Tuff (Zbrc). Basal unit is an olive-green volcaniclastic diamictite to poorly sorted sandstone like found in the basal unit of the Lynn Volcanic Complex in the Pine Hill area. Lithologies in this unit change locally.
3) Intruded by Lawrence Woods Granophyre (Zlwg) along Woodland and East Border Roads. In some places the base has an intensely reddish-brown color suggestive of oxidation by weathering or oxidation related to contact metamorphism near its contact with the Lawrence Woods.
4) Well preserved volcanic structures: units with banding and flattened pumice with rapid facies changes.
5) Many dark reddish- to purplish-gray to reddish-brown banded tuff and crystal tuff lithic fragments.
6) Red porphyritic rhyolite unit (Zlvp) seems to form a fissure cutting across the older Boojum Rock Tuff (Zbrc), likely as a branch of the nearby Lawrence Woods Granophyre (Zlwg).

Boojum Rock Tuff Member of the Lynn Volcanic Complex (Zbrc, Zbrl, Zbrv): dacitic to andesitic crystal and lithic tuff that is dark greenish-gray on fresh faces with a dominance of broken plagioclase crystals (up to 50% of rock), scattered, but conspicuous, hornblende crystals in various states of alteration, and very rare, tiny, broken quartz crystals (xenocrysts from quartzite). All units have steeply eastward-dipping features. Unit contains no coarse embayed quartz crystals like all younger felsic volcanic units in the Lynn Volcanic Complex.

Zbrv - an area of vitric, faintly-banded tuff on the southeastern side of the Fells that has small crystals that are difficult to detect in outcrops.

Zbrl - traceable zone of lithic crystal tuff within Zbrc that has volcanic and quartzite lithic fragments, some up to 10 cm across. A fiammé zone occurs at the top (eastern side) of this unit.

Zbrc - crystal tuff occurring over a wide area in the southeastern Fells and eastward into Malden and Melrose.

Zbrr – red crystal tuff identical to the Zbrc unit in the Fells in the Malden and Melrose area (near and around Pine Banks Park). The red color may be a hydrothermal alteration.

Entire unit is massive and pyroclastic with no flows or intrusive component.

1) Volcanic (felsic) and quartzite/argillite lithic fragments but no granitic fragments or debris.
2) Has only rare, fine-grained, angular and broken quartz fragments that are xenocrysts from the Westboro Fm. Unlike all other felsic volcanic units in the Fells, it has no coarse embayed or resorbed quartz inherited from granitic plutonic bodies.
3) Subtle cleavage-like fractures that are not found in the younger volcanic units suggest a period of light deformation not experienced by the younger units. This deformation is associated with slickensided surfaces that have hematite mineralization and epidote veins, especially near the MIT Observatory on Boojum Rock.
4) Basal breccias and conglomerates of the Upper Lynn Volcanic Complex at Boojum Rock (Zlvc) lie unconformably on the Boojum Rock Tuff near the MIT Observatory.
5) U-Pb age on zircon crystals (Zbrc) near Pinnacle Rock: 596.35 $\pm$ 0.21 Ma (CA-ID-TIMS). This date is from high in the tuff unit in its youngest part. The chemistry of this unit is dacitic to andesitic and its age is like the age of the Rams Head Porphyry (Zrhp) that may be subvolcanic to the tuff.
6) The Boojum Rock Tuff may unconformably overlie the Westboro Fm. (Zvwq) south of Virginia Wood, but this contact is concealed by glacial sediment. Further east in Malden and Melrose at Pine Banks Park and in the East Wyoming Ave area of Melrose the Boojum Rock Tuff unconformably overlies the Westboro Formation.
7) A contact with the Spot Pond Granodiorite (Zsg) is exposed east of Woodland Road, but age relationships are hard to interpret and are revealed only by radiometric ages in both units, which indicate the Spot Pond is older by about 13 Myr. No granite debris has been found in the base of the Boojum Rock. It appears that the Boojum Rock unconformably overlies the Spot Pond because the contact is too irregular to be a fault.
8) The Boojum Rock Tuff is unconformably overlain by the Upper Lynn Volcanic Complex and is interpreted to be the basal unit of the Lynn in the Fells area and further east in Malden and Melrose.

The Dedham Complex

Spot Pond Granodiorite (Zsg): coarse mostly granodiorite with minor granite and tonalite. Has perthitic alkali feldspar and a high quartz content. Plagioclase dominates feldspar. This rock type is the "ideal" Dedham Granodiorite and is considered here to be a part of the Dedham (Granodiorite) Complex but previous works (Kaye, 1980; Smith and Hon, 1984; Smith, 1985) lumped three other units with them, the Lawrence Woods Granophyre (Zlwg), Rams Head Porphyry (Zrhp), and Stoneham Granodiorite (Zst) that are now known to be younger by at least 13 Myr.

1) Rare xenoliths of felsic volcanic rock (Zfi) of uncertain origin and age are in the unit.
2) An indistinct contact with the Boojum Rock Tuff Member of the Lynn Volcanic Complex (Zbrc) is exposed east of Woodland Road and west of the Fells Reservoir, but age relationships are hard to interpret in the field and are revealed only by radiometric ages in both units, which indicate the Spot Pond is older. No granite debris has been found in the base of the Boojum Rock. It appears that the Boojum Rock unconformably overlies the Spot Pond.
3) Abundant large xenoliths of the Westboro Fm. (Zvwq) are found in the Spot Pond at the south end of Spot Pond, along Rt. 28, and west of Rt. 93 near the Winchester Reservoirs. These inclusions and Zsg get truncated along contacts with the Lawrence Woods Granophyre (Zlwg) and Rams Head Porphyry (Zrhp).
4) The contact area with the Westboro Fm. west of Rt. 93 has a well-defined vertical foliation paralleling the contact with the Westboro Formation (Zvwq) and paralleling a major E-W fault. The foliation is interpreted to be the result of shearing of weak (warm) granodiorite but not associated with the fault. The fault has brittle fracturing that allowed deep glacial erosion of the fault zone, and it displaces dolerite dikes that cut the foliation in the granodiorite. Therefore, the fault appears to be younger than foliation in the granodiorite. Magnetic susceptibility shows a well-defined lineation that indicates shear in the foliation plane with an east-west trend (i.e., horizontal shear on the nearly vertical foliation plane).
5) Pieces of Zsg occur in the Lynn Volcanic Complex (Zlvc) that rests on an unconformity on the Spot Pond on Pine, Little Pine, and Middle Hills.
6) Contains areas of leucocratic alkali granite (Zsgk) of two types. Are these xenoliths or alkali enclaves? Some resemble the Ball Quarry Granite (Smith and Hon, 1984; Smith, 1985) to the east. Alkali feldspar syenite outcrops north of the Fells and occurs as glacial erratics.
7) U-Pb ages: near Red Cross Path is 609.45 $\pm$ 0.25 Ma (zircon, CA-ID-TIMS), south of Spot Pond is 609.11 $\pm$ 0.22 Ma (zircon, CA-ID-TIMS), and near Doleful Pond is 609.08 $\pm$ 0.24 Ma.

BIG Q1: What is the source of the felsic volcanic inclusions (Zfi)?

BIG Q2: Are the alkali granite blocks xenoliths or crystallization enclaves?

Winchester Granite (Zwg): Dark reddish- to orangish-pink, alkaline appearing, medium-grained, equigranular mostly granodiorite with secondary granite and tonalite. In places has red-colored K-spar and elongate lenticular pinkish-red rhyolite dikes. Unit is never porphyritic, even in contact areas. This rock type is finer than the "ideal" Dedham Granodiorite in the Spot Pond Granodiorite (Zsg) but is part of the Dedham Complex. Previous works (Kaye, 1980; Smith and Hon, 1984; Smith, 1985) lumped it into the Dedham with other units now known to be younger by 13 Myr: the Rams Head Porphyry (Zrhp) and Stoneham Granodiorite (Zst). The unit is more alkaline than either of these units.

1) Intrudes the Nanepashemet Formation (Znpm) over a wide area of the northwest Fells creating altered (baked) basalt in the Nanepashemet. Along the contact the Nanepashemet may recrystallize to amphibolite with course hornblende crystals.
2) Dark orangish-red, very fine chill zone along contact with the Nanepashemet at the north end of Middle Reservoir.
3) Intrudes the Westboro Fm. (Zvwq) with relatively smooth intrusive contact over long distances and sparse Westboro xenoliths.
4) Has many light-colored rhyolite dikes (fp) that do not occur in the Stoneham Granodiorite (Zst).
5) Separated from Stoneham Granodiorite by a major fault at the west side of Bear Hill and does not have a contact with the Stoneham.
6) Contains xenoliths or enclaves (?) of alkali granite (mapped as Zsgk like in the Spot Pond) and a large xenolith of quartz diorite (Zwgd) on Money Hill in Winchester. This unit, because of its quartz content, does not appear to be related to rock that is more mafic and assimilated into the Winchester Granite (next item).
7) At the northeastern corner of North Reservoir there are areas of highly assimilated mafic rock that gives the Winchester a mafic and spotted appearance and reduced quartz content. These areas ("spotted facies") are mapped as part of the granite.
8) U-Pb age east of Long Pond: 609.72 $\pm$ 0.24 Ma (zircon, CA-ID-TIMS). This age is significantly older than the Lynn Volcanic Complex and Stoneham Granodiorite by 13 Myr.

Nanepashemet Formation (Znpm): Altered dark (almost black) to medium gray to greenish-gray basalt, dark greenish-black baked, basaltic fine sediment to breccia, basaltic tuff, and volcanic-pebble conglomerates, all baked. Unit appears massive in outcrop and is usually altered by younger intrusions: Stoneham Granodiorite (Zst), Winchester Granite (Zwg), and mafic dikes (d, dp). Amphibolite due to recrystallization in some contact areas that sometimes have garnet. It has a quartzite-bearing gray conglomerate/breccia and red to black laminated sandstone/mudstone in its base along Molly's Spring Road. It has baked, mafic volcanic pebble conglomerate (with a few felsic pebbles) and a marble (skarn) unit at the north end of Middle Reservoir.

1) Unit unconformably overlies the Westboro Formation (Zvwq) along the north side of Molly's Spring Road. This contact is rarely exposed due to faulting and intrusions. There is a change in metamorphic grade across the contact and truncation of regional metamorphic foliation below in the Westboro Formation. The base of the unit contains conglomerate, breccia, and mudstone with clasts from the Virginia Wood and occasionally well-preserved sedimentary layering that has not been altered by metamorphism.
2) Unconformably overlies the Westboro Fm. (Zvwq) at the south end of Sheepfold where both rock units have been baked to hornfels by intrusion of the Stoneham Granodiorite (Zst).
3) At the north end of Middle Reservoir steep bedding in hornfels is truncated by gently dipping layering in rhyolitic pyroclastic and flow units in the Lynn Volcanic Complex (Zlvf) indicating an unconformity.
4) Structures in this unit are recrystallized and obscured by contact metamorphism across most of the Fells, forming mostly a basaltic hornfels with abundant epidote and chlorite.
5) Radiometric ages cannot likely be obtained from this unit. It post-dates the Westboro Formation (Zvwq), which is less than ~910 Ma, and is intruded by the Winchester Granite at ~610 Ma and these are the only numerical constraints on its age.

Mapping has reinterpreted areas previously mapped as quartz vitrophyre and vitrophyre by Kaye (1980) as altered basalt. No basaltic flow or pillow structures or vesicular units have been found in the Fells although amygdaloidal basalt pebbles occur in the unit's breccias and conglomerates. Previously, the Nanepashemet Formation and basaltic areas of the Lynn Volcanic Complex of this map at Straw Point on Spot Pond and further north in Stoneham were mapped together as the Middlesex Fells Volcanic Complex. New radiometric ages make it impossible for them to be part of a single unit. So far, no felsic volcanic units have been found associated with the Nanepashemet Fm. as mapped here,

BIG Qs: In what tectonic environment did this unit form? How can we date this unit?

The Westboro Formation – Two areas of the Westboro Formation have been mapped separately because of lithologic differences and differences in metamorphism.

Westboro Formation on Whip Hill (Zwp): Gray, laminated to massive, rusty-weathering mudstone, siltstone, and fine sandstone with light to medium gray sandstone olistoliths with soft-sediment deformation in muddy mass flow units. The olistoliths have pinched ends and extremely round, medium sand grains that are not deformed or sutured, and have no indication of metamorphism. The sand grains are almost exclusively quartz. The whole unit has no foliation resulting from regional metamorphism and has well preserved laminated bedding that strikes ~E-W and dips steeply (+75° in most places with some slightly overturned) with up to the north. Unit has ripple crossbeds and cut and fill structures. Laminated mudstone and siltstone with preserved bedding has a strong anisotropy of magnetic susceptibility (AMS) foliation at a low angle to bedding but a weak lineation that suggests a sedimentary fabric. Could be a candidate for a paleomagnetic pole position if not rotated or overprinted by local intrusions and volcanic rocks.

This part of the Westboro Formation is separated in mapping from the rest of the Westboro because of several characteristics that are different than the Westboro in other areas, especially Virginia Wood.
A. The unit has well preserved bedding and sedimentary structures.
B. The unit is not regionally metamorphosed and has no cleavage. Sand grains are very well rounded and not deformed and sutured. Hornfels does occur in the unit near intrusions.
C. The unit has no calcium-magnesium silicate zones resulting from an original carbonate component.

1) Includes a small contact area with volcanic rock of the Lynn Volcanic Complex at north end of Whip Hill. This contact is very irregular, is not a fault surface, and indicates that the volcanic rock lies unconformably on the unit.

2) Its southern boundary is a fault contact with the Lynn Volcanic Complex (Zwh) in a fault block to the south.

3) Unit is heavily baked by Stoneham Granodiorite (Zst) in some areas forming a hornfels, especially along the northeast shore of Spot Pond next to the Stone Zoo.

4) U-Pb zircon ages (LA-ICPMS) on 210 zircon grains from a quartz sandstone olistolith on Whip Hill indicate a maximum age of ~910 Ma and an age distribution identical to other parts of the Westboro Formation in Virginia Wood and further east outside the Fells.

BIG Q: This appears to be an unmetamorphosed section of the Westboro Formation. How did this happen?

Westboro Formation (Zvwq) of Virginia Wood and west of Spot Pond:
Interlayered white to dark gray quartzite and foliated siliceous argillite with areas of calcium/magnesium silicate rocks containing tremolite, diopside, calcite, and zoisite. Unit has mylonitic and necked quartzite layers and units with highly stretched and flattened, sutured, and polycrystalline quartz grains with muscovite tails and shadows in some places. Has preserved bedding in isolated places with a bedding parallel metamorphic foliation and a well-developed AMS (anisotropy of magnetic susceptibility) foliation parallel to layering with a weak lineation indicating flattening parallel to bedding (pure shear). Small scale folds of the unit's foliation occur in a few places but are most common in calcium/magnesium-silicate units.

1) Unit is metamorphosed with a distinct metamorphic fabric not seen in any other unit in the Fells except for one zone in the Spot Pond Granodiorite (Zsg).
2) On Wamoset Hill, foliation is truncated by an unconformity beneath a rhyolitic flow in the overlying Upper Lynn Volcanic Complex (Zlvf).
3) Forms large xenoliths in the Spot Pond Granodiorite (Zsg).
4) Forms lithic fragments in the Boojum Rock Tuff of the Lynn Volcanic Complex (Zbrc) and all younger volcanic units.
5) Has the same zircon age population as quartzites further east near Breakheart Reservation in the Westboro Formation (Thompson et al., 2012). Detrital zircon crystals yielded a youngest U-Pb age of 909 +/-24 Ma (LA-ICPMS; F. MacDonald, pers. com.) with the youngest zircon having a precise age of 912 $\pm$ 0.6 Ma (CA-ID-TIMS, F. MacDonald, per. com.)
6) Occurs as pebbles in the base of the Nanepashemet Formation west of South Reservoir along Molly's Spring Road.