CONGLOMERATE IN AND AROUND THE BOSTON, BASIN, MASSACHUSETTS: U-PB GEOCHRONOLOGY, STRATIGRAPHY AND AVALONIAN TECTONIC SETTING

by

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INTRODUCTION

The bedrock geology of the Boston Basin presents numerous difficulties. The lack of outcrops in some areas impedes definitive conclusions on the stratigraphy and structure… The scarcity of fossils prevents their use in correlation. Moreover, many of the major rock units cannot be dated with any precision.
— Marland P. Billings (1976)

So begins Billings' enduring synthesis of Boston Basin geology. At that time, Dedham Granite unconformably overlain by fossiliferous Cambrian strata was clearly known to be Precambrian (Billings, 1929; Dowse, 1950), but stratified units within and around the Basin still appeared as *Mississippian (?)* and *Pennsylvanian (?)*. Microfossils (Vendian of Lenk et al., 1982) found in the Cambridge Argillite portion of the Boston Bay Group (LaForge, 1932) together with results of pioneering U-Pb geochronology by Robert Zartman and colleagues (Kaye and Zartman, 1980; Zartman and Naylor, 1984; Hermes and Zartman, 1985) soon provided evidence for more widespread Precambrian age. Thirty years later, many additional U-Pb results now establish latest Precambrian—specifically Ediacaran—ages for plutonic and volcanic rocks here and across southeastern New England (Table 1). Dates based on other chronometers (especially K-Ar and Rb-Sr) can be found in Zartman and Marvin (1991), but these are no longer useful for stratigraphic or tectonic interpretation because they have rarely been confirmed by subsequent U-Pb analyses from the same rocks. Even U-Pb dates obtained earlier than about 1985 (first column of Table 1) are best avoided because then available techniques could not overcome problems of Pb loss and inheritance in samples numbering many hundreds of zircons (further discussion in Thompson et al., 2010). In most cases, pre-1985 entries based on "batch" zircon analyses have been superseded by more accurate and precise results in the right hand columns of Table 1. The latest entries (Thompson et al., 2014) now provide age constraints on deposits traditionally assigned to the Roxbury Conglomerate portion of the Boston Bay Group.

Currently available U-Pb zircon dates summarized here also bear on several broader tectonic issues. The 595-585 Ma interval established for Roxbury Conglomerate deposition, first of all, extends the chronology of subduction-related activity across southeastern New England past the 609-589 Ma interval previously obtained from regionally more extensive plutonic and volcanic units (Table 1). This record of arc magmatism in the southeastern New England segment of the terrane now known as Avalonia (Hibbard et al., 2006), moreover, is largely composed of high precision CA-TIMS [chemical abrasion-thermal ionization mass spectrometry] analyses from single zircons. This method leads to more accurate and precise age constraints than those generated earlier in more northerly terranes extending through Atlantic Canada to Newfoundland where Avalonian tectono-stratigraphic relationships were first articulated. U-Pb zircon geochronology around Boston, therefore, not only clarifies the litho-stratigraphic relationships in southeastern New England, but has implications for other Avalonian terranes as well (complete discussion in Thompson et al., 2014).

The trip will proceed stratigraphically from basement on the south side of the Boston Basin through a variety of sedimentary units within the Basin itself. The colored map showing stop locations cannot be re-produced here, but will be handed out to participants (or can be obtained as a pdf by emailing the author). Here, approximate stratigraphic positions of field trip stops are numbered in Figure 1. These locations have been chosen to highlight the most recently completed U-Pb zircon dates (Thompson et al., 2010 and 2014). The new constraints reveal several problems with Billings' traditional stratigraphic interpretation, and these will be discussed at various stops during the trip.

TABLE 1

U-Pb geochronological constraints on Neoproterozoic bedrock in the SE New England Avalon Zone

ROCK FORMATION	CURRENT CONSTRAINT (MILLIONS OF YEARS)					
	Through 1985†	Current Constraint				
		Lower intercept date	Upper intercept date	Wted mean $^{207}Pb/^{206}Pb$ date	Wted mean $^{206}Pb/^{238}U$ date	Source
Cambridge Argillite	no data			≤ 570		1
Brighton Igneous Suite	"				584.19 ± 0.70	*2*
					585.37 ± 0.72	″
Roxbury Conglomerate						
Squantum, MA	"				< 596.39 ± 0.79	″
Newton, MA	"				< 598.87 ± 0.71	″
Franklin Park, Boston	"				< 595.14 ± 0.90	″
Westwood quartz diorite	"		589 ± 2			3
Dartmouth Pluton	"		595 ± 5			4
Lynn Volcanic Complex	"				595.8 ± 1.2	5
			596 ± 3			6
Mattapan Volcanic	602 ± 3[7]				593.2 ± 0.7	*2*
Complex				597.4 ± 1.5		5
					596.0 ± 1.4	"
					595.7 ± 1.6	"
			596 ± 2			3
Esmond Granite	621 ± 8[8]				599 ± 2	9
Westwood Granite	no data		599 ± 1			3
Cohasset Granite	"		599 ± 2			10
Fall River Granite	584 ± 7[11]				604.4 ± 1.2	9
	631 ± 10[11]					
Gneisses	621 ± 25[8]					
Hope Valley Alaskite				606 ± 5[§]		12
Northbridge Gneiss				607 ± 5[§]		"
Ponagansett Gneiss				612 ± 5[§]		"
Milford Granite	630 ± 15[11]				606 ± 1.2	9
Dedham Granite	no data	606 ± 3				6
North of Boston		607 ± 4				"
		609 ± 4				"
Dedham Granite	630 ± 15[11]				608.9 ± 1.2	9
					609.1 ± 1.1	"
					609.5 ± 1.1	"
Westboro Formation	< 1500[13]				< 912.23 ± 0.70	14

† $^{207}Pb/^{206}Pb$ date for Fall River Granite; otherwise entries in this column are upper intercept U-Pb dates.

§ Obtained via Sensitive High-resolution Ion Microprobe [SHRIMP]; all other entries in table from Thermal Ionization Mass Spectroscopy [TIMS].

Sources of dates are: 1— Thompson and Bowring, 2000; 2—Thompson and others, 2014; 3—Thompson and others 1996; 4— Hermes and Zartman, 1992; 5—Thompson and others, 2007; 6— Hepburn and others, 1993; 7— Kaye and Zartman, 1980; 8—Hermes and Zartman, 1985; 9—Thompson and others, 2010; 10—Dillon and others, 1993; 11—Zartman and Naylor, 1984; 12—Walsh and others, 2009; 13—Olszewski, 1980; 14—Thompson and others, 2012.

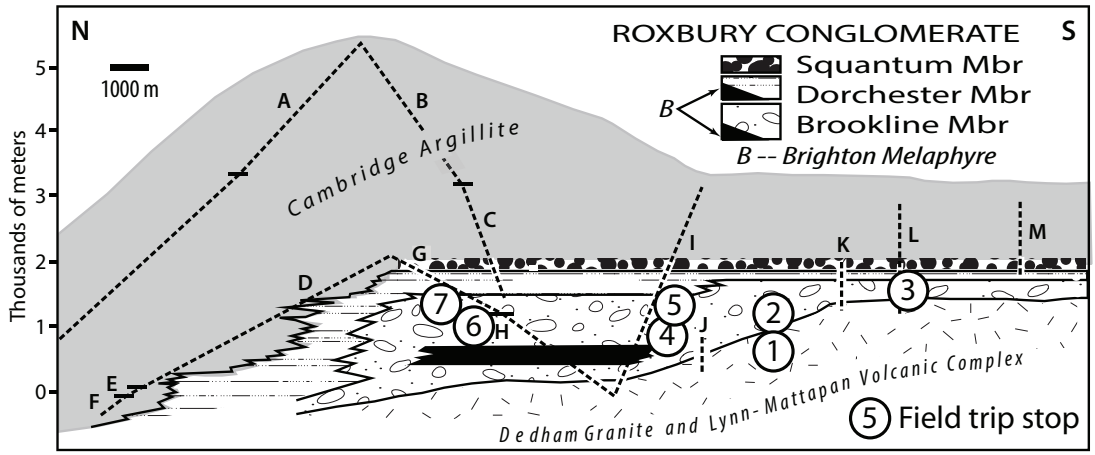

Figure 1. Boston Basin stratigraphy in palinspastic cross section after Billings (1976). Lettered segments show control lines from surface and tunnel mapping: A,B—North Metropolitan Relief Tunnel (Billing, 1975); C—Main Drainage Tunnel (Rahm, 1962); D—north part of City Tunnel Extension (Billings and Tierney, 1964); E—surface geology in Malden, MA; F—Malden Tunnel (Billings and Rahm, 1966); G—south part of City Tunnel Extension; H—surface geology, Brookline, MA; I—surface geology from Brookline to Dorchester, MA; J,K—surface geology in Mattapan, MA;L—surface geology, Dorchester Lower Mills, MA; M—surface geology, Quincy, MA.

ROAD LOG

Meet at 8AM in parking lot east of the Wellesley College Science Center.

Mileage (accuracy ± 0.1 mi pending variable traffic congestion)

0.0 Exit Science Center parking lot.
0.1 Left onto College Road.
0.3 Left at light onto Washington Street.
0.6 Left onto Weston Road.
0.9 Straight across Central Street at light and over railroad tracks.
1.9 Left onto ramp for Route 9 east.
8.2 Exit Route 9 and right at top of ramp onto Parker Street.
9.0 Left onto Dedham Street (which becomes Baker Street).
11.0 Straight across VFW Parkway at light.
11.9 Cross Spring Street.
12.3 Right on Centre Street.
12.5 Straight onto Grove Street (Centre Street turns right).

Park along curb heading south and cross street to office of West Roxbury Crushed Stone Company at 10 Grove Street, West Roxbury, MA. **Day-to-day quarry operations preclude "dropping in" at this site. Our visit here today is facilitated through the kindness of General Manager Ed Sonia.**

STOP 1. DEDHAM GRANITE, UTM 19T $^{03}21^{733}$ E, $^{46}81^{906}$ N (30 minutes).

The Roxbury Crushed Stone Quarry, active since 1887 and 350 feet deep in its lowest level, penetrates Dedham Granite that borders southern and western margins of the Boston Basin. Dedham Granite, like other granitoid bodies that underlie much of Avalonia in southeastern New England, contains variable proportions quartz, plagioclase and K-feldspar vary regionally so that modal compositions range from granite to plagioclase-rich granodiorite and tonalite, as well as quartz-poor monzonite and diorite (Wones and Goldsmith, 1991; Fig 2A). Samples from this quarry are granite, including both coarse-grained and aplitic varieties. Major element compositions of the collective

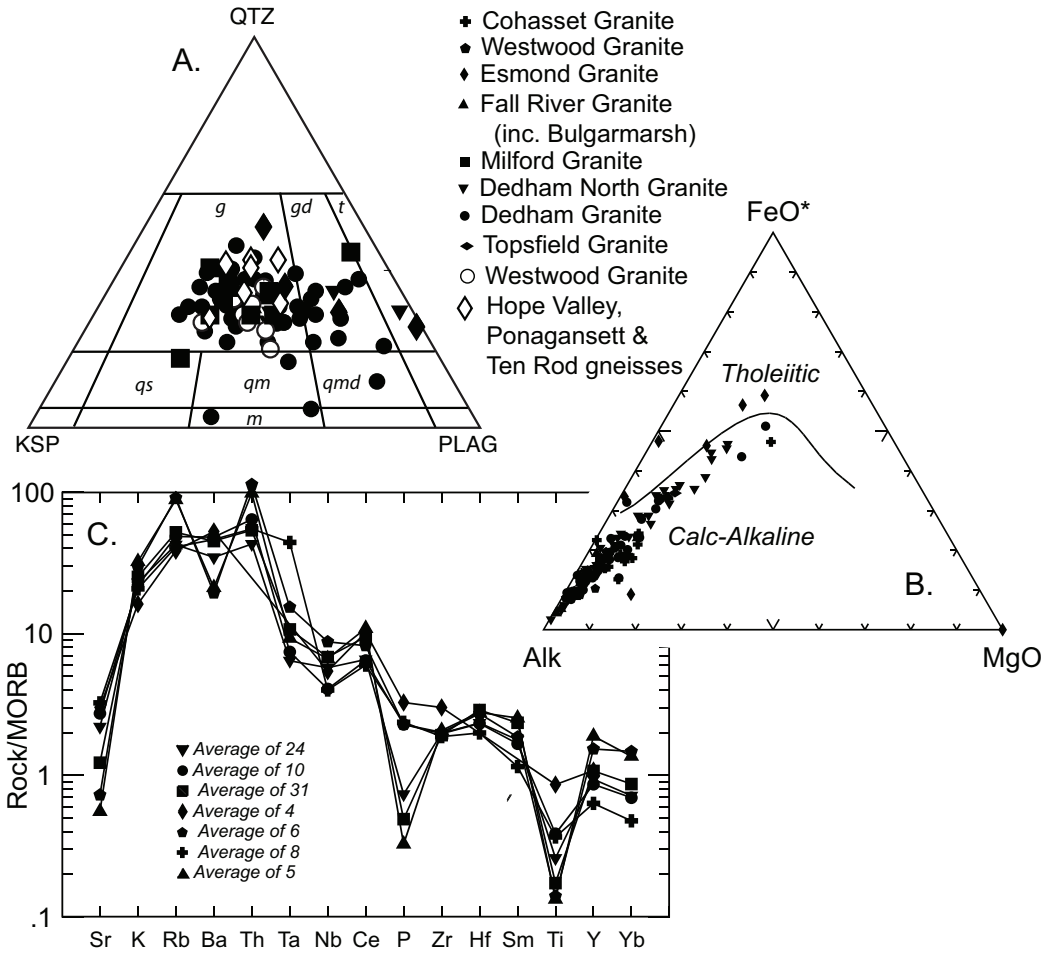

Figure 2. A. IUGS classification of Ediacaran granitoid rocks in southeastern New England based on data in Wones and Goldsmith (1991) and Mancuso et al. (1996). B. AFM plot (Irvine and Baragar, 1971) of all analyses listed in Appendix Table A1 of Thompson et al. (2010). B. MORB-normalized spider diagram (Pearce, 1983) showing elemental values averaged from analyses with most complete REE data (italicized entries in Table A1 of Thompson et al., 2010).

granitoid suite follow a calc-alkaline trend in an AFM plot (Fig. 2B), and trace element patterns (Fig. 2C) are typical of subduction-related granitoid and volcanic rocks (Winter, 2001). Lithotectonically, this suite represents "younger Neoproterozoic magmatic arcs" recognized by Hibbard et al. (2006) in northern Appalachian Avalonian terranes extending all the way to Newfoundland.

Granite from this quarry was among the earliest samples to be dated by U-Pb geochronology in southeastern New England (sample 2 of Zartman and Naylor, 1984). Two batch zircon fractions from this sample yielded discordant $^{207}Pb/^{206}Pb$ dates of 585 ± 6 Ma and 590 ± 5 Ma. These were combined with discordant analyses from both Dedham and Milford granites in other localities to define the 630 ± 15 Ma upper concordia intercept date that has long been cited as the age of Avalonian arc magmatism in southeastern New England. While this work was crucial for establishing late Precambrian ages for these rocks, advances in U-Pb geochronology now permit more precise and accurate analyses of single zircons pre-treated by acid leaching to minimize Pb-loss. Such results are now available from granite in this quarry (sample MT29A2 of Thompson et al., 2010) containing quartz, epidotized plagioclase (now albite), salmon-colored K-feldspar measuring up to 1 cm. Intergrown with these are masses of chlorite, titanite and iron oxides replacing hornblende and accessory allanite and zircon. Five single zircons from this sample give rise to a weighted mean $^{206}Pb/^{238}U$ date of 609.1 ± 1.1 Ma. Closely comparable dates from Dedham

Granite in Hingham, MA and Natick, MA are 608.9 ± 1.2 Ma and 609.5 ± 1.1 Ma, respectively (details in Thompson et al., 2010).

12.5 Continue south on Grove Street.
13.1 Cross Washington Street (Grove becomes Bussey Street).
13.8 Crossing Mill Pond, Bussey Street becomes Milton Street.
14.0 Left on Sawmill Lane (which becomes Dedham Boulevard, then Dedham Parkway).
15.1 Right on Turtle Pond Parkway.
15.5 Bear left at blinking yellow light.
15.8 Left into parking lot between Olsen Pool and Bajko Rink facilities.

Walk north on paved Rooney Rock path leading from east side of swimming complex. At trail marker #104, continue north for approximately 150 m to low knoll west of path.

STOP 2. NEPONSET GORGE MEMBER OF THE LYNN-MATTAPAN VOLCANIC COMPLEX. UTM 19T ^{03}23 ^{538}E, ^{46}79^{756} N (60 minutes).

The Turtle Pond Parkway leading to this site passes through a variety of granitoid rocks that are texturally distinct from Dedham Granite in the West Roxbury Crushed Stone Quarry. This outcrop includes both pale pink to gray medium-grained granite adjoining the path and a finer phase on the southwest face of the exposure. The latter contains 1-2 mm single and clustered quartz phenocrysts along with smaller feldspar euhedra studded through a pale pink or purple micrographic matrix (Fig 3A from a

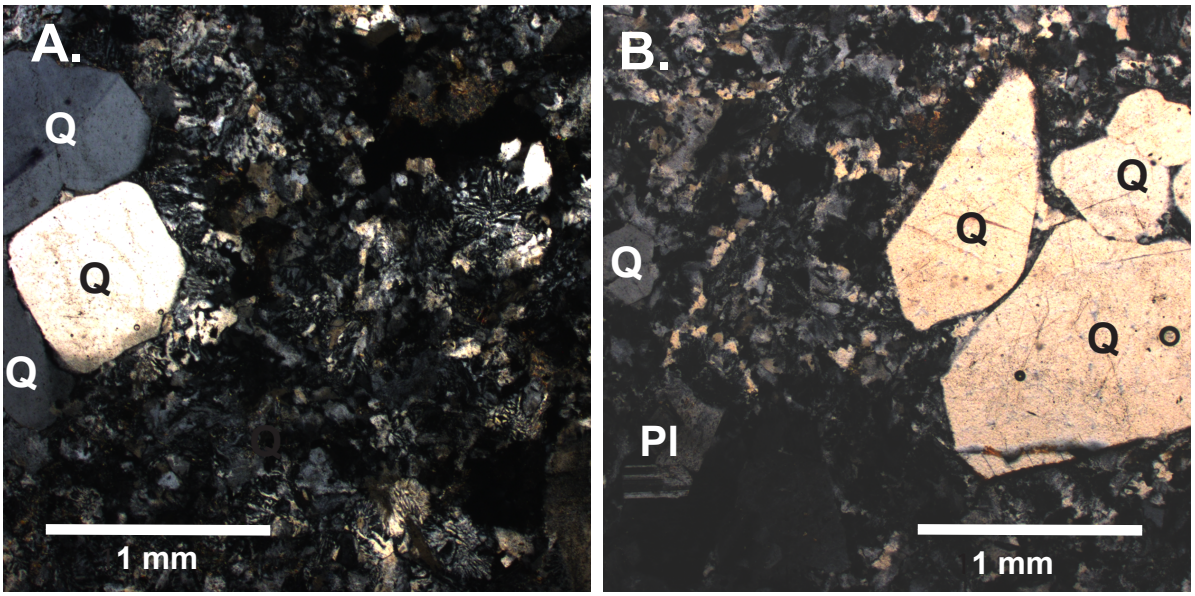

Figure 3. Photomicrographs of porphyry containing phenocrysts of quartz (Q), plagioclase (Pl) and K-feldspar (not shown) surrounded by micrographic matrix of quartz and feldspar. A. Stony Brook Reservation. B. Clast from Squantum "tillite" Member of Roxbury Conglomerate. The clast has been dated at 610 ± 2 Ma (see text).

sample collected approximately 500 m to the north) mapped by previous workers as rhyolite (Bascom, 1900) or quartz porphyry (Crosby, 1905). LaForge (1932) assigned this porphyry and microcrographic granite not visible at this outcrop to the Mattapan Volcanic Complex. Later interpretations treat the micrographic granite as a chilled contact facies of the Dedham Granite (Kaye, 1980) or as part of the typically fine-grained Westwood Granite (Thompson, 1985). Although the quartz porphyry in the Stony Brook Reservation has not been dated, a texturally similar clast from diamictite at Squantum, MA (Fig. 3B) has yielded a Dedham-like 610 ± 2 Ma upper concordia intercept date (Thompson and Bowing, 2000). This tempting but geochronologically unsubstantiated correlation would be consistent with Kaye's chilled border hypothesis.

Medium-grained granite and quartz porphyry continue as low exposures up the northern slope of Rooney Rock (19T ^{03}23 ^{591}E, ^{46}79^{733} N) where they are unconformably overlain by SE-dipping conglomerate. The conglomerate is clast supported and poorly sorted with sub-angular to sub-rounded clasts. The largest clasts in the glaciated pavement on the summit of the hill range from 5-10 cm, though much larger clasts are present elsewhere. Clast lithotypes include both medium and coarse grained granite as well as massive gray, cream and pale green felsites and a variety of porphyries. The latter include examples containing embayed quartz and blocky feldspars measuring a few mm in a purple groundmass resembling the Dedham phases we have just crossed. Notably absent from the clast assemblage are quartzites (lithic arenite of Bailey et al., 1989) that are typical and conspicuous components of conglomerate farther north in the Boston Basin. Coarse pebbly sandstones defining crude bedding oriented N50E/65SE can be seen by descending the southwest side of Rooney Rock and examining cliffs east of the path back to the parking area.

Conglomerate at Rooney Rock occupies the western end of a belt traced by W.O. Crosby (1880) along the south side of the Boston Basin. Crosby reports conglomerate in this belt "lying irregularly in and upon volcanic rocks," making it difficult in some places to distinguish from associated volcanic breccia. The latter have since been identified as ash-flow tuff (Thompson, 1985; Thompson and Hermes, 1990), suggesting that the conglomerates here are also part of the volcanic assemblage. Other members of this sequence will be examined at the next stop.

16.1 Right out of parking lot onto Turtle Pond Parkway.
16.5 Right onto West Smithfield Road.
16.6 Bear left at triangle to continue on West Smithfield Road.
16.9 Right on Eneking Parkway.
17.3 Right onto Gordon Avenue.
17.5 Left onto River Street.
17.6 Straight across Hyde Park Avenue.
17.7 First right out of circle onto Fairmount Avenue.
18.0 Left after bridge onto Truman Parkway (becomes Brush Hill Road).
19.3 Right onto Brook Road.
19.5 Cross Blue Hill Avenue.
19.6 Cross Blue Hills Parkway.
20.3 Left lane to stay straight on Brook Road.
20.7 Easy left on Canton Avenue (no light).
21.4 Easy left as Randolph Avenue merges on right and immediate left onto Adams Street.
21.6 Right after bridge into parking lot at Extra Space Storage; park on S side by pine trees and follow drive around west end of storage facility to outcrop area.

STOP 3. NEPONSET GORGE MEMBER OF THE LYNN-MATTAPAN VOLCANIC COMPLEX. UTM 19T ^{03} 29^{553} E, ^{46}81^{711} N (45 minutes).

This stop lies on the south side of the Neponset River, downstream from the former Baker Chocolate Factory that was founded in colonial times and operated until 1969. Here conglomerate measuring approximately 250 m in thickness upholds a prominent ridge bordering the river. Like conglomerate at the previous stop, this has generally been mapped as Roxbury (Billings, 1929 and 1976; LaForge, 1932; Zen, 1983), but it too contains only igneous fragments both as clasts and as sand-sized matrix grains (Khoo and others, 2008). Most abundant are volcanic clasts, including basalts and rhyolites (flow banded and pyroclastic varieties) that are derived from diverse Mattapan volcanic rocks in Milton (including 593.19 ± 0.79 Ma rhyolite; weighted mean ^{206}Pb/^{238}U date of Thompson et al., 2014) and Mattapan itself farther upstream. Similar conglomerate in gradational contact with felsic volcanic rocks is reported to the north in the Dorchester Tunnel (Richardson, 1977).

The conglomerate is sandwiched between thinner sandstones in shades of brownish gray, olive gray and medium dark gray. The sandstones are fine-grained in thin section and contain mostly highly altered volcanic rock fragments along with subordinate angular quartz and feldspar. A bedding surface under the bridge leading to the upper story of the storage warehouse on the property preserves current ripples indicating a nearly due north flow direction. A joint surface striking N15E approximately 30 m west of the bridge provides a cross sectional view showing mud-draped rippled surfaces recording waning flow conditions. Coarser sandstone with cross bedding and

slump structures (Fig. 4) and finer-grained argillaceous horizons alternate with volcanic-rich conglomerate in drill core from Shaft 7D at the southern terminus of the Dorchester Tunnel located east of this stop.

Figure 4. Drill core from Shaft 7D at the south end of the Dorchester Tunnel (Box 3 from Hole 40 of MDC Contract 312). Slumped sandstone left of DNAG scale is at depth of 62'. Run continues in alternating conglomerate, sandstone and argillite to -182 feet.

The volcanic-dominated conglomerate was first noted by Crosby (1880) and called the Neponset Conglomerate by Dodge (1881). This unit continues eastward into Hingham and Hull, Massachusetts (field trip stop 5 in Thompson and Grunow, 2004) where volcaniclastic sedimentary rocks are interbedded with Mattapan volcanic ash that has yielded a weighted mean $^{206}Pb/^{238}U$ date of 595.7 ± 1.6 Ma (Thompson and others, 2007) and unconformably overlie 608.9 ± 1.2 Ma Dedham Granite (weighted mean $^{206}Pb/^{238}U$ date of Thompson et al., 2010). The sedimentary sequence throughout this belt has lately been re-interpreted as part of the Lynn-Mattapan Volcanic Complex (Thompson et al., 2014).

21.7 From parking lot, right into right lane of Adams Street.
21.8 Drift left into middle lane to proceed straight through traffic light onto Dorchester Avenue.
22.3 Left onto Gallivan Boulevard which becomes Morton Street (Route 203).
23.8 Straight across Blue Hill Avenue.
25.1 Straight through light.
25.2 First right out of rotary onto Jewish War Veterans Drive (Google says Forest Hills Drive), which loops around Franklin Park (Google says Circuit Drive), Dorchester, MA.
25.9 Left into parking lot. (If gate locked, continue straight until wide enough to park on right hand side of bike path).

Walk northwest across grass to Gate 7 (UTM 19T $^{03}27^{143}$ E, $^{46}85^{623}$ N). Follow paved path ~120 m north from Gate 7 past sign on left to Wilderness Picnic Grove. Diverge right onto grassy cut-through and after ~30 m, follow west branch of gravel trail at hairpin curve (UTM 19T $^{03}27^{020}$ E, $^{46}85^{700}$ N). Trail narrows to dirt track and turns more westerly after picnic table on left. Continue ~ 100 m past picnic table to access outcrop on the right.

STOP 4. FRANKLIN PARK MEMBER OF THE ROXBURY CONGLOMERATE (50 minutes).

This stop is located in "The Wilderness" section bordering the northwest side of Frederick Law Olmstead's Franklin Park. Glaciated exposures continuing some 100 m along the crest of the ridge lie in the center of a conglomerate-dominated belt extending from the Dorchester district of Boston on the east to West Roxbury on the west. This belt of conglomerate has long been grouped with the Brookline Member of the Roxbury Conglomerate (Crosby, 1880; Emerson, 1917; LaForge, 1932; Billings, 1976) but has been differentiated as the Franklin Park Member (Thompson et al., 2014) based on lithologic criteria exemplified here and detrital zircon age distribution to be discussed at stops 5 and 6.

The proposed Franklin Park Member of the Roxbury Conglomerate is generally coarse-grained with clasts locally reaching 20-30 cm in length (Crosby, 1880; Thompson and Grunow, 2004). Typical clasts at this particular location measure 4-10 cm, with an observed maximum of 32 cm. Volcanic rocks, including volcaniclastic sedimentary varieties, found in the Lynn-Mattapan suite dominate the clast assemblage (dark symbols in Fig. 5A), although granite and quartzite are common among the largest clasts. Unlike the massive conglomerate through much of this belt that W.O. Crosby (1880) described as offering "comparatively few points where satisfactory observations of the dip can be made," this outcrop contains a conspicuous, ~ 10 cm thick layer of gray sandstone. Determining its attitude, however, proves challenging because of its very irregular footprint where the erosion surface glances across the gently dipping bed. Using measurements of two divergent traces of the contact between the sandstone and overlying conglomerate, the bedding orientation can be constructed stereographically as shown in Figure 5B below. Applying the same method to other Franklin Park exposures demonstrates southerly dips throughout this area as Crosby reported but did not show on the 1877 map accompanying his 1880 monograph. No such observations appear in much later maps by Billings (1976) and Kaye (1980), though north-dipping bedding appears erroneously in several places (Kaye, 1980) where aligned clasts define a planar structure that is in fact pervasive, north-dipping cleavage.

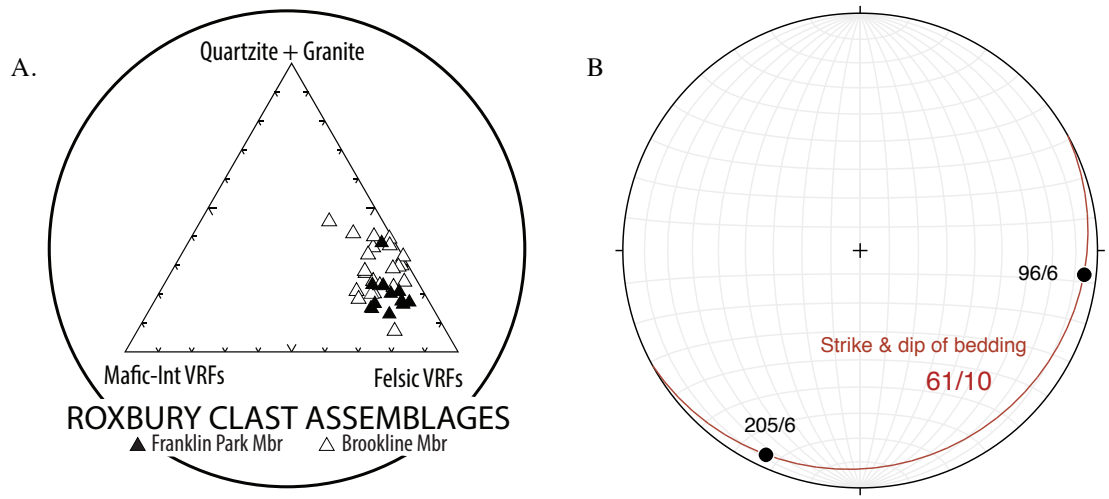

Figure 5. A. Clast assemblages in Roxbury Conglomerate based on stretched line counts of 100 clasts (Summa, 1983; Thompson, 1993). B. Stereographically constructed bedding orientation of sandstone interbedded with Roxbury Conglomerate in Franklin Park "Wilderness".

25.9 Left from parking lot on JWV/Circuit Drive (or continue straight if parked by bike path).

26.3 Left into Franklin Zoo parking lot and walk across JWV/Circuit Drive to William J. Devine Golf Course for **lunch under the trees** and public bathrooms in golf clubhouse (60 minutes).

26.4 Exit parking lot right onto JWV/Circuit Drive.

27.2 Left on far side of circular flowerbed onto Boston Park Maintenance Road.

27.6 U-turn in area adjoining gate marked "Boston Park Department Maintenance Yard" and park on east shoulder after bridge. Cross road to conglomerate escarpment bordering north side of Scarboro Pond.

STOP 5. FRANKLIN PARK CONGLOMERATE AND SANDSTONE, UTM 19T $^{03}26^{890}$ E, $4^{6}84^{721}$ N (35 minutes).

Conglomerate here is conspicuously finer grained here than at the previous stop with the largest clasts ranging from 7 cm to 11.5 cm in maximum diameter. The clast assemblage features quartzite, felsite, a few mafic volcanic rocks and one well stratified argillite, with very sparse granite. Also in contrast to the previous stop, a lens of coarse, dusky red, pebbly sandstone in this conglomerate (maximum thickness ~100 cm) makes the 60-65º south dip obvious. Petrographic study shows that this sandstone is lithic arenite containing 28.8% Q, 7.6 % F and 64.0% L (with volcanic rock fragments >> co-equal amounts of sedimentary rock fragments and granite). Sample MT04-20 from this sandstone also yielded an abundant detrital zircon suite for which the ages were determined using U-Pb methods summarized below (details and U-Pb isotopic data in Thompson et al., 2014).

The MT04-20 detrital suite was analyzed using a two-phase approach. First, representative zircons from the detrital suite (in which rounded grains are more abundant than sharply facetted morphologies) were mounted in epoxy and subjected to laser-ablation-inductively coupled plasma mass spectrometry (LA- ICPMS). Results from 91 zircons shown in the probability density distribution below (Fig. 6 after Thompson et al., 2014) reveal the full range of detrital zircon ages, including the youngest grains. The principal frequency maximum in the probability diagram lies at ca. 611 Ma and reflects contributions from 28/91 analyses (31%). Older peaks, chiefly in the Mesoproterozoic range but also including Paleoproterozoic and Archean components, encompass the majority

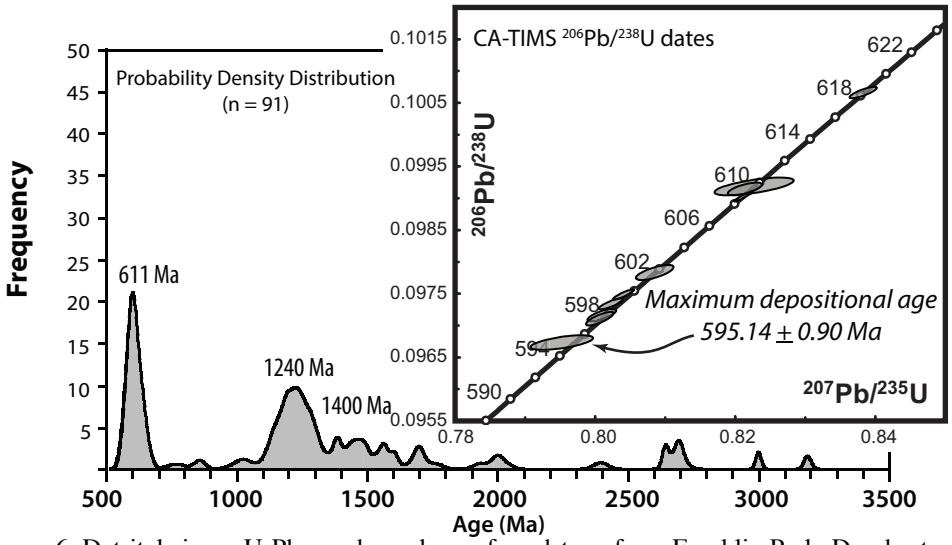

Figure 6. Detrital zircon U-Pb geochronology of sandstone from Franklin Park, Dorchester, MA (after Thompson et al., 2014). Left hand side shows probability density distribution of LA-ICPMS analyses; right hand side shows U-Pb concordia plot for CA-TIMS analyses of zircons related to the youngest probability peak. Ages in Ma are marked on the concordia curve, and individual analyses of single zircons are shown as 2σ error ellipses. Maximum age of this sandstone based on the youngest $^{206}Pb/^{238}U$ CA-TIMS date reported with analytical error only.

of analyses. In the second phase, ten zircons contributing to the youngest probability peak were re-analyzed via more precise CA-TIMS methods to constrain the 611 Ma frequency maximum. These zircons yielded concordant U-Pb data, with $^{206}Pb/^{238}U$ dates ranging from 618.31 ± 0.83 Ma to 595.14 ± 0.90 Ma (see Thompson et al., 2014 for complete discussion of error reporting). The maximum age of the sample is thus 595.14 ± 0.90 Ma (concordia inset in Fig. 4), but half of the CA-TIMS analyses were > 600 Ma. Dates from the re-analyzed Ediacaran zircons are consistent with sources in granites and volcanic rocks surrounding the Boston Basin (Dedham, Dedham North, Esmond, Westwood and Cohasset granites, as well as Lynn-Mattapan Volcanic Complex in Table 1). The pre-Ediacaran detrital age spectrum for MT04-20, with its concentration in the 1.3 to 1.0 Ga "Grenvillian" range, a smaller peak around 2Ga and minor Archean components, allows for sources in pre-Dedham basement units like the Westboro Formation (LA-ICPMS and CA-TIMS dates in Thompson et al., 2012).

The topographic escarpment at this stop with its steeply dipping sandstone continues westward across Morton Street into the Forest Hills Cemetery. South of the escarpment, outcrop is very sparse because finer grained rocks in this part of the section have been more deeply eroded and covered with glacial drift. These units, including pinkish feldspathic sandstones and finely laminated pinkish purple argillite representing the Dorchester Member of the Roxbury Conglomerate have been transected in the Dorchester Tunnel (Richardson, 1977) that runs outside Franklin Park's southwest boundary.

27.9 Return JWV/Circuit Drive and turn left
28.2 Exit rotary onto Route 203 overpass. ***This is the second of two closely spaced exits make sure to avoid the first one leading down the hill!***
29.3 Straight at light to skirt rotary and continue on Arborway (becomes Jamaicaway).
29.9 Right at light onto Pond Street.
30.0 Left on Centre Street.
30.4 Easy left on South Huntington Avenue (Moraine Street is hard left).
30.5 Left on Perkins Street.
30.8 Straight at light across Jamaicaway.
30.9 Straight through light (Chestnut Street on right).
31.5 Right onto Cottage Street.
31.8 Right at T intersection onto Warren Street (no sign other than stop).
32.1 Pass Frederick Law Olmstead National Historic Site on left.
32.2 Stay left on Warren Street (Walnut Street forks to the right).
32.3 Left on Boylston Street (Route 9).
34.0 Right on Hammond Street.
34.8 Left on Beacon Street.
35.2 Left on Hammond Pond Parkway.
35.4 Pull off on right shoulder for path into Webster Conservation Area, Newton, MA.

Proceed ~110 m along path to UTM 19T $^{03}20^{256}$ E, $^{46}88^{593}$ N and climb up to overhanging ledges.
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STOP 6. BROOKLINE MEMBER OF ROXBURY CONGLOMERATE AND BRIGHTON VOLCANIC FLOW (60 minutes). No hammers please and watch out for poison ivy.

The sequence here typifies Roxbury deposits across the northern half of the Boston Basin, and "Brookline Member" is retained as a name for these because they underlie all but the southernmost portion of the town of Brookline (Thompson et al., 2014). Distinctive features of the restricted Brookline Member include generally smaller clasts and clast assemblages typically containing slightly higher proportions of quartzite and granite than Franklin Park conglomerate (open symbols in Fig. 3A). The Brookline Member, as seen here, also contains more abundant sandy interbeds (Crosby, 1880; Billings, 1976; Thompson and Grunow, 2004). Another important distinction is the presence of Brighton igneous rocks at various levels in the Brookline section. An example can be seen by following the low branch of the path some 80 m farther west (UTM 19T $^{03}20^{186}$ E, $^{46}88^{560}$ N) to a series of basaltic flows (49.84 to 51.86 wt % SiO_2 in three analyzed samples) with amygdaloidal tops that shed clasts into the overlying sandstone. The flows themselves have yielded sparse xenocrystic zircons with discordant, widely differing $^{207}Pb/^{206}Pb$ dates in previous attempts at U-Pb geochronology. More recently, detrital zircons have been extracted from sandstone immediately overlying the flow sequence (UTM 19T $^{03}20^{168}$ E, $^{46}88^{568}$ N).

The fine-grained, brownish gray sandstone sampled as MT10-12 contains feldspar > lithic fragments > quartz in matrix varying from 19% to 70% of the rock (Meghani, 2011). Several thousand detrital zircon crystals were separated from this sample and analyzed using the same two-phase approach outlined at stop 5. Ninety LA-ICPMS analyses from grains representing the range of morphologies in this suite are plotted as a probability density distribution in Figure 7 (after Thompson et al, 2014). The dominant Ediacaran frequency maximum (ca. 594 Ma) in the probability distribution reflects 81/90 analyses (90%). Nine zircons contribute to tiny, older frequency maxima scattered from Lower Neoproterozoic to Paleoproterozoic. Six zircons were re-analyzed via CA-TIMS to constrain the Ediacaran probability peak for this sample. These grains yielded concordant U-Pb data, with a range of $^{206}Pb/^{238}U$ dates from 602.72 ± 0.79 to 598.46 ± 0.81 Ma (isotopic data and explanation of uncertainties in Thompson et al., 2014). The five youngest grains yielded a weighted mean $^{206}Pb/^{238}U$ date of 598.87 ± 0.71 Ma that is the best estimate of the maximum age for sample MT10-12 (concordia inset in Fig. 7). The dates from these five zircons suggest sources in granites post-dating the Dedham (Westwood, Cohasset, Esmond Granite in Table 1).

NEIGC- and GSA-related field trips have visited this location many times in the last 40 years. A wealth of other observations, including debate over the origin of the sedimentary sequence here can be found in earlier guidebook articles (Caldwell, 1964; Rehmer and Roy, 1976; Bailey et al., 1976; Cameron and Jeanne, 1976; Caldwell, 1981; Bailey, 1986; Hepburn and Bailey, 1998).

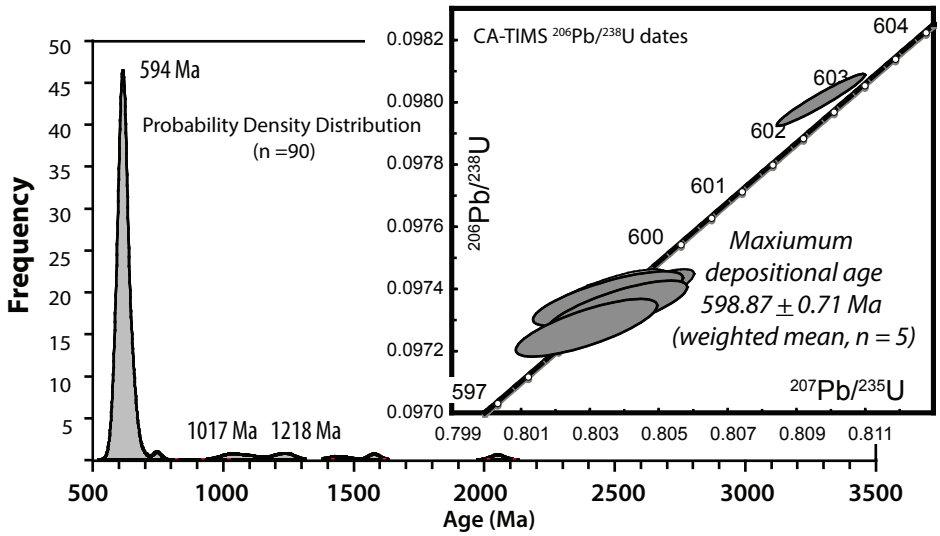

Figure 7. Detrital zircon U-Pb geochronology of sandstone from Webster Conservation Area, Newton, MA (after Thompson et al., 2014). Left hand side shows probability density distribution of LA-ICPMS analyses; right hand side shows U-Pb concordia plot for CA-TIMS analyses of zircons related to the youngest probability peak. Ages in Ma are marked on the concordia curve, and individual analyses of single zircons are shown as 2σ error ellipses. Maximum age of each sandstone based on the youngest $^{206}Pb/^{238}U$ CA-TIMS date reported with analytical error only (full discussion in Thompson et al., 2014).

35.4 Continue south on Hammond Pond Parkway.
35.9 Straight at light.
36.2 Straight at light, then immediate right on ramp to Route 9 west.
37.7 **Slow past Aberdeen and Boylston streets on right as approaching exit ramp from Route 9.**
37.9 Hard right onto Walnut Street immediately before ramp.
38.0 Straight at light across Centre Street.
38.7 Cross Beacon Street.
39.1 Left on Homer Street.
39.4 Left onto Commonwealth Avenue.
39.5 Right onto Valentine Street.
39.6 Park on shoulder for roadcut on right.

STOP 7. BRIGHTON IGNEOUS SUITE, UTM 19T $^{03}17^{461}$ E, $^{46}89^{589}$ N (30 minutes). Again, please no hammers.

Exposures in this neighborhood expand our view of igneous rocks within the Boston Basin. These are traditionally known as the Brighton "Melaphyre" (altered basalt and andesite of early workers through Billings, 1976), but more recently have been treated simply as Brighton Volcanics (Cardoza et al., 1990; Hepburn et al., 1993; Hepburn and Bailey, 1998; Thompson and Grunow, 2004 for example). The original term, though arcane, has the advantage of allowing for both volcanic and intrusive Brighton occurrences. Debate over Brighton emplacement appears in the earliest reports of Boston Basin geology, with Crosby (1880) and Woodward (unpublished work cited *in* Burr, 1901) arguing for successive lava flows, while others presented detailed evidence for intrusions into Roxbury Conglomerate (Benton, 1881; Burr, 1901). LaForge (1932, p. 42) states, without citing specific examples, that both flows and sills are present in different places and that all are contemporaneous with Roxbury sedimentation. According to Tierney and others (1968, p. 76-77), Brighton occurrences in the western end of the City Tunnel could be one or more concordant sheets of either extrusive or shallow intrusive rocks. The WNW-

trending subsurface section in the latter report runs under the surface outcrops at this stop, but the igneous horizon does not appear in Figure 1 because it lies west of Billings' line of section.

In contrast to the basaltic flow at the last stop, the dark greenish gray, generally massive rock sampled here as BOS22A yields a major element composition in the andesitic range (Fig. 8A). Plotting this along with other available Brighton analyses reveals a range of compositions that overlap but are slightly more

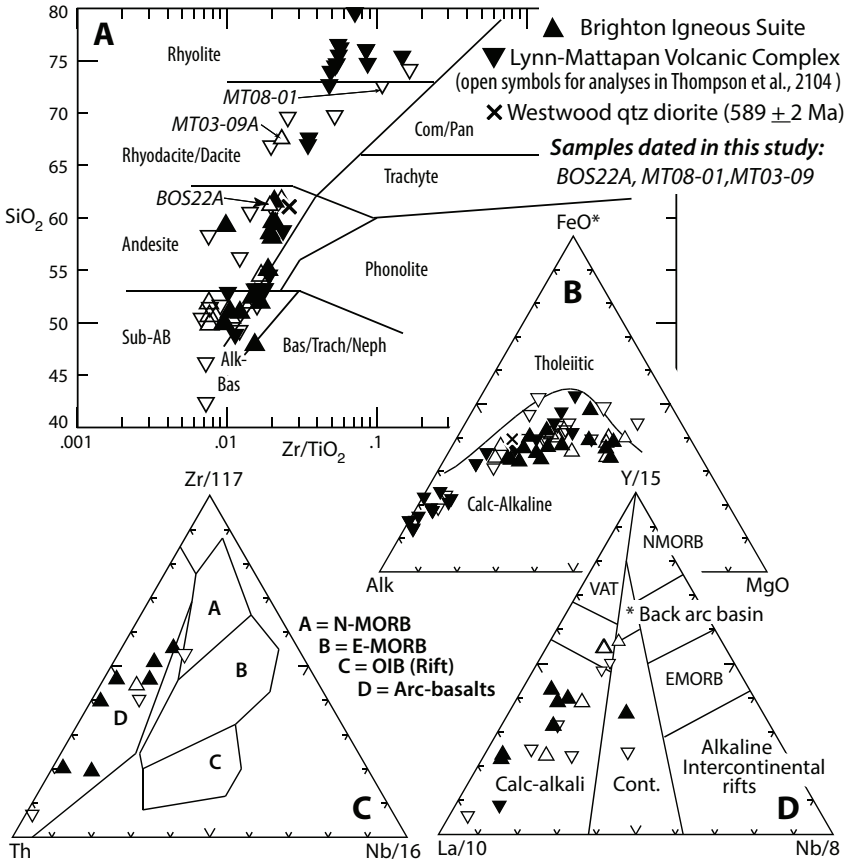

Figure 8. Geochemical characteristics of 585-584 Ma Brighton Igneous Suite and 597-593 Ma Lynn-Mattapan Volcanic Complex in and around the Boston Basin (after Thompson et al., 2014). Plotted data include published analyses from Cardoza and others (1990), Thompson and Hermes (1990), Thompson (1993), Thompson et al. (1996, 2007, 2014). A. Zr/TiO_2 plot of Winchester and Floyd (1977); B. AFM plot of Irvine and Baragar (1971); C. Th-Zr/117-Nb/16 plot of Wood (1980) showing only basaltic analyses in sources above; D. La/10-Y/15-Nb/8 plot of Cabanis and Lecolle (1989) likewise showing only basaltic analyses.

restricted than the basaltic to rhyolitic Lynn-Mattapan Volcanic Complex. Brighton and Lynn-Mattapan analyses collectively define a calk-alkaline evolution trend (Fig. 8B), and basalts from both suites plot in the volcanic arc fields of trace element discrimination diagrams (Figs. 8C and 8D). While the Brighton suite geochemically resembles members of Lynn-Mattapan Volcanic Complex, U-Pb geochronology of BOS22A demonstrates significantly younger magmatism.

The high silica content of BOS22A (61.16 wt % SiO_2) translates petrographically into quartz along with more abundant albite phenocrysts. Patchy quartz is also present in the groundmass otherwise containing albite laths < 0.1 mm to 0.5 mm in length, interstitial chlorite, epidote and ubiquitous titanite. Sparse vesicles are filled with various combinations of chlorite + titanite ± epidote ± quartz ± Fe oxides. Micro-probing confirmed zircon as an accessory mineral (besides barite, chromite, apatite and Cu sulfide). Four single zircon grains analyzed from this sample by the CA-TIMS method form a statistically coherent cluster with a weighted mean $^{206}Pb/^{238}U$ date of 585.37 ± 0.72 Ma interpreted as the crystallization age of the andesite (details and isotopic data in Thompson et al., 2014).

The 585.37 ± 0.72 Ma date from BOS22A would also be the age of the conglomerate near the top of the Roxbury section if the andesite is extrusive. If however, as Tierney et al. (1968) could not rule out, this unit is a shallow sill, that date represents a minimum depositional age for associated conglomerate. The latter interpretation is preferable because it best explains why a dacitic Brighton sample (MT03-09A in Fig. 8A) collected near the base of the Brookline Member in Brookline, MA yields a nearly identical weighted mean $^{206}Pb/^{238}U$ date of 584.19 ± 0.70 Ma (details and isotopic data in Thompson et al., 2014). The presence of Brighton intrusive rocks in addition to volcanic flows at the last stop also argues that Brighton Igneous Suite (Thompson et al., 2014) is more appropriate than Brighton "Volcanics" as the name for Roxbury-related igneous rocks.

Roxbury sedimentation took place before 585-584 Ma Brighton intrusions, but after 595 Ma based on the youngest detrital zircons at earlier stops. These dates place the Roxbury-Brighton sequence along with 610-589 Ma granitoids and 597-593 Ma volcanic rocks (Table 1) within the 630-580 Ma interval of "younger Neoproterozoic magmatic arcs" recognized in more northerly segments of Avalonia (Hibbard et al., 2006). This chronology reinforces the earlier interpretation of the Roxbury-Brighton assemblage as rift-related deposits filling and intra-arc basin (Thompson, 1993) rather than rift or wrench basins post-dating Avalonian subduction (Murphy and Nance, 1989, for example).

End of trip. For those returning to Wellesley for the banquet:

40.0 Easy left onto Hampshire Street which then curves left (intersection with Burnham Road) and then right (intersection with Barnstable Road).
40.1 Left on Chestnut Street.
40.4 Right on Commonwealth Avenue (& descend Heartbreak Hill of Boston Marathon fame).
41.3 Left on Washington Street (Route 16).
42.8 Cross Charles River into Wellesley, MA.
43.9 Route 16 crosses over Route 9.
45.6 Wellesley Square—*right lane to stay straight through light* onto Central Street (Route 135).
45.9 Straight at light (Wellesley College sign on left marks pedestrian entrance).
46.4 Left onto College Road.
47.0 Left up the hill to the Science Center parking lot.

ACKNOWLEDGEMENTS

U-Pb geochronology summarized here was funded by the National Science Foundation (Grant EAR96-28520), by Wellesley College via Brachman Hoffman Small Grants, and by the U. S. Defense Threat Reduction Agency and U.S. Air Force Research Laboratory under Contract No. FA8718-09-C-0051. Former students, especially Catherine Summa, Alexis Ault, Kristin Morell, Nooreen Meghani and MeiAi Khoo, have contributed greatly to this work over many years. I also thank Bill Levy for access to archival drill core at the Massachusetts Water Resources Authority and General Manager Ed Sonia for facilitating our visit to the West Roxbury Crushed Stone quarry.

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