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# New dimensions of Ediacaran Magmatism in the southeastern New England Avalon zone, USA
# Nouvelles dimensions du magmatisme édiacarien dans la zone d'Avalon du sud-est de la Nouvelle-Angleterre, aux États-Unis

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Article abstract

High precision CA-ID-TIMS U-Pb zircon dates presented here establish 627.68 ± 0.66 Ma (2s internal uncertainty) Diorite at Rowley and associated granite near Topsfield, Massachusetts as the earliest arc-related magmatic rocks recognized so far in the Southeastern New England Avalon Zone. Granite dated at 609.10 ± 0.18 Ma on the southern extremity of this terrane in Newport, Rhode Island corresponds in age to previously dated Dedham Granite that is widespread in the vicinity of Boston, Massachusetts. Slightly younger diorite (605.48 ± 0.21 Ma) in an upfaulted block west of Boston clusters with previous dates from the Milford and Fall River granites, and Westwood Granite re-dated at 595.17 ± 0.50 Ma proves to be co-eval with Lynn-Mattapan volcanic rocks. LA-ICPMS age spectra from the same samples (except Westwood Granite) also show inherited components. The Ediacaran crystallization ages for the southeastern New England suite overlap LA-ICPMs ages from numerous samples in the Nova Scotia's Cobequid and Antigonish Highlands. These ages both reinforce previous comparisons between these terranes and reveal patterns of incremental intrusion like those documented for continental arc-related plutons of the western United States. Mesoproterozoic and older inherited components in both cases reflect West Avalonian origins as a series of volcanic arcs developed on metasedimentary deposits that detached from the Timanide margin of Baltica. By the time <630 Ma Jeffers block tuffs and Topsfield Granite acquired Cryogenian xenocrysts, these terranes were drifting towards collision with Ganderia, precluding Baltica provenance for ~680-640 Ma zircon. The source of this inheritance remains unresolved.

# New dimensions of Ediacaran magmatism in the southeastern New England Avalon zone, USA†

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## ABSTRACT

High precision CA-ID-TIMS U–Pb zircon geochronology establishes 627.68 ± 0.66 Ma (2σ internal uncertainty) diorite at Rowley and associated tonalite near Topsfield, Massachusetts as the earliest arc-related magmatic rocks recognized so far in the southeastern New England Avalon zone. Granite dated at 609.10 ± 0.18 Ma on the southern extremity of this terrane in Newport, Rhode Island corresponds in age to previously dated Dedham Granite that is widespread in the vicinity of Boston, Massachusetts. Slightly younger diorite (605.48 ± 0.21 Ma) in an upfaulted block west of Boston clusters with previous dates from the Milford and Fall River granites. Westwood Granite redated at 595.17 ± 0.50 Ma proves to be co-eval with Lynn–Mattapan volcanic rocks. LA-ICP-MS age spectra from the same samples (except Westwood Granite) also show inherited components. The Ediacaran crystallization ages for the southeastern New England suite overlap LA-ICP-MS ages from numerous samples in Avalonia exposed in Nova Scotia's Cobequid and Antigonish highlands. These ages both reinforce previous comparisons between these terranes and reveal patterns of incremental intrusion like those documented for continental arc-related plutons of the western United States. Mesoproterozoic and older inherited components in both cases reflect West Avalonian origins as a series of volcanic arcs developed on metasedimentary deposits that detached from the Timanide margin of Baltica. By the time ca. <630 Ma Jeffers Group tuffs (Nova Scotia) and Topsfield Granodiorite (Massachusetts) acquired Cryogenian xenocrysts, their respective West Avalonian terranes were drifting towards collision with Ganderia, precluding Baltica provenance for ca. 680–640 Ma zircon. The source of this inheritance remains unresolved.

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## RÉSUMÉ

Une datation U-Pb sur zircon par CA-ID-TIMS de haute précision établit que la diorite de Rowley et la tonalite associée près de Topsfield, Massachusetts, sont âgées de 627,68 ± 0,66 Ma (incertitude interne de 2σ), ce qui en fait les roches magmatiques d'arc les plus anciennes reconnues jusqu'à présent dans la zone d'Avalon du sud-est de la Nouvelle-Angleterre. Le granite remontant à 609,10 ± 0,18 Ma dans l'extrémité sud du terrane à Newport, Rhode Island, correspond en âge au granite de Dedham précédemment daté, qui est répandu dans les environs de Boston, Massachusetts. La diorite légèrement plus récente (605,48 ± 0,21 Ma) dans un bloc relevé par une faille à l'ouest de Boston correspond aux dates précédentes des granites de Milford et de Fall River. Le granite de Westwood, redaté à 595,17 ± 0,50 Ma, s'avère contemporain des roches volcaniques de Lynn-Mattapan. Les spectres d'âge LA-ICP-MS des mêmes échantillons (à l'exception du granite de Westwood) font également état de composants hérités. Les âges de cristallisation édiacariens de la suite du sud-est de la Nouvelle-Angleterre chevauchent les âges LA-ICP-MS de nombreux échantillons de l'Avalonie affleurant dans les hautes terres de Cobequid et d'Antigonish en Nouvelle-Écosse. Les âges en question renforcent à la fois les comparaisons précédentes entre ces terranes et révèlent des régimes d'intrusion progressive similaires à ceux documentés dans le cas des plutons d'arcs continentaux de l'ouest des États-Unis. Les composants hérités mésoprotérozoïques et plus anciens dans les deux cas témoignent d'origines de l'ouest de l'Avalonie sous la forme d'une série d'arcs volcaniques provenant de dépôts métasédimentaires qui se sont détachés de la marge timanide de Baltica. Au moment où les tufs du Groupe de Jeffers (Nouvelle-Écosse) d'environ <630 Ma et la granodiorite de Topsfield (Massachusetts) se sont garnis de xénocristaux cryogéniens, leurs terranes respectifs de l'ouest de l'Avalonie dérivaient vers une collision avec Ganderia, ce qui écarte la possibilité que les zircons d'environ 680 à 640 Ma proviennent de Baltica. La source des composants hérités reste incertaine.

[Traduit par la redaction]

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## INTRODUCTION AND PREVIOUS WORK

Legacy uranium-lead geochronology by Zartman and Naylor (1984) remains the cornerstone for establishing the Precambrian origins of widespread granites in southeastern New England that were shown as Devonian (?) in the geologic map of Emerson (1917). The transformative 630 ± 15 Ma concordia upper intercept date from combined batches of multi-grain zircon from Dedham and Milford granites (Fig. 1) was not published until after the current Bedrock Geologic Map of Massachusetts (Zen 1983) superseded Emerson's portrayal, but the work in progress allowed compilers of the new map to treat these and associated intrusive rocks as "Neoproterozoic Z" in age (Ediacaran in modern timescales). Another U–Pb upper intercept date between ca. 650–600 Ma for granite near Assonet, Massachusetts (Fall River Granite in Fig. 1; fig. 3B in Zartman and Naylor 1984), further extended the Dedham-Milford footprint to the southeastern coast of Massachusetts, thus prompting the name Milford–Dedham zone for the area lying east of the Bloody Bluff Fault (Fig. 1). Concordia upper intercept dates of Hermes and Zartman (1985) for the Esmond Granite (621 ± 8 Ma) and gneissic rocks (601 ± 5 Ma) located farther to the south (Fig. 1) soon demonstrated the presence of Milford–Dedham age plutonic rocks across Rhode Island as well. The brief summary that appeared shortly after publication of the new Massachusetts map (Hatch *et al.* 1984) ended with passing reference to similarities between the Milford–Dedham zone and the Avalon zone of Newfoundland, a topic already drawing considerable tectonic interest (Rast *et al.* 1976; Williams 1978; Williams and Hatcher 1982, 1983; Rast and Skehan 1983).

Remarkable advances in U–Pb zircon geochronology (Krogh 1982a, b; Parrish and Krogh 1987) concurrent with and following publication of the 1983 Massachusetts Bedrock Geologic Map placed numerous other intrusive and volcanic igneous rocks across southeastern New England within the Ediacaran main phase of Avalonian arc magmatism (ca. 640–565 Ma of van Staal *et al.* 2021). Dated units are shown in the legend of Figure 1, and complete dates and sources are listed in Table 1. Improved U–Pb analyses of this era typically came from small, hand-picked zircon fractions that were pre-treated by mechanical air abrasion to reduce the effects of radiation-induced Pb loss. Even so, discordance arising from open system behavior in zircon (inherited zircon components and/or Pb loss) remained a problem, necessitating data regression and calculation of concordia intercept dates (Table 1). The advent of Chemical Abrasion-Thermal Ionization Mass Spectrometry ("CA-TIMS" of Mattinson 2005; chemical abrasion-isotope dilution-thermal ionization mass spectrometry in this study)—in which zircons are pre-treated by thermal annealing and partial dissolution to effectively eliminate Pb loss and then analyzed as single grains—ushered in a new era of age precision and accuracy. This allowed the more robust $^{206}Pb/^{238}U$ chronometer to be exclusively employed for accurate date calculation and coherent age interpretation. Dates obtained using this method for Dedham, Milford, Fall River, and Esmond granites (Thompson *et al.* 2010) are significantly younger, tighter in range and outside the stated uncertainties of legacy geochronology of Zartman and Naylor (1984). They range without overlap from 609.52 ± 0.14 to 599 ± 2 Ma (Table 1), suggesting closer links with widespread Ediacaran plutonism in the Cobequid and Antigonish Highlands of northern mainland Nova Scotia than with West Avalonian terranes in Cape Breton Island, Nova Scotia or eastern Newfoundland (Fig.1 inset; Fig. 2).

New dates presented from nine plutonic units in this study greatly enlarge the high precision CA-ID-TIMS database for Ediacaran igneous rocks in southeastern New England. These results expand the duration of the Ediacaran magmatic interval in this part of West Avalonia, extend the regional extent of previously documented ca. 610 Ma Dedham plutonism and link redated Westwood Granite with ca. 597–593 Ma volcanic rocks of the Lynn and Mattapan volcanic complexes of Zen (1983; shortened in Fig. 1 and text below to Lynn–Mattapan volcanic complex). On a broader scale, the new geochronology strengthens comparisons with magmatic assemblages in the Cobequid and Antigonish Highlands of northern mainland Nova Scotia.

## SYNOPSIS OF EDIACARAN PLUTONISM IN SE NEW ENGLAND

Ediacaran magmatic rocks across southeastern New England comprise an arc-related assemblage described in detail by Thompson *et al.* (2010). For purposes of the present study, it suffices to say that modal data available at that time (Wones and Goldsmith 1991; Mancuso *et al.* 1996, and unpublished data of O.D. Hermes) showed granitoid rocks including mainly granite, granodiorite, and tonalite, locally ranging into quartz-poor monzonite and diorite. A considerable major-element database from the same plutons shown in Figure 1 (Hermes and Zartman 1985; Wones and Goldsmith 1991; Sheridan 1988; Markus 1993; Dillon 1994; Mancuso *et al.* 1996) also established calc-alkaline affinity for this compositionally diverse group. High precision CA-ID-TIMS dates from the 2010 study (Table 1) were interpreted in terms of discrete intrusive events between ca. 610 to 590 Ma, much shorter than the ca. 650–600 myr magmatic interval of Zartman and Naylor (1984).

Eight of nine dated samples discussed in the next section come from the Massachusetts portion of the southeastern New England Avalon zone (Fig. 1). The final sample from Newport, Rhode Island is granite for which the previous 595 ± 12 Ma age constraint derives from the slope of a Rb–Sr isochron (Smith 1978). These and nine other samples that were not dated fall within "Neoproterozoic Z" units on the respective bedrock geologic maps of Massachusetts and Rhode Island (Zen 1983; Hermes *et al.* 1994). As for previously investigated rocks summarized above, lithologies broadly include granite, granodiorite, tonalite and diorite, along with minor monzodioritic varieties (Fig. 2a). At the same time, sampled outcrops within plutons delineated

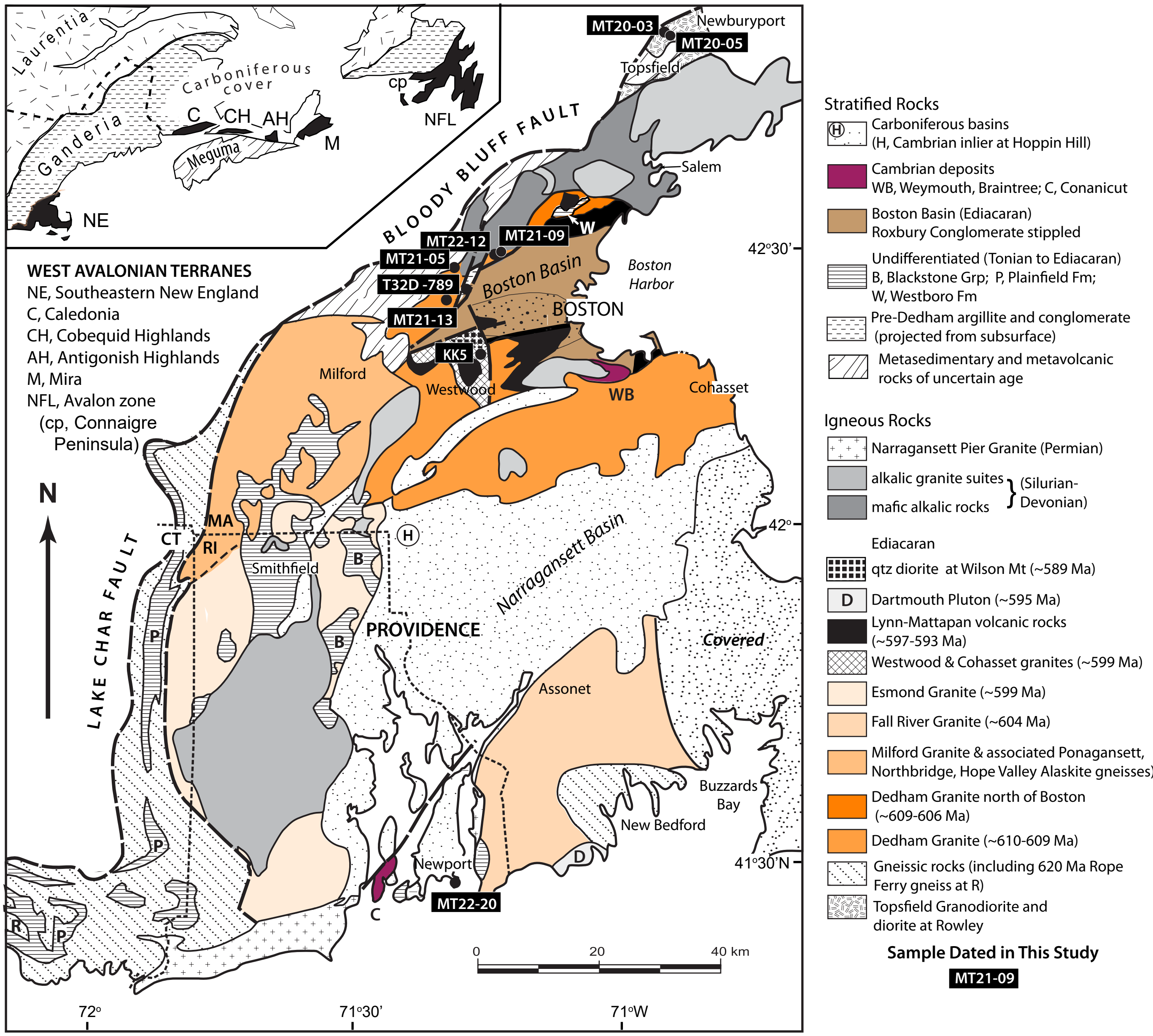



**Figure 1. Geologic sketch map of southeastern New England indicating locations of samples dated in this study (latitudes and longitudes given in Table 3). Inset on upper left shows position of southeastern New England with respect to other West Avalonian terranes. Main map adapted from Bedrock Geologic Map of Massachusetts (Zen 1983) and Bedrock Geologic Map of Rhode Island (Hermes *et al.* 1994). Inset map after Hibbard *et al.* (2006).**

in Figure 1 typically consist of more than one lithology. Co-magmatic relationships are present in both the Topsfield Granodiorite sample MT20-03 (Fig. 3a) and the informally named diorite at Rowley (Dennen 1981) sampled as MT20-05 (Fig. 1, Fig. 3b). The diorite mass sampled as MT21-13, for example, shows a hybridized contact zone with fine-grained granite (Fig. 3c). Granite sampled as MT21-05 falls within a belt of undifferentiated Neoproterozoic gabbro and diorite in the Bedrock Geological Map of Massachusetts Bedrock Map (Zdigb of Zen 1983), a suite now known to include Late Devonian gabbro (unpublished CA-ID-TIMS data of Thompson and Ramezani). Dark, dyke-like masses invaded by apophyses of granite (arrows in Fig. 3d) suggest the latter was not fully crystallized at the time of dyke intrusion. Similar lithologic variability was encountered in exposures the vicinity of MT21-09 that were sampled but not dated. These include monzodioritic sample MT21-10 in Table 2.

Chemical compositions of samples in this study also align with long held views that Ediacaran magmatic rocks in southeastern New England, like those in northern Appalachian Avalonian terranes sensu stricto (Barr and Raeside 1989; Barr and White 1996) and the larger peri-Gondwanan array extending into southern Britain (Nance *et al.* 1991; Nance and Murphy 1994), developed during wide-

**Table 1.** Current U–Pb Age constraints for Avalonian arc related granitoid and volcanic rocks in southeastern New England.

| Rock Formation | U-Pb Isotopic Date* (millions of years) | | | | |
|---|---|---|---|---|---|
| | Lower intercept date | Upper intercept date | $^{207}Pb/^{206}Pb$ date | $^{206}Pb/^{238}U$ date | Source |
| Brighton Igneous Suite | | | | **584.19 ± 0.70**<br>**585.37 ± 0.72** | Thompson *et al*. (2014) |
| Wilson Mt Qtz Diorite | | 589 ± 2 | | | Thompson *et al*. (1996) |
| Lynn-Mattapan volcanic complex | | | | **593.19 ± 0.26** | Thompson *et al*. (2014) |
| Westwood Granite | | | | **595.17 ± 0.50** | KK5 |
| Dartmouth Pluton | | 595 ± 5 | | | Hermes and Zartman (1992) |
| Lynn-Mattapan volcanic complex | | | | **595.81 ± 0.42** | Thompson *et al.* (2007) |
| | | | | **596.65 ± 0.87** | Thompson *et al.* (2007) |
| | | | 595.97± 0.74 | | Thompson *et al.* (2007) |
| | | 596 ± 2 | | | Thompson *et al.* 1996 |
| | | 596 ± 3 | | | Hepburn *et al.* 1993 |
| | | | 597.41 ± 0.89 | | Thompson *et al*. (2007) |
| Esmond Granite | | | | **599 ± 2** | Thompson *et al*. 2010 |
| | | | | **≤ 598.82 ± 0.48** | MT21-05 |
| Cohasset Granite | | | 598.7 ± 1.8 | | Dillon *et al*. 1993 |
| | | | | **≤ 598.96 ± 1.79** | MT21-12 |
| Fall River Granite | | | | **604.39 ± 0.23** | Thompson *et al.* 2010 |
| Gneisses | | | | | |
| Hope Valley Alaskite | | | 606 ± 5$^{\S}$ | | Walsh *et al*. 2011 |
| Northbridge Gneiss | | | 607 ± 5$^{\S}$ | | Walsh *et al*. 2011 |
| Ponagansett Gneiss | | | 612 ± 5$^{\S}$ | | Walsh *et al*. 2011 |
| Rope Ferry Gneiss | 620 ± 3 | | | | Wintsch and Aleinikoff 1987 |
| | | | | **605.21 ± 0.21** | MT21-13 |
| Milford Granite | | | | **606.25± 0.20** | Thompson *et al*. (2010) |
| Dedham Granite | 606 ± 3 | | | | Hepburn *et al*. (1993) |
| North of Boston | 607 ± 4 | | | | Hepburn *et al*. (1993) |
| | 609 ± 4 | | | | Hepburn *et al*. (1993) |
| | | | 611 ± 2$^{\ddagger}$ | | Hanson and McFadden 2014 |
| Dedham Granite | | | | **608.87 ± 0.21** | Thompson et al. (2010) |
| | | | | **609.10 ± 0.12** | MT21-09 |
| | | | | **609.11 ± 0.12** | Thompson *et al.* (2010) |
| | | | | **609.52 ± 0.14** | Thompson *et al.* (2010) |
| | | | | **609.93 ± 0.18** | MT22-20 |
| | | | | **618.60 ± 0.66** | T32D -789 |
| Diorite at Rowley | | | | **627.68 ± 0.17** | MT20-05 |
| Topsfield Granodiorite | | | | **≤ 629.44 ± 0.57** | MT20-03 |

* *Date* (used throughout the paper to denote what has been measured) is interpreted as crystallization *age.* Unless otherwise indicated, all dates obtained using Thermal Ionization Mass Spectroscopy [TIMS]. **CA-ID-TIMS dates in bold (analytical uncertainties only).**

$^{\S}$ Obtained via Sensitive High-resolution Ion Microprobe [SHRIMP]

$^{\ddagger}$ Obtained via Laser Ablation-Inductively Coupled Plasma Mass Spectrometry [LA-ICPMS]

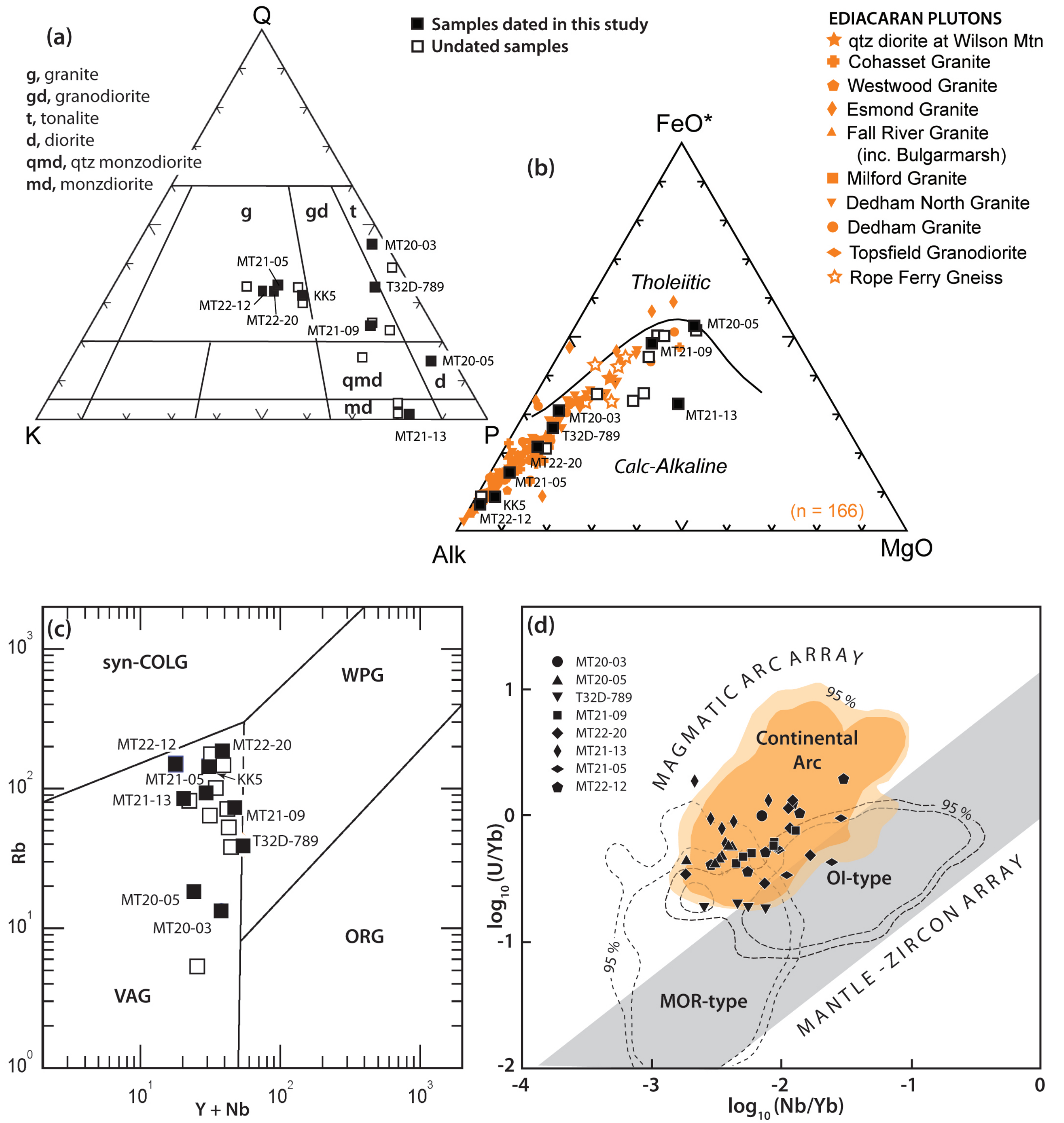



**Figure 2.** Rock types and geochemical characteristics of samples dated in this study. (a) Igneous rock classification based on proportions of quartz, plagioclase and alkali feldspar (Q-P-K) after Streckheisen (1973). (b) AFM plot (after Irving and Baragar 1971) showing all analyses in Table 2. In orange are granitoid rock compositions across southeastern New England compiled in table A1 of Thompson *et al.* (2010) from data of Hermes and Zartman (1985), Wones and Goldsmith (1991), Sheridan (1988), Markus (1993), and Mancuso *et al.* (1996). (c) Tectonic discrimination diagram after Pearce *et al.* (1984) showing fields for volcanic-arc granite (VAG), ocean-ridge granite (ORG), within-plate granite (WPG) and syncollisional granite (syn-COLG). (d) Plot of $\log_{10}$(U/Yb) versus $\log_{10}$(Nb/Yb) after Grimes *et al.* (2015) of LA-ICP-MS trace element analyses of single zircons flagged in Supplemental Data Files S9-S18 that were redated via CA-ID-TIMS.


**Figure 3.** **Complex magmatic textures in several plutonic units shown in Figure 1 that were dated in this study. (a) Dashed lines surround dioritic enclaves in Topsfield Granodiorite on Merrills Way near MT20-03 sampling site on Wethersfield Road, Rowley, Massachusetts. (b) Mixing between granitic crystal mush and diorite at Rowley sampled as MT20-05 on Green Needle Lane, Rowley Massachusetts. (c) Hybridized contact zone between fine grained and monzodiorite sampled as MT21-13 in roadcut on westbound lane Massachusetts Turnpike, Weston, Massachusetts. Scale is engineering rule calibrated in tenths of a foot. (d) Apophyses from granite sampled as MT21-05 on Border Road, Waltham, Massachusetts penetrates attenuated mafic dikes (orange arrows), suggesting co-magmatic intrusions.**

**Table 2.** Major and trace element compositions of samples in this study.

| Field # | 1 **MT20-03** | 2 MT20-09 | 3 **MT20-05** | 4 **T32D-789*** | 5 MT21-08 | 6 **MT21-09** | 7 MT21-10 | 8 **MT22-20** | 9 MT22-04 | 10 **MT21-13** | 11 MT21-14 | 12 **MT21-15** | 13 MT23-1 | 14 MT23-2 | 15 MT21-05 | 16 MT22-11 | 17 **MT22-12** | 18 **KK5*** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Major elements (wt %) | | | | | | | | | | | | | | | | | | |
| $SiO_2$ | 75.68 | 71.59 | 54.12 | 72.15 | 58.92 | 60.30 | 62.56 | 71.87 | 59.58 | 55.17 | 67.80 | 76.23 | 61.56 | 72.95 | 73.94 | 49.58 | 75.37 | 75.98 |
| $TiO_2$ | 0.24 | 0.36 | 0.75 | 0.73 | 1.06 | 1.00 | 0.93 | 0.50 | 1.06 | 0.99 | 0.67 | 0.09 | 0.95 | 0.44 | 0.22 | 1.95 | 0.10 | 0.14 |
| $Al_20_3$ | 12.95 | 14.79 | 19.27 | 14.56 | 16.92 | 16.45 | 15.69 | 14.89 | 16.66 | 16.53 | 13.82 | 12.95 | 14.19 | 13.53 | 13.98 | 15.93 | 14.00 | 13.33 |
| $Fe_2O_3^T$ | 2.73 | 3.13 | 9.49 | 2.91 | 8.55 | 7.75 | 7.27 | 2.85 | 8.27 | 6.64 | 5.17 | 0.85 | 6.69 | 2.83 | 1.59 | 12.80 | 0.72 | 0.95 |
| MnO | 0.05 | 0.06 | 0.16 | 0.05 | 0.15 | 0.14 | 0.13 | 0.07 | 0.15 | 0.14 | 0.09 | 0.01 | 0.13 | 0.05 | 0.04 | 0.20 | 0.03 | 0.05 |
| MgO | 0.55 | 1.04 | 4.23 | 0.79 | 3.17 | 2.72 | 2.91 | 0.84 | 2.94 | 5.97 | 3.08 | 0.15 | 4.01 | 0.99 | 0.39 | 6.00 | 0.14 | 0.35 |
| CaO | 2.37 | 4.80 | 8.71 | 2.12 | 6.05 | 6.21 | 4.41 | 0.46 | 6.06 | 7.72 | 2.67 | 0.43 | 5.34 | 1.05 | 1.80 | 8.49 | 1.00 | 1.02 |
| $Na_2O$ | 4.43 | 3.92 | 2.81 | 5.31 | 3.11 | 2.92 | 3.13 | 3.71 | 2.71 | 4.41 | 2.62 | 3.17 | 4.52 | 4.30 | 3.14 | 2.88 | 3.40 | 4.45 |
| $K_2O$ | 0.52 | 0.21 | 0.66 | 1.27 | 1.39 | 1.89 | 2.07 | 4.73 | 1.81 | 1.98 | 3.57 | 6.06 | 2.53 | 4.09 | 4.77 | 1.88 | 5.45 | 4.13 |
| $P_2O_5$ | 0.07 | 0.07 | 0.15 | 0.18 | 0.20 | 0.19 | 0.20 | 0.14 | 0.21 | 0.20 | 0.14 | 0.02 | 0.18 | 0.11 | 0.07 | 0.25 | 0.04 | 0.07 |
| Total | 99.57 | 99.70 | 100.33 | 100.07 | 99.52 | 99.57 | 99.30 | 100.04 | 99.43 | 99.75 | 99.62 | 99.95 | 100.08 | 100.33 | 99.93 | 99.95 | 100.25 | 100.47 |
| Trace elements (ppm) | | | | | | | | | | | | | | | | | | |
| Nb | 3.1 | 3.0 | 5.2 | 15.0 | 17.4 | 17.4 | 17.6 | 16.2 | 15.6 | 5.3 | 11.9 | 14.3 | 9.7 | 12.7 | 17.6 | 10.9 | 10.2 | 11.0 |
| Zr | 75 | 69 | 89 | 226 | 206 | 191 | 179 | 169 | 201 | 76 | 129 | 90 | 127 | 197 | 152 | 128 | 67 | 119 |
| Y | 34.8 | 21.8 | 18.8 | 40.0 | 27.9 | 28.3 | 26.0 | 22.5 | 27.3 | 14.8 | 22.7 | 17.9 | 22.0 | 26.4 | 13.4 | 11.9 | 7.7 | 19.0 |
| Sr | 146 | 175 | 395 | 153 | 421 | 335 | 335 | 145 | 475 | 480 | 218 | 127 | 180 | 163 | 288 | 375 | 226 | 139 |
| U | | | | | | | | | | | 0.7 | 1.5 | 1.0 | 1.0 | 1.1 | | 1.0 | |
| Rb | 13.5 | 5.4 | 18.3 | 39.0 | 38.3 | 74.1 | 74.8 | 179.3 | 53.2 | 86.1 | 99.9 | 173.5 | 63.9 | 142.7 | 143.1 | 81.4 | 150.1 | 91.0 |
| Th | 1.7 | 2 | 2 | | 1.5 | 2.4 | 4 | 15 | 4.6 | 2.1 | 8.8 | 12.5 | 5 | 7 | 11.2 | 1 | 12 | |
| Pb | 2.1 | 5 | 7 | | 15.9 | 14.8 | 14.7 | 53 | 16 | 5.5 | 7 | 17.2 | 10 | 4 | 24.5 | 5 | 32 | |
| Ga | 10.9 | 13 | 20 | | 18.8 | 17.9 | 14.4 | 16 | 17.7 | 11.6 | 12.9 | 10.6 | 12 | 12 | 14.1 | 20 | 13 | |
| Zn | 32 | 23 | 97 | 30 | 97 | 89 | 90 | 60 | 95 | 55 | 54 | 7 | 64 | 64 | 18 | 114 | 11 | 14 |
| Ni | | 1 | 8 | | 15 | 14 | 13 | 8 | 14 | 45 | 52 | 2 | 58 | 58 | 1 | 69 | 1 | 8 |
| Cr | 5 | 5 | 25 | | 14 | 17 | 17 | 1 | 16 | 157 | 168 | 2 | 168 | 168 | 7 | 1343 | 1 | |
| V | 26 | 34 | 182 | | 169 | 149 | 132 | 47 | 161 | 170 | 96 | 7 | 122 | 122 | 14 | 288 | 6 | |

Bold entries are for dated samples.

*Sample analyzed at University of Rhode Island XRF Lab; all other analyses from the Ronald B. Gilmore X-ray Analytical Facility, University of Massachusetts.

spread arc-related volcanism and plutonism. In a plot of $Na_2O + K_2O$ - FeO - MgO, major element compositions in Table 2 follow the same calc-alkaline trajectory presented in the compilation of Thompson *et al.* (2010; Fig. 2b). All but Sample MT22-11 (analysis 16 in Table 2) meet Pearce *et al.*'s (1984) criterion loosely defining granite as "any plutonic igneous rock containing more than 5 per cent of modal quartz." The remaining samples—ranging from 55.17 to 75.98 wt.% $SiO_2$—yield trace element concentrations that fall within the volcanic arc field in a plot of Rb vs Y + Nb (Pearce *et al.* 1984; Fig. 2c). In addition, LA-ICP-MS trace element analyses of single zircons (Supplementary Data Files S3–S10) for which precise dates were also obtained via CA-ID-TIMS (bold entries in Table 2) fall within the magmatic arc array of the $\log_{10}$(U/Yb) vs $\log_{10}$(Nb/Yb) plot in Figure 2d (after Grimes *et al.* 2015). Excluded from this diagram are ratios from zircons with pre-Ediacaran inherited components that will be discussed in results sections for samples MT20-03 and MT22-20.

## GEOCHRONOLOGY

### Methods

Igneous samples for U–Pb geochronology were collected from eight localities surrounding Boston, Massachusetts and from one near Newport, Rhode Island (Fig. 1). Separated zircon grains from these samples were subjected to chemical abrasion to overcome Pb loss using standard techniques. For all but sample KK5, complete age spectra were investigated via laser ablation-inductively coupled mass spectrometry (LA-ICP-MS) at the Isotope Geology Laboratory, Boise State University. Selected grains were then removed from the epoxy mounts and reanalyzed using chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) to obtain precise $^{206}Pb/^{238}U$ dates. Details of both methods can be found in Supplementary Data File S1. Results from both types of analyses for each sample are summarized below. CA-ID-TIMS isotopic data are shown in Table 3 and illustrated by concordia diagrams in Figure 4. These diagrams show weighted mean $^{206}Pb/^{238}U$ dates calculated from statistically equivalent data (probability of fit >0.05) and plotted with error at the 95% confidence interval. Errors on the weighted mean dates are internal errors. Errors on dates from individual analyses are reported at 2σ. Cathodoluminescence (CL) images of zircons analysed via LA-ICP-MS can be viewed in Supplementary Data File S2; LA-ICP-MS isotopic data tables are in Supplemental Data Files S3–S10. These tables omit analyses with discordance, defined as the relative difference between the $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ dates, outside of uncertainty of 5%. Errors are reported at 2σ.

The ninth sample (KK5) was analyzed by CA-ID-TIMS only in the MIT Isotope Laboratory (isotopic data in Table 4) following the detailed procedures described in Ramezani *et al.* (2022). The corresponding concordia diagram (Fig. 5) shows date errors as ± X/Y/Z (Schoene *et al.* 2006), where X is the internal uncertainty alone, Y incorporates X with the addition of U–Pb tracer calibration errors, and Z includes the latter as well as the decay constant errors of Jaffey *et al.* (1971). Errors in this format are also reported in Table 3 and in sections below for samples analyzed at Boise State University.

Excel versions of CA-ID-TIMS data in Tables 3, 4 are available in Supplementary Data Files S11 and S12.

## Results

### *Sample MT20-03 (42.724°N, 70.893°W, NAD27 datum)*

This sample comes from the west side of Wethersfield Road, Rowley, Massachusetts in an area mapped as Topsfield Granodiorite (Toulmin 1964; Zen 1983; Fig. 1). Later discussion of this pluton (Wones and Goldsmith 1991) indicates compositions ranging from granite to tonalite. Sample MT20-03 is composed of subequal amounts of plagioclase (largely altered to sericite and epidote) and quartz with minor chloritized biotite. Its normalized modal composition calculated from Analysis 1 in Table 2 falls in the tonalite field of the Q - P - K plot (Fig. 2a). This and modes for samples below were calculated using calculator devised by Brady (2024).

This sample contained sparse zircon of stubby prismatic morphology (CL images in Supplementary Data File S2, p.1). The youngest of 14 grains analyzed via LA-ICP-MS yielded a $^{206}Pb/^{238}U$ date of 629.44 ± 0.57 Ma (z3 in Table 3, Fig. 4a) that is interpreted as the maximum crystallization age of the granite. This date is significantly younger than the 639 ± 19 Ma LA-ICP-MS date for z3 (Supplementary Data File S3). Five other zircons with LA-ICP-MS dates between 672 ± 25 Ma and 624 ± 28 Ma all yielded Cryogenian $^{206}Pb/^{238}U$ dates (z1, z2, z4, z5, z6 in Table 3; Fig. 4a) interpreted as arising from grains with inherited components.

### *Sample MT20-05 (42.722°N, 70.891°W, NAD27 datum)*

This sample was collected on the west side of Green Needle Lane, Rowley, Massachusetts near the northwest margin of a roughly circular pluton shown in maps as diorite at Rowley (Dennen 1981; Zen 1983). K/Ar hornblende dates (656 ± 16 Ma of Zartman *et al.* 1965, 646 ± 6 Ma of Zartman and Naylor 1984) placed this body at the base of the intrusive sequence in the Bedrock Geologic Map of Massachusetts (Zen 1983). The sample dated here is medium-grained diorite (Analysis 3 in Table 2; Fig. 3b) dominated by plagioclase and hornblende along with minor quartz and accessory apatite, ilmenite, rutile, titanite and zircon. Extracted zircon is commonly prismatic with growth zoning, but stubbier grains are also present (CL images in Supplementary Data File S2, p. 1).

LA-ICP-MS dates from 35 grains range from 661± 14 to 582 ± 36 Ma and define a unimodal peak in the probability density diagram (ProbDens1 tab in Supplementary Data File S4). CA-ID-TIMS dates from six grains spanning most of this age range yield a weighted mean $^{206}Pb/^{238}U$ date of 627.68 ± 0.22/0.28/ 0.71 Ma (MSWD = 0.8, probability of fit = 0.54; Table 3; Fig. 4b). This date is interpreted as the igneous crystallization age.

### *Sample T32D -789 (42.34°N, 71.263°W, NAD27 datum)*

This is a subsurface sample from a sill identified in a horizontal boring transecting the faulted western border of the Boston Basin (Fig. 1) during construction of the MetroWest Water Supply Tunnel. The sample was collected ~225 ft below the topographic surface, and the symbol in Figure 1 directly overlies that position. The sill intrudes an argillaceous sequence assumed at the time to represent the Cambridge Formation, the top of which contains a volcanic ash bed now dated at 551.22 ± 0.20 Ma [weighted mean $^{206}Pb/^{238}U$ date of Thompson and Crowley (2020) superseding the ca. 570 Ma estimate of Thompson and Bowring (2000)]. The sample dated in this study was collected from the tunnel itself before it was activated in 2003.

The rock is composed of individual and clustered, variably altered plagioclase phenocrysts in a matrix of cryptocrystalline quartz and feldspar. Accessory minerals include apatite, magnetite and sparse zircon. The normalized Q - P - K ratio based on its CIPW norm calculated from Analysis 4 in Table 2 plots as granodiorite in Figure 2a. Six LA-ICP-MS

**Table 3.** CA-TIMS zircon U–Pb isotopic data for samples dated at Boise State University.

| Sample (a) | LA-ICP-MS label | Th/U (b) | $^{206}$Pb* ($\times10^{-13}$ mol) (c) | mol % $^{206}$Pb* (c) | Pb* (pg) (c) | $Pb_c$ (pg) (c) | Pb*/$Pb_c$ (c) | $^{206}$Pb/$^{204}$Pb (d) | Radiogenic Isotope Ratios: $^{208}$Pb/$^{206}$Pb (e) | $^{207}$Pb/$^{206}$Pb (e) | % err (f) | $^{207}$Pb/$^{235}$U (e) | % err (f) | $^{206}$Pb/$^{238}$U (e) | % err (f) | corr. coef. | Isotopic Dates (Ma): $^{207}$Pb/$^{206}$Pb (g) | ± (f) | $^{207}$Pb/$^{235}$U (g) | ± (f) | $^{206}$Pb/$^{238}$U (g) | ± (f) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MT20-03 (42.724°N, 70.893°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z1 | 141 | 0.793 | 0.4891 | 99.69% | 13.2 | 0.12 | 106 | 5887 | 0.246 | 0.062070 | 0.144 | 0.948336 | 0.202 | 0.110859 | 0.079 | 0.822 | 675.57 | 3.08 | 677.24 | 1.00 | 677.74 | 0.51 |
| z4 | 147 | 0.764 | 0.0747 | 98.46% | 2.0 | 0.10 | 21 | 1173 | 0.237 | 0.062200 | 0.535 | 0.948830 | 0.615 | 0.110685 | 0.176 | 0.566 | 680.04 | #### | 677.49 | 3.04 | 676.73 | 1.13 |
| z6 | 148 | 1.094 | 0.3561 | 99.49% | 10.3 | 0.15 | 68 | 3546 | 0.339 | 0.061989 | 0.176 | 0.944823 | 0.231 | 0.110593 | 0.092 | 0.732 | 672.78 | 3.76 | 675.40 | 1.14 | 676.19 | 0.59 |
| z5 | 152 | 0.952 | 0.1322 | 99.05% | 3.7 | 0.11 | 35 | 1896 | 0.295 | 0.062239 | 0.432 | 0.946035 | 0.490 | 0.110291 | 0.127 | 0.558 | 681.36 | 9.23 | 676.04 | 2.42 | 674.44 | 0.81 |
| z2 | 146 | 0.645 | 0.1632 | 99.22% | 4.2 | 0.11 | 40 | 2300 | 0.200 | 0.061706 | 0.225 | 0.916702 | 0.283 | 0.107795 | 0.094 | 0.723 | 662.96 | 4.81 | 660.61 | 1.38 | 659.93 | 0.59 |
| z3 | 150 | 0.486 | 0.2571 | 99.46% | 6.4 | 0.12 | 56 | 3352 | 0.151 | 0.060932 | 0.239 | 0.861313 | 0.298 | 0.102567 | 0.095 | 0.719 | 635.87 | 5.14 | 630.84 | 1.40 | 629.44 | 0.57 |
| **MT20-05 (42.722°N, 70.891°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z5 | 115 | 0.510 | 2.6890 | 99.95% | 67.6 | 0.12 | 573 | 34130 | 0.159 | 0.060705 | 0.067 | 0.856005 | 0.131 | 0.102316 | 0.070 | 0.960 | 627.84 | 1.44 | 627.94 | 0.61 | **627.97** | **0.42** |
| z7 | 130 | 0.465 | 2.5375 | 99.95% | 63.1 | 0.11 | 587 | 35347 | 0.145 | 0.060729 | 0.068 | 0.856006 | 0.132 | 0.102276 | 0.070 | 0.955 | 628.69 | 1.47 | 627.94 | 0.62 | **627.73** | **0.42** |
| z3 | 99 | 0.485 | 2.3966 | 99.94% | 59.9 | 0.13 | 471 | 28226 | 0.151 | 0.060671 | 0.069 | 0.855148 | 0.133 | 0.102271 | 0.070 | 0.952 | 626.63 | 1.50 | 627.47 | 0.62 | **627.70** | **0.42** |
| z1 | 123 | 0.498 | 2.6673 | 99.95% | 66.9 | 0.10 | 650 | 38846 | 0.155 | 0.060688 | 0.068 | 0.855380 | 0.131 | 0.102270 | 0.070 | 0.958 | 627.24 | 1.46 | 627.60 | 0.61 | **627.70** | **0.42** |
| z4 | 117 | 0.457 | 3.3420 | 99.96% | 82.9 | 0.12 | 685 | 41362 | 0.142 | 0.060735 | 0.065 | 0.855900 | 0.129 | 0.102254 | 0.069 | 0.965 | 628.88 | 1.40 | 627.88 | 0.60 | **627.61** | **0.41** |
| z6 | 113 | 0.524 | 3.7005 | 99.96% | 93.4 | 0.12 | 758 | 44964 | 0.163 | 0.060677 | 0.065 | 0.854778 | 0.129 | 0.102217 | 0.069 | 0.961 | 626.83 | 1.41 | 627.27 | 0.60 | **627.39** | **0.41** |
| **Weighted mean from dates in bold (95% confidence error): 627.68 ± 0.22 (0.28) [0.71] MSWD = 0.8, pof = 0.54, n = 6 [h]** | | | | | | | | | | | | | | | | | | | | | | |
| **MT21-05 (43.387°N, 71.259°W,NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z2 | 174 | 0.510 | 1.0343 | 99.75% | 26.0 | 0.22 | 119 | 7110 | 0.159 | 0.060231 | 0.096 | 0.820081 | 0.168 | 0.098794 | 0.091 | 0.891 | 610.91 | 2.08 | 608.09 | 0.77 | 607.34 | 0.53 |
| z6 | 187 | 0.614 | 0.3509 | 99.31% | 9.1 | 0.20 | 45 | 2632 | 0.191 | 0.060002 | 0.236 | 0.812655 | 0.295 | 0.098273 | 0.100 | 0.698 | 602.68 | 5.11 | 603.94 | 1.34 | 604.28 | 0.58 |
| z7 | 186 | 0.538 | 0.7290 | 98.55% | 18.5 | 0.89 | 21 | 1235 | 0.167 | 0.060048 | 0.206 | 0.811829 | 0.257 | 0.098099 | 0.080 | 0.731 | 604.31 | 4.45 | 603.48 | 1.17 | 603.26 | 0.46 |
| z1a | 158 | 0.182 | 2.7727 | 99.85% | 63.8 | 0.34 | 187 | 12167 | 0.057 | 0.060031 | 0.070 | 0.809850 | 0.135 | 0.097887 | 0.073 | 0.954 | 603.71 | 1.51 | 602.37 | 0.62 | 602.01 | 0.42 |
| z1b | 158 | 0.237 | 0.9327 | 99.63% | 21.8 | 0.28 | 77 | 4919 | 0.074 | 0.059995 | 0.110 | 0.808557 | 0.169 | 0.097789 | 0.078 | 0.859 | 602.42 | 2.38 | 601.64 | 0.77 | 601.44 | 0.45 |
| z4 | 162 | 0.621 | 0.0848 | 97.32% | 2.2 | 0.19 | 11 | 674 | 0.193 | 0.059760 | 0.707 | 0.805031 | 0.797 | 0.097745 | 0.218 | 0.523 | 593.92 | #### | 599.66 | 3.61 | 601.18 | 1.25 |
| z8 | 177 | 0.699 | 0.5782 | 98.79% | 15.2 | 0.59 | 26 | 1485 | 0.217 | 0.059851 | 0.242 | 0.802940 | 0.289 | 0.097343 | 0.085 | 0.656 | 597.22 | 5.23 | 598.49 | 1.30 | 598.82 | 0.48 |
| **MT21-09 (42.389°N, 71.21°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z6 | 228 | 0.775 | 0.7789 | 99.78% | 20.9 | 0.14 | 148 | 8255 | 0.241 | 0.060212 | 0.112 | 0.822632 | 0.172 | 0.099133 | 0.078 | 0.863 | 610.22 | 2.42 | 609.52 | 0.79 | **609.33** | **0.45** |
| z1 | 199 | 0.665 | 0.9804 | 99.81% | 25.6 | 0.16 | 163 | 9343 | 0.207 | 0.060253 | 0.082 | 0.822973 | 0.144 | 0.099106 | 0.072 | 0.929 | 611.71 | 1.77 | 609.71 | 0.66 | **609.17** | **0.42** |
| z5 | 221 | 0.641 | 0.7441 | 99.83% | 19.3 | 0.11 | 182 | 10497 | 0.199 | 0.060259 | 0.098 | 0.822965 | 0.156 | 0.099095 | 0.073 | 0.881 | 611.93 | 2.12 | 609.70 | 0.72 | **609.10** | **0.42** |
| z2 | 204 | 0.593 | 0.8365 | 99.85% | 21.5 | 0.10 | 211 | 12349 | 0.184 | 0.060198 | 0.083 | 0.822100 | 0.145 | 0.099091 | 0.072 | 0.927 | 609.73 | 1.80 | 609.22 | 0.67 | **609.08** | **0.42** |
| z3 | 203 | 0.567 | 1.3954 | 99.89% | 35.6 | 0.12 | 289 | 16998 | 0.176 | 0.060160 | 0.076 | 0.821481 | 0.138 | 0.099079 | 0.070 | 0.943 | 608.37 | 1.63 | 608.87 | 0.63 | **609.01** | **0.41** |
| z4 | 214 | 0.690 | 0.8909 | 99.84% | 23.4 | 0.12 | 197 | 11209 | 0.215 | 0.060204 | 0.099 | 0.822013 | 0.160 | 0.099072 | 0.073 | 0.907 | 609.93 | 2.13 | 609.17 | 0.73 | **608.97** | **0.42** |
| **Weighted mean from dates in bold (95% confidence error): 609.10 ± 0.22 (0.28) [0.69] MSWD = 0.2, pof = 0.89, n = 6 [h]** | | | | | | | | | | | | | | | | | | | | | | |
| **MT21-13 (42.399°N, 71.27°W,NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z2 | 246 | 0.894 | 2.4295 | 99.94% | 67.1 | 0.13 | 536 | 29048 | 0.278 | 0.060115 | 0.072 | 0.816099 | 0.134 | 0.098505 | 0.069 | 0.949 | 606.73 | 1.57 | 605.87 | 0.61 | **605.64** | **0.40** |
| z6 | 255 | 0.396 | 2.0834 | 99.92% | 50.8 | 0.14 | 367 | 22553 | 0.123 | 0.060073 | 0.070 | 0.815507 | 0.133 | 0.098501 | 0.069 | 0.955 | 605.23 | 1.51 | 605.54 | 0.61 | **605.62** | **0.40** |
| z4 | 251 | 0.468 | 3.2061 | 99.95% | 79.7 | 0.14 | 552 | 33260 | 0.146 | 0.060057 | 0.077 | 0.815221 | 0.135 | 0.098493 | 0.070 | 0.912 | 604.65 | 1.67 | 605.38 | 0.62 | **605.57** | **0.40** |
| z1 | 245 | 0.426 | 0.6164 | 99.58% | 15.2 | 0.22 | 70 | 4302 | 0.133 | 0.060113 | 0.118 | 0.815944 | 0.173 | 0.098488 | 0.073 | 0.847 | 606.69 | 2.55 | 605.78 | 0.79 | **605.54** | **0.42** |
| z3 | 247 | 0.147 | 1.5253 | 99.75% | 34.8 | 0.32 | 108 | 7111 | 0.046 | 0.060121 | 0.083 | 0.815734 | 0.145 | 0.098450 | 0.071 | 0.929 | 606.96 | 1.80 | 605.67 | 0.66 | **605.32** | **0.41** |
| z5 | 257 | 0.714 | 1.8333 | 99.90% | 48.5 | 0.15 | 332 | 18808 | 0.222 | 0.060044 | 0.073 | 0.814482 | 0.136 | 0.098426 | 0.070 | 0.946 | 604.17 | 1.59 | 604.97 | 0.62 | **605.18** | **0.40** |
| **Weighted mean from dates in bold (95% confidence error): 605.48 ± 0.21 (0.27) [0.68] MSWD = 0.9, pof = 0.51, n = 6 [h]** | | | | | | | | | | | | | | | | | | | | | | |
| **MT22-12 (42.388°N, 71.212°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z1 | 153 | 0.240 | 3.0844 | 99.94% | 72.4 | 0.16 | 456 | 29078 | 0.074 | 0.064786 | 0.071 | 1.005682 | 0.134 | 0.112635 | 0.070 | 0.951 | 766.45 | 1.50 | 706.69 | 0.68 | 688.03 | 0.46 |
| z6 | 160 | 0.649 | 1.0030 | 99.71% | 26.1 | 0.24 | 110 | 6326 | 0.202 | 0.060243 | 0.094 | 0.821598 | 0.153 | 0.098957 | 0.073 | 0.892 | 611.35 | 2.03 | 608.94 | 0.70 | 608.29 | 0.42 |
| z5 | 167 | 0.599 | 0.9790 | 99.82% | 25.2 | 0.15 | 169 | 9857 | 0.186 | 0.060172 | 0.086 | 0.819181 | 0.148 | 0.098782 | 0.074 | 0.912 | 608.79 | 1.86 | 607.59 | 0.68 | 607.27 | 0.43 |
| z4 | 164 | 0.730 | 1.4609 | 99.84% | 38.8 | 0.19 | 205 | 11556 | 0.227 | 0.060032 | 0.079 | 0.811694 | 0.140 | 0.098108 | 0.070 | 0.935 | 603.75 | 1.70 | 603.40 | 0.64 | 603.31 | 0.40 |
| z3 | 159 | 0.939 | 2.6920 | 99.93% | 75.1 | 0.15 | 491 | 26348 | 0.292 | 0.059917 | 0.073 | 0.804327 | 0.135 | 0.097404 | 0.069 | 0.950 | 599.61 | 1.58 | 599.27 | 0.61 | **599.17** | **0.39** |
| z2 | 157 | 1.259 | 0.7887 | 99.75% | 23.6 | 0.16 | 147 | 7336 | 0.392 | 0.059916 | 0.087 | 0.803706 | 0.150 | 0.097330 | 0.070 | 0.936 | 599.57 | 1.89 | 598.92 | 0.68 | **598.74** | **0.40** |
| **Weighted mean from dates in bold (95% confidence error): 598.96 ± 1.79 (1.80) [1.91] MSWD = 2.3, pof = 0.13, n = 2 [h]** | | | | | | | | | | | | | | | | | | | | | | |
| **MT22-20 (41.455°N, 71.304°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z1 | 265 | 0.381 | 4.4714 | 99.96% | 109.6 | 0.15 | 748 | 45667 | 0.117 | 0.072227 | 0.064 | 1.431091 | 0.128 | 0.143768 | 0.070 | 0.962 | 991.43 | 1.29 | 902.01 | 0.77 | 865.93 | 0.57 |
| z6 | 233 | 0.862 | 3.5599 | 99.91% | 97.6 | 0.26 | 371 | 20293 | 0.268 | 0.060232 | 0.067 | 0.824160 | 0.131 | 0.099284 | 0.070 | 0.958 | 610.95 | 1.44 | 610.37 | 0.60 | **610.21** | **0.41** |
| z2b | 213 | 0.933 | 0.9419 | 99.82% | 26.3 | 0.14 | 183 | 9870 | 0.290 | 0.060182 | 0.080 | 0.823320 | 0.145 | 0.099265 | 0.072 | 0.943 | 609.16 | 1.74 | 609.90 | 0.66 | **610.10** | **0.42** |
| z7 | 245 | 0.817 | 3.1140 | 99.90% | 84.5 | 0.25 | 333 | 18409 | 0.254 | 0.060184 | 0.070 | 0.823205 | 0.132 | 0.099249 | 0.069 | 0.950 | 609.21 | 1.51 | 609.83 | 0.61 | **610.00** | **0.40** |
| z2a | 213 | 0.944 | 1.8202 | 99.77% | 50.9 | 0.35 | 147 | 7910 | 0.294 | 0.060234 | 0.086 | 0.823547 | 0.145 | 0.099206 | 0.070 | 0.912 | 611.03 | 1.86 | 610.03 | 0.66 | **609.75** | **0.41** |
| z3 | 215 | 0.737 | 4.3643 | 99.94% | 116.1 | 0.22 | 520 | 29284 | 0.229 | 0.060198 | 0.065 | 0.822780 | 0.130 | 0.099174 | 0.071 | 0.960 | 609.72 | 1.40 | 609.60 | 0.59 | **609.57** | **0.41** |
| z5 | 232 | 0.861 | 2.8593 | 99.87% | 78.4 | 0.30 | 261 | 14294 | 0.268 | 0.060207 | 0.068 | 0.822248 | 0.133 | 0.099094 | 0.072 | 0.956 | 610.07 | 1.48 | 609.30 | 0.61 | 609.10 | 0.42 |
| **Weighted mean from dates in bold (95% confidence error): 609.93 ± 0.18 (0.31) [0.73] MSWD = 1.6, pof = 0.16, n = 5 [h]** | | | | | | | | | | | | | | | | | | | | | | |
| **T32D-789 (42.34°N, 71.263°W, NAD27 datum)** | | | | | | | | | | | | | | | | | | | | | | |
| z5 | 279,280 | 0.598 | 0.3021 | 99.44% | 7.8 | 0.14 | 55 | 3201 | 0.186 | 0.060517 | 0.165 | 0.840570 | 0.224 | 0.100783 | 0.090 | 0.768 | 621.15 | 3.56 | 619.46 | 1.04 | **619.00** | **0.53** |
| z4 | 281 | 1.085 | 0.2539 | 99.55% | 7.3 | 0.10 | 76 | 3967 | 0.337 | 0.060594 | 0.163 | 0.840903 | 0.219 | 0.100696 | 0.079 | 0.794 | 623.87 | 3.52 | 619.64 | 1.02 | **618.49** | **0.47** |
| z3 | 282 | 0.700 | 0.1001 | 98.54% | 2.6 | 0.12 | 21 | 1233 | 0.218 | 0.060517 | 0.423 | 0.839486 | 0.483 | 0.100654 | 0.108 | 0.628 | 621.14 | 9.13 | 618.86 | 2.24 | **618.24** | **0.64** |
| **Weighted mean from dates in bold (95% confidence error): 618.60 ± 0.66 (0.68) [0.93] MSWD = 1.9, pof = 0.15, n = 3 [h]** | | | | | | | | | | | | | | | | | | | | | | |

(a) z1, z2, etc. are labels for analyses composed of single zircon grains that were annealed and chemically abraded (Mattinson 2005).

(b) Model Th/U ratio calculated from radiogenic $^{208}$Pb/$^{206}$Pb ratio and $^{207}$Pb/$^{235}$U date.

(c) Pb* and Pbc are radiogenic and common Pb, respectively. mol % $^{206}$Pb* is with respect to radiogenic and blank Pb.

(d) Measured ratio corrected for spike and fractionation only. Pb fractionation correction for analyses done with tracer solution BSU1B is 0.18 ± 0.03 or 0.20 ± 0.03 (1σ) %/amu (atomic mass unit) for single-collector Daly analyses, based on recent analyses of EARTHTIME $^{202}$Pb-$^{205}$Pb ET2535 tracer solution.

(e) Corrected for fractionation and spike. Common Pb in zircon analyses is assigned to procedural blank with composition of $^{206}$Pb/$^{204}$Pb = 18.04 ± 0.61%; $^{207}$Pb/$^{204}$Pb = 15.54 ± 0.52%; $^{208}$Pb/$^{204}$Pb = 37.69 ± 0.63% (1σ). $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb ratios corrected for initial disequilibrium in $^{230}$Th/$^{238}$U using a D(Th/U) of 0.20 ± 0.05 (1σ).

(f) Errors are 2σ, propagated using algorithms of Schmitz and Schoene (2007) and Crowley *et al*. (2007).

(g) Calculations based on the decay constants of Jaffey *et al*. (1971). $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb dates corrected for initial disequilibrium in $^{230}$Th/$^{238}$U using a D(Th/U) of 0.20 ± 0.05 (1σ).

(h) $^{206}$Pb/$^{238}$U date (Ma) ± random (+tracer) [+decay constant]. MSWD = Mean Square Weighted Deviation. pof = probability of fit.

analyses from three stubby prisms and two prism fragments (Supplementary Data File S2, p. 1) produced an age spectrum with a single ca. 629 Ma peak (ProbDens1 tab Supplementary Data File S5). CA-ID-TIMS analyses for three of these grains yield a weighted mean $^{206}Pb/^{238}U$ date of 618.60 ± 0.66/0.68/0.93 Ma (MSWD = 1.9, probability of fit = 0.15) that is interpreted as the igneous crystallization age (Table 3, Fig. 4c).

### *Sample MT21-09 (42.389°N, 71.21°W, NAD27 datum)*

This sample was collected from an exposure located east of Tarbell Hall on the grounds of the former Fernald School in Waltham, Massachusetts (Fig. 1). Access to this permanently closed property was arranged by the Massachusetts Water Resources Authority during preliminary investigations for the Metropolitan Water Tunnel Project in greater Boston, Massachusetts. In early maps (Clapp 1910; Emerson 1917; LaForge 1932), this location lies within a belt of Devonian (?) Newburyport quartz diorite, but the current Bedrock Geologic Map of Massachusetts (Zen 1983) shows the same area as Dedham Granite of "Neoproterozoic Z" age. The primary minerals in sample MT21-09 are plagioclase, biotite and quartz, accompanied by accessory apatite, Fe-oxide, titanite, and zircon. Its major element composition including 60.31 wt.% $SiO_2$ (Analysis 6 in Table 2) and its modal composition (Fig. 2a) calculated from the norm based on that analysis, however, indicate granodiorite rather than granite.

LA-ICP-MS analyses from 41 of 42 prismatic zircons or fragments of such grains typically with oscillatory zoning (Supplementary Data File S2, p. 2) give rise to an age spectrum with a peak at ca. 606 Ma (ProbDens2 tab in Supplementary Data File S6). A Paleoproterozoic $^{207}Pb/^{206}Pb$ date (1778 ± 29 Ma) from the core of the remaining grain (spot 224 in Supplementary Data File S2, p. 2) represents an inherited component. Six zircons with LA-ICP-MS dates between 645 ± 30 and 584 ± 21 Ma (Supplementary Data File S6) yield a weighted mean $^{206}Pb/^{238}U$ date of 609.10 ± 0.22/0.28/0.69 Ma (MSWD = 0.2, probability of fit = 0.89; Table 3 and Fig. 4d). This is the interpreted igneous crystallization age.

### *Sample MT22-20 (41.455°N, 71.304°W, NAD27 datum)*

This sample was pried at low tide from ledges bordering the Newport (Rhode Island) Cliff Walk where it ascends to Rough Point (Fig. 1) at the south tip of Aquidneck Island. Previous maps (Quinn 1971; Hermes *et al.* 1994) show this area as coarse porphyritic granite. The medium to light grey granite sample (Analysis 8 in Table 2; Fig. 2a) is composed of quartz, plagioclase, feldspar and minor chloritized biotite as previously reported, but it contains few phenocrysts. Ac-cessory minerals include apatite, Fe-oxide, monazite (?), titanite, and zircon.

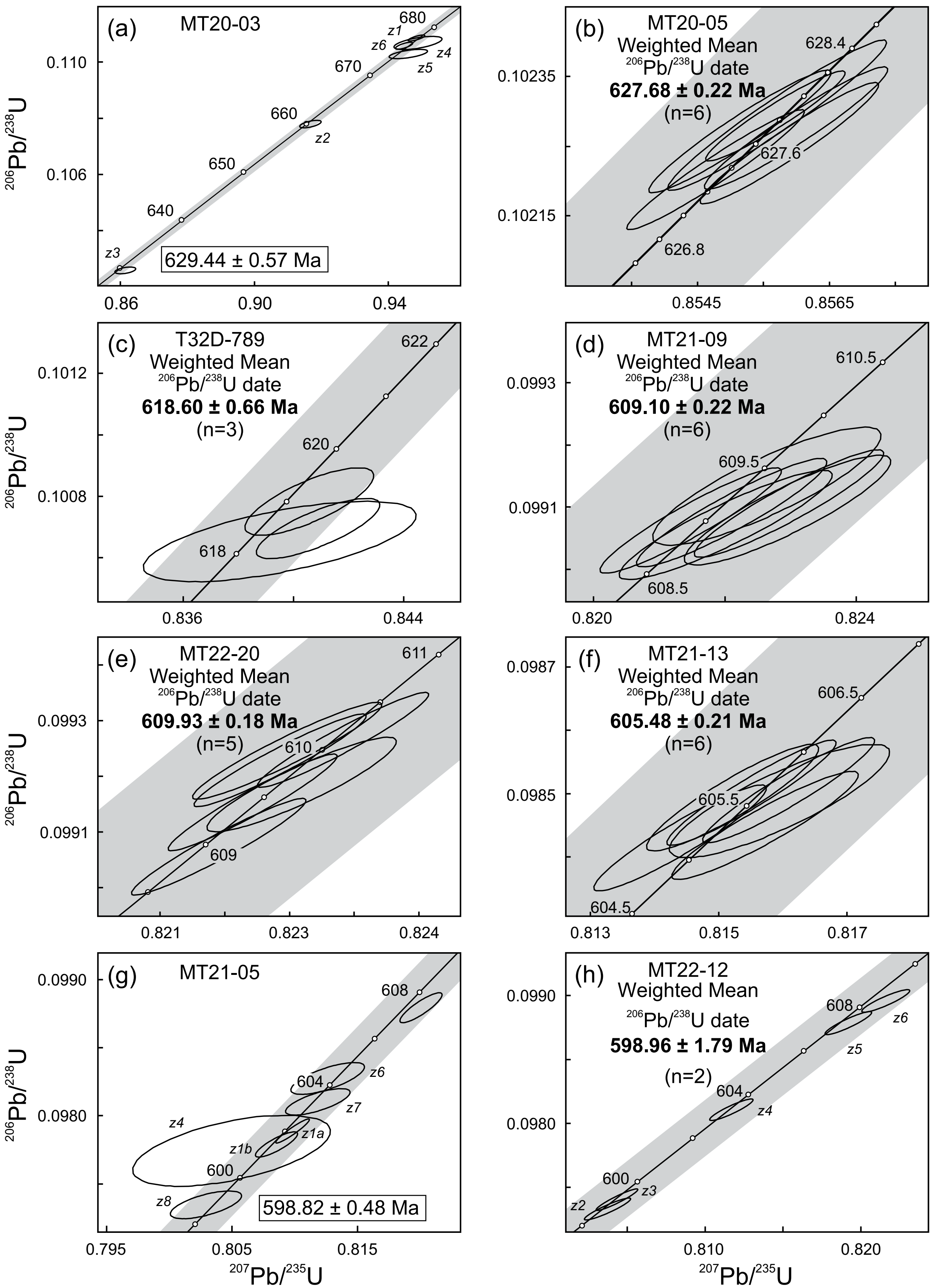
The Cliff Walk sampling location lies east of granite at Newport Neck where five samples were collected for previous Rb–Sr dating (595 ± 12 Ma of Smith 1978; Lily Pond Granite in fig.1 of Skehan *et al.* 1987). However, a sample from the Cliff Walk yielded a data point close to Smith's isochron. Not surprisingly, U–Pb geochronology establishes a significantly older age. LA-ICP-MS dates of 662 ± 45 to 566 ± 21 Ma from 74 grains cluster around a peak at ca. 614 Ma in the probability density distribution (isotopic data and PPD plot in Supplementary Data File S7). The inherited core in LA-ICP-MS spot 265 (Supplementary Date File S2, p. 3) yielded the oldest LA-ICP-MS date of 1167 ± 33 Ma. The CA-ID-TIMS date of 865.93 ± 0.57 Ma from this zircon (z1 in Table 3) is likely meaningless because it also includes a component from a younger rim. The weighted mean $^{206}Pb/^{238}U$ date of 609.93 ± 0.18/0.25/0.71 Ma (MSWD = 1.6, probability of fit = 0.16) for five analyses from four grains contributing to the probability density maximum (Fig. 4e; bold entries in Table 3 include two analyses from z2) is interpreted as the crystallization age. Still younger is 609.10± 0.42 z5 (Fig. 4e) which was excluded from the weighted mean.

### *Sample MT21-13 (42.399°N, 71.27°W, NAD27 datum)*

This sample location on the westbound lane of the Massachusetts State Turnpike (Fig. 1) appears as hornblende gabbro surrounded by Dedham Granite in the 1:24 000 Natick geologic quadrangle map of Nelson (1975). The sample collected for this study during remapping undertaken in conjunction with preliminary investigations for the Metropolitan Water Tunnel Project, however, proves to be coarse grained monzodiorite with 55.17 wt.% $SiO_2$ (Analysis 10 in Table 2; Fig. 3c). Mineralogy in this sample includes variably altered hornblende and plagioclase, along with trace amounts of quartz and K-feldspar, as well as accessory apatite, pyrite, rutile, titanite and abundant prismatic, but poorly zoned zircon (Supplementary Data File S2, pp. 4).

Thirty-five such zircons yielded LA-ICP-MS analyses ranging from 690 ± 30 to 560 ± 21 Ma. These define a prominent ca. 614 Ma peak in the probability density distribution

**Figure 4. (next page) Concordia diagrams plotted with Isoplot 3.0 (Ludwig 2003). Ages in Ma are marked on the concordia curve, and individual analyses of single zircons are shown as 2σ error ellipses. Grey areas behind concordia lines represent decay constant uncertainties. Errors reported as ± X. Complete U–Pb isotopic data and errors listed in Table 3. (a) Sample MT20-03 from Topsfield Granite. (b) Sample MT20-05 from Diorite at Rowley. (c) Sample T32D from sill intruding pre-Dedham sequence in the MetroWest Tunnel. (d) Sample MT21-09 from Dedham Granite. (e) Sample MT22-20 from Cliff Walk Granite. (f) Sample MT21-13 diorite intruding Dedham Granite. (g) Sample MT21-05 is possibly related to the Esmond Granite. (h) Sample MT22-12 is also possibly related to the Esmond Granite.**



(a) MT20-03
629.44 ± 0.57 Ma
(b) MT20-05 Weighted Mean 206Pb/238U date 627.68 ± 0.22 Ma (n=6)
(c) T32D-789 Weighted Mean 206Pb/238U date 618.60 ± 0.66 Ma (n=3)
(d) MT21-09 Weighted Mean 206Pb/238U date 609.10 ± 0.22 Ma (n=6)
(e) MT22-20 Weighted Mean 206Pb/238U date 609.93 ± 0.18 Ma (n=5)
(f) MT21-13 Weighted Mean 206Pb/238U date 605.48 ± 0.21 Ma (n=6)
(g) MT21-05
598.82 ± 0.48 Ma
(h) MT22-12 Weighted Mean 206Pb/238U date 598.96 ± 1.79 Ma (n=2)
206Pb/238U
207Pb/235U

**Table 4.** U-Pb isotopic data for analyzed zircons from Westwood Granite.

| | | | | | Radiogenic Isotope Ratios | | | | | | | | Isotopic Dates (Ma) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Fractions (a) | Pb(c) (pg) (b) | $\frac{Pb^*}{Pb_c}$ | U (pg) (c) | $\frac{Th}{U}$ | $\frac{^{206}Pb}{^{204}Pb}$ (d) | $\frac{^{208}Pb}{^{206}Pb}$ (e) | $\frac{^{206}Pb}{^{238}U}$ (f) | err (2σ%) | $\frac{^{207}Pb}{^{235}U}$ (f) | err (2σ%) | $\frac{^{207}Pb}{^{206}Pb}$ (f) | err (2σ%) | $\frac{^{206}Pb}{^{238}U}$ | err (2σ) | $\frac{^{207}Pb}{^{235}U}$ | err (2σ) | $\frac{^{207}Pb}{^{206}Pb}$ | err (2σ) | corr. coef. |
| KK5 (42.246°N, 71.208°W, NAD27 datum) | | | | | | | | | | | | | | | | | | | |
| **z5** | 0.23 | 8.4 | 18.2 | 0.65 | 493.3 | 0.203 | 0.096809 | (.29) | 0.81672 | (2.26) | 0.06121 | (2.19) | **595.68** | **1.66** | 606.2 | 10.3 | 646 | 47 | 0.32 |
| **z2** | 0.26 | 3.9 | 9.2 | 0.81 | 234.0 | 0.253 | 0.096802 | (.64) | 0.79883 | (5.41) | 0.05988 | (5.17) | **595.64** | **3.67** | 596.17 | 24.39 | 598.2 | 112.0 | 0.42 |
| **z4** | 0.20 | 45 | 73.2 | 1.40 | 2160 | 0.435 | 0.096732 | (.12) | 0.79987 | (.63) | 0.06000 | (.59) | **595.23** | **0.70** | 596.75 | 2.83 | 602.5 | 12.7 | 0.40 |
| **z3** | 0.23 | 23 | 47.8 | 0.96 | 1256.9 | 0.297 | 0.096724 | (.15) | 0.80720 | (.86) | 0.06055 | (.82) | **595.18** | **0.85** | 600.88 | 3.88 | 622.4 | 17.7 | 0.32 |
| **z1** | 0.23 | 7.4 | 15.5 | 0.86 | 420.6 | 0.268 | 0.096393 | (.40) | 0.81132 | (2.63) | 0.06107 | (2.53) | **593.24** | **2.29** | 603.2 | 12.0 | 640.8 | 54.3 | 0.33 |

(a) Thermally annealed and pre-treated single zircon.
(b) Total common-Pb in analyses.
(c) Total sample U content.
(d) Measured ratio corrected for spike and fractionation only.
(e) Radiogenic Pb ratio.
(f) Corrected for fractionation, spike and blank. Also corrected for initial Th/U disequilibrium using radiogenic $^{208}Pb$ and $Th/U_{magma}$ = 2.8.
Mass fractionation correction of 0.25%/amu ± 0.04%/amu (atomic mass unit) was applied to single-collector Daly analyses.
All common Pb assumed to be laboratory blank. Total procedural blank less than 0.1 pg for U.
Blank isotopic composition: $^{206}Pb/^{204}Pb$ = 18.15 ± 0.47, $^{207}Pb/^{204}Pb$ =15.30 ± 0.30, $^{208}Pb/^{204}Pb$ = 37.11 ± 0.87.
Corr. coef. = correlation coefficient.
Ages calculated using the decay constants $\lambda_{238}$ = 1.55125E-10 and $\lambda_{235}$ = 9.8485E-10 (Jaffey *et al*. 1971).

plot (Supplementary Data File S8). Six concordant CA-ID-TIMS analyses (Fig. 4f), including one contributing to the minor probability concentration at ca. 570 Ma, yield a weighted mean date of 605.48 ± 0.21/0.27/0.68 Ma (MSWD = 0.9, probability of fit = 0.51) that is the interpreted crystallization age of the diorite.

### *Sample MT21-05 (43.387°N, 71.259°W, NAD27 datum)*

This sample was collected near the north end of a 400 m roadcut created during recent redevelopment of the former Polaroid Corporation headquarters located east of Route 128 in Waltham, Massachusetts (Fig. 1). The rock is medium grained grey granite (Analysis 15 in Table 2; Figs. 2a, 3d) composed of K-feldspar, quartz, plagioclase and minor chloritized biotite, along with accessory apatite, magnetite, ilmenite and zircon showing diverse morphologies and zoning characteristics (CL images Supplementary Data File S2, p. 5.

LA-ICP-MS dates from 35 zircons in this sample are equally varied. The majority of analyses give rise to Ediacaran dates contributing to a 601 Ma maximum in the age spectrum (ProbDens1Tab in Supplementary Data File S9), but numerous grains also yielded pre-Ediacaran dates. These range from Paleoproterozoic to possible Tonian or Cryogenian ages (1927 ± 38 to 707 ± 40 Ma in Supplemen-

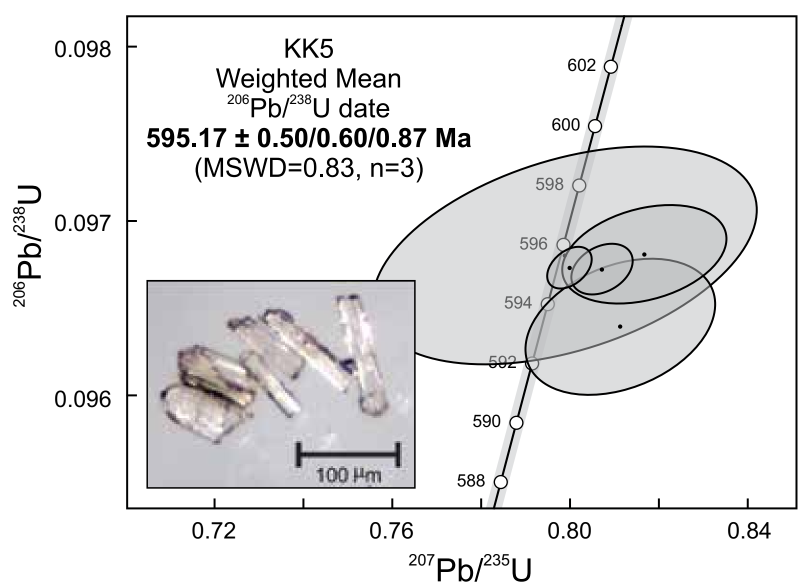



**Figure 5. U–Pb concordia plot for Westwood Granite sample KK5 made using ET redux. Ages in Ma are marked on the concordia curve, and individual analyses of single zircons are shown as 2σ error ellipses. Grey area behind concordia line represents decay constant uncertainties. Errors reported as ± X/Y/Z. Complete U–Pb isotopic data listed in Table 4. Inset shows KK5 zircons remaining from study of Thompson *et al.* (2010) prior to chemical abrasion. Five of these were dissolved for CA-ID-TIMS dating.**

tary Data File S9). Further complexity emerges from CA-ID-TIMS reanalysis of Ediacaran zircons contributing to the ca. 601 Ma probability peak in the LA-ICP-MS age spectrum. Six CA-ID-TIMS dates from 607.34 ± 0.53 to 598.82 ± 0.48 Ma in Table 3 include two from separately analyzed fragments of z1. The corresponding error ellipses are dispersed along concordia (Fig. 4g), so that the youngest date must be interpreted as a maximum igneous crystallization age. Some of the older grains in Figure 4g may have been inherited from the magma chamber, but the pre-Ediacaran ages documented by LA-ICP-MS surely involve xenocrystic components.

### *Sample MT22-12 (42.388°N, 71.212°W, NAD27 datum)*

The sampled outcrop is located on the north bank of Clematis Brook approximately 840 ft northwest of the bend in Chapel Road on the Fernald School grounds, Waltham, Massachusetts (Fig. 1). This area lies within a belt currently mapped as Dedham Granite north of Boston (Zen 1983). Granodiorite and tonalite are the typical rocks in this belt, but small masses of granite are also present (Wones and Goldsmith 1991). Sample MT22-12 appears to be one of these: a fine-grained, pink granite (Analysis 17 in Table 2; Fig. 2a) composed of co-equal amounts of K-feldspar, sericitized plagioclase and quartz, along with minor biotite that is largely replaced by chlorite. Accessory apatite, opaque minerals, rutile (?) and zircon are also present.

LA-ICP-MS analyses of 41 zircons separated from MT22-12 (Supplementary Data File S10) yielded dates ranging from 2639 ± 19 Ma to 541 ± 24 Ma. CA-ID-TIMS dates from six zircons include 688.03 ± 0.46 Ma from a grain with an inherited core (spot 153 in Supplementary Data File S2, p. 6; z1 in Table 3), and five with error ellipses dispersed along concordia between 608.29 ± 0.42 and 598.74 ± 0.40 Ma (Fig. 4h). The youngest two grains (z2, z3 in Table 3) yield a weighted mean date of 598.96 ± 1.79/1.80/1.91 Ma (MSWD = 2.3, probability of fit = 0.13) representing the maximum igneous crystallization age. The larger-than-usual errors arise because the weighted mean for two analyses expands the 95% confidence interval. The older dates are interpreted as being from grains with inherited components. Several LA-ICP-MS dates younger than the maximum crystallization age may be due to Pb loss, but the large errors in all cases overlap the 553 ± 22 Ma LA-ICP-MS date for z2 which proves via CA-ID-TIMS to be >40 Ma older.

### *Sample KK5 (42.246°N, 71.208°W, NAD27 datum)*

Sample KK5 was collected from pink, fine-grained Westwood Granite mapped in the northwest corner of the Norwood quadrangle (Chute 1966) along the off-ramp of Route 128 S onto Route 109. The granite (Analysis 18 in Table 2 from Thompson *et al.* 1996; Fig. 2a) contains subequal proportions of K-feldspar, plagioclase and quartz, along with accessory apatite, pyrite and zircon. Legacy ID-TIMS analyses of air-abraded, multigrain, zircon fractions from KK5 using an in-house U–Pb isotopic tracer produced four variably discordant analyses, which upon regression to a discordia line, yielded an upper concordia intercept date of 599 ± 1 Ma interpreted at the time as the crystallization age of the granite (Thompson *et al.* 1996). A fifth multigrain analysis, which was excluded from the age calculation, yielded a concordant date at ca. 605 Ma indicating an inherited component.

For the present study, single zircons in splits leftover from KK5 (Fig. 5 inset) were analyzed by the CA-ID-TIMS technique at the MIT Isotope Lab, using the EARTHTIME ET535 isotopic tracer and modern analytical protocols (2022; isotopic data in Table 4). Careful zircon selection and efficient elimination of Pb loss by chemical abrasion helped produce five overlapping analyses without any outlier (Fig. 5), from which a weighted mean $^{206}Pb/^{238}U$ date of 595.17 ± 0.50/0.60/0.97 Ma (MSWD = 0.83) is calculated. The new results place a tight constraint on the emplacement of the Westwood Granite, which does not overlap with its reported legacy age even considering the total propagated uncertainties (Z). This is not unexpected given the significantly improved accuracy (and not just precision) of modern, single-zircon, CA-ID-TIMS geochronology (e.g., Thompson *et al.* 2010).

## IMPLICATIONS OF UPDATED MAGMATIC CHRONOLOGY IN SOUTHEASTERN NEW ENGLAND

The new geochronology presented above provides fresh insights into the history of Ediacaran magmatism across the southeastern New England Avalon zone. Diorite at Rowley (sample MT20-05 in Fig. 1) with a crystallization age of 627.68 ± 0.22 Ma remains the oldest pluton in the area, although it now proves to be early Ediacaran rather than Cryogenian as implied by K/Ar dates (Zartman *et al.* 1965; Zartman and Naylor 1984) quoted earlier. Field relationships linking diorite at Rowley with the Topsfield Granodiorite (Fig. 2a, b) support co-magmatic origin as previously suggested by Dennen (1981) in spite of the slightly older 629.44 ± 0.57 Ma maximum crystallization age of sample MT20-03 (Fig. 1; z3 in Table 3). Cryogenian CA-ID-TIMS dates between 677.74 ± 0.51 and 659.93 ± 0.59 Ma from five Topsfield zircons with inherited components will be discussed in a later section. Both the Topsfield Granodiorite and diorite at Rowley cut undated mafic and felsic metavolcanic rocks in the belt extending northeast of Topsfield, Massachusetts (Fig. 1; Zv in map of Zen 1983; Middlesex Fells Volcanic Complex of Bell and Alvord 1976).

Unmetamorphosed argillite intruded by 618.60 ± 0.66 Ma dacitic porphyry in the MetroWest Tunnel (sample T32D-789 in Fig. 1) represents a hitherto unrecognized sedimentary chapter in the Avalonian magmatic arc. Pale coloration of these argillites contrasts with dominantly grey strata documented throughout the Cambridge Formation (Thompson and Crowley 2020) at the top of the Boston Basin section (unstippled in Fig. 1). Minor associated conglomerate lacks red rhyolitic clasts typical of Roxbury

Conglomerate within the basin. Similar conglomerate—although described in the City Tunnel (Tierney 1950) near its much later junction with the MetroWest Tunnel—went unacknowledged in the Billings' (1976) synthesis that was largely replicated in the 1983 Bedrock Geologic Map of Massachusetts. The presence of these conglomerates also distinguishes this sequence from the Westboro Formation as described by Bell and Alvord (1976).

Crystallization ages clustering with those of previously dated Dedham Granite (Table 1) were obtained from samples both northwest of Boston, Massachusetts and from the Newport, Rhode Island Cliff Walk, although nearly identical ages do not translate into lithological uniformity. Granodiorite dated at 609.10 ± 0.22 Ma (MT21-09 in Fig. 1) falls within the typical Dedham compositional range in the northern Milford–Dedham zone (compilation of Thompson *et al.* 2010). However, Quinn (1971) found "no lithologic resemblance or other evidence" for correlating Dedham Granodiorite in Emerson's (1917) map with sparsely porphyritic granite in the Newport area (MT22-20 in Fig. 1) that was dated during this study as 609.93 ± 0.18 Ma. Winchester Granite of similar age in the Middlesex Fells Reservation north of Boston based on unpublished CA-ID-TIMS data (Ridge 2024) and varies from alkali granite to tonalite.

By contrast, monzodiorite (MT21-13 in Fig. 1; analysis 10 in Table 2)—shown as hornblende gabbro that was treated as co-magmatic with surrounding Dedham Granite by Nelson (1975)—is significantly younger than Dedham dates in Table 1. This finding is consistent with field relationships farther east in the sampled outcrop. Here, fine-grained granite in hybridized contact with the 605.48 ± 0.21 Ma diorite (Fig. 3c) can be seen cross-cutting typical coarse-grained Dedham Granite. Incorporating this intrusion into the established plutonic divisions across southeastern New England is problematic because the crystallization age of MT21-13 lies squarely between the 606.25 ± 0.20 Milford Granite and 604.39 ± 0.23 Fall River Granite (Table 1) located, respectively, to the west and south (Fig. 1). What can be said is that the new high precision CA-ID-TIMS analyses undermine the notion of "discrete magmatic events" (Thompson *et al.* 2010) and point instead to a succession of more closely spaced intrusive pulses.

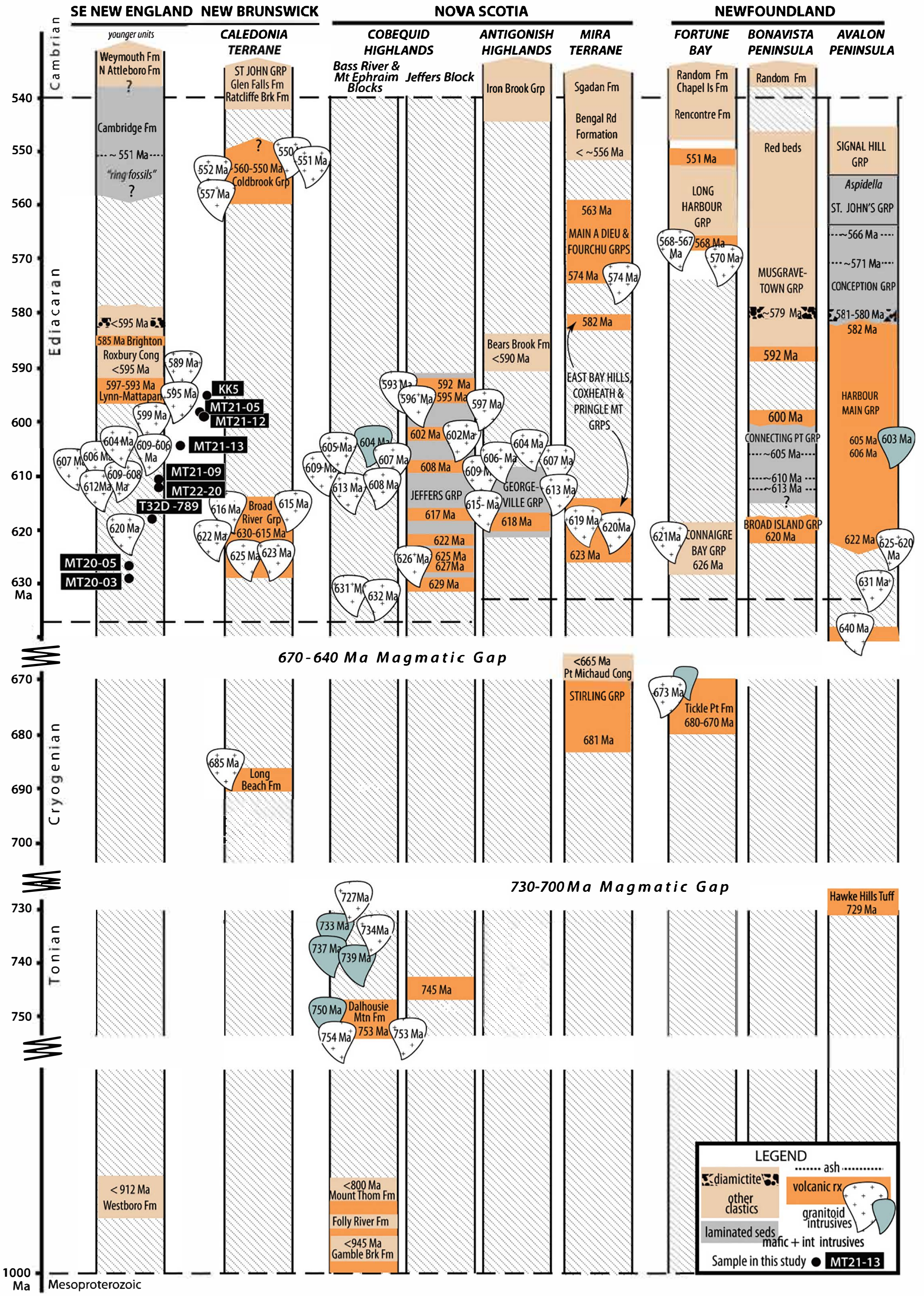
Neighboring granite samples MT21-05 and MT22-12 (Fig. 1) present other problems of interpretation because of inherited zircon components. Although the dominant probability peaks in both LA-ICP-MS age spectra are Ediacaran, error ellipses for CA-ID-TIMS analyses from redated grains contributing to those peaks are dispersed along concordia, establishing maximum crystallization ages of ca. 599 Ma in both cases (Fig. 4g, h). The presence of pre-Ediacaran zircons with LA-ICP-MS dates ranging into the Paleoproterozoic for MT21-05 (Supplemental Data File S9) and into the Mesoproterozoic for MT22-12 (Supplemental Data File S10) further complicates this picture. The youngest of these zircons within error straddle the Cryogenian/Tonian boundary, making <912 Ma quartzite in the Westboro Formation north of Boston (Thompson *et al.* 2012; Fig. 1) an unlikely source of incorporated xenocrysts. Interestingly, the maximum crystallization ages of MT21-05 and MT22-12 agree with the two youngest of six CA-ID-TIMS dates based on concordant analyses from the Esmond Granite in Smithfield RI (Fig. 1; z1, z2 in table 3 of Thompson *et al.* 2010 shown without 2σ uncertainty). The other five Esmond dates are likewise dispersed along concordia to 598.81 Ma, an unresolved problem that prompted reporting 599 ± 2 Ma as a reasonable interval for a complex crystallization history.

The legacy 599 ± 1 Ma upper intercept age interpretation for the Westwood Granite (Thompson *et al.* 1996) agrees with results cited above from the Esmond Granite and with a 599 ± 2 Ma upper intercept date from the Cohasset Granite (Dillon *et al.* 1993). The significantly younger 595.17 ± 0.5 Ma $^{206}Pb/^{238}U$ date obtained in this study, however, links Westwood intrusion with Lynn–Mattapan volcanism between ca. 597 and ca. 593 Ma. Entries for the latter in Table 1 include 595.81± 0.42 rhyolite porphyry, 595.65 ± 0.87 Ma dacite and 593.19 ± 0.73 banded rhyolite (CA-ID-TIMS dates of Thompson *et al.* 2007, 2014).

## CROSS TERRANE CORRELATIONS

Discussion below builds on previously suggested parallels between arc-related Ediacaran lithotectonic assemblages in the Southeastern New England Avalon zone and West Avalonian terranes of northern mainland Nova Scotia (Thompson *et al.* 2010); Cobequid and Antigonish Highlands in Fig. 1 inset). Simplified views of these sequences in Figure 6 incorporate plutonic and volcanic units recently documented in the fault bounded Bass River, Jeffers and Mt. Ephraim blocks of the Cobequid Highlands (White *et al.* 2022), as

**Figure 6. (next page) Tectonostratigraphic comparison between the southeastern New England Avalon zone and more northerly West Avalonian terranes of New Brunswick, Nova Scotia, and Newfoundland, Canada. Data sources: southeastern New England—Wintsch and Aleinikoff (1987); Hepburn *et al.* (1993); Dillon *et al.* (1993), Thompson *et al.* (1996, 2007, 2010, 2014) and this study, Walsh *et al.* (2011); Thompson and Crowley (2020): Caledonia terrane—Bevier and Barr (1990); Barr *et al.* (1994, 2019, 2020); Miller *et al.* (2000); Barr and White (2004): Antigonish and Cobequid Highlands—Murphy *et al.* (1997); Pe-Piper and Piper (2002); White *et al.* (2021, 2022): Mira terrane—Barr *et al.* (1990); Bevier *et al.* (1993); Wilner *et al.* (2013): Newfoundland—Krogh *et al.* (1988); Tucker and McKerrow 1995; O'Brien *et al.* (1995, 1996, 2001); Hinchey (2001); Pu *et al.* (2016); Mills *et al.* (2021 and references therein). Magmatic gaps are from van Staal *et al.* (2021). Abbreviations: Fm—Formation, Cong—Conglomerate, Grp—group, Brk—Brook, int—intermediate, Is—Island, Mtn/Mt—Mountain, Pt—Point, seds—sediments, rx—rocks.**



SE NEW ENGLAND
NEW BRUNSWICK
NOVA SCOTIA
NEWFOUNDLAND
CALEDONIA TERRANE
COBEQUID HIGHLANDS
ANTIGONISH HIGHLANDS
MIRA TERRANE
FORTUNE BAY
BONAVISTA PENINSULA
AVALON PENINSULA
Bass River & Mt Ephraim Blocks
Jeffers Block
Cambrian
Ediacaran
Cryogenian
Tonian
Mesoproterozoic
540
550
560
570
580
590
600
610
620
630 Ma
670
680
690
700
730
740
750
1000 Ma
younger units
Weymouth Fm
N Attleboro Fm
Cambridge Fm
~ 551 Ma
"ring fossils"
<595 Ma
585 Ma Brighton
Roxbury Cong <595 Ma
597-593 Ma Lynn-Mattapan
KK5
MT21-05
MT21-12
MT21-13
MT21-09
MT22-20
T32D -789
MT20-05
MT20-03
ST JOHN GRP
Glen Falls Fm
Ratcliffe Brk Fm
560-550 Ma Coldbrook Grp
Broad River Grp 630-615 Ma
Long Beach Fm
Iron Brook Grp
Bears Brook Fm <590 Ma
JEFFERS GRP
GEORGEVILLE GRP
Sgadan Fm
Bengal Rd Formation < ~556 Ma
MAIN A DIEU & FOURCHU GRPS
EAST BAY HILLS, COXHEATH & PRINGLE MT GRPS
<665 Ma Pt Michaud Cong
STIRLING GRP
Random Fm
Chapel Is Fm
Rencontre Fm
LONG HARBOUR GRP
CONNAIGRE BAY GRP 626 Ma
Tickle Pt Fm 680-670 Ma
Red beds
MUSGRAVE-TOWN GRP
CONNECTING PT GRP
BROAD ISLAND GRP 620 Ma
SIGNAL HILL GRP
Aspidella
ST. JOHN'S GRP
~566 Ma
~571 Ma
CONCEPTION GRP
581-580 Ma
582 Ma
HARBOUR MAIN GRP
Hawke Hills Tuff 729 Ma
670-640 Ma Magmatic Gap
730-700 Ma Magmatic Gap
Dalhousie Mtn Fm
745 Ma
<800 Ma Mount Thom Fm
Folly River Fm
<945 Ma Gamble Brk Fm
< 912 Ma Westboro Fm
LEGEND
diamictite
ash
other clastics
volcanic rx
granitoid intrusives
laminated seds
mafic + int intrusives
Sample in this study
MT21-13

well as positions of samples dated in the present study. Relationships are more easily seen in Figure 7 in which Cobequid crystallization ages from LA-ICP-MS weighted mean $^{206}Pb/^{238}U$ dates (SuppTab 5 of White *et al.* 2022) are compared to CA-ID-TIMS weighted mean $^{206}Pb/^{238}U$ dates from southeastern New England (Thompson *et al.* 2007, 2011, 2014 and this study). For the purpose of this comparison, CA-ID-TIMS ages have been illustrated with their systematic error Y (2σ internal uncertainty plus U–Pb tracer calibration errors). The collective results paint a picture of incremental plutonic assembly and associated volcanism in three successive ca. 10 myr intervals.

In the ca. 632–621 myr early Ediacaran interval (Fig. 7), arc-related intrusive activity begins with the Gunshot Brook

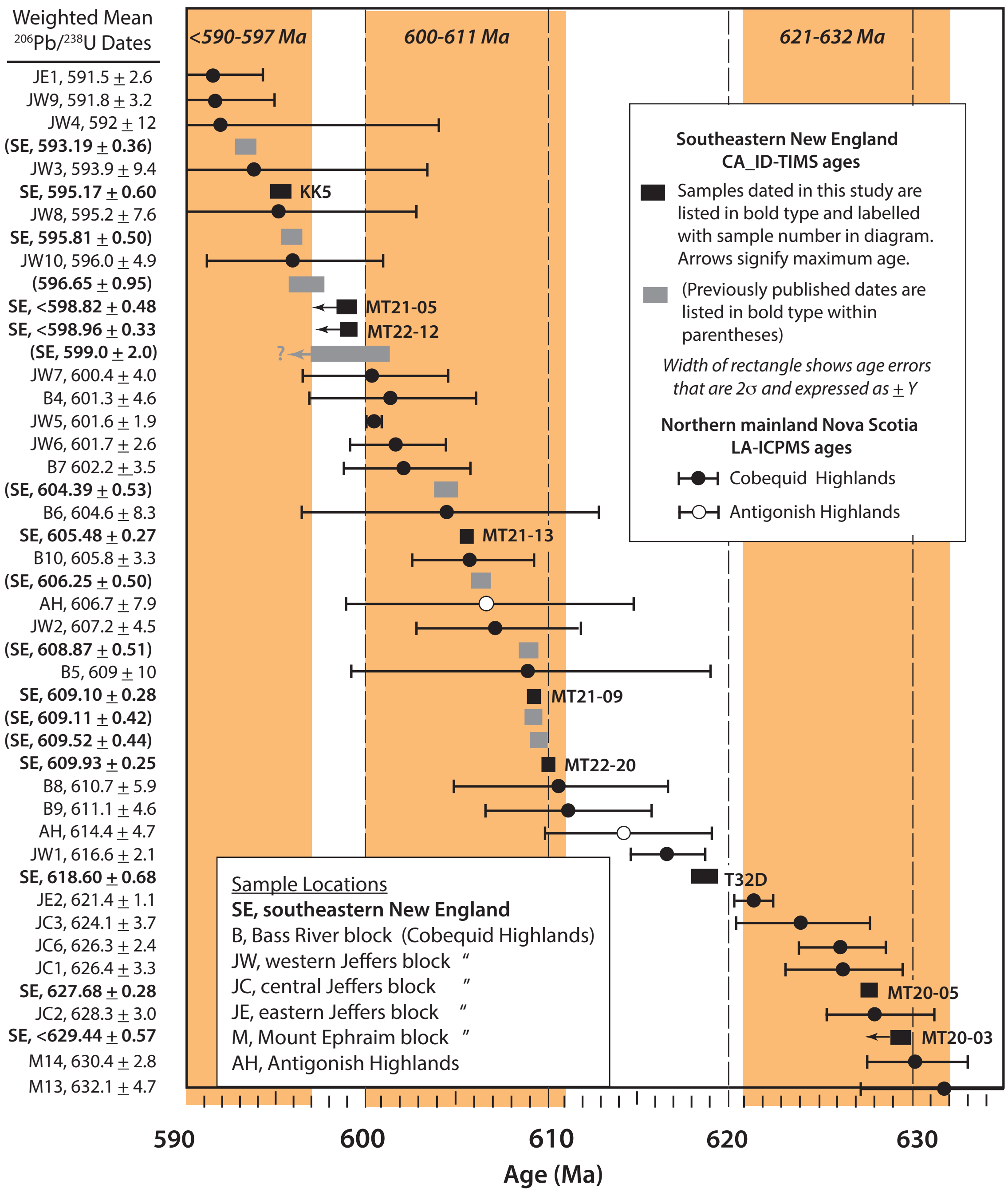



**Figure 7. Magmatic chronologies in southeastern New England and northern mainland Nova Scotia compared in terms of weighted mean $^{206}Pb/^{238}U$ dates. Southeastern New England ages are from CA-ID-TIMS in this study and previously published analyses (Thompson *et al.* 2007, 2010, 2014). These are shown with their systematic error Y (2σ internal uncertainty plus U–Pb tracer calibration errors). LA-ICP-MS ages from the Antigonish and Cobequid Highlands are from White *et al.* 2021 and 2022 (SupTab5). Collective ages define three apparent Ediacaran magmatic intervals shown in orange. The youngest of these may end after ca. 590 Ma in southeastern New England as noted in the text.**

Pluton (Pe-Piper and Piper 2005) in the Mount Ephraim block (Fig. 8). Granodiorite and tonalite samples from this body are now dated at ca. 632 and ca. 630 Ma (M14, M13 in Fig. 7). Granodiorite from the Bulmer Lake Pluton in the central Jeffers block (Fig. 8) is slightly younger at ca. 626 Ma (JC6 in Fig. 7). The Gilbert Hills rhyolite with a previously reported 630 ± 2 Ma upper concordia intercept date (Murphy *et al.* 1997; not plotted in Fig. 7) represents volcanism of similar age in the western Jeffers block. Sporadic volcanism recorded in the Jeffers Group produced felsic lithic and/or crystal tuffs as young as ca. 621 Ma in the central and eastern Jeffers block (JC1, JC2, JC3, JE2 in Figs. 7, 8). The significantly more precise $^{206}Pb/^{238}U$ date for sample JE2 was calculated from CA-ID-TIMS data (554-07_SupTab 4 of White *et al.* 2022). Counterparts of this early Ediacaran Cobequid assemblage in southeastern New England include <629 Ma Topsfield Granodiorite and ca. 628 diorite at Rowley (MT20-03 and MT20-05 in Figs. 6, 7). Volcanic elements have not yet been detected but could be present among metavolcanic rocks of uncertain origin in Figure 1 (Zv of Zen 1983).

Magmatism may have tapered off after ca. 621 Ma. In southeastern New England the only documented intrusion is a ca. 619 Ma sill in the pre-Dedham sequence transected by the MetroWest Tunnel (T32D-789 in Figs. 1, 7), and activity was similarly limited in northern mainland Nova Scotia. In the Antigonish Highlands, the Keppoch Formation at the base of the Georgeville Group contains 617.7 ± 1.6 Ma rhyolite (upper intercept date of Murphy *et al.* 1997 not plotted in Figure 7). Slightly younger are dacitic tuff in the western Jeffers block (JW1 in Figs. 7, 8) and ca. 614 Ma granite in the Jeffers Pluton (Fig. 7) of the Antigonish Highlands. Whether this is a true magmatic gap, or a function of sampling bias remains open to question.

Middle Ediacaran magmatism between ca. 611 and ca. 600 Ma (Fig. 7) features mostly plutonic activity that shows similarities in age, composition and continental arc setting (White *et al.* 2022) to previously dated Dedham–Milford–Fall River granites in southeastern New England and to samples dated in this study (Fig. 7). Cobequid examples come largely from the Bass River block (Fig. 8) and include the alkalic McCallum Settlement Pluton and the gabbroic Frog Lake Pluton which is intruded by the mainly granodioritic Debert River Pluton (Pe-Piper *et al.* 1996). CA-ID-TIMS dates from Boston-area tonalite sample MT21-09 (ca. 609 Ma) and Newport, Rhode Island granite sample MT22-20 (ca. 610 Ma) most closely agree with ca. 609 Ma Debert River tonalite (B5 in Figs. 7, 8). They also fall within uncertainties for ca. 611–605 Ma Bass River intrusives (B9, B8, B10, B6 in Fig, 7, 8), for ca. 607 Ma crystal tuff in the western Jeffers block (JW2 in Figs. 7, 8) and for the ca. 607 Ma granite in the Antigonish Harbor pluton (White *et al.* 2021, Fig. 7). Younger plutons in this interval include the ca. 602 Ma Frog Lake diorite (B7), ca. 601 Ma Debert River granite (B4), as well as ca. 602 Ma granodiorite of the Jeffers Brook pluton which intrudes metasedimentary and metavolcanic units of the Jeffers Group in the western Jeffers block (Pe-Piper *et al.* 1996; JW6 in Figs. 7, 8). The ca. 605 Ma CA-ID-TIMS date from Boston-area diorite sample MT21-13 lies within the error bars of all but the ca. 611 Ma granite from the McCal-

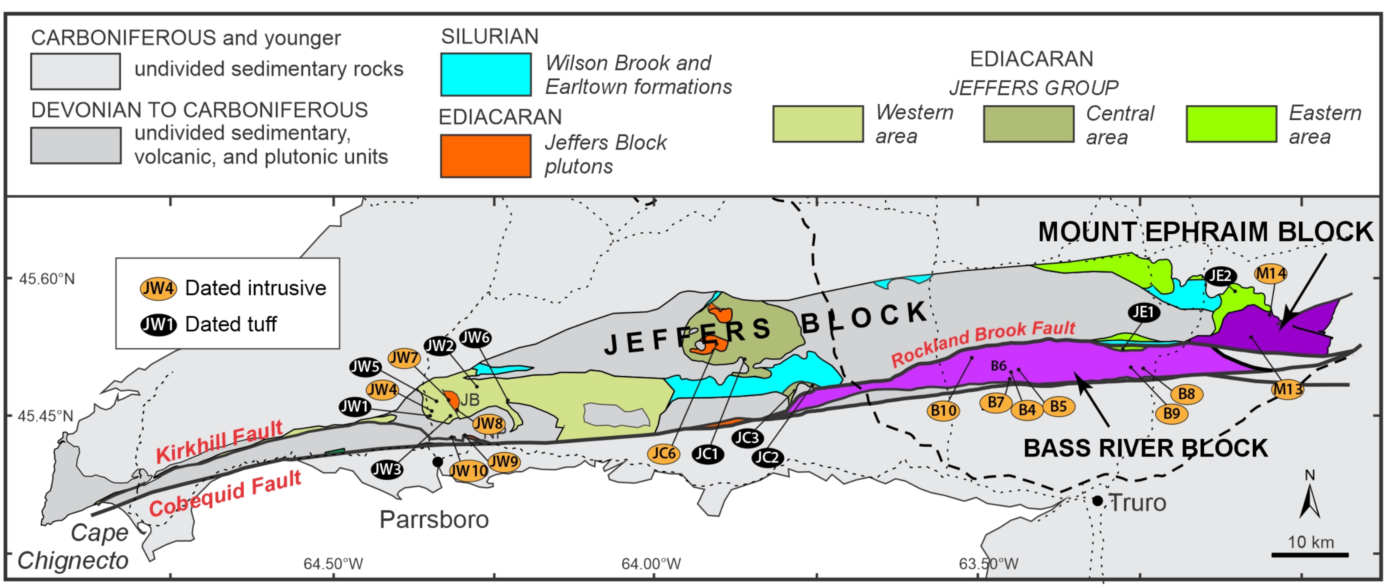



**Figure 8. Simplified geologic map of the Cobequid Highlands (modified with permission) after White *et al.* (2022) showing locations of Ediacaran igneous samples dated in that study and discussed in the present investigation. Samples shown in black are volcanic tuffs from the Jeffers Group, whereas samples shown in orange represent plutons that are named in the text. Weighted mean $^{206}Pb/^{238}U$ LA-ICP-MS dates of those samples are listed in Figure 7. The Bass River block (light purple) and Mount Ephraim block (dark purple) also include older Neoproterozoic rocks that cannot be differentiated at the scale of this map.**

lum Settlement pluton (B9 in Fig. 7) and ca. 600 Ma granodiorite of the Jeffers Brook pluton (JW7 in Fig. 8) at the extremities of this interval. Another magmatic lapse is shown after ca. 600 Ma because the ca. 599 Ma dates for samples MT22-12 and MT21-05 are both maximum ages. The same is likely true for 599 ± 2 Ma Esmond Granite (grey bar in Fig. 7) which yielded a similar array of analyses dispersed along concordia (Thompson *et al.* 2010).

The youngest magmatic interval in Figure 7 starting at ca. 597 Ma comprises ca. 597–593 Ma felsites from the Lynn–Mattapan volcanic complex (grey bars, Thompson *et al.* 2007) as well as ca. 595 Ma Westwood Granite dated in this study. These crystallization ages fall within larger errors of most if not all ca. 596 to 592 Cobequid LA-ICP-MS dates from samples including granodiorites from the New Prospect and Jeffers Brook plutons (JW10, JW8, JW9 in Fig. 7) and felsic porphyries and tuffs from the Jeffers Group (JW3, JW4, JE1 in Fig. 7). Plutonism in southeastern New England extends to ca. 589 Ma [quartz diorite at Wilson Mountain in Fig. 1; upper intercept date of Thompson *et al.* (1996)], and although this date cannot be plotted in Figure 7 because it is not a weighted mean $^{206}Pb/^{238}U$ date, the lower boundary of this magmatic interval is shown as younger than 590 Ma.

The pattern of closely spaced (and possibly overlapping) ca.10 myr magmatic events recorded in southeastern New England, Cobequid and Antigonish suites is consistent with documented periods of incremental intrusion to form continental arc-related plutons in the western United States [Tuolumne Intrusive Suite of Coleman *et al.* (2004); Mount Stuart batholith of Matzel *et al.* (2006)]. Complementing the Cobequid LA-ICP-MS results are the more precise southeastern New England CA-ID-TIMS dates that provide glimpses of more closely spaced injections within the same three intervals. Co-magmatic Topsfield Granodiorite (MT20-03) and diorite at Rowley (MT20-05) are separated at most by ca. 2 Ma, slightly shorter than the duration of emplacement of the 2.6 Ma Tenpeak intrusion in Washington's North Cascade Range (Matzel *et al.* 2006). And Dedham-equivalent intrusions represented by MT22-20 and MT21-09 differ by <1 Ma. The <599 Ma dates for MT22-12 and MT21-05 mean that the lull between those intrusions and the ca. 595 Ma Westwood Granite (KK5) is <4 Ma. Within such plutonic timeframes, analyses dispersed along concordia in MT21-05 (Table 3; Fig. 4g) could be from zircon "antecrysts" (Miller *et al.* 2007 and references therein) that crystallized during the preceding ca. 611–600 myr magmatic pulse and were subsequently incorporated into the younger magma. The same applies to older zircons except ca. 688 Ma z6 in MT22-12 (Table 3) which must have been incorporated as a xenocryst from older host rocks. Zircons of possible Cryogenian age are also found in the Topsfield Granodiorite (Table 3, Fig. 4a) and in numerous Cobequid samples (M14 in 554-07_SuppTab1 of White *et al.* 2022, M13 and JC1, JC2, JC3, JC6 all in 554-07_SuppTab2 of White *et al.* 2022). Tonian zircon suites are present in samples from the Mount Ephraim block (table 2 in White *et al.* 2022), and one zircon in the Cliff Walk Granite yielded a nominal Tonian CA-ID-TIMS date (z1 in Table 3). These as well as a broad array of older components are discussed below.

## SIGNIFICANCE OF DETRITAL AND INHERITED ZIRCON IN SOUTHEASTERN NEW ENGLAND AND COBEQUID SAMPLES

Southeastern New England granite of possible ca. 599 Ma Esmond age (MT22-12 in Fig. 1) and combined samples from the Jeffers block in the Cobequid Highlands (JW5, JW6, JE1 in Fig. 8) yielded Mesoproterozoic and older zircons ranging, respectively, from 1008 to 2639 Ma (LA-ICP-MS dates in Supplementary Data File S10) and from 1008 to 3046 Ma (LA-ICP-MS dates in SuppTab1 of White *et al.* 2022). The distribution of intervening ages is also similar (Fig. 9a, b), with Mesoproterozoic zircon dominating both assemblages. These grains are most abundant in dacitic tuffs of the Jeffers Group (JW6 and JE1 in Fig. 8), and they also occur as detrital components in associated epiclastic wacke (JW5 not shown). The combined age spectrum for these samples (Fig. 9b) resembles the distribution based on fewer analyses from MT22-12 (Fig. 9a). Probability peaks in both cases center around ca. 1100–1000 and ca. 1300–1200 Ma within the hatched "Grenvillian" interval, and both show an older 1500 Ma concentration. Paleoproterozoic peaks at ca. 1823 and ca. 1685 Ma in MT22-12 overlap the older part of the distribution in the Jeffers block samples and, within error, the ca. 2639 Ma Archean zircon in MT22-12 nearly overlaps the youngest Archean grain (ca. 2598 Ma) in the combined Jeffers samples. These assemblages are most simply interpreted as recycled detrital zircon previously documented in quartzites from the Westboro Formation north of Boston, MA [ID-TIMS dates of Thompson and Bowring (2000); CA-ID-TIMS and LA-ICP-MS dates of Thompson *et al.* (2012); LA-ICP-MS dates of Severson *et al.* (2022)] and from the Gamble Brook Formation in the Cobequid Bass River block (LA-IPC-MS dates of Henderson *et al.* 2016 and White *et al.* 2022).

The prominent ca. 1.3–1.0 Ma Mesoproterozoic components in Westboro and Gamble Brook detrital assemblages have variously been attributed to tectonic provinces bordering the Amazonian craton (Nance and Murphy 1994; Keppie *et al.* 1998; Satkoski *et al.* 2010; Willner *et al.* 2013) or to supracrustal deposits in the Taoudini Basin overlying the West African Craton (Bradley *et al.* 2013, 2022). The probability density distributions in Figures 9c, d show similarities with Bradley *et al.*'s "Assabet barcode". However, arguments based on available West African Lu–Hf isotopic signatures are more consistent with sources in Baltica (Henderson 2016; fig. 10 in Thompson *et al.* 2022). Although the provenance question will continue to be debated (e.g., Severson et al. 2022), discussion below will focus on sources in Baltica. Within this framework, both Mesoproterozoic and Paleoproterozoic zircon in the Westboro and Gamble Brook detrital suites can be derived from supracrustal metasedimentary rocks in the Sveconorwegian Telemark Province, and Paleoproterozoic contributions from the more northerly Svecofennian Province are also possible based on Sm–Nd isotopic signatures (Thompson *et al.* 2012).

The meaning of sparse Neoproterozoic zircon dates from southeastern New England that are older than Ediacaran samples is less clear. LA-ICP-MS turned up one zircon of nominal Tonian age in each of three granitoid rocks north and west of Boston, Massachusetts: 737 ± 14 Ma in MT22-12, 707 ± 40 Ma in MT21-05 and 704 ± 36 Ma in MT20-03 (Figs. 1 and 4; Supplemental Data Files S10, S4, S3), although in two cases, the uncertainties range into the Cryogenian. As previously indicated under Results, the only Tonian CA-ID-TIMS date from zircon z1 in sample MT22-20 (865.93 ± 0.57 Ma in Table 3) must be disregarded because that analysis includes components from an inherited core and a younger magmatic rim.

More abundant are Cryogenian dates which were obtained from six of the eight samples that were investigated using LA-ICP-MS (MT20-03, MT20-05, MT21-09, MT22-20, MT21-13, MT22-12 in Fig. 1; Supplementary Data Files S3, S4, S6, S7, S8, S10). Each of these yielded 3–8 Cryogenian dates between ca. 680 and ca. 640 Ma, as well as others with uncertainties overlapping that range. Reanalyzing some of the same zircons via CA-ID-TIMS confirmed Cryogenian age for z1, z2, z4, z5, z6 in sample MT20-03 and for z1 in MT22-12 (Table 3). Inherited populations of similar age are reported for tuffaceous samples JC1 (659 ± 7 Ma, n = 5), (JC2 (658 ± 6 Ma, n = 6) and JW2 (654 ± 14 Ma, n = 3) in the Jeffers block of the Cobequid Highlands (concordia ages in table 2 of White *et al.* 2022), but the provenance of all such zircon remains perplexing.

A glance at Figure 6 makes it clear that Cryogenian rocks of this age are not common in West Avalonian terranes. For starters, there are no such examples in either southeastern New England or in the Cobequid/Antigonish Highlands of northern mainland Nova Scotia (AH in Fig. 1 inset). Cryogenic arc-related suites are found on the Connaigre Peninsula of southern Newfoundland (O'Brien *et al.* 1996 and references therein; cp in Fig. 1 inset). Here calc-alkaline plutons and associated volcanic rocks of the 682 ± 3 Ma Tickle Point Formation are intruded by gran-ites and gabbros of the 673 ± 2 Ma Furby's Cove Intrusive

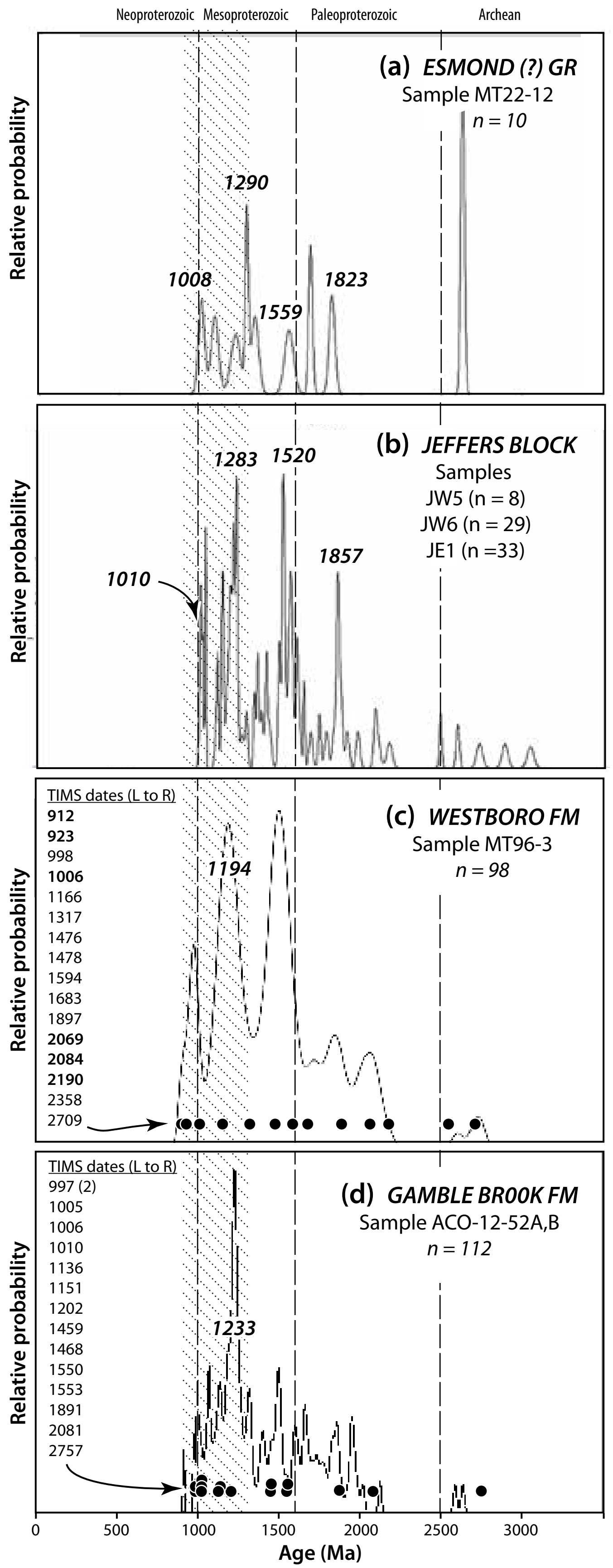



**Figure 9. Probability density distributions comparing pre-Ediacaran inheritance in southeastern New England and Jeffers block samples with detrital assemblages in metasedimentary basement units in those terranes. (a) Esmond (?) Granite Sample MT22-12 (location in Fig. 1; LA-ICP-MS data in Supplemental Data File S10). (b) Combined results from Jeffers block samples JW5, JW6 and JE1 (locations in Fig. 8; LA-ICP-MS data in 554-07 SuppTab2 of White *et al.* 2022). (c) Quartzite from the Westboro Formation (W in Fig. 1; LA-ICP-MS data in Data Repository item 2012030 of Thompson *et al.* 2012). (d) Quartzite from the Gamble Brook Formation (Bass River block in Fig. 8; LA-ICP-MS data in 554-07 SuppTab3 of White *et al.* 2022).**

suite (unpublished dates of O'Brien *et al.* 1994, 1995). Similar assemblages in the 681 +6/-2 Ma Stirling Group (upper intercept date of Bevier *et al.* 1993) form the oldest sequence in the Mira terrane of Cape Breton Island, Nova Scotia (M in Fig.1 inset). Granitoid clasts from overlying Point Michaud conglomerate establish a maximum depositional age of 665.7 ± 4.3 Ma (weighted mean $^{206}Pb/^{238}U$ date for sample 10Ca43C of Wilner *et al.* 2013). In the Caledonia terrane (C in Fig. 1 inset), a quartz-feldspar porphyry dyke cutting mafic volcanic rocks of the Long Beach Formation has recently been dated at 685 ± 10 Ma (concordia age of Barr *et al.* 2020 in Fig. 6). The ca. <647 Ma Hammondvale Metamorphic Suite higher in the Caledonia section contains numerous detrital zircons with 678.9 ± 26.9 to 658 ± 7 Ma LA-IPC-MS dates (± 1σ errors in table A1 of Satkoski *et al.* 2010) which, within error, overlap ca. 680–640 Ma inheritance in the samples from the Boston area and from the Jeffers block, but several of these are also consistent with sources suggested by Satkowski *et al.* (2010) in the older Stirling Group. Arguing against Stirling sources, however, are low positive to slightly negative εNd values from New England granitoid rocks (Dedham, Milford, Fall River, Esmond, Westwood in Fig. 1; Thompson *et al.* 2012). Similar values have previously been reported from suites in the Cobequid and Antigonish Highlands (Murphy *et al.* 1996; Pe-Piper and Piper 1998) and in the Caledonia terrane (Whalen *et al.* 1994; Samson *et al.* 2000; Satkoski *et al.* 2010), and the majority of recent Cobequid analyses show the same pattern (table 3 in White *et al.* 2022). These isotopic signatures indicate mantle-derived magma with minor contributions from continental crust, in contrast to more strongly positive εNd values typical of Newfoundland and the Mira terrane that record more juvenile, mantle dominated sources. Possible source rocks in Baltica are explored below.

## CRYOGENIAN CONNECTIONS WITH BALTICA?

Tectonic links between the southeastern New England Avalon zone and Baltica were first recognized in Mesoproterozoic and older detrital zircon suites of the ca. <912 Ma Westboro Formation and in Sm–Nd isotopic signatures from ca. 610–600 Ma granites (Thompson *et al.* 2012). This interpretation was soon broadened by similar detrital zircon dates and related Hafnium arrays obtained from single zircons in Neoproterozoic sedimentary sequences of the Cobequid and Antigonish highlands (Henderson *et al.* 2016). As summarized in that study, West Avalonian terranes originated as a sliver of ca. 2.0–1.0 Ga "Grenville type crust" that detached from Baltica after deposition of the ca. <945 Ma Gamble Brook Formation and prior to onset of arc magmatism at ca. 800–700 Ma. Subsequent history of this "ribbon continent" as elaborated by van Staal *et al.* (2021) starts with obduction of the ca. 763–760 Ma juvenile oceanic mafic magmatic rocks comprising Newfoundland's Burin Group (Murphy *et al.* 2008) followed by Tonian (ca. 750–730 Ma), Cryogenian (ca. 700–670 Ma) and mainly Ediacaran (ca. 640–595 Ma) arc magmatism and intervening ca. 730–700 Ma and ca. 670–640 Ma magmatic gaps (Fig. 6). Curiously, the ages of Cryogenian zircons discussed above slightly overlap the longer-lasting final phase of West Avalonian magmatism, but fall largely within the preceding ca. 670–640 Ma gap. Establishing Baltica provenance for these inherited components is not so easy.

In a paleogeographic reconstruction at ca. 650 Ma (Fig.10 modified from van Staal *et al.* 2021), West Avalonia is pictured after drifting from its Tonian origins off the Timanide margin of Baltica at a position that cannot be uniquely constrained paleomagnetically. The earliest activity along that margin (Kuzetsov *et al.* 2010, 2014 and references therein) is recorded in ca. 734–656 Ma plutons of the Pechora arc, associated ca. 697–656 Ma crystalline complexes (Supplementary Document Table 1 of Kuznetsov *et al.* 2014) and back arc sedimentation contemporaneous with early Neoproterozoic pyroclastic eruptions in the Engane-Pe Formation (* in Fig. 10). The Engane-Pe age spectrum (Fig. 10 inset) plotted for sample 05-033 of Kuznetzov *et al.* (2010) features prominent Tonian (ca. 703 Ma) and Cryogenian (ca. 654 Ma) peaks, along with a minor Ediacaran concentration (ca. 626 Ma). The tiny ca. 590 Ma peak arising from a single analysis was reported as the maximum depositional age. Although the Cryogenian peak in this distribution encompasses dates for inherited components in the Topsfield Granodiorite and the several Jeffers tuffs (Fig. 10), it is unlikely that the Pechora arc was located near West Avalonia during the ca. 632–621 myr interval when the Topsfield Granodiorite and tuffs in the Jeffers Group would have incorporated Cryogenian xenocrysts. At this time West Avalonia would have been moving through the Tornquist Ocean en route to collision with Ganderia on the Amazonian margin (model of van Staal *et al.* 2021) whereas the Pechora arc was in place to be accreted to the Baltica margin during Pre-Uralides Timanides orogenesis brought on by collision with the incoming Arctida paleocontinent of Kuznetsov *et al.* (2014).

Possible source rocks of Cryogenian age are found in the Ganderian Isleboro block of Maine's Penobscot Bay. Here sedimentary protoliths and basaltic dykes, sills and flows of the Seven Hundred Acre Island Formation experienced lower amphibolite grade metamorphism prior to ca. 670 Ma based on a cooling age inferred from $^{40}Ar/^{39}Ar$ release spectra in two hornblende samples (Stewart *et al.* 2001). This sequence was subsequently intruded by 647.7 ± 2.7 Ma pegmatite (weighted mean $^{207}Pb/^{206}Pb$ zircon date of Stewart *et al.* 2001), establishing a minimum age of the formation. This assemblage has variously been interpreted as having originated off the Amazonian margin of West Gondwana (van Staal *et al.* 2012) or bordering the West African segment of that margin (Reusch *et al.* 2018), so its location after ca. 630 Ma when Cryogenian zircons were acquired by the Topsfield Granodiorite and Jeffers tuffs is far from certain. Even if the Isleboro position could be established at that time, matching U–Pb zircon dates can only provide part of the answer. High precision geochronology should be coupled with Hf isotopic investigation like those of Pollock *et al.* (2022) that can

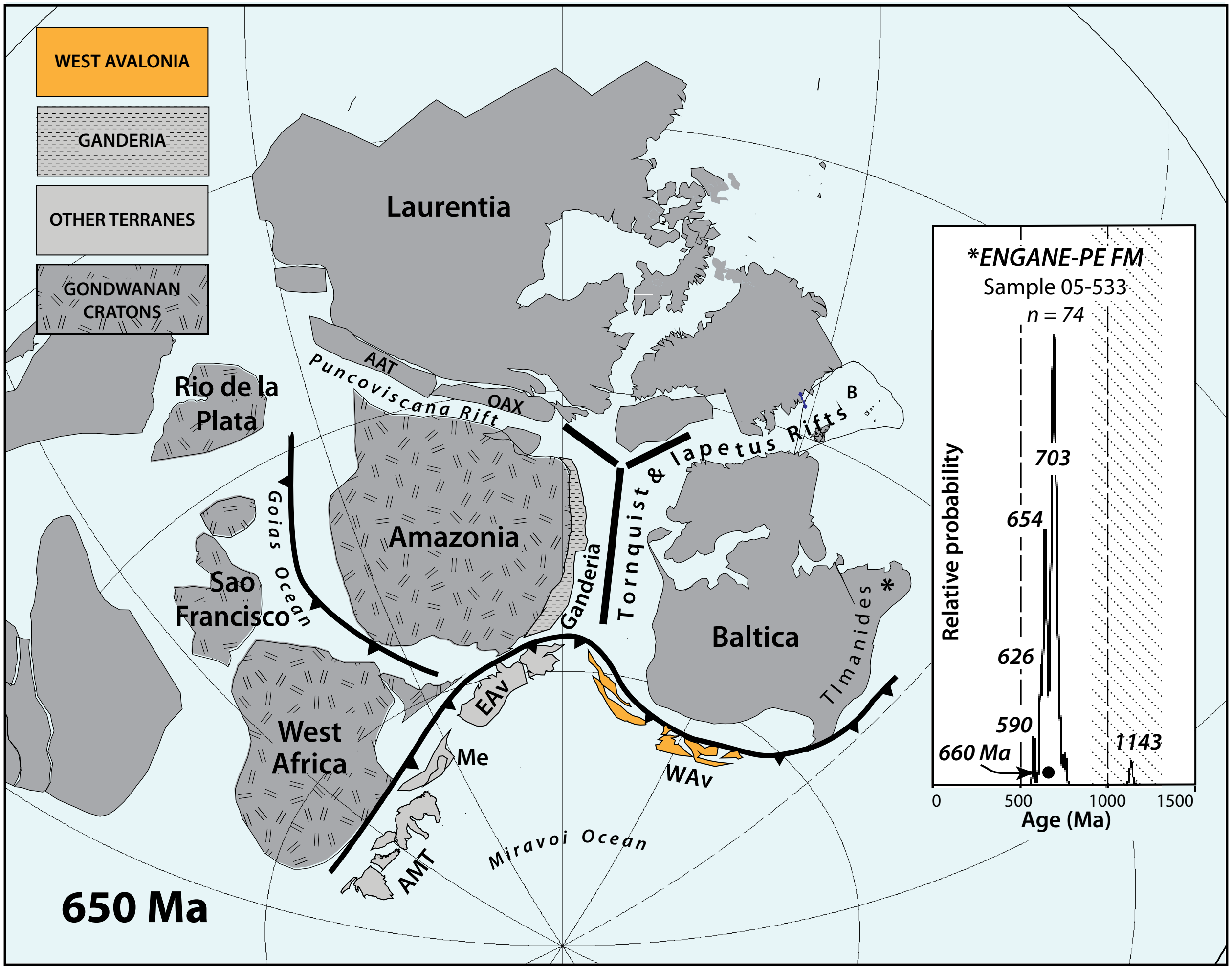



**Figure 10. Conceptual paleogeographic reconstruction (after van Staal *et al.* 2021) illustrating the position of West Avalonia after it migrated from its Tonian origins along the northeast margin of Baltica. West Avalonia's proposed entry into the developing Tornquist Ocean after ca. 650 Ma falls within the ca. 670–640 Ma magmatic gap that preceded the main phase of West Avalonian arc magmatism recorded in southeastern New England and Cobequid samples. Inset shows probability density distribution from the Engane-Pe Formation (Supplemental tables of Henderson *et al.* 2016 at contain LA-ICP-MS data from sample 05-033 of Kuzetsolv *et al.* 2010). The Cryogenian peak at ca. 654 Ma encompasses the 659.93 ± 0.59 CA-ID-TIMS date for z2 in the Topsfield Granite (black dot labelled 660 Ma) as well as collective LA-ICP-MS concordia dates from Cryogenian inherited populations in Jeffers samples JW1, JC1, and JC2 quoted in the text from table 2 in White *et al.* (2022). Abbreviations: AAT—Arequipa-Antofalla terrane, AMT—Amorican terrane assemblage, B—Barentsia, EAv—East Avalonia, Me—Maine, OAX—Oaxaca, WAv—West Avalonia.**

characterize origins and tectonic settings of crust involved in the generation of the early Ediacaran magmas.

## CONCLUSION

CA-ID-TIMS dates presented here significantly lengthen the interval of early Ediacaran arc-related magmatism in the southeastern New England Avalon zone and broaden the footprint of precisely dated plutons to the northern- and southernmost reaches of this terrane. The new geochronology shows that intrusive activity started with the 627.68 ± 0.17 Ma diorite at Rowley and tonalite associated with the Topsfield Granodiorite in the vicinity of Topsfield, Massachusetts, some twenty million years before ca. 610–609 Ma emplacement of the Dedham Granite formerly recognized as the oldest pluton. Redating the Westwood Granite establishes a 595.17 ± 0.50 Ma crystallization age linking this intrusion with the previously dated ca. 597–593 Ma Lynn–Mattapan volcanic complex Also among the new dates are several that are at odds with ages of mapped plutons in the sampling locations. Monzodiorite west of Boston, for example, falls within the Dedham Granite, but its 605.48 ± 0.21 Ma crystallization age more closely resembles the ca. 606 Ma Milford Granite and the ca. 604 Ma Fall River Granite, respectively located to the west and south. Other granites west of Boston dated at ca. ≤599 Ma overlap with the Esmond Granite in Rhode Island. Such geographic spread points to a close succession of broad ranging magmatic pulses rather than localized, discrete events previously suggested on the basis of fewer dates.

Similar clustering has lately been recognized in dates from LA-ICP-MS geochronology from northern mainland Nova Scotia with which southeastern New England has increasingly been compared. Despite uncertainties of differing magnitudes, the new southeastern New England CA-ID-TIMS dates overlap weighted mean $^{206}Pb/^{238}U$ dates from the Cobequid and Antigonish Highlands samples to define ca. 632–621, ca. 611–600 and ca. 597–<590 myr magmatic intervals with intervening periods of reduced or no activity. The Cobequid dates come mainly from the Jeffers block but also include samples from the Bass River and Mount Ephraim blocks. The ca. 10 myr duration of Cobequid magmatic intervals accords with incremental intrusive histories in continental arc-related plutons in the western United States. The more tightly constrained New England samples also reveal closely spaced injections within the active intervals, suggesting that analyses dispersed along concordia for a couple of samples are from zircons formed earlier in the same magma chamber.

LA-ICP-MS age spectra from Cobequid and southeastern New England samples both show widespread xenocrystic inheritance as well. Mesoproterozoic and older components are easily interpreted as recycled from quartzites in the Gamble Brook Formation (Cobequid Bass River block) and Westboro Formation (north of Boston, Massachusetts) that originated along the margin of Baltica prior to multiple phases of West Avalonian arc magmatism. Also common are nominally Tonian and Cryogenian inherited components, but these are more difficult to interpret in terms of Baltica provenance. The best constrained Cryogenian inheritance is based on three multi-grain populations from Jeffers Group tuffs that are overlapped by the 659.93 ± 0.59 Ma CA-ID-TIMS date from a Topsfield Granodiorite zircon. However, migration of West Avalonia into the Tornquist Ocean after ca. 650 Ma culminating in diachronous collision with Ganderia on the Gondwanan margin means that West Avalonia was no longer proximal to Baltica during the ca. 632–622 Ma Ediacaran interval when the Jeffers-Topsfield assemblage acquired its Cryogenian zircons. The Ganderian Isleboro block of coastal Maine experienced Cryogenian tectonic activity and magmatism at that time but establishing such a linkage will require isotopic data in addition to high precision U–Pb zircon geochronology.

## ACKNOWLEDGEMENTS

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## URL LINK TO SUPPLEMENTARY DATA

S1: U-Pb methods in PDF format. S2: Cathodoluminescence (CL) zircon images. S3-S10: U-Pb geochronologic analyses and trace element concentrations for samples MT20-03, MT20-05, T32D-789, MT21-09, MT22-20, MT21-13, MT21-05, and MT22-12 in Excel format. S11: Excel copy of Table 3: CA-TIMS zircon U-Pb isotopic data for samples dated at Boise State University. S12: Excel copy of Table 4: U-Pb isotopic data for analyzed zircons from Westwood Granite. https://doi.org/10.25545/KQDOCF

## REFERENCES

Barr, S.M. and Raeside, R.P. 1989. Tectono-stratigraphic terranes in Cape Breton Island, Nova Scotia: implications for the configuration of the northern Appalachian orogen. Geology, 17, pp. 822–825. https://doi.org/10.1130/0091-7613(1989)017<0822:TSTICB>2.3.CO;2

Barr, S.M. and White, C.E. 1996. Contrasts in late Precambrian-early Paleozoic tectonothermal history between Avalon composite terrane *sensu stricto* and other possible peri-Gondwanan terranes in southern New Brunswick and Cape Breton Island, Canada. *In* Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic. *Edited by* R.D. Nance, and M.D. Thompson. Geological Society of America, Special Paper 304, pp. 95–108. https://doi.org/10.1130/0-8137-2304-3.95

Barr, S.M. and White, C.E. 2004. Geo-compilation of the Caledonia belt of southern New Brunswick. New Brunswick Department of Natural Resources, Minerals, Policy and Planning Division, Map Plate 2004-138, scale 1:100 000.

Barr, S.M., Dunning, G.R., Raeside, R.P., and Jamieson, R.A. 1990. Contrasting U–Pb ages from plutons in the Bras d'Or and Mira terranes of Cape Breton Island, Nova Scotia. Canadian Journal of Earth Sciences, 27, pp. 1200–1208. https://doi.org/10.1139/e90-127

Barr, S.M., Bevier, M.L., White, C.E., and Doig, R. 1994. Magmatic history of southern New Brunswick, Canada based on U–Pb (zircon) geochronology. Journal of Geology, 102, pp. 399–409. https://doi.org/10.1086/629682

Barr, S.M., Johnson, S.C., van Rooyen, D., White, C.E., Park, A.F., and Crowley, J. 2019. U–Pb (zircon) dating in the Caledonia Highlands, southern New Brunswick—Progress Report. *In* Geoscience Summaries and Other Activities 2019. *Edited by* E.A. Keith. New Brunswick Department of Energy and Resource Development Information Circular 2019-1, pp. 10–14.

Barr, S.M., Johnson, S.C., Dunning, G.R., White, C.E., Park, A.F., Wälle, M., and Langille, A. 2020. New Cryogenian, Neoproterozoic, and mid-Paleozoic U–Pb zircon ages from the Caledonia terrane, southern New Brunswick: better constrained but more complex volcanic stratigraphy. Atlantic Geology, 56, pp. 163–187. https://doi.org/10.4138/atlgeol.2020.007

Bell, K.G. and Alvord, D.C. 1976, Pre-Silurian stratigraphy of northeastern Massachusetts. Geological Society of America Bulletin, 148, pp. 179–216. https://doi.org/10.1130/MEM148-p179

Bevier, M.L. and Barr, S.M. 1990. U–Pb age constraints on the stratigraphy and tectonic history of the Avalon terrane, New Brunswick, Canada. The Journal of Geology, 98, pp. 53–63. https://doi.org/10.1086/629374

Bevier, M.L., Barr, S.M., White, C.E., and Macdonald, A.S. 1993. U–Pb geochronologic constraints on the volcanic evolution of the Mira (Avalon) terrane, southeastern Cape Breton Island, Nova Scotia. Canadian Journal of Earth Sciences, 30, pp. 1–10. https://doi.org/10.1139/e93-001

Billings., M.P. 1976. Geology of the Boston Basin. *In* Studies in New England Geology. *Edited by* P.C. Lyons and A.H. Brownlow. Geological Society of America, Memoir 146, pp. 5–28. https://doi.org/10.1130/MEM146-p5

Bradley, D.C., O'Sullivan, P.O., Cosca, M.A., Motts, H.A., Horton, J.D., Taylor, C.D., Beaudoin, G., Lee, G.K., Ramezani, J., Bradley, D.B., Jones, J.V., and Bowring, S. 2013. Synthesis of Geological, Structural, and Geochronologic Data (phase V, deliverable 53). *In* Second Projet de Renforcement Insitutionnel du Secteur Minier de Rébublique Islamique de Mauritanie (PRISM II). *Edited by* C.D. Taylor. U.S. Geological Survery Open File Report 2013-1280, 328 p.

Bradley, D.C., Evans, D.A.D., O'Sullivan, P., Taylor, C.D., and Eglington, B.M. 2022. The Assabet barcode: Mesoproterozoic detrital zircons from Neoproterozoic strata in Mauritania, West Africa. American Journal of Science, 322, pp. 939–992. https://doi.org/10.2475/08.2022.01

Brady, J.B. 2024. Igneous and Metamorphic Rocks. Interactive diagrams, investigative tools, images, and information for students and teachers of petrology. Smith College. CIPW norm calculation tool. URL <https://www.science.smith.edu/~jbrady/petrology/igrocks-tools/norm-calc.php> 12 December 2024.

Chute, N.E. 1966. Geology of the Norwood Quadrangle, Norfolk and Suffolk Counties, Massachusetts. US Geological Survey Bulletin 1163-B, 78 p.

Clapp, C.H. 1910. Geology of the igneous rocks of Essex County, Massachusetts. U.S. Geological Survey Bulletin 704, 132 p.

Coleman, D.S., Gray, W., and Glazner, A.F. 2004. Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology, 32, pp. 433–436. https://doi.org/10.1130/G20220.1

Crowley, J.L., Schoene, B., Bowring, S.A. 2007. U–Pb dating of zircon in the Bishop Tuff at the millennial scale: Geology, 35, pp. 1123–1126. https://doi.org/10.1130/G24017A.1

Dennen, W.H. 1981. Bedrock geology of the Cape Ann Area, Massachusetts. U.S. Regulatory Commission Document NUEG/CR0881, 83 p.

Dillon, P.M. 1994. Geochemistry and petrogenesis of the Late Precambrian plutonic series south of Boston, eastern Massachusetts. Unpublished Masters Thesis, Boston College, Chestnut Hill, Massachusetts, 150 p.

Dillon, P., Dunning, G., and Hon, R. 1993. Geochemical and geochronological evidence for two distinct Avalonian magmatic suites, eastern Massachusetts. Geological Society of America Abstracts with Programs, 25, p. 12.

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

Grimes, C.B., Wooden, J.L., Cheadle, M.J., and John, B.E. 2015. "Fingerprinting" tectono-magmatic provenance using trace elements in zircon. Contributions to Mineralogy and Petrology, 170, pp. 45–72. https://doi.org/10.1007/s00410-015-1199-3

Hanson, L. and McFadden, R. 2014. Rocks and landforms of the Lynn Woods and Breakheart Reservations: what they reveal about the local geologic history and what still needs to be explored. *In* Guidebook to field trips in southeastern New England (MA-NH-RI). *Edited by* M.D. Thompson. 106th Meeting of the New England Intercollegiate Geologic Conference, Wellesley, MA, pp. C2-1-C2-24.

Hatch, N.L., Zen, E-An, Goldsmith, R., Robinson, P., Ratcliffe, N.M., Stanley, R.S., and Wones, D.R. 1984. Lithotectonic assemblages as portrayed on the new Bedrock Geologic Map of Massachusetts. American Journal of Science, 284, p. 1026–1034. https://doi.org/10.2475/ajs.284.9.1026

Henderson, B.J., Collins, W.J., Murphy, J.B., Gutiérrez-Alonso, G., and Hand, M. 2016. Gondwanan basement terranes of the Variscan-Appalachian orogen: Baltican, Saharan and West African Hafnium isotopic fingerprints in Avalonia, Iberia and the American terranes. Tectonophysics, 681, pp. 278–304. https://doi.org/10.1016/j.tecto.2015.11.020

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

Hermes, O.D. and Zartman, R.E. 1985.Late Proterozoic and Devonian plutonic terrane within the Avalon zone of Rhode Island. Geological Society of America Bulletin, 96, pp. 272–282. https://doi.org/10.1130/0016-7606(1985)96<272:LPADPT>2.0.CO;2

Hermes, O.D. and Zartman, R.E. 1992. Late Proterozoic and Silurian alkaline plutons within the southeastern New England Avalon zone. Journal of Geology 100, pp. 477–486.

https://doi.org/10.1086/629599
Hermes, O.D., Gromet, L.P., and Murray, D.P. (compilers). 1994. Bedrock geologic map of Rhode Island: Kingston, RI. Rhode Island Map Series No. 1, scale 1:100 000.
Hibbard, J.P., van Staal, C.R., Rankin, D.W., and Williams, H. 2006. Lithotectonic map of the Appalachian Orogen, Canada-United States of America. Geological Survey of Canada Map 2096a, scale 1:1 500 000. https://doi.org/10.4095/221932
Hinchey, J.G. 2001. An integrated geochemical, petrologic, geochronological and metallogenic study of the Powder Horn Intrusive Suite and the associated Lodestar prospect—a magmatic-hydrothermal auriferous breccia zone that linje epithermal and porphyry systems, northern Burin Peninsula, Newfoundland. Unpublished M.Sc. theses, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, 333 p.
Irving, T.N. and Baragar, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Sciences, 8, pp. 523–548. https://doi.org/10.1139/e71-055
Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M. 1971. Precision measurements of half-lives and specific activities of $^{235}$U and $^{238}$U. Physical Review C, 4, pp. 1889–1906. https://doi.org/10.1103/PhysRevC.4.1889
Keppie, J.D., Davis, D.W., and Krogh, T.E. 1998. U–Pb geochronological constraints on Precambrian stratified units in the Avalon composite terrane of Nova Scotia, Canada. Canadian Journal of Earth Sciences, 35, pp. 222–236. https://doi.org/10.1139/e97-109
Krogh, T. E. 1982a. Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air abrasion technique. Geochimica Et Cosmochimica Acta, 46, pp. 637–649. https://doi.org/10.1016/0016-7037(82)90165-X
Krogh, T. E. 1982b. Improved accuracy of U–Pb zircon dating by selection of more concordant fractions using a high-gradient magnetic separation technique. Geochimica Et Cosmochimica Acta, 46, pp. 631–635. https://doi.org/10.1016/0016-7037(82)90164-8.
Krogh, T.E., Strong, D.F., O'Brien, S.J., and Papezik, V.S. 1988. Precise U–Pb zircon dates from the Avalonian terrane in Newfoundland. Canadian Journal of Earth Sciences, 25, pp. 442–453. https://doi.org/10.1139/e88-045
Kuznetsov, N.B., Natapov, L.M., Belousova, E.A., O'Reilly, S.Y., and Griffin, W.L. 2010. Geochronological, geochemical and isotopic study of detrital zircon suites from late Neoproterozoic clastic strata along the NE margin of the East European craton: implication for plate tectonic models. Gondwana Research, 17, pp. 583–601. https://doi.org/10.1016/j.gr.2009.08.005
Kuznetsov, N.B., Belousova, E.A., Alekseev, A.S., and Romanyuk, T.V. 2014. New data on detrital zircons from the sandstones of the lower Cambrian Brusov Formation (White Sea region, East European craton): unravelling the timing of the onset of the Arctida-Baltica collision. International Geology Review, 556, pp. 1945–1963. https://doi.org/10.1080/00206814.2014.977968
LaForge, L. 1932. Geology of the Boston area, Massachusetts. U.S Geological Survey Bulletin 839, 105 p.
Ludwig, K.R. 2003. User's Manual for Isoplot 3.00. Berkeley Geochronology Center, Berkeley, CA, 70 p.
Mancuso, C.I., Gates, A.E., and Puffer, J.H. 1996. Geochemical and petrologic evidence of Avalonian arc to rift transition from granitoids in southeastern Rhode Island. *In* Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic. *Edited by* R.D. Nance, and M.D. Thompson. Geological Society of America, Special Paper 304, pp. 193–206. https://doi.org/10.1130/0-8137-2304-3.193
Markus, R.S. 1993. The geochemistry of the Dedham Granite suite north of Boston, Massachusetts. Unpublished Masters Thesis, Boston College, Chestnut Hill, Massachusetts, 215 p.
Mattinson, J.M. 2005. Zircon U–Pb chemical abrasion ("CA-TIMS") method: combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology, 220, pp. 47–66. https://doi.org/10.1016/j.chemgeo.2005.03.011
Matzel, J.E.P, Bowring, S.A., and Miller, R.B. 2006. Time scales of pluton construction at differing crustal levels: examples from the Mount Stuart and Tenpeak intrusions, North Cascades, Washington. Geological Society of America Bulletin, 118, pp. 1412–1430. https://doi.org/10.1130/B25923.1
Miller, B.V., Barr, S.M., Fyffe, L.R., and White, C.E. 2000. New U–Pb ages from southern New Brunswick: preliminary results. *In* Current Research 1999. *Edited by* B.M.W. Carroll. New Brunswick Bureau of Natural Resources and Energy, Minerals and Energy Division, Mineral Resource Report 2000-4, pp. 39–50.
Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D., and Miller, R.B. 2007. Zircon growth and recycling during the assembly of large, composite arc plutons. Journal of Volcanology and Geothermal Research, 167, pp. 282–299. https://doi.org/10.1016/j.jvolgeores.2007.04.019
Mills, A.J., Dunning, G.R., and Sandeman, H.A. 2021. Lithogeochemical, isotopic, and U–Pb (zircon) age constraints on arc to rift magmatism, north-western and central Avalon terrane, Newfoundland, Canada: implications for local lithostratigraphy. Canadian Journal of Earth Sciences, 58, pp. 332–354. https://doi.org/10.1139/cjes-2019-0196
Murphy, J.B., Keppie, J.D., Dostal, J., and Cousens, B.L. 1996. Repeated Late Neoproterozoic-Silurian crustal melting beneath the Antigonish Highlands, Nova Scotia: Nd isotopic evidence and tectonic interpretations. *In* Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. *Edited by* R.D. Nance, and M.D. Thompson. Geological Society of America, Special Paper 304, pp. 109–120. https://doi.org/10.1130/0-8137-2304-3.109
Murphy, J.B., Keppie, J.D., Davis, D., and Krogh, T.E. 1997. Regional significance of new U–Pb age data for Neopro-

terozoic igneous units in Avalonian rocks of northern mainland Nova Scotia. Geological Magazine, 134, pp. 113_120. https://doi.org/10.1017/S0016756897006596

Murphy, J.B., McCausland, P.J.A., O'Brien, S.J., Pisarevski, S., and Hamilton, M.A. 2008. Age, geochemistry and Sm–Nd isotopic signature of the 0.76 Ga Burin Group: compositional equivalent of Avalonian basement? Precambrian Research, 165, pp. 37-48. https://doi.org/10.1016/j.precamres.2008.05.006

Nance, R.D. and Murphy, J.B. 1994. Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens: example from the Neoproterozoic Avalonian-Cadomian belt. Geology, 22, pp. 617–620. https://doi.org/10.1130/0091-7613(1994)022<0617:CBISAT>2.3.CO;2

Nance, R.D., Murphy, J.B., Strachan, R.A., D'Lemos, R.S., and Taylor, G.K. 1991. Late Proterozoic tectonostratigraphic evolution of the Avalonian and Cadomian terranes. Precambrian Research, 53, 41–78. https://doi.org/10.1016/0301-9268(91)90005-U

Nelson, A.E. 1975. Geologic map of the Natick quadrangle, Middlesex and Norfolk Counties, Massachusetts. U.S. Geological Survey Map GQ-1208, scale 1:24 000.

O'Brien, S.J., Tucker, R.D., and O'Driscoll, C.F. 1994. Neoproterozoic basement-cover relationships and the tectono-magmatic record of the Avalon zone on the Hermitage Peninsula and environs, Newfoundland: new perspectives in the Appalachian-Caledonian orogen. *In* Program and Abstracts, Geological Association of Canada Nuna Conference, pp. 21–22.

O'Brien, S.J., O'Driscoll, C.F., Greene, B.A., and Tucker, R.D. 1995. Pre-Carboniferous geology of the Connaigre Bay Peninsula and the adjacent coast of Fortune Bay, southern Newfoundland. *In* Current Research (1995): Newfoundland Department of Natural Resources, Geological Survey Report 95-1, pp. 267–297.

O'Brien, S.J., O'Brien, B.H., Dunning, G.R., and Tucker, R.D. 1996. Late Neoproterozoic Avalonian and related per-Gondwanan rocks of the Newfoundland Appalachians. *In* Avalonian and related peri-Gondwanan terranes of the circum-North Atlantic. *Edited by* R.D. Nance, and M.D. Thompson. Geological Society of America, Special Paper 304, pp. 9–28. https://doi.org/10.1130/0-8137-2304-3.9

O'Brien, S.J., Dunning, G.R., Dubé, B., O'Driscoll, C.F., Sparks, B., Israel, S., and Ketchem, J. 200l. Insights into the Neoproterozoic geology of the central Avalon Peninsula (parts of NTS map areas 1N/6, 1N/7 and 1N/3), eastern Newfoundland. *In* Current Research (2001): Newfoundland Department of Natural Resources, Geological Survey Report 2001-1, pp. 169–189.

Parrish, R. R. and Krogh, T. E. 1987. Synthesis and purification of $^{205}$Pb for U–Pb geochronology. Chemical Geology, Isotope Geoscience section, 66, pp. 103–110. https://doi.org/10.1016/0168-9622(87)90033-9

Pearce, J.A., Harris, N.B., and Tindle A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, 25, pp. 956–983. https://doi.org/10.1093/petrology/25.4.956

Pe-Piper, G. and Piper, D.J.W. 1998. Geochemical evolution of Devonian-Carboniferous igneous rocks of the Magdalen Basin, eastern Canada: Pb- and Nd-isotopic evidence for mantle and lower crustal sources. Canadian Journal of Earth Sciences, 35, pp. 201–221. https://doi.org/10.1139/e97-106

Pe-Piper, G. and Piper, D.J.W. 2002. A synopsis of the geology of the Cobequid Highlands, Nova Scotia. Atlantic Geology, 38, pp. 145–160. https://doi.org/10.4138/1259

Pe-Piper, G. and Piper, D.J.W. 2005. Bedrock geology map of the Earltown area (parts of NTS sheets 11E/06, 11E/10 and 11E/11), Cobequid Highlands, Nova Scotia. Nova Scotia Bureau of Natural Resources, Mineral Resources Branch, Open-File Map ME-2005-117, scale 1:50 000.

Pe-Piper, G., Piper, D.J.W., and Koukouvelas, I. 1996. Precambrian plutons of the Cobequid Highlands, Nova Scotia: Geological Society of America, Special Paper 304, pp. 121–132. https://doi.org/10.1130/0-8137-2304-3.121

Pollock, J.C., Barr, S.M., van Rooyen, D., and White, C.W. 2022. Insights from Lu–Hf zircon isotopic data on the crustal evolution of Avalonia and Ganderia in the northern Appalachian orogen. *In* New Developments in the Appalachian-Caledonian-Variscan orogen. *Edited by* Y.D. Kuiper, J.B. Murphy, R.D. Nance, R.A. Strachan and M.D. Thompson. Geological Society of America, Special Paper 554, pp. 173–207. https://doi.org/10.1130/2021.2554(08)

Pu, J.P., Bowring, S.A., Ramezani, J., Myrow, P., Raub, T.D., Landing, E., Mills, A., Hodgin, E., and Macdonald, F.A. 2016. Dodging snowballs: geochronology of the Gaskiers glaciation and the first appearance of the Ediacaran biota. Geology, 44, pp. 955–958. https://doi.org/10.1130/G38284.1

Quinn, A.W. 1971. Bedrock geology of Rhode Island. U.S. Geological Survey Bulletin 1295, 65 p.

Ramezani, J., Beveridge, T. L., Rogers, R. R., Eberth, D. A., and Roberts, E. M. 2022. Calibrating the zenith of dinosaur diversity in the Campanian of the Western Interior Basin by CA-ID-TIMS U–Pb geochronology. Scientific Reports, 12, Article no. 16026, 22 pp. https://doi.org/10.1038/s41598-022-19896-w

Rast, N. and Skehan, J.W., 1983. The evolution of the Avalonian plate. Tectonophysics, 100, pp. 257–286. https://doi.org/10.1016/0040-1951(83)90191-9

Rast, N., O'Brien, B.H., and Wardle, R.J. 1976. Relationships between Precambrian and Lower Palaeozoic rocks of the 'Avalon Platform' in New Brunswick, the northeast Appalachians and the British Isles. Tectonophysics, 30, pp. 325–338. https://doi.org/10.1016/0040-1951(76)90192-X

Reusch, D.N., Holm-Denoma, C.A., and Slack, J.E. 2018. U–Pb zircon geochronology of Proterozoic and Paleozoic rocks, North Isleboro, coastal Maine (US): links to West Africa and Penobscottian orogenesis in southeastern Ganderia? Atlantic Geology, 54, pp. 189–221. https://doi.org/10.4138/atlgeol.2018.007

Ridge, J.C. 2024. Bedrock Geology of the Middlesex Fells

Reservation and Adjoining Parks and Preserves in Malden, Medford, Melrose, Stoneham, and Winchester in Middlesex County, Massachusetts, USA. Map and explanation, 245 p., scale 1:4600 (last update March 8, 2024). URL <https://sites.tufts.edu/fellsgeology/>, 8 March 2024.

Samson, S.D., Barr, S.M., and White, C.E. 2000. Nd isotopic compositions of terranes within the Avalon zone, southern New Brunswick. Canadian Journal of Earth Sciences, 37, pp. 1039–1052. https://doi.org/10.1139/e00-015

Satkoski, A.M., Barr, S.M., and Samson, S.D. 2010. Provenance of late Neoproterozoic and Cambrian sediments in Avalonia: constraints from detrital zircon ages and Sm–Nd isotopic compositions in southern New Brunswick, Canada. Journal of Geology, 118, pp. 187–200. https://doi.org/10.1086/649818

Schmitz, M.D. and Schoene, B. 2007. Derivation of isotope ratios, errors and error correlations for U–Pb geochronology using $^{205}$Pb-$^{235}$U-($^{233}$U)-spiked isotope dilution thermal ionization mass spectrometric data. Geochemistry, Geophysics, Geosystems (G3) 8. Article no. Q08006. https://doi.org/10.1029/2006GC001492

Schoene, B., Crowley, J.L., Condon, D.J., Schmitz, M.D., and Bowring, S.A. 2006. Reassessing the uranium decay constants for geochronology using ID-TIMS U–Pb data. Geochimica et Cosmochimica Acta, 70, pp. 426–445. https://doi.org/10.1016/j.gca.2005.09.007

Severson, A.R., Kuiper, Y.D., Eby, N.G., Lee, Han-Yang., and Hepburn, J.C. 2022. New detrital zircon U–Pb ages and Lu–HF isotopic data from metasedimentary rocks along the western boundary of the composite Avalon terrane in the southeastern New England Appalachians. *In* New Developments in the Appalachian-Caledonian-Variscan orogen. *Edited by* Y.D. Kuiper, J.B. Murphy, R.D. Nance, R.A. Strachan and M.D. Thompson. Geological Society of America, Special Paper 554, pp. 73–91. https://doi.org/10.1130/2021.2554(04)

Sheridan, A.W. 1988. Geochemistry of the Milford plutonic suite (Massachusetts). Unpublished Masters Thesis, Boston College, Chestnut Hill, Massachusetts, 153 p.

Skehan, J.W., Webster, M.J., and Logue, D.F. 1987. Cambrian stratigraphy and structural geology of south Narragansett Bay. *In* Centenniel Field Guide Volume 5. *Edited by* D.C. Roy. Northeastern section field guide of the Geological Society of America, pp. 195–200. https://doi.org/10.1130/0-8137-5405-4.195

Smith, B.M. 1978. The geology and Rb–Sr age of granitic rocks of Aquideck and Conanicut Islands, Rhode Island. Unpublished Masters Thesis, Brown University, Providence, Rhode Island, 100 p.

Stewart, D.B., Tucker, R.D., Ayuso, R.A., and Lux, D.R. 2001. Minimum age of the Neoproterozoic Seven Hundred Acre Island Formation, Isleboro block, Maine. Atlantic Geology, 37, pp. 41–59. https://doi.org/10.4138/1971

Streckheisen, A.W. 1973. Plutonic rocks: classification and nomenclature recommended by the IUGS Subcommission on the systematics of igneous rocks. Geotimes, 18, pp. 26–30.

Thompson, M.D., Barr, J.M., and Pollock, J.C. 2022. Evolving views of West Avalonia: Perspectives from southeastern New England, USA. *In* New developments in the Appalachian-Caledonian–Variscan orogen. *Edited by* Y.D. Kuiper, J.B. Murphy, R.D. Nance, R.A. Strachan and M.D. Thompson. Geological Society of America, Special Paper 554, pp. 47–72. https://doi.org/10.1130/2022.2554(03)

Thompson, M.D. and Bowring, S.A. 2000. Age of the Squantum "Tillite," Boston Basin, Massachusetts: U–Pb zircon constraints on terminal Neoproterozoic glaciation. American Journal of Science, 300, pp. 630–655. https://doi.org/10.2475/ajs.300.8.630

Thompson, M.D. and Crowley, J.L. 2020. Avalonian arc-to-platform transition in southeastern New England: U–Pb geochronology and stratigraphy of Ediacaran Cambridge "argillite", Boston Basin, Massachusetts, USA. American Journal of Science, 320, pp. 405–449. https://doi.org/10.2475/05.2020.01

Thompson, M.D., Hermes, O.D., Bowring, S.A., Isachsen, C.E., Besancon, J.B., and Kelly, K.L. 1996. Tectonostratigraphic implications of Late Proterozoic U–Pb zircon ages in Avalon zone of southeastern New England. *In* Avalonian and Related Peri-Gondwanan Terranes of the Circum-North Atlantic. *Edited by* R.D. Nance and M.D. Thompson. Geological Society of America Special, Paper 304, pp. 171–191. https://doi.org/10.1130/0-8137-2304-3.179

Thompson, M.D., Grunow, A.M., and Ramezani, J. 2007. Late Neoproterozoic paleogeography of the Southeastern New England Avalon Zone: insights from U–Pb geochronology and paleomagnetism. Geological Society of America Bulletin, 119, pp. 681–696. https://doi.org/10.1130/B26014.1

Thompson, M.D., Ramezani, J., Barr, S.M., and Hermes, O.D. 2010. High-precision U–Pb zircon dates for Ediacaran granitoid rocks in SE New England: revised magmatic chronology and correlation with other Avalonian terranes. *In* From Rodinia to Pangea: the Lithotectonic Record of the Appalachian Region. *Edited by* R.P. Tollo, M.J. Bartholomew, J.P. Hibbard, and P.M. Karabinos. Geological Society of America, Memoir 206, pp. 231–250. https://doi.org/10.1130/2010.1206(11)

Thompson, M.D., Barr, S.M., and Grunow, A.M. 2012. Avalonian perspectives on Neoproterozoic paleogeography: evidence from Sm–Nd isotope geochemistry and detrital zircon geochronology in SE New England, USA. Geological Society of America Bulletin, 124, pp. 517–531. https://doi.org/10.1130/B30529.1

Thompson, M.D., Ramezani, J., and Crowley, J.L. 2014. U–Pb zircon geochronology of Roxbury Conglomerate, Boston Basin, Massachusetts: tectono-stratigraphic implications for Avalonia in and beyond SE New England. American Journal of Science, 314, pp. 1009–1040. https://doi.org/10.2475/06.2014.02

Tierney, F.L. 1950. Geologic report of descriptions of rock bodies, faults and geologic phenomena found in excavating the City Tunnel. Massachusetts Water Resources Authority Report G 15, 49 p.

Toulmin, P. III 1964. Bedrock geology of the Salem quadrangle and vicinity, Massachusetts. U.S. Geological Survey Professional Paper 1163-A, 79 p.

van Staal, C.R., Barr, S.M., and Murphy, J.B. 2012. Provenance and tectonic evolution of Ganderia: constraints on the evolution of the Iapetus and Rheic oceans. Geology, 40, pp. 987–990. https://doi.org/10.1130/G33302.1

van Staal, C.R., Barr, S.M., McCausland, P.J.A., Thompson, M.D., and White, C.E. 2021. Tonian–Ediacaran tectonomagmatic evolution of West Avalonia and its Ediacaran-Early Cambrian interactions with Ganderia: an example of complex terrane transfer due to arc-arc collision? Geological Society of London Special Publications, 503, pp. 143–167. https://doi.org/10.1144/SP503-2020-23

Walsh, G.J., Aleinikoff, J.N., and Dorais, M.J. 2011. Bedrock Geologic Map of the Grafton Quadrangle, Worcester County, Massachusetts. U.S. Geological Survey Scientific Investigations Map 3171, scale 1:24 000. https://doi.org/10.3133/sim3171

Whalen, J.B., Jenner, G.A., Currie, K.L, Barr, S.M., Longstaffe, F.J., and Hegner, E. 1994. Geochemical and isotopic characteristics of granitoids of the Avalon zone, southern New Brunswick: possible evidence for repeated delamination events. Journal of Geology, 102, pp. 269–282. https://doi.org/10.1086/629670

White, C.E., Barr, S.M., Hamilton, M.A., and Murphy, J.B. 2021. Age and tectonic setting of Neoproterozoic granitoid rocks, Antigonish Highlands, Nova Scotia, Canada: Implications for Avalonia in the northern Appalachian orogen. Canadian Journal of Earth Sciences, 58, pp. 396–412. https://doi.org/10.1139/cjes-2020-0110

White, C.E., Barr, S.M., Crowley, J.L., van Rooyen, D., and MacHattie, T.G. 2022. U–Pb zircon ages and Sm–Nd isotopic data from the Cobequid Highlands, Nova Scotia, Canada: new contributions to understanding the Neoproterozoic geological history of Avalonia. *In* New developments in the Appalachian-Caledonian-Variscan orogen. *Edited by* Y.D. Kuiper, J.B. Murphy, R.D. Nance, R.A. Strachan and M.D. Thompson. Geological Society of America, Special Paper 554, pp. 135–172. https://doi.org/10.1130/2021.2554(07)

Williams, H. (compiler) 1978. Tectonic lithofacies map of the Appalachian orogen. Memorial University of Newfoundland Map no. 1, scale 1:1 000 000.

Williams, H. and Hatcher, R.D., Jr. 1982. Suspect terranes and accretionary history of the Appalachian orogen. Geology, 10, pp. 530–536. https://doi.org/10.1130/0091-7613(1982)10<530:STAAHO>2.0.CO;2

Williams, H. and Hatcher, R.D., Jr. 1983. Appalachian suspect terranes. *In* Contributions to the tectonics and geophysics of mountain chains. *Edited by* R.D. Hatcher and H. Williams. Geological Society of America, Memoir 158, pp. 33–54. https://doi.org/10.1130/MEM158-p33

Willner, A.P., Barr, S.M., Gerdes, A., Massonne, H.-J., and White, C.E. 2013. Origin and evolution of Avalonia: evidence from U–Pb and Lu–Hf isotopes in zircon from the Mira terrane, Canada, and the Stavelot—Venn Massif, Belgium. Journal of the Geological Society of London, 170, pp. 769–784. https://doi.org/10.1144/jgs2012-152

Wintsch, R.P. and Aleinikoff, J.N. 1987. U–Pb isotopic and geologic evidence for Late Paleozoic anatexis, deformation, and accretion of the Late Proterozoic Avalon terrane, southcentral Connecticut. American Journal of Science, 287, pp. 107–126. https://doi.org/10.2475/ajs.287.2.107

Wones, D.R. and Goldsmith, R. 1991. Intrusive rocks of eastern Massachusetts. U.S. Geological Survey Professional Paper 1366-I, 61 p.

Zartman, R.E. and Naylor, R.S. 1984. Structural implications of some radiometric ages of igneous rocks in southeastern New England. Geological Society of America Bulletin, 95, pp. 522–539. https://doi.org/10.1130/0016-7606(1984)95<522:SIOSRA>2.0.CO;2

Zartman, R.E., Snyder, G.L., Stern, T.W., Marvin, R.F., and Buckman, R.C. 1965. Implications of new radiometric ages in eastern Connecticut and Massachusetts. U.S. Geological Survey Professional Paper 525-D, pp. D1–D10.

Zen, E-an 1983. Bedrock geologic map of Massachusetts. Reston, U.S. Geological Survey, 1:250 000, 2 sheets.

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