5-1-2017

Bridging the Gap Between the Foreland and Hinterland I: Geochronology and Plate Tectonic Geometry of Ordovician Magmatism and Terrane Accretion on the Laurentian Margin of New England

Paul M. Karabinos
Williams College

Francis A. Macdonald
Harvard University

James L. Crowley
Boise State University

This document was originally published in the *American Journal of Science* by HighWire Press. Copyright restrictions may apply. doi: 10.2475/05.2017.01

[American Journal of Science, Vol. 317, May, 2017, P. 515–554, DOI 10.2475/05.2017.01]

American Journal of Science

MAY 2017

BRIDGING THE GAP BETWEEN THE FORELAND AND HINTERLAND I: GEOCHRONOLOGY AND PLATE TECTONIC GEOMETRY OF ORDOVICIAN MAGMATISM AND TERRANE ACCRETION ON THE LAURENTIAN MARGIN OF NEW ENGLAND

PAUL KARABINOS*,†, FRANCIS A. MACDONALD**, and JAMES L. CROWLEY***

ABSTRACT. U-Pb dates on magmatic and detrital zircon from samples in the hinterland of the Taconic orogen place new constraints on the timing and plate tectonic geometry of terrane accretion and magmatic arc activity. The Moretown terrane, a Gondwanan-derived exotic block, extends from the Rowe Schist-Moretown Formation contact in the west to the Bronson Hill arc in the east. Arc-related plutonic and volcanic rocks formed above an east-dipping subduction zone under the western leading edge of the Moretown terrane from approximately 500 to 475 Ma, until collision with hyperextended distal fragments of Laurentia, represented by the Rowe Schist, at 475 Ma. Magmatic arc rocks formed during this interval are primarily located in the Shelburne Falls arc, although some are also located in the Bronson Hill arc to the east. Metasedimentary rocks in the Shelburne Falls arc contain detrital zircon derived from mixing of Gondwanan, Laurentian, and arc sources, suggesting that the Moretown terrane was proximal to Laurentia by 475 Ma. Explosive eruptions at 466 to 464 Ma preserved in the Barnard Volcanic Member of the Missisquoi Formation in Vermont and as ash beds in the Indian River Formation in the Taconic allochthons may record slab-breakoff of subducted lithosphere following collision of the Moretown terrane with distal Laurentian crustal fragments. Between 466 and 455 Ma a reversal in subduction polarity lead to a west-dipping subduction zone under Laurentia and the newly accreted Moretown terrane. Magmatic arc rocks in the Bronson Hill arc formed above this west-dipping subduction zone along the eastern trailing edge of the Moretown terrane at approximately 455 to 440 Ma. The western boundary of Ganderia in New England is east of the Bronson Hill arc, buried beneath Silurian and Devonian rocks deformed during the Acadian orogeny.

Key words: Appalachians, Taconic orogeny, Laurentia, Gondwana, Moretown terrane, detrital zircon, Shelburne Falls arc, Bronson Hill arc

INTRODUCTION

Integrating information from the foreland basin and hinterland of an orogen has tremendous potential for advancing our understanding of the plate tectonic evolution and crustal dynamics of an active margin. The foreland stratigraphy is a time-ordered record of the depositional history in the basin. However, the foreland basin record does not provide direct evidence of the plate tectonic activity or geometry in the hinterland. It is a valuable time-integrated record of sediment transfer from the hinterland to the foreland, which is controlled by the relative elevation between the basin and the tectonically active hinterland, climate, and drainage patterns. Thus,

* Department of Geosciences, Williams College, Williamstown, Massachuestts 01267
** Department of Earth and Planetary Science, Harvard University, 20 Oxford Street, Cambridge, Massachusetts, 02138
*** Department of Geosciences, Boise State University, Boise, Idaho 83725
† Corresponding author: pkarabin@williams.edu

once time-calibrated, the foreland basin stratigraphy provides a robust record of sedimentation rates and patterns, but it does not fully explain what caused the variations in rates and thicknesses. On the other hand, our knowledge of the stratigraphy, depositional setting, relative age, and tectonic affinity of rocks in the hinterland is commonly incomplete. To make up for this deficiency, however, field mapping combined with structural, metamorphic, geochemical, geophysical, geochronological, and paleomagnetic studies from the hinterland provide direct evidence for subduction, accretion of arcs and microcontinents, rifting, tectonic exhumation, and crustal thickening in the hinterland. In other words, studies of the foreland basin and hinterland have complementary strengths and weaknesses.

Long before plate tectonic theory was first applied to the Appalachians (Bird and Dewey, 1970; St. Julien and Hubert, 1975), and even before absolute radiometric ages were available, three major orogenies were recognized based on paleontological constraints on deformed rocks below angular unconformities: the Ordovician Taconic, the Devonian Acadian, and the Pennsylvanian to Permian Alleghenian orogenies. During the 1970s and 1980s, it was common for geologists working in western New England to ascribe deformation to either the Taconic or Acadian orogeny. This simplified view of early Paleozoic tectonism held that the Taconic orogeny resulted from the collision of Laurentia with a '*Taconic arc*' (for example, Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985) and that the Acadian orogeny marked the collision of a Gondwanan-derived microcontinent called Avalonia (for example, Rast and Skehan, 1993). The Alleghenian orogeny occurred when the main Gondwanan continent arrived in the Late Paleozoic, and it was believed to have only affected rocks in southeastern New England (for example, Quinn and Moore Jr., 1968).

Detailed work in New England and in the Canadian Appalachians, where oceanic tracts, arcs, and Gondwanan-derived microcontinents are better preserved, has resulted in a much more intricate and complex history of arc and microcontinent accretion, reversals in subduction polarity, and intermittent back-arc rifting (for example, Van Staal and others, 1998; Zagorevski and others, 2008; Tremblay and Pinet, 2016). More recent tectonic syntheses have expanded the number of orogenies to the Taconic, Salinic, Acadian, Neoacadian, and Alleghenian, and some of these involve multiple phases (for example, Van Staal and Barr, 2012). Gondwanan-derived microcontinents now include the Moretown terrane (Macdonald and others, 2014), Ganderia (Van Staal and others, 1998), Avalonia (Rast and Skehan, 1993), and Meguma (Schenk, 1997; White and Barr, 2010). Furthermore, we now know that Alleghenian deformation affected rocks as far west as the Bronson Hill arc and Connecticut Valley Trough in western Massachusetts (for example, Robinson and others, 1992). The expanding geochronological database in the northern Appalachians suggests that the Laurentian margin was active from approximately 475 to 270 Ma.

Advances in both throughput and precision of U-Pb dating of zircon have made it possible to integrate more fully data from the foreland basin and the hinterland of the Taconic orogen. Detrital zircon studies allow us to constrain the provenance of metamorphic rocks more effectively than was possible through compositional analysis alone. This approach has led to the recent identification of fundamental terrane boundaries (for example, Macdonald and others, 2014). Moreover, the recognition and precise dating of K-bentonites in the foreland basin (Tucker and McKerrow, 1995; Tucker and others, 1998; Macdonald and others, 2017, this issue), combined with an expanded database of the age and tectonic significance of volcanic and plutonic rocks in the hinterland (Tucker and Robinson, 1990; Karabinos and others, 1998; Moench and Aleinikoff, 2003; Aleinikoff and others, 2011; Macdonald and others, 2014), allow us to identify specific tectonic events that were coeval with the formation of air-fall tephras in the foreland basin. Because the dated K-bentonite layers correspond with explosive volcanism and potentially with tectonic reorganizations in the hinterland, it is possible to test models of how tectonism in the hinterland affects foreland basin evolution (Ver Straeten, 2010).

Here we present constraints on the timing and plate geometry of Ordovician tectonism along the Laurentian margin in the hinterland of the Taconic orogen in the New England Appalachians. We expand on the contributions of Macdonald and others (2014), who identified a new Laurentian-Gondwanan suture in western New England and proposed that the Ordovician Shelburne Falls arc formed above an east-dipping subduction zone on a Gondwanan-derived microcontinent, the Moretown terrane. We suggest that the Moretown terrane extends eastward to the Bronson Hill arc, which formed, at least in part, after a reversal in subduction polarity created a west-dipping subduction zone under Laurentia and the newly accreted Gondwanan-derived microcontinent. We also present evidence suggesting that much of the arc magmatism in the Shelburne Falls and Bronson Hill arcs occurred in close proximity to Laurentia. In the second part of our contribution (Macdonald and others, 2017) we integrate the timing and plate geometry constraints of Ordovician tectonism with stratigraphic evidence preserved in the Taconic foreland basin.

GEOLOGIC FRAMEWORK

Laurentian Margin

The Neoproterozoic breakup of Rodinia created a south-facing rifted margin on Laurentia at approximately 20° S latitude (Torsvik and others, 2012). The age of rifting in western New England is constrained by 570 to 555 Ma volcanic and plutonic rocks (Kumarapeli and others, 1989; Walsh and Aleinikoff, 1999). Remnants of the rift shoulders are found as structural inliers in the Berkshire and Green Mountain massifs, located in western Massachusetts and Vermont (fig. 1), which are composed of *ca.* 0.95 to 1.4 Ga Mesoproterozoic para- and ortho-gneiss that are correlated with the Grenville Province of Canada and the Adirondack Mountains of New York (Ratcliffe and Zartman, 1976; Zen and others, 1983; Karabinos and Aleinikoff, 1990; Karabinos and others, 2008). The Dalton Formation (Neoproterozoic to Cambrian) in western Massachusetts and Vermont was deposited unconformably on Mesoproterozoic basement of the Berkshire and Green Mountain massifs. The Dalton Formation is compositionally heterogeneous and large variations in the thickness and relative abundance of the diverse lithologies present reflect deposition in an active rift environment (Williams and Hiscott, 1987; Allen and others, 2010). Typically, the Dalton Formation is exposed along the western margins of the Berkshire and Green Mountain massifs, and the lowest unit is a quartz-pebble conglomerate directly above basement gneisses (fig. 1). Stratigraphically above the conglomerate, the Dalton Formation includes metamorphosed arkose and black shale. Quartz-feldspar-rich meta-arkose is commonly the dominant lithology, and the black shale was metamorphosed to a distinctive graphitic phyllite that, where exposed, is stratigraphically below the Cambrian Cheshire Quartzite (Landing, 2012). The Cheshire Quartzite was deposited as a mature quartz arenite in a stable shelf environment, and it marks the transition from the rift to drift phase of the opening of the Iapetus Ocean (Williams and Hiscott, 1987; Allen and others, 2010). Continued tectonic stability of the Laurentian margin to the Early Ordovician is recorded by the extensive Early Paleozoic carbonate platform preserved throughout the Appalachians. The Mesoproterozoic basement gneisses of the Berkshire and Green Mountain massifs, together with the clastic cover rocks, were thrust westward over the Early Cambrian to Early Ordovician carbonate platform margin (Zen and others, 1983; Karabinos, 1988; Ratcliffe and others, 2011).

Outboard of the Laurentian continental shelf, an Ediacaran to Early Ordovician sequence of deep-water deposits formed on the continental slope and rise (Rowley and

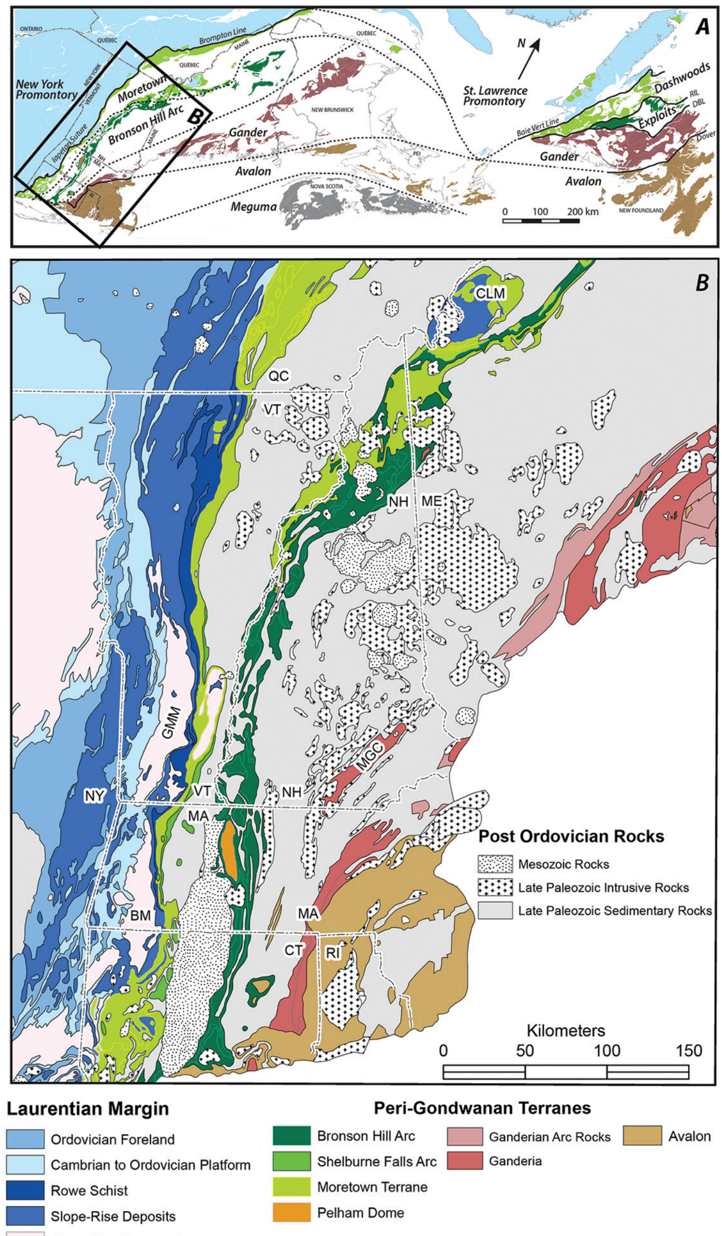

Fig. 1. (A) Tectonic map of the Appalachians modified from Hibbard and others (2006). Outline shows location of more detailed tectonic map of New England in 1B. (B) Tectonic map of New England modified from Hibbard and others (2006). Abbreviations are: BM- Berkshire massif, CLM- Chain Lakes massif, GMM- Green Mountain massif, MGC- Massabesic Gneiss Complex. (C) Location map of samples collected for LA-ICPMS detrital zircon analysis. Units use the same colors and patterns as shown in figure 1B. (D) Location map of samples dated by U-Pb zircon CA-IDTIMS. Units use the same colors and patterns as shown in figure 1B.

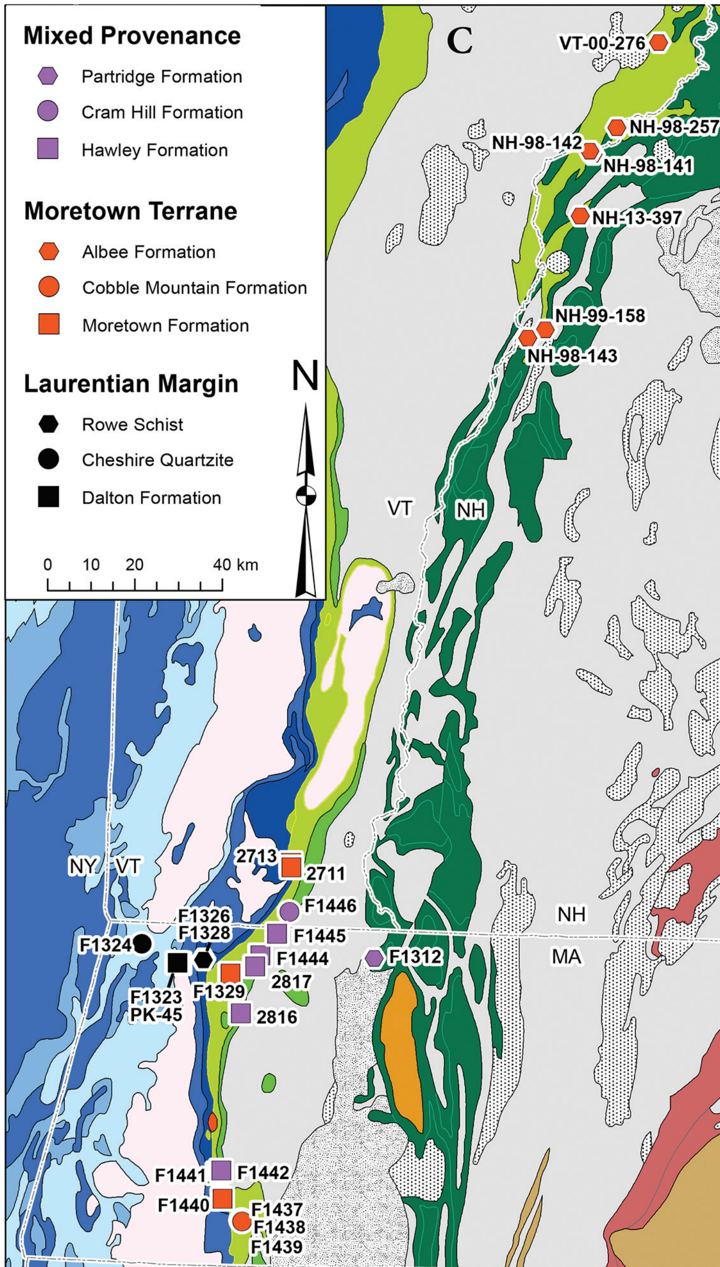

Fig. 1. (continued).

Kidd, 1981). These rocks are now preserved in the older units of the Taconic klippen west of the Green Mountain and Berkshire massifs and the Hoosac Formation and Rowe Schist east of the massifs (figs. 1 and 2; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985; Karabinos, 1988). The Rowe Schist is a quartz-rich schist correlated with the Pinney Hollow, Stowe, and Ottauquechee Formations in Vermont by Stanley

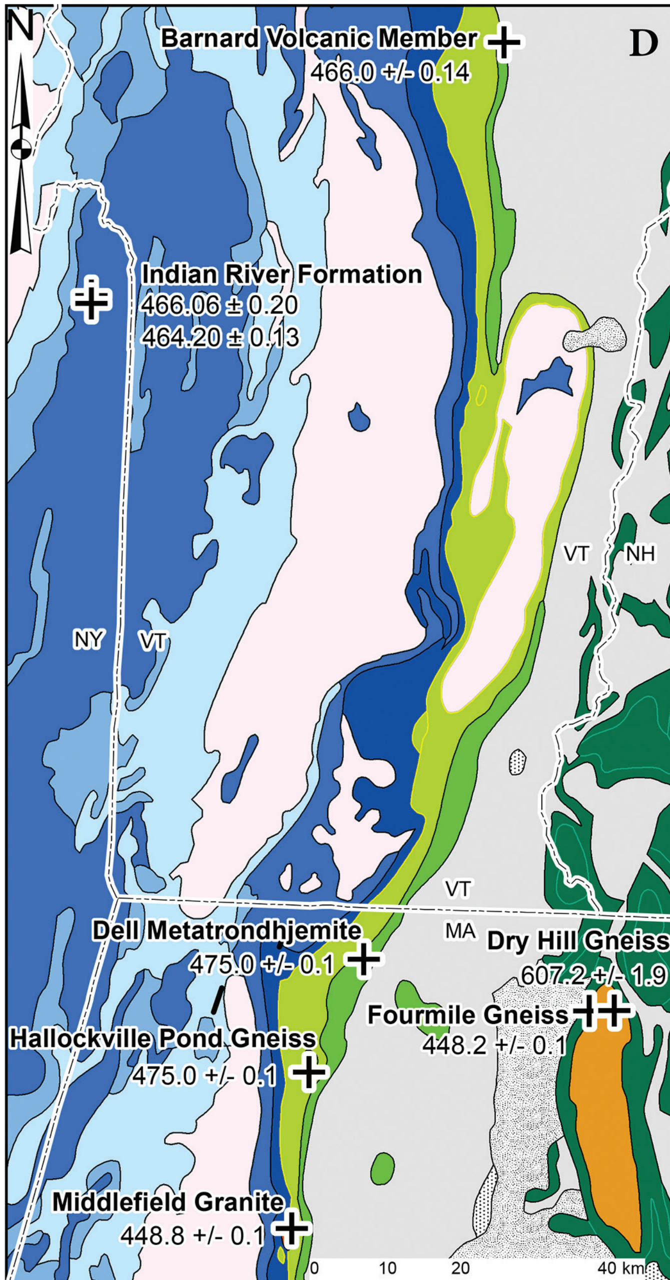

Fig. 1. (continued).

and Ratcliffe (1985). These rocks may have formed on hyper-extended Laurentian crust, and been separated from the Laurentian passive margin by the Taconic Seaway (Waldron and van Staal, 2001; Macdonald and others, 2014). Walsh and Aleinikoff (1999) reported a 571 ± 5 Ma U-Pb zircon age for a meta-felsite from the Pinney

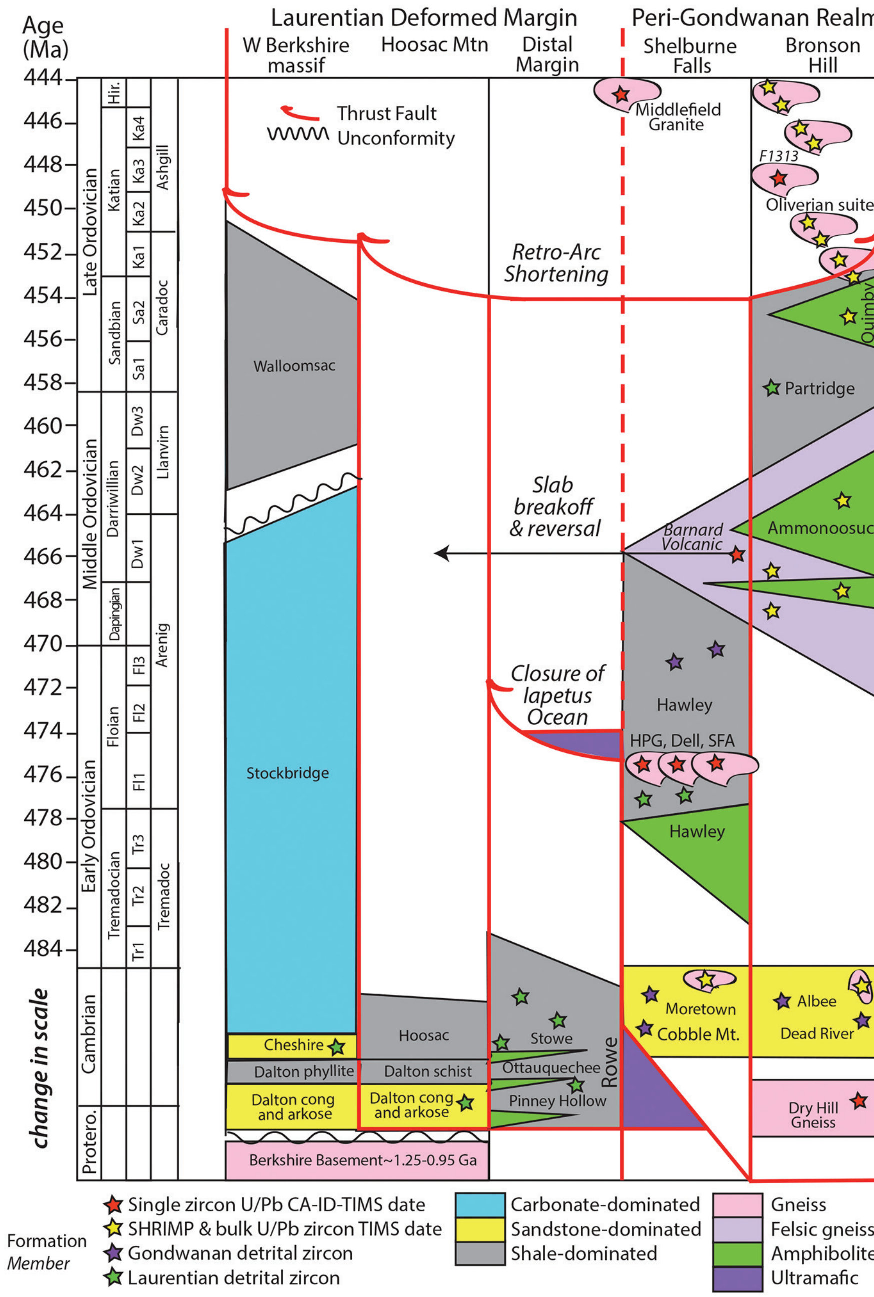

Fig. 2. Time-space diagram of Neoproterozoic to Ordovician rocks involved in the Taconic orogeny in New England. Laurentian deformed margin stratigraphy based on Karabinos (1988), Zen and others (1983), and Doll and others (1961). Peri-Gondwanan realm stratigraphy based on Macdonald and others (2014), Tucker and Robinson (1990), and Moench and Aleinikoff (2003). HPG-Hallockville Pond Gneiss, Dell-Dell Metatrondhjemite, SFA-Shelburne Falls arc.

Hollow Formation from Vermont, but the age of the other units is not constrained by radiometric dating. The youngest detrital zircon grains from the Rowe Schist are Neoproterozoic to Cambrian (585 ± 30, 566 ± 19, 560 ± 29, 536 ± 27 Ma, Macdonald and others, 2014), placing an approximate lower limit on the age of deposition (fig. 3). The structurally lower part of the Rowe Schist is predominantly non-graphitic, whereas the upper part is typically graphitic. Mafic and ultramafic lenses are common in the Rowe Schist, especially near its upper contact with the Moretown Formation (Chidester and others, 1967).

Exotic Units

Ordovician and older rocks east of the Rowe Schist formed within the Iapetus Ocean or on Gondwanan-derived microcontinents. The Moretown Formation occurs immediately east of the Rowe Schist (fig. 1). In Massachusetts and in Vermont it was mapped as an Ordovician unit (Doll and others, 1961; Zen and others, 1983; Ratcliffe and others; 2011), and interpreted by Rowley and Kidd (1981) and Stanley and Ratcliffe (1985) as a forearc deposit of the '*Taconic arc*'. It is a light gray to buff, fine-grained pinstriped granofels and schist, and contains numerous mafic layers 1 to 3 m thick. The mafic layers originated as tholeiitic basalt or basaltic-andesite that probably formed during crustal extension above an Early Ordovician east-dipping subduction zone and, possibly, above a Late Ordovician to Silurian west-dipping subduction zone (Coish and others, 2012). Locally, the mafic layers contain 1 to 5 mm plagioclase crystals in the center and aphanitic crystals near one or both margins, suggesting that some of the mafic layers are dikes with chilled margins. Macdonald and others (2014) demonstrated that detrital zircon in the Moretown Formation was derived from Gondwanan sources, and suggested a Cambrian age for the unit. The Cambrian age assignment of Macdonald and others (2014) is inconsistent with the interpretation that the Moretown Formation formed as an Ordovician forearc deposit (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985).

Both the Rowe Schist and Moretown Formation host numerous ultramafic lenses near their contact (Chidester and others, 1967; Zen and others, 1983; Ratcliffe and others, 2011), consistent with the interpretation that this contact is a major suture zone similar to the Birchy Complex in Newfoundland (van Staal and others, 2013). In northern Vermont the equivalent contact between rocks formed on or near the Laurentian margin and the Moretown Formation also contains lenses of ultramafic rocks and rare mafic schist preserving evidence for Early Ordovician blueschist metamorphism (Laird and others, 1984). Continuing north across the Canadian border, this contact is marked by the Mont-Orford, Lac-Brompton, Asbestos, and Thetford-Mines ophiolites (Tremblay and others, 2009; Tremblay and Pinet, 2016). The west vergence of faults and folds in this zone of concentrated ultramafic rocks and evidence for high-pressure metamorphism has been used as critical evidence for an east-dipping subduction zone prior to the Taconic collision of Laurentia with an arc terrane (for example, Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985).

The age of suturing of the Rowe Schist-Moretown Formation contact is constrained by the Middlefield Granite in Middlefield, Massachusetts, (figs. 1D and 1E). The Middlefield Granite intruded both the Rowe Schist and Moretown Formation at their contact but is not offset by motion along this major suture zone. Furthermore, xenoliths of pelitic and mafic schist in the Middlefield granite contain a folded schistosity, indicating that they were deformed prior to intrusion (Karabinos and Williamson, 1994). Thus, the CA-IDTIMS age of 444.8 ± 0.1 Ma for this pluton (Macdonald and others, 2014) indicates that Taconic displacement along this major suture ended before 445 Ma, while arc magmatism was active to the east in the Bronson Hill arc and to the south in western Connecticut (Sevigny and Hanson, 1993, 1995).

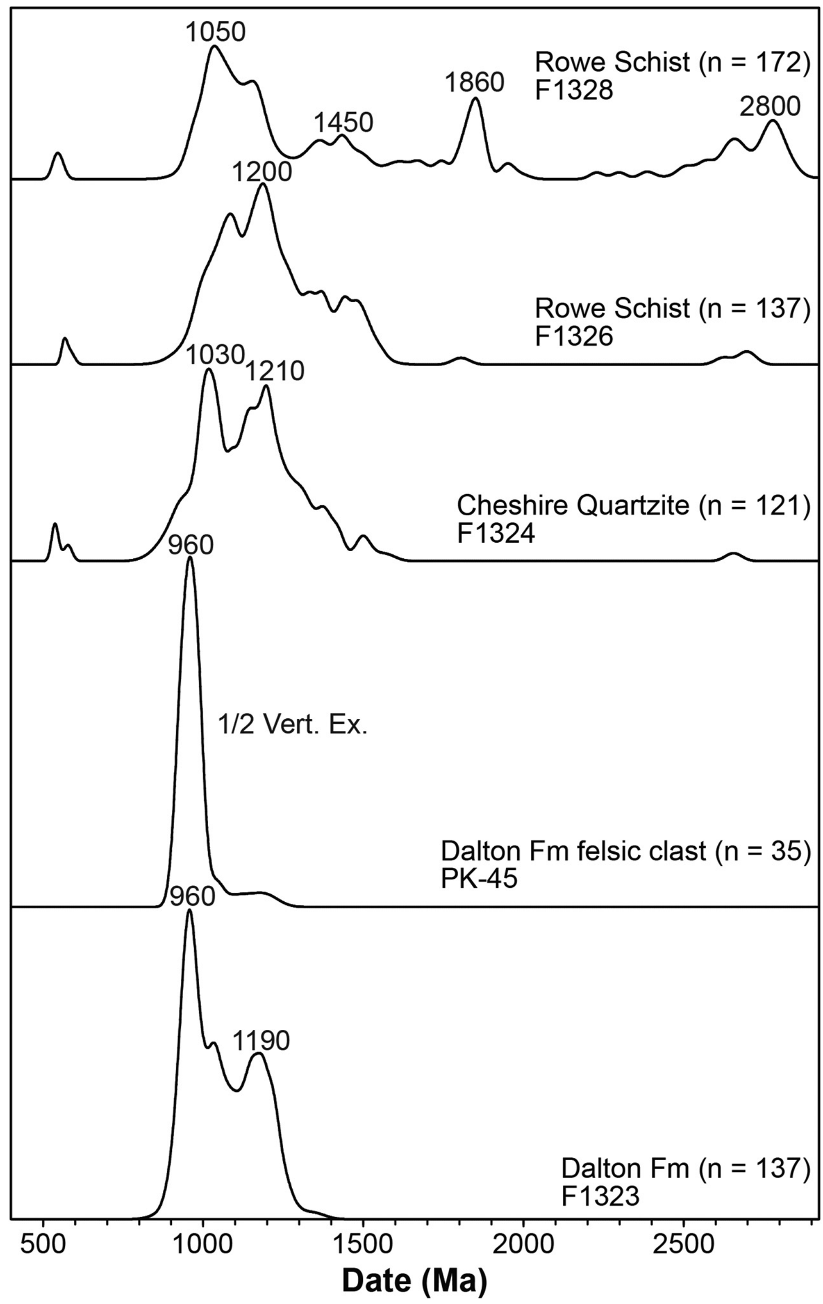

Fig. 3. Detrital zircon normalized probability density plots of samples from Laurentian margin deposits. Locations are shown in figure 1C. Note that the plot for sample PK-45 is shown at ½ vertical exaggeration to save space.

Metasedimentary units correlated with the Moretown Formation include the Cobble Mountain Formation in southwestern Massachusetts (Stanley and Hatch, 1988) and the Albee Formation in northeastern Vermont and adjacent New Hampshire (Doll and others, 1961). The Cobble Mountain Formation outcrop belt begins in southwestern Massachusetts, near the southern-most exposures of the Moretown Formation, and continues into Connecticut (Zen and others, 1983; Rodgers, 1985). The Cobble Mountain Formation was mapped as an Ordovician unit, and was considered by Stanley and Hatch (1988) as a facies equivalent of the Moretown Formation. It is dominated by non-rusty quartz, feldspar-rich schist, but the lithology is variable.

The Albee Formation outcrop belt is located in northeastern Vermont (Doll and others, 1961; Ratcliffe and others, 2011). The Albee Formation is a light gray quartzite and feldspathic quartzite with interbedded slate, phyllite, or schist, depending on the grade of metamorphism. Micaceous quartzite commonly displays a distinctive pin-stripe texture, similar to the Moretown Formation. Correlative rocks occur in adjacent New Hampshire (Lyons and others, 1997), where Moench and others (1995) mapped them as Dead River Formation, following the convention of Osberg and others (1985), who reassigned rocks originally mapped as Albee Formation in Maine to the Dead River Formation. The age of the Albee Formation is constrained to be older than a 492.5 $\pm$ 7.8 Ma intrusive tonalitic sill (U-Pb zircon SHRIMP age) east of West Bath, New Hampshire (Rankin and others, 2013).

The Neoproterozoic Dry Hill Gneiss is exposed in the core of the Pelham dome in the Bronson Hill arc (fig. 1). It is a microcline-biotite and microcline-hornblende gneiss containing microcline megacrysts, and interpreted as a metamorphosed alkali rhyolite (Zen and others, 1983). Tucker and Robinson (1990) reported a TIMS upper intercept age of 613 $\pm$ 3 Ma, which they interpreted as the eruption age, and a lower intercept age of 289 $\pm$ 4 Ma, which they attributed to Alleghenian metamorphism. The Neoproterozoic age of the Dry Hill Gneiss suggests a Gondwanan affinity (Hodgkins, ms, 1985). Aleinikoff and others (1979), and Wintsch and others (1990) suggested that the core of the Pelham dome, along with the Willimantic dome in Connecticut, were the western-most exposures of Avalonia in New England. Evidence presented by Macdonald and others (2014) demonstrated that the Moretown Formation includes metasedimentary rocks with Gondwanan provenance, and raises the possibility that the Dry Hill Gneiss is basement to the Moretown terrane.

Ordovician Arc-Related Units

East and structurally above the Moretown Formation is the outcrop belt of the Hawley Formation, and equivalent units in Vermont (the Barnard Volcanic, Whetstone Hill, and Cram Hill Members of the Missisquoi Formation of Doll and others, 1961). The Hawley Formation in Massachusetts contains diverse rock types. The formation is mostly mafic schist and gneiss, which have island arc tholeite, mid-ocean ridge basalt / back arc-basin basalt, and boninitic geochemical characteristics (Kim and Jacobi, 1996). The Legate Hill Brook Metadacite and the intrusive Dell Metatrondhjemite have arc or fore-arc geochemical signatures (Kim and Jacobi, 1996). The Hawley Formation contains a western and eastern belt of graphitic pelitic schist, a quartz-rich granofels, and layers of volcanoclastic garnet-hornblende schist (garbenschiefer) derived from interlayered mafic and pelitic schist. The Hawley Formation also includes the Charlemont Mafic Intrusive Suite, which Kim and Jacobi (1996) suggested formed during an episode of Ordovician back-arc extension. Kim and Jacobi (1996) observed that amphibolites from the eastern portion of the Moretown Formation are geochemically similar to mid-ocean ridge basalt found in the Hawley Formation, and that trondhjemites and mafic sills from the Shelburne Falls dome (Collinsville Formation) are geochemically similar to the Dell Metatrondhjemite and boninites in the Hawley Formation. Although the boninitic geochemistry of mafic rocks in the Hawley Formation has been used as evidence for formation in a forearc setting (for example Kim and Jacobi, 1996), it is also compatible with an intra-arc extensional environment.

Macdonald and others (2014) presented a CA-IDTIMS U-Pb zircon age for the intrusive Dell Metatrondhjemite of 475.5 ± 0.2 Ma (fig. 1D), thus constraining the Hawley Formation to be at least this old. The age of the Dell Metatrondhjemite is in excellent agreement with U-Pb zircon ages for rocks in the Shelburne Falls and Goshen domes presented by Karabinos and others (1998), and along with the geochemical data described above, firmly links the Hawley Formation to the Shelburne Falls arc. Further, the Dell Metatrondhjemite age is very similar to the 475.0 ± 0.1 Ma U-Pb zircon age for the Hallockville Pond Gneiss (fig. 1D), which intruded the Moretown Formation (Karabinos and Williamson, 1994; Macdonald and others, 2014).

On its eastern margin, the Hawley Formation is structurally overlain by Silurian and Devonian formations of the Connecticut Valley trough (Hatch, 1988; fig. 1). Several domes in the Connecticut Valley trough expose the Collinsville Formation (of Zen and others, 1983; Rodgers, 1985) composed of 475 to 470 Ma arc-related bimodal mafic and felsic plutonic rocks (Karabinos and others, 1998). Karabinos and others (1998) also dated samples of the Barnard Volcanic Member of the Missisquoi Formation (of Doll and others, 1961) in Vermont that range in age from 475 to 470 Ma. Older felsic plutons dated between 502 to 483 Ma have been reported from southern Vermont (Aleinikoff and others, 2011). Together, the Hallockville Pond Gneiss, the Hawley and Collinsville Formations in Massachusetts and the Barnard Volcanic Member in Vermont preserve a record of a magmatic arc, the Shelburne Falls arc of Karabinos and others (1998) that formed on the Moretown terrane (Macdonald and others, 2014). The common occurrence of arc-related rocks in the time interval 475 to 470 Ma suggests that a significant tectonic event triggered widespread magmatism in the Shelburne Falls arc at this time.

The Moretown terrane and the Shelburne Falls arc continue southward into western Connecticut (fig. 1) where Sevigny and Hanson (1993, 1995) reported U-Pb zircon ages of 454 to 438 Ma from small intrusive bodies that belong to the Brookfield plutonic suite and the Newtown, Harrison, and Beardsley Gneisses, which they suggested formed in a Late Ordovician to Early Silurian arc along the eastern Laurentian margin. Although no 485 to 465 Ma arc-related rocks have been reliably dated in southwestern Connecticut, it is important to note that the 454 to 438 Ma gneisses intruded older arc-related rocks of the Collinsville Formation that, according to Sevigny and Hanson (1993, 1995), were already deformed during an early Taconic event. Thus, older arc-related rocks, possibly coeval with 475 to 470 Ma rocks dated in Massachusetts and Vermont, must exist in southwestern Connecticut, although overprinting by high-grade Acadian metamorphism has made it difficult to date them.

East of the Connecticut Valley trough and the Mesozoic Basin, Ordovician meta-igneous rocks are also preserved in structural domes (Thompson and others, 1968; Hibbard and others, 2006; fig. 1). Tucker and Robinson (1990) presented precise U-Pb zircon TIMS ages from rocks in the Bronson Hill arc in central Massachusetts and southern New Hampshire. Late Ordovician plutonic rocks of the Swanzey, Pauchaug, Monson, and Fourmile Gneisses range in age from 454 +3/−2 to 442 +3/−2 Ma. In addition, they dated rhyolite from the upper member of the Ammonoosuc Volcanics at 453 ± 2 Ma, and from the Partridge Formation at 449 +3/-2 Ma. Tucker and Robinson (1990) demonstrated that the plutonic and volcanic rocks have overlapping ages. More importantly, they highlighted the problem that Late Ordovician arc-related rocks in the Bronson Hill belt are younger than the classic Taconic deformation and metamorphism recognized in western New England. The authors offered strikingly different proposals to explain the age discrepancy. Tucker suggested that the Bronson Hill arc collided with an already assembled "*Taconia*", and that the Taconic orogeny resulted from collision of Laurentia with an older arc, possibly represented by the "*Ascot-Weedon-Hawley-Collinsville terrane*". In contrast, Robinson suggested that the Ascot-Weedon and Hawley-Collinsville sequences are not sufficiently distinct nor are they definitely older than rocks in the Bronson Hill arc, and he proposed the existence of a single arc system. Karabinos and others (1998) showed that rocks in the Hawley-Barnard-Collinsville sequence are significantly older than lithologically similar rocks in the Bronson Hill arc studied by Tucker and Robinson (1990), and they argued that the younger arc rocks formed after a reversal in subduction polarity after collision of the Shelburne Falls arc with the Laurentian margin.

North of the area studied by Tucker and Robinson (1990), Valley and others (2015) reported new U-Pb zircon SHRIMP ages from the Bronson Hill arc in west central New Hampshire of 475 ± 5, 466 ± 8, 460 ± 3, 454 ± 3, 450 ± 4, 448 ± 5, and 445 ± 7 Ma. They suggested that the overlap between older and younger arc rocks in the Shelburne Falls and Bronson Hill arcs can best be explained by a single long-lived arc.

Lyons and others (1986) presented U-Pb zircon ages from the Highlandcroft Plutonic Suite in northern New England ranging from *ca.* 453 ± 4 to 443 ± 4 Ma, similar to ages reported to the south by Tucker and Robinson (1990). Moench and Aleinikoff (2003) also dated arc-related volcanic and plutonic rocks in the 456 ± 3 to 442 ± 4 Ma range, in northern New England, but they also discovered older 469 ± 2 and 467 ± 4 Ma plutons and suggested that the older plutons intruded the lowermost Ammonoosuc Volcanics near the type locality of the formation. Uppermost Ammonoosuc Volcanics gave ages of 465 ± 6 and 461 ± 8 Ma. Moench and Aleinikoff (2003) also dated a younger series of felsic volcanics in the Quimby Formation at 443 ± 4 Ma. They suggested that the older volcanic and plutonic rocks formed above an older east-dipping subduction zone and that the younger Quimby Formation and the Highlandcroft and Oliverian Plutonic Suites formed after a reversal in subduction polarity.

Gerbi and others (2006a) studied rocks in the Chain Lakes massif in Maine and presented U-Pb zircon TIMS ages of 477 +7/−5 Ma for the Boil Mountain Complex, and U-Pb SHRIMP ages of 472 ± 6 Ma for the Skinner Pluton and 443 ± 3 Ma for the Attean Pluton. Gerbi and others (2006b) presented detrital zircon SHRIMP ages from rocks in the Chain Lakes massif that indicate a Laurentian source for the detritus. The presence of both Early and Late Ordovician plutons in this part of the Bronson Hill arc is similar to the segment studied by Moench and Aleinikoff (2003). Two rocks were sampled for detrital zircons, the McKenney Stream and Sarampus Falls facies. The provenance of the detrital grains is convincingly Laurentian, but because the age of these rocks is poorly constrained, it is possible that they were deposited after collision with Laurentia.

Working in the southern part of the Bronson Hill arc in Connecticut, Aleinikoff and others (2007) reported U-Pb zircon SHRIMP ages of 456 ± 6 Ma for the Boulder Lake Gneiss, 449 ± 4 Ma for the Middletown Formation, and 459 ± 4 Ma for the Higganum Gneiss from the Killingworth dome. Pb and Nd isotopic geochemistry of these rocks suggests that rocks of the Killingsworth complex in the dome resulted from mixing of more radiogenic (high $^{207}Pb/^{204}Pb$ and intermediate ε_{Nd}) Gondwanan terrane sources and less radiogenic (low $^{207}Pb/^{204}Pb$ and low ε_{Nd}) Laurentian components, whereas rocks of the Middletown complex were derived from mixing of more radiogenic rocks and primitive (low $^{207}Pb/^{204}Pb$ and high ε_{Nd}) material (Aleinikoff and others, 2007). They identified Ganderia as the Gondwanan component, but at the time of their study the existence of a more westerly Gondwanan-derived crustal fragment, the Moretown terrane, (Macdonald and others, 2014) was unknown. Aleinikoff and others (2007) suggested that the Killingworth complex (mixing of Gondwanan and Laurentian components) formed above an east-dipping subduction zone on the western margin of Ganderia, and that the Middletown complex (mixing of

Gondwanan and more primitive components) formed to the east in a back-arc rift environment.

Detailed accounts of Appalachian orogenesis in the Canadian Appalachians have been presented recently for Quebec (Tremblay and Pinet, 2016), New Brunswick (van Staal and others, 2016), and Newfoundland (van Staal and others, 2007; van Staal and Baar, 2012). These authors provide valuable summaries of the geochronological data base that constrains the timing of arc magmatism and accretion of terranes to the Laurentian margin. As discussed at the end of this paper, fundamental questions concerning terrane affinity, and the timing of collision of terranes with the Laurentian margin, are shared by the New England and Canadian Appalachians.

METHODS

Siliciclastic units and igneous rocks were sampled for U-Pb zircon geochronological studies, which were performed at Boise State University. All zircon populations were first analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). Igneous samples and critical detrital zircon populations were then picked off the mounts for chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS). Analytical methods are described in detail in the Appendix. Complete U and Pb isotopic and whole rock geochemical data are given in tables A1 and A2 (http://earth.geology.yale.edu/~ajs/SupplementaryData/2017/Karabinos) and plotted in figures 3, 4, 5, and 6.

GEOCHRONOLOGY RESULTS

Laurentian Margin

Dalton Formation.—Two samples of the Dalton Formation come from an unusual facies on Hoosac Mountain (figs. 1C and 2), which is part of an isolated thrust sheet in the northeastern part of the Berkshire massif. Hoosac Mountain is the only part of the Berkshire massif underlain by 960 Ma post-Grenvillian rocks of the Stamford Granite Gneiss (Zen and others, 1983; Karabinos and Aleinikoff, 1990). The overlying basal conglomerate of the Dalton Formation is not dominated by quartz pebbles, but instead contains numerous granitic pebbles and, locally, boulders. The conglomerate grades upward into an albitic schist with pebbly beds, and is stratigraphically overlain by albitic schist of the Hoosac Formation.

PK45: Dalton Formation.—A granitic boulder extracted from the conglomerate on Hoosac Mountain at 42° 39.838'N, 73° 4.470'W. LA-ICPMS on 35 zircon grains showed a dominant peak at ~960 Ma and four older dates between 1.0 and 1.2 Ga (fig. 3). The thirty-one youngest grains have a weighted mean date of 958 ± 16 Ma (MSWD = 1.4, probability of fit = 0.09).

F1323: Dalton Formation.—Matrix and granitic pebbles collected on Hoosac Mountain at 42° 39.770'N, 73° 4.159'W. LA-ICPMS on 137 zircon grains showed a dominant peak at 960 Ma and another peak at 1190 Ma (fig. 3).

Exotic Units

Moretown Formation.—Macdonald and others (2014) presented data for three samples of the Moretown Formation from Massachusetts that indicated a Gondwanan provenance for the meta-sediments. Here we present the results from two additional samples (fig. 4). The new samples are from the southern end of the Moretown Formation outcrop belt in Massachusetts near the Connecticut border (fig. 1C).

F1440: Moretown Formation. Quartz-rich granofels collected at 42° 10.798'N, 72° 57.031'W. LA-ICPMS on 108 zircon grains showed a dominant peak at ~630 Ma and smaller peaks at ~550, 800, 1200, 1550, and 2000 Ma (fig. 4). The three youngest grains have a weighted mean date of 516 ± 12 Ma (MSWD = 0.05, probability of fit = 0.95).

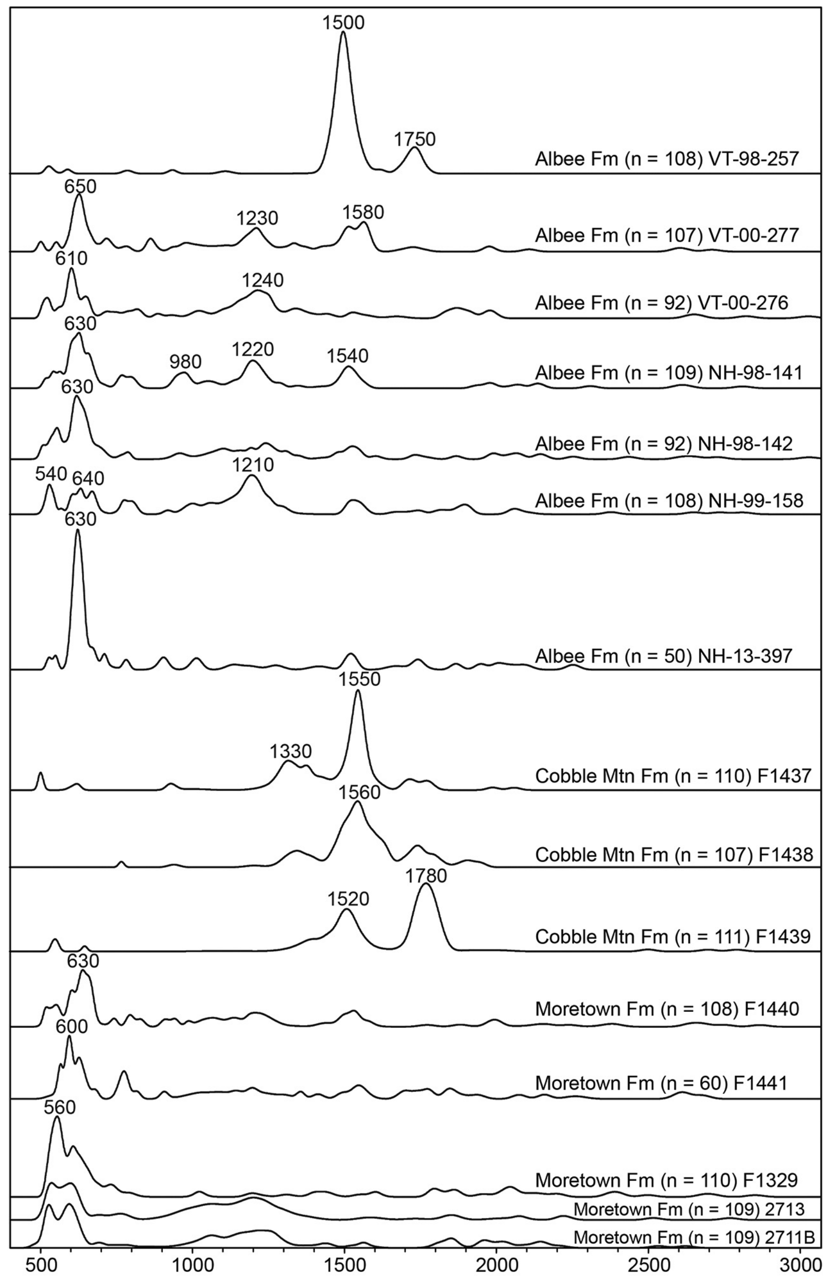

Fig. 4. Detrital zircon normalized probability density plots of samples interpreted to come from units belonging to the Gondwanan-derived Moretown terrane. Locations are shown in figure 1C.

F1441: Moretown Formation. Quartz-rich granofels collected at 42° 13.992'N, 72° 57.805'W. LA-ICPMS on 60 zircon grains showed a dominant peak at ~600 Ma and another large peak at ~770 Ma. There are many small peaks between 0.9 and 2.2 Ga, and another at 2.6 Ga. The three youngest grains have a weighted mean date of 563 ± 12 Ma (MSWD = 0.5, probability of fit = 0.59).

Cobble Mountain Formation.—Figure 4 shows the detrital zircon data from three samples of the Cobble Mountain Formation from southern Massachusetts (fig. 1C).

F1437: Cobble Mountain Formation. Quartz-rich biotite schist collected at 42° 7.953'N, 72° 53.824'W. LA-ICPMS on 110 zircon grains showed a dominant peak at 1.55 Ga and another peak at 1.33 Ga. There are five <0.9 Ga grains, three with a weighted mean date of 501 ± 11 Ma (MSWD = 0.2, probability of fit = 0.84) and others are 606 ± 31 and 623 ± 23 Ma.

F1438: Cobble Mountain Formation. Quartz-rich biotite schist collected at 42° 8.076'N, 72° 53.931'W. LA-ICPMS on 107 zircon grains showed a dominant peak at 1.56 Ga and other peaks at 1.35 and 1.75 Ga. One grain yielded a LA-ICPMS date of 766 ± 18 Ma.

F1439: Cobble Mountain Formation. Quartz-rich biotite schist collected at 42° 8.076'N, 72° 53.931'W. LA-ICPMS on 111 zircon grains showed a dominant peak at 1.78 Ga and another large peak at 1.52 Ga. There are four <0.9 Ga grains, three with a weighted mean LA-ICPMS date of 547 ± 12 Ma (MSWD = 0.9, probability of fit = 0.42) and one yielded a LA-ICPMS date of 646 ± 20 Ma.

Albee Formation.—We analyzed detrital zircon from seven samples provided by J.N. Aleinikoff, which were originally selected by D.W. Rankin and R.H. Moench to test the stratigraphic assignment of rocks in northern Vermont and New Hampshire. Our LA-ICPMS results (fig. 4) are consistent with unpublished SHRIMP ages obtained by J.N. Aleinikoff, but we were able to analyze a larger number of grains to create more robust age spectra.

VT-00-257: Albee Formation. Quartz-rich granofels collected at 44° 22.949'N, 71° 49.680'W. LA-ICPMS on 108 zircon grains showed a dominant peak at 1.5 Ga and another peak at 1.75 Ga. Four <0.9 Ga grains (4%) are 524 ± 22, 536 ± 29, 590 ± 26, and 786 ± 34 Ma.

VT-00-277: Albee Formation. Quartz-rich granofels collected at 44° 37.396'N, 71° 33.391'W. LA-ICPMS on 107 zircon grains showed a dominant peak at 650 Ma and other peaks at 1230 Ma and 1580 Ma. Forty-two grains gave LA-ICPMS dates <0.9 Ga (39%). The two youngest yielded LA-ICPMS dates of 492 ± 18 and 503 ± 22 Ma.

VT-00-276: Albee Formation. Quartz-rich granofels collected at 44° 32.242'N, 71° 43.559'W. LA-ICPMS on 92 zircon grains showed a dominant peak at 610 Ma and other peaks at 520, 800 and 1240 Ma. Thirty-four grains gave LA-ICPMS dates <0.9 Ga (37%). The five youngest yielded a LA-ICPMS weighted mean date of 519 ± 11 Ma (MSWD = 1.3, probability of fit = 0.29).

NH-98-141: Albee Formation (Dead River Formation in NH). Quartz-rich granofels collected at 44° 19.248'N, 71° 53.574'W. LA-ICPMS on 109 zircon grains showed a dominant peak at 630 Ma and other peaks at 800, 980, 1220 and 1540 Ma. Forty-eight grains gave LA-ICPMS dates <0.9 Ga (44%). The two youngest yielded LA-ICPMS dates of 517 ± 20 and 519 ± 22 Ma.

NH-98-142: Albee Formation (Dead River Formation in NH). Quartz-rich granofels collected at 44° 20.073'N, 71° 54.186'W. LA-ICPMS on 97 zircon grains showed a dominant peak at 620 Ma and other peaks at 550, 1250 and 1520 Ma. Forty-seven grains gave LA-ICPMS dates <0.9 Ga (48%). The three youngest yielded a LA-ICPMS weighted mean date of 511 ± 14 Ma (MSWD = 0.7, probability of fit = 0.47).

NH-99-158: Albee Formation (Dead River Formation in NH). Quartz-rich granofels collected at 43° 57.873'N, 72° 3.127'W. LA-ICPMS on 108 zircon grains showed a dominant peak at 1210 Ma and other peaks at 540 and 640 Ma. Thirty-three grains gave LA-ICPMS dates <0.9 Ga (31%). The six youngest yielded a LA-ICPMS weighted mean date of 526 ± 10 Ma (MSWD = 0.5, probability of fit = 0.75).

NH-13-397: Albee Formation (Dead River Formation in NH). Quartz-rich granofels collected at 44° 12.102'N, 71° 55.991'W. LA-ICPMS on 50 zircon grains showed a dominant peak at 630 Ma and no other peak. Thirty grains gave LA-ICPMS dates <0.9 Ga (60%). The two youngest yielded LA-ICPMS dates of 528 ± 20 and 550 ± 16 Ma.

Dry Hill Gneiss.—F1314: Microcline-biotite gneiss containing microcline megacrysts collected at 42° 36.362'N, 72° 25.6748'W. LA-ICPMS on 71 zircon grains from sample yielded scattered dates between 607 ± 23 and 537 ± 19 Ma. The scatter is due to rims with metamorphic zoning seen in CL images that surround grains with igneous zoning. Nine fragments from four grains were analyzed by CA-IDTIMS. All analyses are discordant and form a line between 607.2 ± 1.9 / 8.6 and 288.8 ± 7.7 / 8.5 Ma (MSWD = 1.2, probability of fit = 0.31). The analyses plot much closer to upper intercept than lower; $^{206}Pb/^{238}U$ dates are 590 to 498 Ma (fig. 5). The igneous crystallization age is interpreted from the upper intercept and the age of metamorphism from the lower intercept. These results are in excellent agreement with the dates reported by Tucker and Robinson (1990).

Ordovician Arc-Related Units

Hawley and Cram Hill Formations.—Macdonald and others (2014) presented detrital zircon data from two samples of the Hawley Formation, and suggested that the detritus was derived from both Laurentian and Gondwanan sources. Here we present results from three additional samples of the Hawley Formation, and one sample of the correlative Cram Hill Formation along strike in southern Vermont.

F1442: Hawley Formation. Graphitic schist collected at 42° 14.321'N, 72° 57.255'W. LA-ICPMS on 8 zircon grains yielded six dates between 1028 ± 61 and 1197 ± 103 Ma, and two others are 460 ± 22 and 469 ± 18 Ma.

F1444: Hawley Formation. Hornblende-garnet schist (garbenschieffer) collected at 42° 39.573'N, 72° 51.706'W. LA-ICPMS on 26 zircon grains showed a dominant peak at ~470 Ma and three older grains at 1.55, 1.59, and 1.88 Ga. The twenty youngest grains have a weighted mean date of 474 ± 12 Ma (MSWD = 1.5, probability of fit = 0.08).

F1446: Cram Hill Formation. Graphitic schist collected at 42° 46.256'N, 72° 45.972'W. LA-ICPMS on 121 zircon grains showed dominant peaks at ~1.34, 1.53, and 1.73 Ga. There are seven <0.9 Ga grains, the three youngest with a weighted mean date of 611 ± 20 Ma (MSWD = 0.6, probability of fit = 0.58).

F1507: Hawley Formation. Graphitic schist collected at 42° 29.629'N, 72° 56.815'W. LA-ICPMS on 109 zircon grains showed a dominant peak at 1020 and 1160 Ma. Four <0.9 Ga grains are 530 ± 26, 563 ± 29, 584 ± 27, and 592 ± 27 Ma.

2836: Barnard Volcanic Member of the Missisquoi Formation (Doll and others, 1961) or Barnard Gneiss (Ratcliffe and others, 2011, Richardson, 1924). Felsic granofels collected at 43° 47.691'N, 72° 37.663'W, just below the contact with the Silurian Shaw Mountain Formation (figs. 1D and 5). LA-ICPMS on 84 zircon grains showed a dominant peak at ~460 Ma and one date at 1.1 Ga. Eighty dates yielded a weighted mean date of 458 ± 5 Ma (MSWD = 0.7, probability of fit = 0.96). Six grains analyzed by CA-TIMS have a weighted mean date of 466.00 ± 0.14 / 0.27 / 0.55 Ma (fig. 5; MSWD = 2.1, probability of fit = 0.06). This is the interpreted eruption age.

F1313: Fourmile Gneiss. Tonalitic gneiss collected at 42° 36.722'N, 72° 28.721'W. LA-ICPMS on 58 zircon grains yielded scattered dates between 469 ± 19 and 378 ± 20 Ma. The scatter is due to narrow rims with metamorphic zoning seen in CL images that surround grains with igneous zoning. Five whole grains and two fragments from each of three other grains were analyzed by CA-TIMS. The three oldest dates, from one whole grain and two fragments from a grain, have a weighted mean date of 448.16 ± 0.52 / 0.56 / 0.73 Ma (fig. 5; MSWD = 3.7, probability of fit = 0.03). This is the interpreted igneous crystallization age. The eight other dates are younger, between

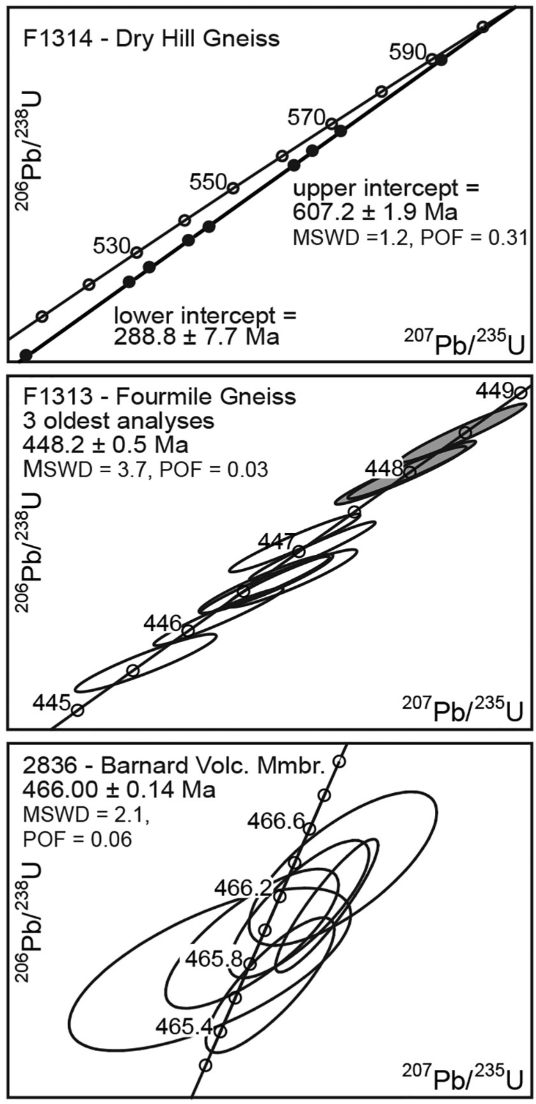

Fig. 5. Concordia plots from single grains and fragments of zircon analyzed by chemical abrasion-thermal ionization mass spectrometry. Locations are shown in figure 1D.

447.11 ± 0.30 and 444.84 ± 0.31 Ma. These dates are thought to be from grains that are mixtures of igneous and metamorphic zircon. Tucker and Robinson (1990) reported an age of 454 +3/−2 Ma for the Fourmile Gneiss from the same locality.

F1312: Partridge Formation. Graphitic schist collected at 42° 40.684'N, 72° 31.009'W. LA-ICPMS on 24 zircon grains from sample (figs. 1C and 6) showed peaks at 1.0, 1.34, and 1.83 Ga. Four <0.9 Ga grains are 452 ± 33, 615 ± 38, 654 ± 40, and 772 ± 36 Ma.

Interpretations of Geochronology

Dalton Formation.—The detrital zircon age spectra found in the Dalton Formation samples (fig. 3) indicate that grains derived locally from the underlying 960 Ma

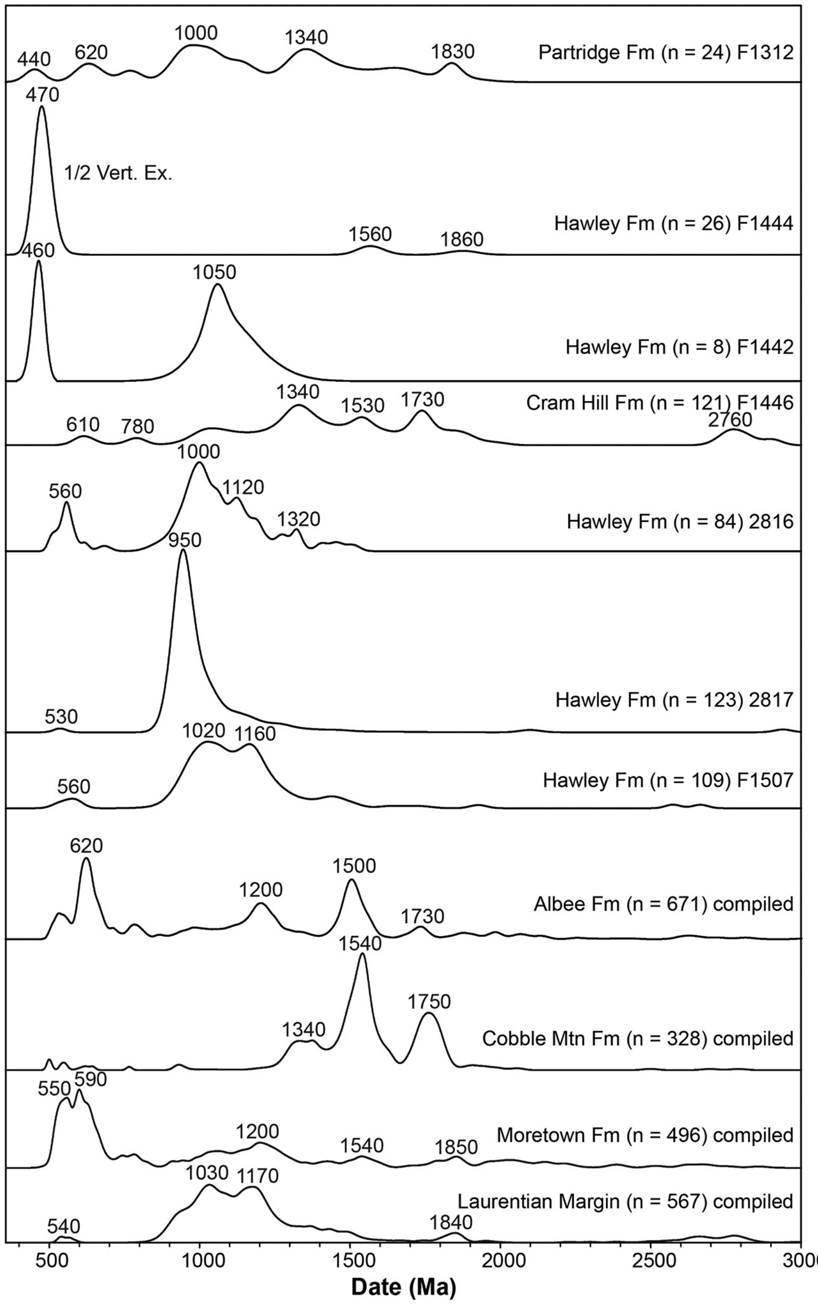

Fig. 6. Detrital zircon normalized probability density plots of samples interpreted as having a mixed Laurentian and Gondwanan provenance. Locations are shown in figure 1C. Note that the plot for sample F1444 is shown at ½ vertical exaggeration to save space.

Stamford Granite Gneiss dominate the population. Typically, major 960 Ma peaks are not observed in detrital zircon age spectra from Laurentian samples (for example Cawood and Nemchin, 2001; Macdonald and others, 2014). The age spectrum from the Dalton Formation matrix sample, F1323, includes numerous grains of more common igneous rocks found in the Grenville basement rocks of the Adirondack Mountains and the Berkshire and Green Mountain massifs (Karabinos and Aleinikoff, 1990; Karabinos and others, 2008; McLelland and others, 2010; Aleinikoff and others, 2011).

As noted by Macdonald and others (2014), detrital zircon age spectra from the Cheshire Quartzite and from the Rowe Schist (fig. 3) are dominated by 1050 to 1200 Ma grains typical of igneous rocks from the Grenville orogeny (Cawood and Nemchin, 2001). Minor components include late Neoproterozoic grains, possibly derived from rift volcanic rocks (Kumarapeli and others, 1989), older Mesoproterozoic grains similar in age to *ca.* 1350 Ma Elzevirian trondhjemitic gneisses in the Green Mountain massif (Ratcliffe and others, 1991), and minor peaks at 1.5, 1.85, and 2.7 Ga.

The restricted age range of the detrital zircon population of the Dalton Formation suggests a local source for the detritus. The Cheshire Quartzite population is much more diverse and typical of the Grenville province of eastern North America (Cawood and Nemchin, 2001). In contrast, the great diversity in detrital zircon ages from the Rowe Schist, in particular sample F1328, is consistent with deposition in a distal continental margin setting offshore from Laurentia, where along shore currents transported far-travelled zircons.

Moretown Formation.—All five samples of the Moretown Formation (fig. 4) display prominent peaks in the 500 to 800 Ma age range, atypical of detritus derived from Laurentia, but typical of Gondwanan sediments (for example, Fyffe and others, 2009). Minor peaks in the interval 1.0 to 1.3 Ga are present in the Moretown samples, but subordinate to the Neoproterozoic peaks. In contrast, zircon grains in the 550 to 700 Ma age range are rare in Neoproterozoic to Cambrian sediments derived from Laurentia, and peaks in the 1.0 to 1.2 Ga range dominate the spectra. The dominant Neoproterozoic age peak in the detrital zircon populations corresponds to widespread arc plutonic and volcanic rocks common on Gondwanan crustal fragments in the Appalachians (Fyffe and others, 2009). Macdonald and others (2014) also suggested that the Moretown Formation is a Cambrian unit based on the youngest detrital zircon grains (514 Ma) dated by TIMS, and the oldest intrusive rocks (496 and 502 Ma, Aleinikoff and others, 2011) found in outcrops that Macdonald and others (2014, 2015) interpreted as likely Moretown Formation correlatives in southern Vermont.

Cobble Mountain Formation.—The Neoproterozic peaks that dominate Moretown Formation samples are only a minor component of the Cobble Mountain Formation detrital zircon population. The Cobble Mountain Formation detrital zircon age spectra are characterized by peaks at 1500 to 1600 Ma, 1700 to 1800 Ma, and 1300 to 1400 Ma, consistent with an Amazonian sediment source (for example, Strachan and others, 2007) or West African (Bradley and others, 2015) sediment source. The contrast in detrital zircon characteristics between the Moretown and Cobble Mountain Formations calls into question the correlation of these units by Stanley and Hatch (1988). Nonetheless, the age spectra of the Cobble Mountain Formation samples indicate a Gondwanan rather than a Laurentian source.

Albee Formation.—Five of the seven samples of the Albee Formation have the most prominent peaks in the interval 600 to 630 Ma (fig. 4). One (NH-98-158) has the most prominent peak at 1200 Ma with strong peaks at 530 and 630 Ma. The same six samples also have prominent peaks at 1.5 to 1.6 Ga. One sample of the Albee Formation, VT-98-257, bears a striking resemblance to the Cobble Mountain Formation detrital zircon populations (fig. 4) with a dominant peak at 1.5 Ga and another peak at 1.7 Ga. One Albee Formation sample, NH-13-397, for which there are only 50 grains analyzed, is quite similar to the Moretown Formation detrital zircon populations (fig. 4). The remaining five samples combine the characteristics of the Moretown and Cobble

Mountain Formations detrital zircon data, except that they also contain robust peaks at 1.2 to 1.3 Ga, and minor peaks in the 800 to 1000 Ma range.

The age spectra shown in figure 4 are compatible with the interpretation that the Albee Formation is part of the Moretown terrane located east of the Connecticut Valley trough (fig. 1). The somewhat more diverse zircon populations in the Albee Formation may reflect a more cosmopolitan provenance in this part of the Moretown terrane.

Hawley Formation.—The Hawley Formation is at least slightly older than the 475 Ma intrusive Dell Trondhjemite (Macdonald and others, 2014). This age constraint, in conjunction with the presence of two Ordovician detrital zircon grains in F1442 (460 ± 22 and 469 ± 18 Ma) and twenty detrital zircon grains in sample F1444 (weighted mean date of 474 ± 12 Ma) (fig. 6), indicates that the sedimentary component of the Hawley Formation was deposited during peak magmatic activity in the Shelburne Falls arc.

We interpret the detrital zircon age spectra from samples 2816, 2817, F1446, and F1507 to represent a mixing of detritus from both Laurentian and Gondwanan sources. Sample 2817 (n = 123) (figs. 1 and 6) is dominated by a sharp 950 Ma peak approximately coeval with the Stamford Granite Gneiss exposed in the Green Mountain and Berkshire massifs (Karabinos and Aleinikoff, 1990). Sample 2816 (n = 84) (figs. 1 and 6) is dominated by peaks at 1000 and 1100 Ma, but also contains a prominent peak at 550 Ma uncharacteristic of Laurentian derived sediments. Sample F1446 (n = 121) (figs. 1 and 6) is from the Cram Hill Formation in southern Vermont, on strike with the eastern graphitic schist belt in the Hawley Formation, the so-called Sanders Brook Black Slate of Kim and Jacobi (1996). The probability plot for this sample is diverse and complex. The most prominent peak is 1300 to 1400 Ma, similar in age to the *ca.* 1350 Ma Elzevirian trondhjemitic gneisses in the Green Mountain massif reported by Ratcliffe and others (1991), but also similar to 1300 to 1400 Ma peaks in two of the three Cobble Mountain Formation samples. There are also significant peaks at 1500 to 1600 and 1700 to 1800 Ma, similar to peaks in the Cobble Mountain Formation samples (fig. 6). There is a broad peak between 1.0 to 1.2 Ga, and less prominent peaks at 600, 800. We interpret the age spectrum to reflect mixed Laurentian and Gondwanan sources, similar to the Cobble Mountain Formation, for the detritus. Sample F1507 (n = 109) (figs. 1 and 6) is dominated by peaks at 960, 1050, and 1170 Ma, but contains a significant peak at 580 Ma.

To summarize, our data suggest that the metasedimentary units of the Hawley Formation were deposited during the Early Ordovician (approximately 475 Ma) and that the sediments received detritus from Laurentian and Gondwanan sources, and from coeval magmatic rocks. Thus, we argue that the collision between the Rowe Schist and the Moretown terrane-Shelburne Falls arc must have occurred at about this time.

Barnard Volcanic Member of the Missisquoi Formation.—The CA-IDTIMS date of 466.00 ± 0.14 Ma (fig. 5) for sample 2836 is younger than the 471.4 ± 3.7 Ma age reported by Karabinos and others (1998) for a sample of the Barnard Volcanic Member near the base of the more than 1 km thick sequence of felsic gneiss at the type locality of the unit (Richardson, 1924). The 466 Ma age of the Barnard Volcanic Member is indistinguishable from the age of an ash layer from the Indian River Formation in the Giddings Brook thrust sheet of the Taconic allochthons (Macdonald and others, 2017). The thick sequence of felsic igneous rocks that make up the Barnard Volcanic Member may preserve a volcanic center or a magma chamber that supplied volcanic eruptions of ash to the Laurentian margin, and the timing of these eruptions may coincide with slab breakoff following collision of the Moretown terrane with Laurentia.

Partridge Formation.—Our small detrital zircon yield (24 grains) from sample F1312 suggests that the Partridge Formation received grains from Ordovician arc magmatism, as well as Laurentian and Gondwanan sources (fig. 6). Merschat and others (2016) presented detrital zircon data from two sample of the Partridge Formation in New Hampshire. The samples contain Mesoproterozoic zircon dates typical of Grenvillian rocks from Laurentia, as well as 1.6 to 1.8 and 2.5 to 2.8 Ga grains likely derived from Laurentian mid-continent sources, and Neoproterozoic grains that are typical of peri-Gondwanan sources (Merschat and others, 2016). Some of the 1.6 to 1.7 Ga grains may also have been sourced from the Cobble Mountain or Albee Formations (see fig. 4). These detrital zircon ages provide critical evidence that the Bronson Hill arc was proximal to Laurentia when arc magmatism was active in the Late Ordovician. Detritus from a Gondwanan source also appears to be represented in the Partridge Formation.

Harwood and Berry (1967) described *C. bicornis* graptolites from the Partridge Formation in New Hampshire, which were later reclassified as *N. gracilis* by Riva (1974), thus establishing a Sandbian age (458.4 ± 0.9 to 453.0 ± 0.7 Ma, Gradstein and others, 2012) for this part of the Partridge Formation. Tucker and Robinson (1990) presented a U-Pb zircon TIMS age of 449 +3/−2 Ma for a volcanic bed from the Partridge Formation in Massachusetts (fig. 7).

The Partridge Formation is an important component of the Bronson Hill arc, and the detrital zircon age spectra indicate that the arc formed in close proximity to Laurentia. We argue below that the Bronson Hill arc formed on the eastern trailing edge of the Moretown terrane rather than on the western leading margin of Ganderia, as proposed by Hibbard and others, 2006).

DISCUSSSION

The Suture Between Laurentia and Gondwanan-derived Terranes

Macdonald and others (2014) used detrital zircon data to demonstrate that the contact between the Rowe Schist and Moretown Formation in Vermont and western Massachusetts is the suture between Laurentia and Gondwanan-derived crust. The Moretown Formation was previously interpreted as a forearc deposit to the Taconic arc (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985), but it contains no Ordovician zircons, which would presumably be common in a Taconic forearc deposit. Instead, the Moretown Formation is dominated by zircon grains derived from Neoproterozoic arcs, similar to Gondwanan-derived terranes studied elsewhere (Fyffe and others, 2009). Lenses of amphibolite and altered ultramafic rocks are especially common near the Rowe Schist-Moretown Formation contact (Chidester and others, 1967; Zen and others, 1983; Ratcliffe and others 2011) consistent with the interpretation that the boundary represents a major suture between Laurentia and Gondwanan-derived crust.

Geologic evidence suggests that the suture formed when the Moretown terrane collided with distal elements of Laurentia above an east-dipping subduction zone. Folds and thrust faults in this zone consistently record west vergence, and evidence for high-pressure metamorphism, including remnant blueschist occurrences, has been reported by Laird and others (1984). The 505 to 473 Ma $^{40}Ar/^{39}Ar$ metamorphic dates from amphibolites near the suture zone (Laird and others, 1984; Castonguay and others, 2012) record exhumation and cooling of rocks from the Iapetan oceanic realm of the Laurentian plate. Further, numerous $^{40}Ar/^{39}Ar$ cooling ages between 471 and 460 Ma from rocks in the Laurentian rift-drift succession and the Rowe Schist record cooling from metamorphic temperatures (Laird and others, 1984; Whitehead and others, 1996; Castonguay and others, 2012; Tremblay and Pinet, 2016) after collision of Laurentia and the Moretown terrane. Most importantly, there is no record of Early Ordovician arc magmatism in rocks of Laurentian affinity that would be expected if the subduction zone had dipped westward under the Laurentian margin.

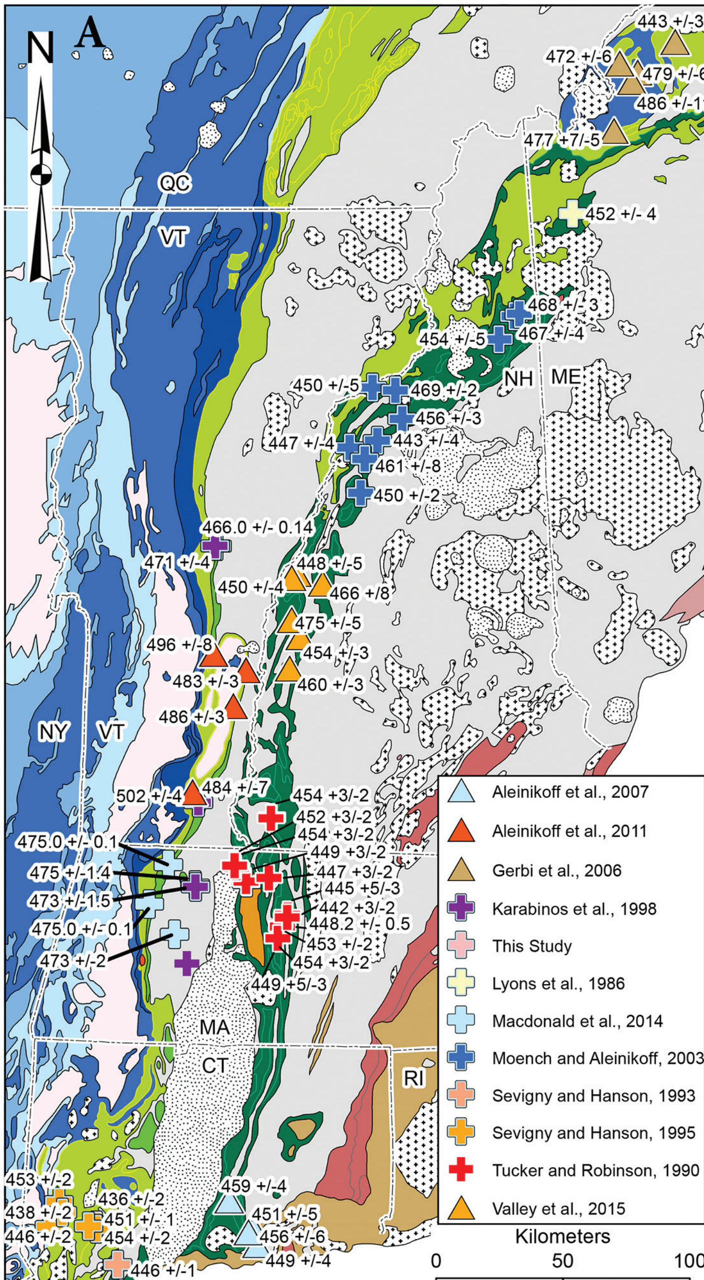

Fig. 7. (A) Tectonic map of New England showing the locations of dated rocks in the Shelburne Falls and Bronson Hill arcs. Triangles are SHRIMP U-Pb zircon ages and pluses are TIMS U-Pb zircon ages. References give data sources. Ages are in Ma. Units use the same colors and patterns as shown in figure 1B. (B) Tectonic map of New England showing the location of dated rocks in the Shelburne Falls and Bronson Hill arcs in 5 m.y. intervals. Units use the same colors and patterns as shown in figure 1B. (C) Normalized probability plot for U-Pb igneous crystallization ages for rocks from the Bronson Hill arc (BHA-dashed curve) and from the Shelburne Falls arc (SFA-solid curve). Locations of dated samples and references are shown in (A).

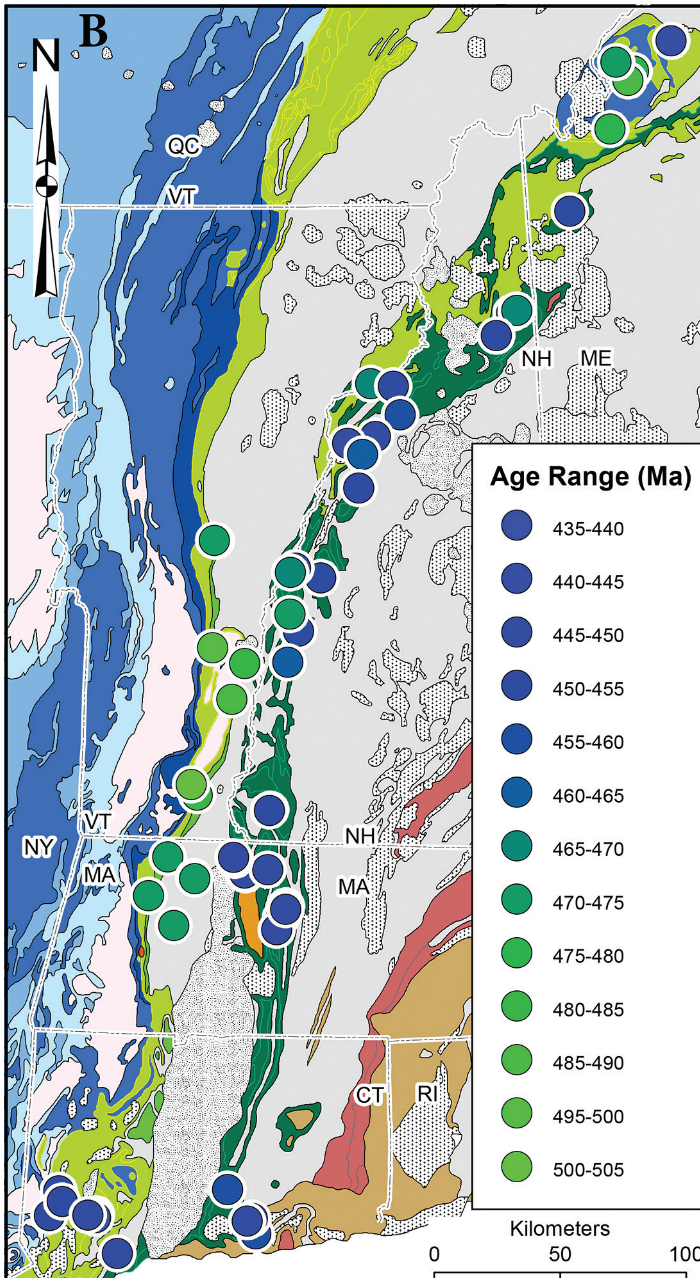

Fig. 7. (continued).

However, there is also no record of Early Ordovician deformation, foreland basin deposits, or air-fall tephras on the Laurentian carbonate platform to the west. Thus, we suggest that the collision occurred outboard of the Laurentian passive margin, perhaps east of an intervening Taconic Seaway (fig. 8).

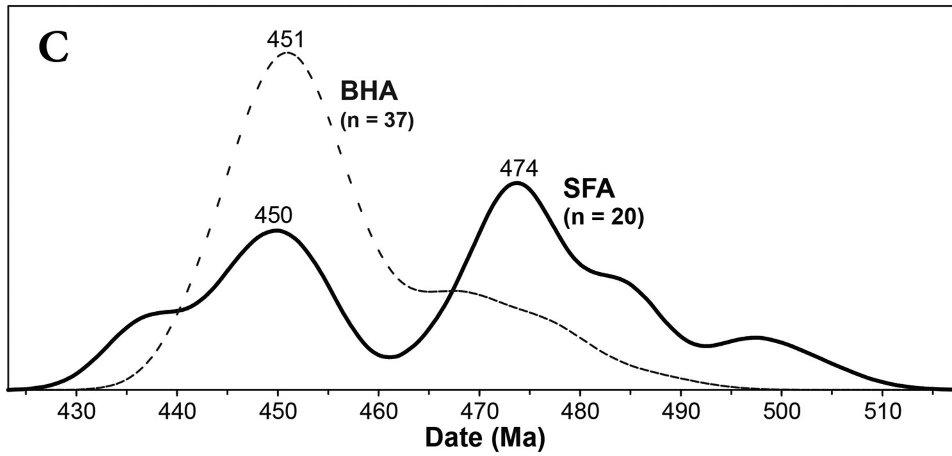

Fig. 7. (continued).

Zircon data from the Hawley Formation, which is an integral component of the Shelburne Falls arc, suggests that collision occurred at approximately 475 Ma. The age of the Hawley Formation is constrained by the time of intrusion of the Dell Metatrondhjemite at 475 Ma, and the youngest, Ordovician, detrital zircon grains in two of our sample (F1442 and F1444, fig. 5). Together these data point to an Early Ordovician age for the Hawley Formation. Detrital zircon data from four of our samples (2816, 2817,

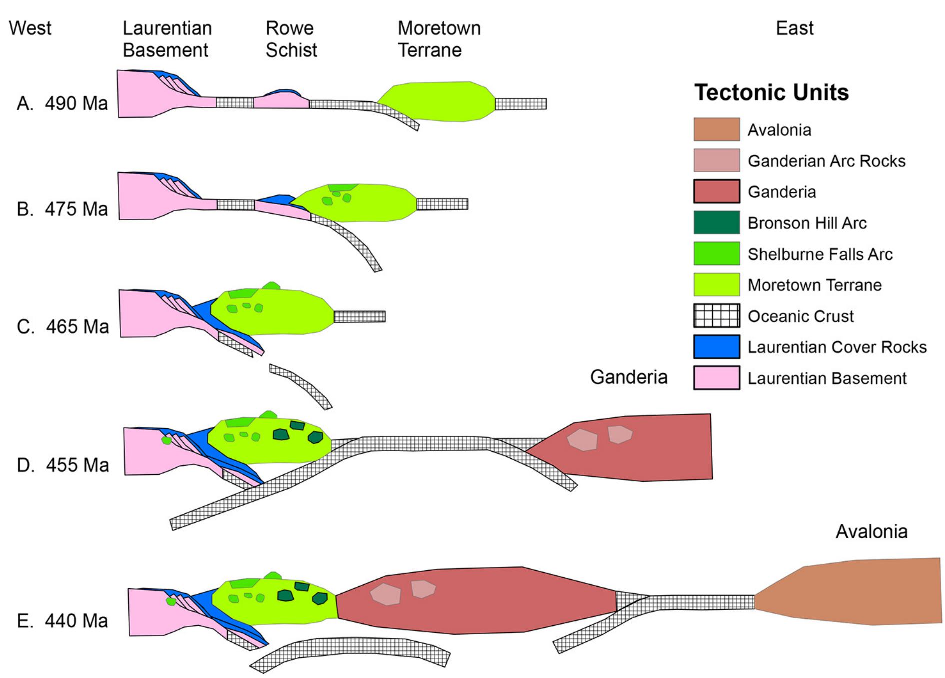

Fig. 8. Schematic cross-sections showing the early Paleozoic tectonic evolution of the New England Appalachians.

F1446, F1507, fig. 6) provide evidence for a mixed Laurentian-Gondwanan provenance for metasedimentary units in the Hawley Formation. The mixed provenance suggests that by 475 Ma the Shelburne Falls arc, which was built on the Moretown terrane, was proximal to the Laurentian margin. Thus, the collision between the Rowe Schist and the Moretown terrane and the subsequent magmatism in the Shelburne Falls arc must have occurred outboard of the passive Laurentian margin, yet close enough for metasedimentary rocks of the Hawley Formation to have incorporated Laurentian detritus.

The common occurrence of 475 to 470 Ma ages in the Shelburne Falls arc (figs. 7 and 8) may be due to subduction of distal extended Laurentian crust and wet sediments just prior to collision.

Extent of the Moretown Terrane

Macdonald and others (2014) demonstrated that the Moretown terrane extends from western Massachusetts to northern Vermont. Our detrital zircon data from the Albee Formation suggest that the Moretown terrane extends as far eastward as the Bronson Hill arc in northern New Hampshire (figs. 1 and 8). Our data from the Cobble Mountain Formation in southwestern Massachusetts, together with Wintsch and others (2015, 2016) data from several formations in western Connecticut suggests that the Moretown terrane continues southward in western New England into Connecticut (fig. 1). Stanley and Hatch (1988) interpreted the Cobble Mountain Formation as a facies equivalent of the Moretown Formation in southern Massachusetts. Our zircon data indicate that the Cobble Mountain Formation had a Gondwanan provenance, but that its source was different than the Moretown Formation; it may be an older unit or have received sediment from a different drainage system. The Albee Formation was correlated with the Moretown Formation by Doll and others (1961), and our detrital zircon data are consistent with this interpretation. The detrital zircon population from one of our samples of Albee Formation (VT-98-297, fig. 4) bears a striking resemblance to the Cobble Mountain Formation. The zircon population from another sample (NH-13-397, fig. 4) is very similar to those from the Moretown Formation. Other Albee Formation samples have age peaks similar to both the Moretown and Cobble Mountain Formations (fig. 4). Furthermore, the age of the Albee Formation is constrained to be older than the SHRIMP U-Pb zircon 492.5 $\pm$ 7.8 Ma age of an intrusive tonalite (Rankin and others, 2013), similar to the age constraints placed on the Moretown Formation by felsic intrusive rocks (Aleinikoff and others, 2011; Macdonald and others, 2014).

Both the Moretown and Albee Formations are likely Cambrian in age (Rankin and others, 2013; Macdonald and others, 2014). The similarity in detrital zircon populations between the Albee Formation and the Moretown and Cobble Mountain Formation (fig. 4) supports the interpretation that the Moretown terrane extends as far east as the Bronson Hill arc. Furthermore, evidence from detrital zircon extracted from the Partridge Formation, discussed next, indicates a Laurentian provenance for Ordovician sediments deposited on the Bronson Hill arc (fig. 8).

Paleogeogeography of the Bronson Hill Arc

The Bronson Hill arc, shown as the eastern arc in figure 1B, extends from southern Connecticut through central Massachusetts and western New Hampshire into Maine. It was interpreted as the '*Taconic arc*' that collided with Laurentia above an east-dipping subduction zone during the Taconic orogeny by Rowley and Kidd (1981) and Stanley and Ratcliffe (1985). Karabinos and others (1998) argued that the Shelburne Falls arc, the western arc in figures 1B, 7, and 9, collided with Laurentia above an older east-dipping subduction zone, and that the Bronson Hill arc formed above a west-dipping subduction zone after a reversal in subduction polarity. Karabinos and others (1998) further suggested that the Shelburne Falls and Bronson Hill arcs formed on a rifted Laurentian-derived ribbon continent, analogous to Dashwoods in Newfoundland (Waldron and van Staal, 2001). Macdonald and others (2014) demonstrated that the Shelburne Falls and Bronson Hill arcs formed on Gondwanan-derived crust, the Moretown terrane. Hibbard and others (2006) interpreted the Bronson Hill arc as the western leading edge of Ganderia. Several studies have also suggested that the Bronson Hill arc is a more complex composite arc that contains multiple arc tracts that formed at different times in different places (Aleinikoff and others, 2007; Karabinos, 2008; Dorais and others, 2011).

As shown in figure 7, the New Hampshire and Maine portions of the Bronson Hill arc contain *ca.* 485 to 465 Ma arc rocks coeval with rocks in the Shelburne Falls arc. This overlap in ages of arc rocks led Ratcliffe and others (1999) and Valley and others (2015) to suggest that the rocks in the western and eastern arc tracts are part of a single long-lived arc. Another interpretation is that there is some spatial overlap in rocks that formed above the older east-dipping and younger west-dipping subduction zones (Karabinos and others, 1998, 1999; Moench and Aleinikoff, 2003; Macdonald and others, 2014).

One sample of the Partridge Formation in Massachusetts (figs. 1C and 6) with a limited number of zircon grains (n = 24) contains some Ordovician grains, and appears to have mixed Laurentian and Gondwanan sources. Merschat and others (2016) presented detrital zircon data from two samples of the Partridge Formation in New Hampshire and concluded that the sediment was derived from both Laurentian and peri-Gondwanan sources, but that the Laurentian source dominated the zircon population. Thus, the detrital zircon evidence from the Partridge Formation provides critical evidence that the Bronson Hill arc was proximal to Laurentia during arc magmatism by approximately 450 to 455 Ma (Tucker and Robinson, 1990), when the Partridge Formation (Harwood and Berry, 1967; Riva, 1974) was deposited.

This constraint on the paleogeography of this portion of the Bronson Hill arc leads us to the interpretation that the *ca.* 455 to 440 Ma arc-related plutonic and volcanic rocks in central Massachusetts and New Hampshire formed on the eastern margin of the already accreted Moretown terrane above a west-dipping subduction zone after a reversal in subduction polarity (fig. 8).

Subduction Polarity Reversal

We suggest that the Moretown terrane collided with distal Laurentian fragments at approximately 475 Ma. Because oceanic lithosphere was no longer available to the east-dipping subduction zone after collision, we argue that younger *ca.* 455 to 440 Ma plutonic and volcanic rocks in the Bronson Hill arc are more likely the product of magmatism above a west-dipping subduction zone under Laurentia and the newly accreted Moretown terrane (fig. 8). The initiation of the younger west-dipping subduction zone must have followed slab breakoff and the subsequent reversal in subduction polarity. Slab breakoff may coincide with the 466 Ma explosive eruption recorded in the Barnard Volcanic Member and in coeval ashes in the Indian River Formation in the Taconic allochthons (Macdonald and others, 2017). Because, detrital zircon data from the Partridge Formation indicate that the Bronson Hill arc formed close enough to Laurentia to receive its detritus, it is unlikely that this segment of the Bronson Hill arc was separated from Laurentia by significant tract of oceanic lithosphere.

Sevigney and Hanson (1993, 1995) proposed that the Brookfield Plutonic Suite and the Newtown, Harrison, and Beardsley Gneisses (454 – 438 Ma) in southwestern Connecticut (fig. 7) form the plutonic roots of a Late Ordovician to Early Silurian magmatic arc that formed above a west-dipping subduction zone on the Laurentian margin. Sevigny and Hanson (1993, 1995) also noted that the younger plutons intruded older rocks of the Collinsville Formation, which had already been deformed during an earlier Taconic event. The Collinsville Formation is a likely correlative with Early Ordovician rocks in the Shelburne Falls arc in Massachusetts and Vermont. The data and interpretations presented by Sevigny and Hanson (1993, 1995) are consistent with a reversal in subduction polarity.

Dated ashes in the Mohawk Valley in New York contain zircon grains with inherited cores of likely Grenvillian origin (Macdonald and others, 2017), further suggesting that a west-dipping subduction zone was established under Laurentia before the *ca.* 453 Ma age of the oldest of these ash deposits.

Is the Moretown Terrane Distinct from Ganderia?

Hibbard and others (2006) showed the boundary between peri-Laurentian and peri-Gondwanan terranes, the Red Indian Line of Williams and others (1988), on the west margin of the Bronson Hill arc in New England, and suggested that the Bronson Hill arc forms the western leading edge of Ganderia. Macdonald and others (2014) demonstrated that the suture zone between Laurentia and peri-Gondwanan terranes is further west at the Rowe Schist-Moretown Formation contact, and our new data indicate that the Moretown terrane extends east to the Bronson Hill arc. We suggest that the Moretown terrane is a peri-Gondwanan fragment distinct from Ganderia. If the Moretown terrane and Bronson Hill arc are not part of Ganderia, the Late Ordovician west-dipping subduction zone proposed by Karabinos and others (1998) and Macdonald and others (2014) could have been just east and outboard of the Bronson Hill arc. If this interpretation is correct, the boundary between the Moretown terrane and Ganderia would be buried under Silurian to Devonian rocks in the Central Maine terrane.

If the Moretown terrane and Bronson Hill arc are part of Ganderia, however, the west-dipping subduction zone would have to be east and outboard of the Massabesic Gneiss Complex in New Hampshire (fig. 1B), which has been identified as part of Ganderia (Hibbard and others, 2006, Dorais and others, 2012; van Staal and others, 2016). Also, if the Moretown terrane and Ganderia are equivalent, it implies that Ganderia reached the Laurentian margin much earlier than the time proposed by van Staal and others (2009) and van Staal and Barr (2012), and blurs the distinction between the Taconic and Salinic orogenies.

Taconic Composite Magmatic Arc

Based on the evidence and arguments presented above, we suggest that the peri-Gondwanan Moretown terrane was the foundation of a composite magmatic arc. Arc magmatism above an east-dipping subduction zone produced Late Cambrian to Early Ordovician plutonic and volcanic rocks found mostly in the western Shelburne Falls arc (figs. 1, 7, and 8) until the Moretown terrane collided with distal hyper-extended Laurentian crust at approximately 475 Ma. After collision and slab break-off, a reversal in subduction polarity led to the initiation of a younger west-dipping subduction zone. Slab breakoff may be recorded by explosive eruptions at 466 preserved in the Barnard Volcanic Member and ashes in the Indian River Formation in the Taconic allochthons. Alternatively, the 466 eruptions may reflect reversal in subduction polarity (figs. 1, 7, and 8). In either case, we suggest that the west-dipping subduction zone must have been established before the onset of major magmatic activity in the eastern Bronson Hill arc at 454 Ma (Tucker and Robinson, 1990). As shown in figure 7, there is some spatial overlap in the age of arc-related rocks in the western and eastern arcs as previously defined. Thus, the terms Shelburne Falls arc and Bronson Hill arc, which have been used to describe different geographic areas, are better thought of as distinguishing arc magmatism above two different subduction zones. For example, there is clearly significant overlap in older and younger arc ages in the New Hampshire portion of the Bronson Hill arc (Moench and Aleinikoff, 2003; Valley and others, 2015; fig. 7). Although we believe that the evidence for a reversal in subduction polarity during Taconic orogenesis is compelling, and that the model we present here can explain many observations in western New England, it is important to acknowledge that the strict *spatial* distinction between an older Shelburne Falls arc and a younger Bronson Hill arc is not viable (Karabinos and others, 1999).

Comparison with Ordovician Arcs in Maine and Maritime Canada

For nearly two decades, tectonic models of the Appalachians have assumed that the Notre Dame arc in Newfoundland (van Staal and others, 1998; Waldron and van Staal, 2001), the Chain Lakes massif in Maine (Gerbi and others, 2006a, 2006b), and the Shelburne Falls arc in Vermont and Massachusetts (Karabinos and others, 1998) formed as east-facing arcs on ribbon continental fragments rifted from Laurentia and separated from it by a narrow Taconic Seaway. However, these models lacked evidence for Laurentian basement at depth, and failed to account for subduction initiation within the proposed narrow oceanic basin. The recent discovery that the Shelburne Falls arc formed on the Gondwanan-derived Moretown terrrane (Macdonald and others, 2014) calls into question tectonic models invoking Early Ordovician arcs built on peri-Laurentian ribbon continents.

For example, Waldron and van Staal (2001) argued that the Dashwoods terrane in Newfoundland rifted from Laurentia in the Neoproterozoic, and that the Early Ordovician Notre Dame arc formed on it above an east-dipping subduction zone. The Laurentian affinity of Dashwoods was based, in part, on the correlation of pre-Ordovician schists from the Dashwoods terrane with Laurentian slope-rise deposits of the Fleur de Lys Supergroup on the Humber margin. However, none of the pre-Ordovician schists from the Dashwoods terrane have been studied for detrital zircon provenance, so this correlation, and the presumed Laurentian affinity, remain untested.

Importantly, the fauna with Laurentian provenance found on Dashwoods is in Ordovician strata (Neuman, 1984; Dean, 1985; Harper and others, 1996), and by that time Dashwoods was already near Laurentia, as verified by the low-latitude Middle Ordovician paleomagnetic pole on Notre Dame arc rocks (Johnson and others, 1991). Ordovician graptolite and conodont collections from the Notre Dame subzone yield faunal assemblages with Laurentian affinity that also demonstrate an Ordovician proximity between Dashwoods and Laurentia (Harper and others, 1996).

Waldron and van Staal (2001) used paleomagnetic data as evidence that Dashwoods had a Laurentian affinity and was separated from the Humber margin by a narrow seaway. Paleomagnetic data from the Middle Ordovician Moreton's Harbour Group yield a paleolatitude for Dashwoods of 11° S, which is indistinguishable from the expected paleolatitude of the Laurentian margin (van der Pluijm and others, 1990; Johnson and others, 1991; Mac Niocaill and others, 1997). However, by the Middle Ordovician, the Dashwoods terrane would have been near the Laurentian margin regardless of its source because tectonic loading began by *ca.* 475 Ma, so these paleomagnetic data do not demonstrate a Laurentian affinity for Dashwoods.

Waldron and van Staal (2001) and van Staal and others (2007) suggested that geochronological and geochemical data from the Cape Ray Granodiorite and other plutons in the Dashwoods and Notre Dame subzones indicate emplacement through Laurentian basement. Specifically, xenocrystic zircons and Nd, O, and Pb isotopic values (Whalen and others, 1997a; Whalen and others, 1997b) show a major contribution from of Paleoproterozoic continental crust. This is older than any of the exposed Grenvillian inliers of the Humber margin. Therefore, although these isotopic data support that Dashwoods was built on old crustal material, the geochemical characteristics are not distinctly Laurentian and could also be sourced from peri-Gondwanan

Paleoproterozoic rocks. Likewise, xenocrystic zircon grains dated from Paleozoic plutons that intruded Dashwoods (Whalen and others, 1987; Dunning and others, 1989; Dubé and others, 1996; Van Staal and others, 2007) fail to provide convincing evidence for Laurentian basement at depth. Out of a total of 44 Xenocrystic zircons dated, only 5 fall in the interval of 1000 to 1250 Ma, the most common age range observed from the Grenville province (Cawood and Nemchin, 2001). In contrast, 11 grains fall in the interval 620 to 1000 Ma, and 19 grains in the interval 1300 to 1800, dates which are common in Gondwanan-derived sediment (fig. 4; Macdonald and others, 2014). Further, Willner and others (2014) presented detrital zircon U-Pb and Hf isotope data from both the peri-Laurentian and peri-Gondwanan zones of Newfoundland. Samples analyzed from Dashwoods were deposited after interaction with the Laurentian margin and are dominated by local sources of young zircon. These samples contain 15 grains ranging from 529 to 617 Ma and 4 grains ranging from 786 to 819 Ma. Though only represented by a handful of grains, these dates indicate that there are underlying Neoproterozoic rocks in Dashwoods, which are uncommon on the Laurentia margin other than zircon-poor rift-related magmatism on Laurentia that is predominantly younger than 580 Ma, with the exception of the 615 Ma Long Range dikes (Hodych and Cox, 2007).

The Chain Lakes massif of Maine has also been interpreted as an arc that formed on peri-Laurentian basement. It consists of volcanic and sedimentary rocks derived in part from Laurentia and diatexite formed during intrusion of arc-related magmas (469 ± 4 Ma U/Pb-monazite age) (Gerbi and others, 2006a). Ultramafic rocks of the Chain Lakes massif are potentially correlative with the Riviere-des-Plantes ultramafic complex in southern Quebec, which was obducted on the Laurentian margin by 465 Ma (De Souza and Tremblay, 2010). However, Gerbi and others (2006a) suggested that the Boil Mountain Complex and Jim Pond Formation do not represent ophiolitic sequences (Kusky and others, 1997), but that the Boil Mountain Complex intruded the Chain Lakes massif at 477 Ma and the Skinner pluton intruded the massif at 472 Ma. Metasediments within the Chain Lakes massif contain Laurentian detrial zircon (Gerbi and others, 2006a); however, like the Hawley belt in Massachusetts, the Laurentian derived sediments may have been deposited during arc-continent collision (Macdonald and others, 2014), and thus, do not necessarily constrain basement affinity of the terrane.

Based on the assumption that Dashwoods is a Laurentian-derived crustal fragment, several authors have proposed that the Red Indian Line (Williams and others, 1988), which separates the Dashwoods terrane from the Exploits subzone in Newfoundland (fig. 1A), represents the principle Iapetan suture (for example, van Staal and others, 2009). However, as discussed above, if Dashwoods is instead Gondwanan-derived and correlative with the Moretown terrane, or if the Laurentian-Gondwanan terrane suture occurs within Dashwoods, then the Red Indian Line, as defined by Williams and others (1988), marks a boundary between arc terranes built on Gondwanan-derived crust. Thus, we suggest that the Notre Dame arc of Newfoundland is equivalent to the Shelburne Falls arc and the Popelogan-Victoria arc (Zagorevski and others, 2008) are correlative with the Bronson Hill arc.

Collision of an arc with a passive margin, followed by slab break-off and subduction polarity reversal is a simple mechanism for establishing an active margin that circumvents the mechanical difficulties of initiating subduction in cold, stiff oceanic lithosphere of a rifted passive margin (Clift and others, 2003). Seeding of subduction during the early Taconic orogeny was recently suggested by Waldron and others (2014). In Newfoundland, Middle Ordovician slab-break off magmatism has been documented in the Dashwoods terrane of Newfoundland (van Staal and others, 2007).

Subduction polarity reversal and the establishment of a west dipping subduction zone below the Red Indian Lake arc was proposed by Zagorevski and others (2008).

Recently, van Staal and others (2016) correlated the Popelogan-Victoria arc in New Brunswick with the Bronson Hill arc and, following Hibbard and others (2006), located both arcs on the leading western edge of Ganderia. In particular, van Staal and others (2016) correlated Paleozoic rocks in the Popelogan, Munsungan-Winterville, and Weeksboro-Lunksoos inliers of central Maine with those of the Mirimichi inlier of coastal Maine and New Brunswick. This correlation is based on 1) Cambrian to Early Ordovician brachiopod fauna of Celtic origin (for example, Neuman, 1984), 2) correlation of the Albee Formation with the Woodstock and Miramichi Groups of the Gander margin (for example, Reusch and van Staal, 2011), 3) the assumption that Early Ordovician unconformities uniquely mark tectonism restricted to Ganderia (for example, Colman-Sadd and others, 1992; Zagorevski and others, 2010), and 4) similarities in detrital zircon populations (for example, Fyffe and others, 2009; van Staal and others, 2016). However, the main pulse of arc magmatism in the Miramichi belt at *ca.* 475 Ma predates that in the central Maine inliers by ~10 Myr (van Staal and others, 2016). Moreover, paleomagnetic data demonstrate that the Mirimichi belt was at a paleolatitude of ~50° S at 470 ± 4 Ma (Liss and others, 1993), whereas the Weeksboro-Lunksoos inlier was situated at ~20° S at 465 ± 4 Ma (Wellensiek and others, 1990). As we described above, many of the Gondwanan derived terranes have similar detrital zircon profiles, and if they were originally derived from the same parent craton we may not expect dramatic differences. Additionally, the Cambrian to Early Ordovician fauna predate accretion to Laurentia, so Celtic fauna on these arc terranes is not surprising, and Early to Middle Ordovician deformation has been described on the Moretown terrane (Macdonald and others, 2014), so this is likely not a feature unique to Gander, and the nature and distribution of the Penobscot orogeny should be revisited with this in mind. Thus, although the Moretown terrane and Ganderia may have both been derived from Gondwana in the Neoproterozoic to Cambrian, the paleomagnetic data suggest that in the Ordovician they were distinct terranes, each with coeval magmatic arcs, that were widely separated. van Staal and others (2016) explained disparate paleomagnetic poles by invoking arc migration and massive back arc rifting.

In Newfoundland, van Staal and Barr (2012) assigned the Victoria arc and the Exploits subzone of Williams (1979) to Ganderia. However, paleomagnetic data do not fully support this proposal. Paleomagnetic poles from the *ca.* 470 Ma Roberts Arm, Summerford, and Chanceport Groups of the Exploits subzone yield a paleolatitude of ~30° S (van der Voo and others, 1991), and poles from the *ca.* 465 ± 2 Ma Lawrence Head Volcanics indicate a paleolatitude for the Victoria arc of ~15° S (Todaro and others, 1996). The similarity of these results to those of coeval rocks in the central Maine inliers (Wellensiek and others, 1990) support our correlation of the Bronson Hill arc with the Victoria-Pelopologan arc, and further suggest that these arc terranes were situated very close to the Laurentian margin by 465 Ma. The close proximity between these 465 Ma arc systems and the Laurentian margin is further supported by the appearance of abundant air-fall tuffs on the Laurentian margin preserved in the *ca.* 465 Ma Indian River Formation of New York. Additionally, Laurentian detritus is present not only in the Partridge Formation in New England (Merschat and others, 2016), but also in the *ca.* 455 Ma Badger Formation of Newfoundland, which overlies the Exploits subzone (Waldron and others, 2012). In contrast, Ganderia did not arrive at the Laurentian margin until *ca.* 436 Ma (Waldron and others, 2012).

In summary, we suggest that the Bronson Hill arc marks the trailing edge of the Moretown terrane, and that the Popelogan-Victoria arc formed on the trailing edge of the Dashwoods terrane rather than on the leading edge of Ganderia.

There is, however, a significant separation between the *ca.* 475 Ma pole from the Notre Dame arc (Johnson and others, 1991) and the *ca.* 470 Ma poles from the Exploits subzone (van der Voo and others, 1991). This implies that the arc terranes on the eastern margin of Dashwoods (that is, Red Indian Lake arc and the proto-Bronson Hill-Pelopologan-Victoria arc) were likely quite distended prior to *ca.* 460 Ma (for example Zagorevski and others, 2008) when paleomagnetic poles on these arcs and the Laurentian margin converge at 10 to 15° S (Potts and others, 1993; Potts and others, 1995; Todaro and others, 1996). Although the exact nature and timing of the accretionary events and processes that drove shortening and foreland deposition between 465 and 450 Ma remain poorly constrained, we argue that this tectonism and basin formation occurred above a west-dipping subduction zone after the accretion of the Moretown and Dashwoods terranes, but before the Salinic orogeny and the Silurian arrival of the Ganderia.

CONCLUSIONS

Based on detrital zircon analysis, we suggest that the western boundary of the Gondwanan-derived Moretown terrane is the Rowe Schist-Moretown Formation contact, and that the eastern boundary is located in the Bronson Hill arc. Magmatic arc rocks in the Shelburne Falls arc ranging in age from *ca.* 500 to 470 Ma formed above an east-dipping subduction zone on the western, leading edge of the Moretown terrane. Collision of the Moretown terrane and the Shelburne Falls arc with distal Laurentina-derived crustal fragments was in progress by approximately 475 Ma. At this time, meta-sediments in the Hawley Formation, part of the Shelburne Falls arc, were receiving detritus from Laurentia. Suturing of the Moretown-Rowe contact was complete by the time of intrusion of the Middlefield Granite at 448.8 ± 0.1 Ma in Massachusetts and the Brookfield Plutonic Suite at 454 ± 2 Ma in Connecticut (Sevigny and Hanson, 1995).

The Early Ordovician collision of the Moretown terrane with distal Laurentian crust left the Laurentian passive margin undeformed, suggesting that an oceanic tract separated the collision zone from the carbonate platform. Slab-breakoff of subducted lithosphere occurred after the 475 Ma collision of the Moretown terrane with the Rowe Schist, but before the initiation of west-dipping subduction. It is possible that slab-breakoff is recorded by the explosive eruption in the Barnard Volcanic Member at 466 Ma, which was likely the source for ash beds in the Indian River Formation in the Taconic allochthons. A reversal in polarity created a west-dipping subduction zone under the Laurentian margin and the newly accreted Moretown terrane. We propose that abundant 455 to 440 Ma magmatic arc rocks in the Bronson Hill arc formed above this west-dipping subduction zone, and that the arc formed along the eastern, trailing edge of the Moretown terrane. The western boundary of Ganderia, represented by the Massabesic Gneiss Complex in New England, is east of the Bronson Hill arc buried under Silurian and Devonian meta-sediments deformed during the Acadian orogeny.

ACKNOWLEDGMENTS

We thank Nizhoni O'Connell, Eben Hodgin, and Camille Dwyer for help in the field and lab. John Aleinikoff kindly provided samples of the Albee Formation for detrital zircon analysis. Reviews by John Dewey, George Gehrels, and Robert Wintsch improved the manuscript.

APPENDIX

LA-ICPMS Methods

Zircon grains were separated from rocks using standard techniques and annealed at 900 °C for 60 hours in a muffle furnace. Grains were randomly selected for the detrital zircon samples. Sharply faceted grains were selected for the volcanic ash samples. Grains were mounted in epoxy and polished until their centers were exposed. Cathodoluminescence (CL) images were obtained with a JEOL JSM-1300 scanning electron microscope and Gatan MiniCL. Zircon was analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) using a ThermoElectron X-Series II quadrupole ICPMS and New Wave Research UP-213 Nd:YAG UV (213 nm) laser ablation system. In-house analytical protocols, standard materials, and data reduction software were used for acquisition and calibration of U-Pb dates and a suite of high field strength elements (HFSE) and rare earth elements (REE). Zircon was ablated with a laser spot of 25 μm wide using fluence and pulse rates of 5 J/cm^2 and 10 Hz, respectively, during a 45 second analysis (15 sec gas blank, 30 sec ablation) that excavated a pit ~25 μm deep. Ablated material was carried by a 1.2 L/min He gas stream to the nebulizer flow of the plasma. Quadrupole dwell times were 5 ms for Si and Zr, 200 ms for ^{49}Ti and ^{207}Pb, 80 ms for ^{206}Pb, 40 ms for ^{202}Hg, ^{204}Pb, ^{208}Pb, ^{232}Th, and ^{238}U and 10 ms for all other HFSE and REE; total sweep duration is 950 ms. Background count rates for each analyte were obtained prior to each spot analysis and subtracted from the raw count rate for each analyte. For concentration calculations, background-subtracted count rates for each analyte were internally normalized to ^{29}Si and calibrated with respect to NIST SRM-610 and -612 glasses as the primary standards. Ablations pits that appear to have intersected glass or mineral inclusions were identified based on Ti and P signal excursions, and associated sweeps were discarded. U-Pb dates from these analyses are considered valid if the U-Pb ratios appear to have been unaffected by the inclusions. Signals at mass 204 were normally indistinguishable from zero following subtraction of mercury backgrounds measured during the gas blank (<1000 cps ^{202}Hg), and thus dates are reported without common Pb correction. Rare analyses that appear contaminated by common Pb were rejected based on mass 204 greater than baseline. Temperature was calculated from the Ti-in-zircon thermometer (Watson and others, 2006). Because there are no constraints on the activity of TiO_2 in the source rocks, an average value in crustal rocks of 0.8 was used.

Data were collected in 24 experiments at the Isotope Geology Laboratory at Boise State University from July 2013 to December 2015 (table A1, http://earth.geology.yale.edu/~ajs/SupplementaryData/2017/Karabinos). For U-Pb and ^{207}Pb/^{206}Pb dates, instrumental fractionation of the background-subtracted ratios was corrected and dates were calibrated with respect to interspersed measurements of zircon standards and reference materials. The primary standard Plešovice zircon (Sláma and others, 2008) was used to monitor time-dependent instrumental fractionation based on two analyses for every 10 analyses of unknown zircon. A secondary correction to the ^{206}Pb/^{238}U dates was made based on results from a combination of the zircon standards that were dated at Boise State University (unpublished data): Seiland (530 Ma) and Zirconia (327 Ma), and Temora (417 Ma). A subset of these standards was treated as unknowns and measured once for every 10 analyses of unknown zircon. These results showed a linear age bias of up to several percent that is related to the ^{206}Pb count rate. The secondary correction is thought to mitigate matrix-dependent variations due to contrasting compositions and ablation characteristics between the Plešovice zircon and other standards (and unknowns).

Radiogenic isotope ratio and age error propagation for all analyses includes uncertainty contributions from counting statistics and background subtraction. Because the detrital zircon analyses are interpreted individually, uncertainties from the standard calibrations are propagated into the errors on each date. These uncertainties are the local standard deviations of the polynomial fits to the interspersed primary standard measurements versus time for the time-dependent, relatively larger U/Pb fractionation factor, and the standard errors of the means of the consistently time-invariant and smaller $^{207}Pb/^{206}Pb$ fractionation factor. These uncertainties are 1.2–3.3% (average of 1.6%) (2σ) $^{206}Pb/^{238}U$ and 0.1–1.6% (average of 0.5%) (2σ) for $^{207}Pb/^{206}Pb$. For the igneous samples and detrital zircon samples with multiple grains that may be part of the same population, weighted mean dates are calculated on equivalent dates (that is, probability of fit >0.05) using Isoplot 3.0 (Ludwig, 2003) from errors on individual dates that do not include the standard calibration uncertainties. However, errors on weighted mean dates include the standard calibration uncertainties within each experiment and are given at 2σ.

Age interpretations are based on $^{207}Pb/^{206}Pb$ dates for analyses with $^{207}Pb/^{206}Pb$ dates >1000 Ma. The $^{206}Pb/^{238}U$ dates are used for analyses with $^{207}Pb/^{206}Pb$ dates <1000 Ma. Analyses with >20% positive discordance and >10% negative discordance are not considered. Errors on the dates from individual analyses are given at 2σ.

CA-IDTIMS Methods

U-Pb dates were obtained by the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-IDTIMS) method from analyses composed of single zircon grains or fragments of grains (table A2, http://earth.geology.yale.edu/~ajs/SupplementaryData/2017/Karabinos), modified after Mattinson (2005). Zircon was separated from rocks using standard techniques and mounted in epoxy and polished until the centers of the grains were exposed. Cathodoluminescence (CL) images were obtained with a JEOL JSM-1300 scanning electron microscope and Gatan MiniCL. Zircon was removed from the epoxy mounts for dating based on CL images and LA-ICPMS data.

Zircon was placed in a muffle furnace at 900 °C for 60 hours in quartz beakers. Single grains or fragments were then transferred to 3 ml Teflon PFA beakers and loaded into 300 μircon was placed in a muffle furnace at 900 °C for 60 hours in quartz beakers. Single grains or fragments were then transferred to 3 ml Teflon PFA beakers and loaded into 300 athodoluminescence (CL) images were obtpsules were returned to 3 ml Teflon PFA beakers, HF removed, and the residual grains or fragments immersed in 3.5 M HNO_3, ultrasonically cleaned for an hour, and fluxed on a hotplate at 80 °C for an hour. The HNO_3 was removed and grains or fragments were rinsed twice in ultrapure H_2O before being reloaded into the 300 μ before being reloaded into the 300 were rinsed twice in ultrapure HC for an hour. The HNOs or fragments were then transferred to 3 ml Teflon PFA beakers and loaded into 300 athodoluminescencer vessels in 120 μ before being reloaded into the 300 we_3 at 220 °C for 48 hours, dried to fluorides, and re-dissolved in 6 M HCl at 180 °C overnight. U and Pb were separated from the zircon matrix using an HCl-based anion-exchange chromatographic procedure (Krogh, 1973), eluted together and dried with 2 μl of 0.05 N H_3PO_4.

Pb and U were loaded on a single outgassed Re filament in 5 μl of a silica-gel/phosphoric acid mixture (Gerstenberger and Haase, 1997), and U and Pb isotopic measurements made on a GV Isoprobe- multicollector thermal ionization mass spectrometer equipped with an ion-counting Daly detector. Pb isotopes were measured by peak-jumping all isotopes on the Daly detector for 100 to 160 cycles, and corrected for 0.18 ± 0.03%/a.m.u (1 sigma error) mass fractionation. Transitory isobaric interferences due to high-molecular weight organics, particularly on ^{204}Pb and ^{207}Pb, disappeared within approximately 30 cycles, while ionization efficiency averaged 10^4 cps/pg of each Pb isotope. Linearity (to $\geq 1.4 \times 10^6$ cps) and the associated deadtime correction of the Daly detector were monitored by repeated analyses of NBS982, and have been constant since installation. Uranium was analyzed as UO_2^+ ions in static Faraday mode on 10^{11} ohm resistors for 200-300 cycles, and corrected for isobaric interference of $^{233}U^{18}O^{16}O$ on $^{235}U^{16}O^{16}O$ with an $^{18}O/^{16}O$ of 0.00206. Ionization efficiency averaged 20 mV/ng of each U isotope. U mass fractionation was corrected using the known $^{233}U/^{235}U$ ratio of the tracer solution.

The Boise State University tracer solution was used with a calibration of $^{235}U/^{205}Pb = 77.93$ and $^{233}U/^{235}U = 1.007066$. CA-IDTIMS U-Pb dates and uncertainties were calculated using the algorithms of Schmitz and Schoene (2007) and U decay constants recommended by Jaffey and others (1971). $^{206}Pb/^{238}U$ ratios and dates were corrected for initial ^{230}Th disequilibrium using a Th/U[magma] $= 3.0 \pm 0.3$ using the algorithms of Crowley and others (2007), resulting in an increase in the $^{206}Pb/^{238}U$ dates of ~0.09 Ma. All common Pb in analyses was attributed to laboratory blank and subtracted based on the measured laboratory Pb isotopic composition and associated uncertainty. U blanks are estimated at 0.075 pg.

Weighted mean $^{206}Pb/^{238}U$ dates from two samples were calculated using Isoplot 3.0 (Ludwig, 2003). For the sample with a probability of fit >0.05, the error on the weighted mean date is the 2σ internal error. For the sample with a probability of fit <0.05, the error on the weighted mean date is the 95% confidence limit, which is the 2σ internal error multiplied by the square root of the MSWD. Errors on the weighted mean dates are given as ± x / y / z, where x is the internal error based on analytical uncertainties only, including counting statistics, subtraction of tracer solution, and blank and initial common Pb subtraction, y includes the tracer calibration uncertainty propagated in quadrature, and z includes the ^{238}U decay constant uncertainty propagated in quadrature. Internal errors should be considered when comparing our dates with $^{206}Pb/^{238}U$ dates from other laboratories that used the same tracer solution or a tracer solution that was cross-calibrated using EARTHTIME gravimetric standards. Errors including the uncertainty in the tracer calibration should be considered when comparing our dates with those derived from other geochronological methods using the U-Pb decay scheme (for example, laser ablation ICPMS). Errors including uncertainties in the tracer calibration and ^{238}U decay constant (Jaffey and others, 1971) should be considered when comparing our dates with those derived from other decay schemes (for example, $^{40}Ar/^{39}Ar$, ^{187}Re-^{187}Os). Isoplot 3.0 (Ludwig, 2003) was used to calculate a line through discordant analyses in one sample. Errors on the intercepts are given as ± x / y, where x is the internal error and y includes the ^{235}U and ^{238}U decay constant uncertainties propagated in quadrature. Errors on dates from individual grains are given at 2σ.

REFERENCES

Aleinikoff, J. N., Zartman, R. E., and Lyons, J. B., 1979, U-Th-Pb geochronology of the Massabesic Gneiss and the granite near Milford, south-central New Hampshire: New evidence for Avalonian basement and Taconic and Alleghanian disturbances in eastern New England: Contributions to Mineralogy and Petrology, v. 71, n. 1, p. 1–11, https://doi.org/10.1007/BF00371877

Aleinikoff, J. N., Wintsch, R. P., Tollo, R. P., Unruh, D. M., Fanning, C. M., and Schmitz, M. D., 2007, Ages and origins of rocks of the Killingworth dome, south-central Connecticut: Implications for the tectonic evolution of southern New England: American Journal of Science, v. 307, n. 1, p. 63–118, https://doi.org/10.2475/01.2007.04

Aleinikoff, J., Ratcliffe, N., and Walsh, G., 2011, Provisional zircon and monazite uranium-lead geochronology for selected rocks from Vermont: US Geological Survey Open-File Report, 2011–1309, p. 46.

Allen, J. S., Thomas, W. A., and Lavoie, D., 2010, The Laurentian margin of northeastern North America, *in* Tollo, R. P., Bartholomew, M. J., Hibbard, J. P., and Karabinos, P. M., editors, From Rodinia to Pangea: The lithotectonic record of the Appalachain region: Geological Society of America Memoirs, n. 206, p. 71–90, https://doi.org/10.1130/2010.1206(04)

Bird, J. M., and Dewey, J. F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, n. 4, p. 1031–1060, https://doi.org/10.1130/0016-7606(1970)81[1031:LPMTAT]2.0.CO;2

Bradley, D. C., O'Sullivan, P., Cosca, M. A., Motts, H., Horton, J. D., Taylor, C. D., Beaudoin, G., Lee, G. K., Ramezani, J., and Bradley, D. N., Jones, J. V., III, and Bowring, S., 2015, Synthesis of geological, structural, and geochronologic data (phase V, deliverable 53): Chapter A in Second projet de renforcement institutionnel du secteur minier de la République Islamique de Mauritanie (PRISM-II): US Geological Survey, Open-File Report 2013-1280-A, https://doi.org/10.3133/ofr20131280A

Castonguay, S., Kim, J., Thompson, P. J., Gale, M. H., Joyce, N., Laird, J., and Doolan, B. L., 2012, Timing of tectonometamorphism across the Green Mountain anticlinorium, northern Vermont Appalachians: ^{40}Ar/^{39}Ar data and correlations with southern Quebec: Geological Society of America Bulletin, v. 124, n. 3–4, p. 352–367, https://doi.org/10.1130/B30487.1

Cawood, P. A., and Nemchin, A. A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, n. 9, p. 1234–1246, https://doi.org/10.1130/0016-7606(2001)113<1234:PDOTEL>2.0.CO;2

Chidester, A. H., Hatch, N. L., Jr., Osberg, P. H., Norton, S. A., and Hartshorn, J. H., 1967, Geologic map of the Rowe quadrangle, Franklin and Berkshire Counties, Massachusetts, and Bennignton and Windham Counties, Vermont, GQ-642: USGS Open File Report 66–14, scale 1: 24,000.

Clift, P. D., Schouten, H., and Draut, A. E., 2003, A general model of arc-continent collision and subduction polarity reversal from Taiwan and the Irish Caledonides: Geological Society, London, Special Publications, v. 219, p. 81–98, https://doi.org/10.1144/GSL.SP.2003.219.01.04

Coish, R., Kim, J., Morris, N., and Johnson, D., 2012, Late stage rifting of the Laurentian continent: Evidence from the geochemistry of greenstone and amphibolite in the central Vermont Appalachians, This article is one of a series of papers published in CJES Special Issue: In honour of Ward Neale on the theme of Appalachian and Grenvillian geology: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 43–58, https://doi.org/10.1139/e11-013

Colman-Sadd, S. P., Dunning, G., and Dec, T., 1992, Dunnage-Gander relationships and Ordovician orogeny in central Newfoundland: A sediment provenance and U/Pb age study: American Journal of Science, v. 292, n. 5, p. 317–355, https://doi.org/10.2475/ajs.292.5.317

Crowley, J. L., Schoene, B., and Bowring, S. A., 2007, U-Pb dating of zircon in the Bishop Tuff at the millennial scale: Geology, v. 35, n. 12, p. 1123–1126, https://doi.org/10.1130/G24017A.1

De Souza, S., and Tremblay, A., 2010, The Rivière-des-Plante ultramafic Complex, southern Québec: Stratigraphy, structure, and implications for the Chain Lakes massif: Geological Society of America Memoirs, v. 206, p. 123–139, https://doi.org/10.1130/2010.1206(07)

Dean, W., 1985, Relationships of Cambrian-Ordovician faunas in the Caledonide-Appalachian Region, with particular reference to trilobites, *in* Gayer, R. A., editor, The Tectonic Evolution of the Caledonide-Appalachian Orogen: Braunschweig/Wiesbaden, Friedrich Vieweg & Sohn, p. 17–47.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., 1961, Centennial geologic map of Vermont: Vermont Geological Survey, scale 1:250,000.

Dorais, M. J., Atkinson, M., Kim, J., West, D. P., and Kirby, G. A., 2011, Where is the Iapetus suture in northern New England? A study of the Ammonoosuc Volcanics, Bronson Hill terrane, New Hampshire, This article is one of a series of papers published in this CJES Special Issue: In honour of Ward Neale on the theme of Appalachian and Grenvillian geology: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 189–205, https://doi.org/10.1139/e10-108

Dorais, M. J., Wintsch, R. P., Kunk, M. J., Aleinikoff, J., Burton, W., Underdown, C., and Kerwin, C .M., 2012, P-T-t conditions, Nd and Pb isotopic composiitons and detrital zircon geochronology of the Massabesic Gneiss Complex, New Hampshire: Isotopic and metamorphic evidence for the identification of Gander basement, central New England: American Journal of Science, v. 312, n. 10, p. 1049–1097, https://doi.org/10.2475/10.2012.01

Dubé, B., Dunning, G., Lauzière, K., and Roddick, J. C., 1996, New insights into the Appalachian Orogen from geology and geochronology along the Cape Ray fault zone, southwest Newfoundland: Geological Society of America Bulletin, v. 108, n. 1, p. 101–116, https://doi.org/10.1130/0016-7606(1996)108<0101:NIITAO>2.3.CO;2

Dunning, G. R., Wilton, D. H. C., and Herd, R. K., 1989, Geology, geochemistry and geochronology of a Taconic batholith, southwestern Newfoundland: Transactions of the Royal Society of Edinburgh: Earth Sciences, v. 80, n. 2, p. 159–168, https://doi.org/10.1017/S0263593300014449

Fyffe, L. R., Barr, S. M., Johnson, S. C., McLeod, M. J., McNicoll, V. J., Valverde-Vaquero, P., van Staal, C. R., and White, C. E., 2009, Detrital zircon ages from Neoproterozoic and Early Paleozoic conglomerate and sandstone units of New Brunswick and coastal Maine: Implications for the tectonic evolution of Ganderia: Atlantic Geology, v. 45, p. 110–144, https://doi.org/10.4138/atlgeol.2009.006

Gerbi, C. C., Johnson, S. E., and Aleinikoff, J. N., 2006a, Origin and orogenic role of the Chain Lakes massif, Maine and Quebec: Canadian Journal of Earth Sciences, v. 43, n. 3, p. 339–366, https://doi.org/10.1139/e05-112

Gerbi, C. C., Johnson, S. E., Aleinikoff, J. N., Bédard, J. H., Dunning, G. R., and Fanning, C. M., 2006b, Early Paleozoic development of the Maine-Quebec boundary Mountains region: Canadian Journal of Earth Sciences, v. 43, n. 3, p. 367–389, https://doi.org/10.1139/e05-113

Gerstenberger, H., and Haase, G., 1997, A highly effective emitter substance for mass spectrometric Pb isotope ration determinations: Chemical Geology, v. 136, n. 3–4, p. 309–312, https://doi.org/10.1016/S0009-2541(96)00033-2

Gradstein, F. M., Ogg, J. G., Schmitz, M., and Ogg, G., 2012, The geologic time scale 2012, 2-volume set: Amsterdam, Elsevier, 1,176 p.

Harper, D. A. T., Mac Niocaill, C., and Williams, S. H., 1996, The palaeogeography of early Ordovician Iapetus terranes: An integration of faunal and palaeomagnetic constraints: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 121, n. 3–4, p. 297–312, https://doi.org/10.1016/0031-0182(95)00079-8

Harwood, D. S., and Berry, W. B. N., 1967, Fossiliferous Lower Paleozoic rocks in the Cupsuptic quadrangle, west-central Maine: US Geological Survey Professional Paper 575-D, p. D16–D23.

Hatch, N. L., Jr., 1988, Some revisions to the stratigraphy and structure of the Connecticut Valley trough, eastern Vermont: American Journal of Science, v. 288, n. 10, p. 1041–1059, https://doi.org/10.2475/ajs.288.10.1041

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, "A" Series Map, n. 2096A, p. 2, https://doi.org/10.4095/221912

Hodgkins, C. E., ms, 1985, Geochemistry and petrology of the Dry Hill Gneiss, and related gneisses, Pelham dome, central Massachusetts: Amherst, Massachusetts, Department of Geology and Geography, University of Massachusetts, Contribution n. 48, M.S. thesis, 135 p.

Hodych, J. P., and Cox, R. A., 2007, Ediacaran U-Pb zircon dates for the Lac Matapédia and Mt. St.-Anselme basalts of the Quebec Appalachians: Support for a long-lived mantle plume during the rifting phase of Iapetus opening: Canadian Journal of Earth Sciences, v. 44, n. 4, p. 565–581, https://doi.org/10.1139/e06-112

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Physical Review C, v. 4, n. 5, p. 1889–1906, https://doi.org/10.1103/PhysRevC.4.1889

Johnson, R. J. E., van der Pluijm, B. A., and Van der Voo, R., 1991, Paleomagnetism of the Moreton's Harbour Group, northeastern Newfoundland Appalachians: Evidence for an Early Ordovician island arc near the Laurentian margin of Iapetus: Journal of Geophysical Research: Solid Earth (1978–2012), v. 96, n. B7, p. 11689–11701.

Karabinos, P., 1988, Tectonic significance of basement-cover relationships in the Green Mountain massif, Vermont: The Journal of Geology, v. 96, n. 4, p. 445–454, https://doi.org/10.1086/629239

——— 2008, Composite arc terrains in the New England Appalachians: Geological Society of America, Abstracts with Programs, v. 40, p. 75.

Karabinos, P. A., and Aleinikoff, J. N., 1990, Evidence for a major middle Proterozoic, post-Grenvillian igneous event in western New England: American Journal of Science, v. 290, n. 8, p. 959–974, https://doi.org/10.2475/ajs.290.8.959

Karabinos, P., and Williamson, B. F., 1994, Constraints of the timing of Taconian and Acadian deformation in western Massachusetts: Northeastern Geology, v. 16, n. 1, p. 1–8.

Karabinos, P., Samson, S. D., Hepburn, J. C., and Stoll, H. M., 1998, Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Geology, v. 26, n. 3, p. 215–218, https://doi.org/10.1130/0091-7613(1998)026<0215:TOITNE>2.3.CO;2

——— 1999, Taconian orogeny in the New England Appalachians: Collison between Laurentia and the Shelburne Falls arc, Reply: Geology, v. 27, n. 4, p. 382.

Karabinos, P., Morris, D., Hamilton, M., and Rayner, N., 2008, Age, origin, and tectonic significance of Mesoproterozoic and Silurian felsic sills in the Berkshire massif, Massachusetts: American Journal of Science, v. 308, n. 6, p. 787–812, https://doi.org/10.2475/06.2008.03

Kim, J., and Jacobi, R. D., 1996, Geochemistry and tectonic implications of Hawley Formation meta-igneous units: Northwestern Massachusetts: American Journal of Science, v. 296, n. 10, p. 1126–1174, https://doi.org/10.2475/ajs.296.10.1126

Krough, T. E., 1973, A low-contamination method for hydrothermal decompostion of zircon and extraction of U and Pb for isotopic age determination: Geochmica et Cosmochimica Acta, v. 37, n. 3, p. 485–494, https://doi.org/10.1016/0016-7037(73)90213-5

Kumarapeli, P. S., Dunning, G. R., Pintson, H., and Shaver, J., 1989, Geochemistry and U-Pb zircon age of comenditic metafelsites of the Tibbit Hill Formation, Quebec Appalachians: Canadian Journal of Earth Sciences, v. 26, n. 7, p. 1374–1383, https://doi.org/10.1139/e89-117

Kusky, T., Chow, J. S., and Bowring, S. A., 1997, Age and origin of the Boil Mountain ophiolite and Chain Lakes massif, Maine: Implications for the Penobscottian orogeny: Canadian Journal of Earth Sciences, v. 34, n. 5, p. 646–654, https://doi.org/10.1139/e17-051

Laird, J., Lanphere, M. A., and Albee, A. L., 1984, Distribution of Ordovician and Devonian metamorphism in mafic and pelitic schists from northern Vermont: American Journal of Science, v. 284, n. 4–5, p. 376–413, https://doi.org/10.2475/ajs.284.4-5.376

Landing, E., 2012, The great American carbonate bank in eastern Laurentia: Its births, deaths, and linkage to paleooceanic oxygenation (Early Cambrian–Late Ordovician), *in* Derby, J., Fritz, R., Longacre, S., Morgan, W., and Sternbach, C., editors, Great American Carbonate Bank: The Geology and Economic Resources of the Cambrian-Ordovician Sauk Megasequence of Laurentia: AAPG Memoir, v. 98, p. 451–524, https://doi.org/10.1306/13331502M983502

Liss, M. J., van der Pluijm, B. A., and Van der Voo, R., 1993, Avalonian proximity of the Ordovician Miramichi terrane, northern New Brunswick, northern Appalachians: Paleomagnetic evidence for rifting and back-arc basin formation at the southern margin of Iapetus: Tectonophysics, v. 227, n. 1–4, p. 17–30, https://doi.org/10.1016/0040-1951(93)90084-W

Ludwig, K. R., 2003, User's manual for Isoplot 3.00: a geochronological toolkit for Microsoft Excel: Berkeley, California, Berkeley Geochronology Center Special Publication, v. 4, p. 1–70.

Lyons, J. B., Aleinikoff, J. N., and Zartman, R. E., 1986, Uranium-thorium-lead ages of the Highlandcroft Plutonic Suite, northern New England: American Journal of Science, v. 286, n. 6, p. 489–509, https://doi.org/10.2475/ajs.286.6.489

Lyons, J. B., Bothner, W. A., Moench, R. H., Thompson, J. B., Jr., 1997, Bedrock geologic map of New Hampshire: US Geological Survey, scale 1:250,000.

Mac Niocaill, C., Van der Pluijm, B. A., and Van der Voo, R., 1997, Ordovician paleogeography and the evolution of the Iapetus ocean: Geology, v. 25, n. 2, p. 159–162, https://doi.org/10.1130/0091-7613(1997)025<0159:OPATEO>2.3.CO;2

Macdonald, F. A., Ryan-Davis, J., Coish, R. A., Crowley, J. L., and Karabinos, P., 2014, A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean: Geology, v. 42, n. 6, p. 539–542, https://doi.org/10.1130/G35659.1

——— 2015, A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications

for the Taconic orogeny and closure of the Iapetus Ocean Forum Reply: Geology, v. 43, n. 4, p. e360, https://doi.org/10.1130/G36575Y.1
Macdonald, F. A., Karabinos, P. M., Crowley, J. L., Hodgin, E. B., Crockford, P. W., and Delano, J. W., 2017, Bridging the gap between the foreland and the hinterland II: Geochronology and tectonic setting of Ordovician magmatism and basin formation on the Laurentian margin of New England and Newfoundland: American Journal of Science, v. 317, n. 5, p. https://doi.org/10.2475/05.2017.02
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, v. 220, n. 1–2, p. 47–66, https://doi.org/10.1016/j.chemgeo.2005.03.011
McLelland, J. M., Selleck, B. W., Hamilton, M. A., and Bickford, M. E., 2010, Late-to post-tectonic setting of some major Proterozoic anorthosite–mangerite–charnockite–granite (AMCG) suites: The Canadian Mineralogist, v. 48, n. 4, p. 729–750, https://doi.org/10.3749/canmin.48.4.729
Merschat, A. J., Walsh, G. J., Holm-Denoma, C. S., and McAleer, R. J., 2016, Detrital zircon geochronology of the Bronson Hill anticlinorium and western facies of the Central Maine terrane, southern NH-VT: Geological Society of America Abstracts with Programs, v. 48, n. 2, https://doi.org/10.1130/abs/2016NE-272887
Moench, R. H., and Aleinikoff, J. N., 2003, Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England: Physics and Chemistry of the Earth, Parts A/B/C, v. 28, n. 1–3, p. 113–160, https://doi.org/10.1016/S1474-7065(01)00003-1
Moench, R. H., Boone, G. M., Bothner, W. A., Boudette, E. L., Hatch N. L., Jr., Hussey, A. M., II, and Marvinney, R. G., 1995, Geologic map of the Sherbrooke–Lewiston area, Maine, New Hampshire, Vermont, United States, and Quebec, Canada, with contributions to geochronology by J.N. Aleinikoff: US Geological Survey pamphlet, 56 p., scale 1:250,000.
Neuman, R. B., 1984, Geology and paleobiology of islands in the Ordovician Iapetus Ocean: Review and implications: Geological Society of America Bulletin, v. 95, n. 10, p. 1188–1201, https://doi.org/10.1130/0016-7606(1984)95<1188:GAPOII>2.0.CO;2
Osberg, P. H., Hussey, A. M., II, and Boone, G. M., 1985, Bedrock geologic map of Maine: Maine Geological Survey, scale 1:500,000.
Potts, S. S., van der Pluijm, B. A., and Van der Voo, R., 1993, Paleomagnetism of the Ordovician Bluffer Pond Formation: Paleogeographic implications for the Munsungun terrane of northern Maine: Journal of Geophysical Research: Solid Earth, v. 98, n. B5, p. 7987–7996, https://doi.org/10.1029/93JB00017
Potts, S. S., van der Pluijm, B. A., and Van der Voo, R., 1995, Paleomagnetism of the Pennington Mountain terrane: A near-Laurentian back arc basin in the Maine Appalachians: Journal of Geophysical Research-Solid Earth, v. 100, n. B6, p. 10,003–10,011, https://doi.org/10.1029/94JB03013
Quinn, A. W., and Moore, G. E., Jr., 1968, Sedimentation, tectonism, and plutonism of the Narragansett Basin region, *in* Zen, E-an, White, W. S., Hadley, J. B., and Thompson, J. B., Jr., editors, Studies of Appalachian Geology: Northern and Maritime: New York, Interscience, p. 269–279.
Rankin, D. W., Tucker, R. D., and Amelin, Y., 2013, Reevaluation of the Piermont-Frontenac allochthon in the Upper Connecticut Valley: Restoration of coherent Boundary Mountains–Bronson Hill stratigraphic sequence: Geological Society of America Bulletin, v. 125, n. 5–6, p. 998–1024, https://doi.org/10.1130/B30590.1
Rast, N., and Skehan, J. W., 1993, Mid-Paleozoic orogenesis in the North Atlantic: The Acadian orogeny: Geological Society of America Special Papers, v. 275, p. 1–26, https://doi.org/10.1130/SPE275-p1
Ratcliffe, N. M., and Zartman, R. E., 1976, Stratigraphy, isotopic ages, and deformational history of basement and cover rocks of the Berkshire Massif, southwestern Massachusetts: Geological Society of America Memoirs, v. 148, p. 373–412, https://doi.org/10.1130/MEM148-p373
Ratcliffe, N. M., Aleinikoff, J. N., Burton, W. C., and Karabinos, P., 1991, Trondhjemitic, 1.35–1.31 Ga gneisses of the Mount Holly Complex of Vermont: Evidence for an Elzevirian event in the Grenville Basement of the United States Appalachians: Canadian Journal of Earth Sciences, v. 28, n. 1, p. 77–93, https://doi.org/10.1139/e91-007
Ratcliffe, N., Hames, W. E., and Stanley, R. S., 1999, Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc: Comment and Reply: Geology, v. 27, n. 4, p. 381, https://doi.org/10.1130/0091-7613(1999)027<0381:toitne>2.3.co;2
Ratcliffe, N. M., Stanley, R. S., Gale, M. H., Thompson, P. J., Walsh, G. J., Rankin, D. W., Doolan, B. L., Kim, J., Mehrtens, C. J., and Aleinikoff, J. N., 2011, Bedrock geologic map of Vermont: US Geological Survey, Scientific Investigations Map 3184, 3 sheets, scale 1:100,000.
Reusch, D. N., and van Staal, C. R., 2011, The Dog Bay–Liberty Line and its significance for Silurian tectonics of the northern Appalachian orogeny, This article is one of a series of papers published in this CJES Special Issue: In honour of Ward Neale on the theme of Appalachian and Grenvillian geology. 2 Geological Survey of Canada Contribution 20100257: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 239–258, https://doi.org/10.1139/e11-024
Richardson, C. H., 1924, The terranes of Bethel, Vermont, *in* Perkins, G. H., Report of the State Geologist on the mineral industries and geology of Vermont, 1923-1924: Vermont Geological Survey [Report of the State Geologist], v. 14, p. 77–103.
Riva, J., 1974, A revision of some Ordovician graptolites of eastern North America: Paleontology, v. 17, p. 1–40.
Robinson, P., Tucker, R., Gromet, L., Ashenden, D., Williams, M., Reed, R., and Peterson, V., 1992, The Pelham dome, central Massachusetts: Stratigraphy, geochronology, structure and metamorphism, *in* Robinson, P., and Brady, J. B., editors Guidebook for Field Trips in the Connecticut Valley Region of Massachusetts and Adjacent States: Amherst, Massachusetts, University of Massachusetts, NEIGC 84th Annual Meeting, Department of Geology and Geography Contribution, p. 132–169.

Rodgers, J., compiler, 1985, Bedrock Geological Map of Connecticut: Hartford, Connecticut, Connecticut Geological and Natural History Survey, 2 sheets, scale 1:125,000.

Rowley, D. B., and Kidd, W. S. F., 1981, Stratigraphic relationships and detrital composition of the medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic orogeny: The Journal of Geology, v. 89, n. 2, p. 199–218, https://doi.org/10.1086/628580

Schenk, P. E., 1997, Sequence stratigraphy and proveance on Gondwana's margin: The Meguma Zone (Cambrian to Devonian) of Nova Scotia, Canada: Geological Society of America Bulletin, v. 109, n. 4, p. 395–409, https://doi.org/10.1130/0016-7606(1997)109<0395:SSAPOG>2.3.CO;2

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, v. 8, n. 8, p. Q08006, https://doi.org/10.1029/2006GC001492

Sevigny, J. H., and Hanson, G. N., 1993, Orogenic evolution of the New England Appalachians of southwestern Connecticut: Geological Society of America Bulletin, v. 105, n. 12, p. 1591–1605, https://doi.org/10.1130/0016-7606(1993)105<1591:OEOTNE>2.3.CO;2

——— 1995, Late-Taconian and pre-Acadian history of the New England Appalachians of southwestern Connecticut: Geological Society of America Bulletin, v. 107, n. 4, p. 487–498, https://doi.org/10.1130/0016-7606(1995)107<0487:LTAPAH>2.3.CO;2

Sláma, J., Košler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchar, J. M., Horstwood, M. S. A., Morris, G. A., Nasdala, L., and Norberg, N., 2008, Plešovice zircon—a new natural reference material for U–Pb and Hf isotopic microanalysis: Chemical Geology, v. 249, n. 1–2, p. 1–35, https://doi.org/10.1016/j.chemgeo.2007.11.005

St. Julien, P. S., and Hubert, C., 1975, Evolution of the Taconian orogen in the Quebec Appalachians, *in* Ostrom, J. H., and Orville, P. M., editors, Tectonics and Mountain Ranges: American Journal of Science, v. 275-A, p. 337–362.

Stanley, R. S., and Hatch, N. L., Jr., 1988, The pre-Silurian geology of the Rowe-Hawley zone, *in* Hatch, N. L., Jr., editor, The Bedrock Geology of Massachusetts: U.S. Geological Survey Professional Paper 1366-A-D, p. A1–A39.

Stanley, R. S., and Ratcliffe, N. M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, n. 10, p. 1227–1250, https://doi.org/10.1130/0016-7606(1985)96<1227:TSOTTO>2.0.CO;2

Strachan, R. A., Collins, A. S., Buchan, C., Nance, R. D., Murphy, J. B., and D'Lemos, R. S., 2007, Terrane analysis along a Neoproterozoic active margin of Gondwana: Insights from U–Pb zircon geochronology: Journal of the Geological Society, v. 164, p. 57–60, https://doi.org/10.1144/0016-76492006-014

Thompson, J. B., Jr., Robinson, P., Clifford, T. N., and Trask, N. J., Jr., 1968, Nappes and gneiss domes in west- central New England, *in* Zen, E., and White, W. S., editors, Studies of Appalachian Geology: Northern and Maritime: New York, John Wiley & Sons, p. 203–218, 2 color plates.

Todaro, S. M., Stamatakos, J., van der Pluijm, B. A., and Van der Voo, R., 1996, Near-Laurentian paleogeography of the Lawrence Head volcanics of central Newfoundland, northern Appalachians: Tectonophysics, v. 263, n. 1–4, p. 107–121, https://doi.org/10.1016/S0040-1951(96)00021-2

Torsvik, T. H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D. J. J., Domeier, M., Gaina, C., Tohver, E., Meert, J. G., McCausland, P. J. A., and Cocks, R. M., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, n. 3–4, p. 325–368, https://doi.org/10.1016/j.earscirev.2012.06.007

Tremblay, A., and Pinet, N., 2016, Late Neoproterozoic to Permian tectonic evolution of the Quebec Appalachians, Canada: Earth-Science Reviews, v. 160, p. 131–170, https://doi.org/10.1016/j.earscirev.2016.06.015

Tremblay, A., Meshi, A., and Bédard, J. H., 2009, Oceanic core complexes and ancient oceanic lithosphere: Insights from Iapetan and Tethyan ophiolites (Canada and Albania): Tectonophysics, v. 473, n. 1–2, p. 36–52, https://doi.org/10.1016/j.tecto.2008.08.003

Tucker, R. D., and McKerrow, W. S., 1995, Early Paleozoic chronology: A review in light of new U-Pb zircon ages from Newfoundland and Britain: Canadian Journal of Earth Sciences, v. 32, n. 4, p. 368–379, https://doi.org/10.1139/e95-032

Tucker, R. D., and Robinson, P., 1990, Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England: Geological Society of America Bulletin, v. 102, n. 10, p. 1404–1419, https://doi.org/10.1130/0016-7606(1990)102<1404:AASOTB>2.3.CO;2

Tucker, R. D., Bradley, D. C., Ver Straeten, C. A., Harris, A. G., Ebert, J. R., and McCutcheon, S. R., 1998, New U–Pb zircon ages and the duration and division of Devonian time: Earth and Planetary Science Letters, v. 158, n. 3–4, p. 175–186, https://doi.org/10.1016/S0012-821X(98)00050-8

Valley, P., Walsh, G. J., and McAleer, R. J., 2015, New U-Pb zircon ages from the Bronson Hill arc, west-central New Hampshire: Geological Society of America Abstracts with Programs, v. 47, n. 3, p. 41.

van der Pluijm, B. A., Johnson, R. J. E., and Van der Voo, R., 1990, Early Paleozoic paleogeography and accretionary history of the Newfoundland Appalachians: Geology, v. 18, n. 9, p. 898–901, https://doi.org/10.1130/0091-7613(1990)018<0898:EPPAAH>2.3.CO;2

van der Voo, R., Johnson, R. J. E., van der Pluijm, B. A., and Knutson, L. C., 1991, Paleogeography of some vestiges of Iapetus: Paleomagnetism of the Ordovician Robert's Arm, Summerford, and Chanceport groups, central Newfoundland: Geological Society of America Bulletin, v. 103, n. 2, p. 1564–1575, https://doi.org/10.1130/0016-7606(1991)103<1564:POSVOI>2.3.CO;2

Van Staal, C., and Barr, S. M., 2012, Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin, *in* Percival, J., Cook, F., and Clowes, R., editors, Tectonic styles in Canada: The LITHOPROBE perspective: Geological Association of Canada Special Paper, v. 49, p. 55.

Van Staal, C. R., Dewey, J. F., Mac Niocaill, C., and McKerrow, W. S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: History of a complex, west and southwest Pacific-type segment of Iapetus: Geological Society, London, Special Publications, v. 143, p. 197–242, https://doi.org/10.1144/GSL.SP.1998.143.01.17

Van Staal, C. R., Whalen, J. B., McNicoll, V. J., Pehrsson, S., Lissenberg, C. J., Zagorevski, A., van Breemen, O., and Jenner, G. A., 2007, The Notre Dame arc and the Taconic orogeny in Newfoundland: Geological Society of America Memoirs, v. 200, p. 511–552, https://doi.org/10.1130/2007.1200(26)

van Staal, C. R., Whalen, J. B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians: Geological Society, London, Special Publications, v. 327, p. 271–316, https://doi.org/10.1144/SP327.13

van Staal, C. R., Chew, D. M., Zagorevski, A., McNicoll, V., Hibbard, J., Skulski, T., Escayola, M. P., Castonguay, S., and Sylvester, P. J., 2013, Evidence of Late Ediacaran hyperextension of the Laurentian Iapetan margin in the Birchy Complex, Baie Verte Peninsula, northwest Newfoundland: Implications for the opening of Iapetus, formation of peri-Laurentian microcontinents and Taconic–grampian orogenesis: Geoscience Canada, v. 40, n. 2, p. 94–117, https://doi.org/10.12789/geocanj.2013.40.006

van Staal, C. R., Wilson, R. A., Kamo, S. L., McClelland, W. C., and McNicoll, V., 2016, Evolution of the Early to Middle Ordovician Popelogan arc in New Brunswick, Canada, and adjacent Maine, USA: Record of arc-trench migration and multiple phases of rifting: Geological Society of America Bulletin, v. 128, n. 1–2, p. 122–146, https://doi.org/10.1130/B31253.1

Ver Straeten, C. A., 2010, Lessons from the foreland basin: Northern Appalachian basin perspectives on the Acadian orogeny: Geological Society of America Memoirs, v. 206, p. 251–282, https://doi.org/10.1130/2010.1206(12)

Waldron, J. W. F., and van Staal, C. R., 2001, Taconian orogeny and the accretion of the Dashwoods block: A peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, n. 9, p. 811–814, https://doi.org/10.1130/0091-7613(2001)029<0811:TOATAO>2.0.CO;2

Waldron, J. W. F., McNicoll, V. J., and van Staal, C. R., 2012, Laurentia-derived detritus in the Badger Group of central Newfoundland: Deposition during closing of the Iapetus Ocean, This article is one of a series of papers published in CJES Special Issue: In honour of Ward Neale on the theme of Appalachian and Grenvillian geology. 2 Geological Survey of Canada Contribution 20110273: Canadian Journal of Earth Sciences, v. 49, n. 1, p. 207–221, https://doi.org/10.1139/e11-030

Waldron, J. W. F., Schofield, D. I., Murphy, J. B., and Thomas, C. W., 2014, How was the Iapetus Ocean infected with subduction?: Geology, v. 42, n. 12, p. 1095–1098, https://doi.org/10.1130/G36194.1

Walsh, G. J., and Aleinikoff, J. N., 1999, U-Pb zircon age of metafelsite from the Pinney Hollow Formation: Implications for the development of the Vermont Appalachians: American Journal of Science, v. 299, n. 2, p. 157–170, https://doi.org/10.2475/ajs.299.2.157

Watson, E. B., Wark, D. A., and Thomas, J. B., 2006, Crystallization thermometers for zircon and rutile: Contributions to Mineralogy and Petrology, v. 151, p. 413–433, https://doi.org/10.1007/s00410-006-0068-5

Wellensiek, M. R., van der Pluijm, B. A., Van der Voo, R., and Johnson, R. J. E., 1990, Tectonic history of the Lunksoos composite terrane in the Maine Appalachians: Tectonics, v. 9, n. 4, p. 719–734, https://doi.org/10.1029/TC009i004p00719

Whalen, J., Currie, K., and Van Breemen, O., 1987, Episodic Ordovician-Silurian plutonism in the Topsails igneous terrane, western Newfoundland: Transactions of the Royal Society of Edinburgh: Earth Sciences, v. 78, n. 1, p. 17–28, https://doi.org/10.1017/S0263593300010920

Whalen, J. B., Jenner, G. A., Longstaffe, F. J., Gariepy, C., and Fryer, B. J., 1997a, Implications of granitoid geochemical and isotopic (Nd, O, Pb) data from the Cambrian-Ordovician Notre Dame arc for the evolution of the Central Mobile belt, Newfoundland Appalachians, *in* Sinha, A. Kr., Whalen, J. B., and Hogan, J. P., editors, The nature of magmatism in the Appalachian orogen: Geological Society of America Memoirs, v. 191, p. 367–395, https://doi.org/10.1130/0-8137-1191-6.367

Whalen, J. B., van Staal, C. R., Longstaffe, F. J., Gariépy, C., and Jenner, G. A., 1997b, Insights into tectonostratigraphic zone identification in southwestern Newfoundland based on isotopic (Nd, O, Pb) and geochemical data: Atlantic Geology, v. 33, n. 3, p. 231–241, https://doi.org/10.4138/2071

White, C. E., and Barr, S. M., 2010, Lithochemistry of the Lower Paleozoic Goldenville and Halifax groups, southwestern Nova Scotia, Canada: Implications for stratigraphy, provenance, and tectonic setting of the Meguma terrane: Geological Society of America Memoirs, v. 206, p. 347–366, https://doi.org/10.1130/2010.1206(15)

Whitehead, J., Reynolds, P. H., and Spray, J. G., 1996, $^{40}Ar/^{39}Ar$ age constraints on Taconian and Acadian events in the Quebec Appalachians: Geology, v. 24, n. 4, p. 359–362, https://doi.org/10.1130/0091-7613(1996)024<0359:AAACOT>2.3.CO;2

Williams, H., 1979, Appalachian orogen in Canada: Canadian Journal of Earth Sciences, v. 16, n. 3, p. 792–807, https://doi.org/10.1139/e79-070

Williams, H., and Hiscott, R. N., 1987, Definition of the Iapetus rift-drift succession in western Newfoundland: Geology, v. 15, n. 11, p. 1044–1047, https://doi.org/10.1130/0091-7613(1987)15<1044:DOTLRT>2.0.CO;2

Williams, H., Colman-Sadd, S., and Swinden, H. S., 1988, Tectonic-stratigraphic subdivisions of central Newfoundland: Geological Survey of Canada, Current Research, Part B, Paper, n. 88-1B, p. 91–98, https://doi.org/10.4095/122425

Willner, A. P., Gerdes, A., Massonne, H.-J., van Staal, C. R., and Zagorevski, A., 2014, Crustal Evolution of the Northeast Laurentian Margin and the Peri-Gondwanan Microcontinent Ganderia Prior to and During Closure of the Iapetus Ocean: Detrital Zircon U–Pb and Hf Isotope Evidence from Newfoundland: Geoscience Canada, v. 41, n. 3, p. 345–364, https://doi.org/10.12789/geocanj.2014.41.046

Wintsch, R. P., Webster, J. R., Bernitz, J. A., and Fout, J. S., 1990, Geochemical and geological criteria for the discrimination of high grade gneisses of intrusive and extrusive origin, southern Connecticut, *in* Socci, A. D., Skehan, J. W., and Smith, G. W., editors, Geology of the composite Avalon terrane of southern New England: Geological Society of America Special Paper, v. 245, p. 187–208, https://doi.org/10.1130/SPE245-p187

Wintsch, R. P., Yi, K., and Han, D., 2015, Evidence from U-Pb SHRIMP ages of detrital zircons for evolving provenances for peri-Gondwanan forearc metasediments, western Connecticut: Geological Society of America Abstracts with Programs, p. 42.

Wintsch, R. P., Yi, K., and Lee, T. H., 2016, More about the Moretown terrane in the Bristol dome, western Connecticut: Geological Society of America Abstracts with Programs, v. 48, n. 2, https://doi.org/10.1130/abs/2016NE-272320

Zagorevski, A., van Staal, C. R., McNicoll, V., Rogers, N., and Valverde-Vaquero, P., 2008, Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians: Geological Society of America Special Papers, v. 436, p. 309–333, https://doi.org/10.1130/2008.2436(14)

Zagorevski, A., van Staal, C. R., Rogers, N., McNicoll, V. J., and Pollock, J., 2010, Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians: Geological Society of America Memoirs, v. 206, p. 367–396, https://doi.org/10.1130/2010.1206(16)

Zen, E. A., Goldsmith, R., Ratcliffe, N. M., Robinson, P., Stanley, R. S., Hatch, N. L., Jr., Shride, A. F., Weed, A., and Wones, D. R., 1983, Bedrock geologic map of Massachusetts: United States Geological Survey, scale 1:250,000.