A TRAVERSE THROUGH THE SUTURE ZONE BETWEEN LAURENTIA AND THE MORETOWN TERRANE IN NORTHWESTERN MASSACHUSETTS

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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 470 Ma, until it collided with hyperextended distal fragments of Laurentia, represented by the Rowe Schist. Magmatic arc rocks formed during this interval are primarily located in the Shelburne Falls arc, although some rocks that formed above the early east-dipping subduction zone are located in the northern part of 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.

INTRODUCTION

Before plate tectonic theory was applied to the Appalachians (e.g. 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 orogenies. 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 et al., 1998; Zagorevski et al., 2008). 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 et al., 2014), Ganderia (Van Staal et al., 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 et al., 1992). The expanding geochronological database in the northern Appalachians suggests that the Laurentian margin was continuously active from approximately 475 to 270 Ma.

Hibbard et al. (2006) mapped the suture between peri-Laurentian and peri-Gondwanan terranes in the New England Appalachians along the western margin of the Bronson Hill arc (Fig. 1). This interpretation required that the Shelburne Falls arc (Fig. 1) formed on a Laurentian-derived microcontinent as proposed for the Dashwoods block in Newfoundland (Waldron and van Staal, 2001), and that the Bronson Hill arc formed on the western leading edge of Ganderia (Hibbard et al., 2006). Based on detrital zircon data from the Moretown Formation in Massachusetts and Vermont, Macdonald et al. (2014) and Karabinos et al. (2017) argued that the suture between Laurentia and Gondwanan-derived terranes is located approximately 50 km further west along the contact between the Rowe Schist and the Moretown Formation, which is characterized by a high concentration of mafic and ultra-mafic lenses, interpreted as remnants of subducted oceanic lithosphere. Because the evidence for a Gondwanan source for the metasedimentary rocks came from the Moretown Formation, we called this newly identified Gondwanan-derived block the Moretown terrane.

The relocation of the suture has some important tectonic implications for the deep crustal structure of the New England Appalachians. 1) It requires that the Shelburne Falls arc formed on Gondwanan-derived crust rather than Laurentian crust. 2) Instead of the Bronson Hill arc having formed above an east-dipping subduction zone on the western leading edge of Ganderia, we suggested that it formed above a west-dipping subduction zone along the eastern trailing edge of the Moretown terrane after a reversal in subduction polarity. 3) If the Moretown terrane is distinct from Ganderia, the suture between these two Gondwanan-derived terranes must be located somewhere under the Silurian-Devonian rocks of the Central Maine basin (Fig. 1).

The focus of this trip is the evidence for a plate suture between Laurentia and a Gondwanan-derived microcontinent, the Moretown terrane, proposed by Macdonald et al. (2014) and Karabinos et al. (2017). In Massachusetts, this suture coincides with the boundary between the Rowe Schist and the Moretown Formation. There is nothing cryptic about this suture; it is characterized by a dramatic difference in sediment source as revealed by detrital zircon populations, and is characterized by a high concentration of mafic and ultramafic lenses, which we interpret as remnants of oceanic crust and mantle from an east-dipping subduction zone. It also coincides with a sharp 10 to 15 km decrease in depth to MOHO from the Laurentian margin to the Moretown terrane (Li et al., 2018). We will also discuss evidence suggesting that much of the 475 Ma arc magmatism in the Shelburne Falls arc occurred in close proximity to Laurentia even though the arc was built on the Gondwanan-derived Moretown terrane.

GEOLOGIC FRAMEWORK

The Laurentian Margin

Rifting and Mesoproterozoic Basement Rocks- The Neoproterozoic breakup of Rodinia created a south-facing rifted margin on Laurentia at approximately 20° S latitude (Torsvik et al., 2012). The age of rifting in western New England is constrained by 570 to 555 Ma volcanic and plutonic rocks (Kumarapeli et al., 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. 1400 to 950 Ma Mesoproterozoic to Early Neoproterozoic para- and ortho-gneiss that are correlated with the Grenville Province of Canada and the Adirondack Mountains of New York (Karabinos et al., 2008; Karabinos and Aleinikoff, 1990; Ratcliffe and Zartman, 1976; Zen et al., 1983).

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 and texturally immature and displays large lateral facies and thickness variations, which reflect deposition in an active rift environment (Allen et al., 2010; Williams and Hiscott, 1987). 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 that lies above basement gneisses (fig. 1). Stratigraphically above the conglomerate, the Dalton Formation includes meta-arkose and graphitic phyllite, which is stratigraphically below the Cambrian Cheshire Quartzite (Landing, 2012).

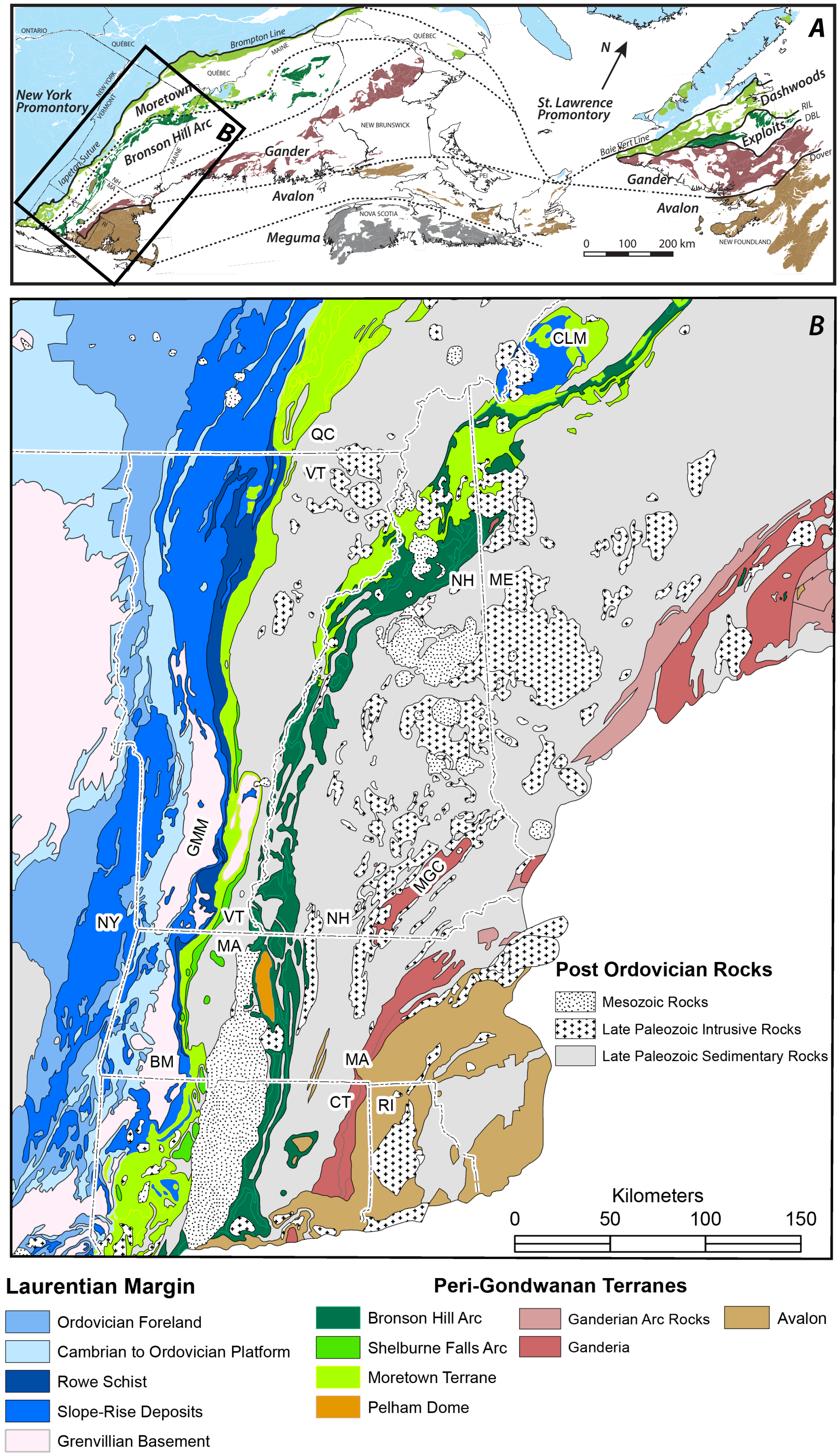

Fig. 1. (A) Tectonic map of the Appalachians modified from Hibbard et al. (2006). Outline shows location of more detailed tectonic map of New England in 1B. (B) Tectonic map of New England modified from Hibbard et al. (2006). Abbreviations are: BM- Berkshire massif, CLM- Chain Lakes massif, GMM- Green 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.

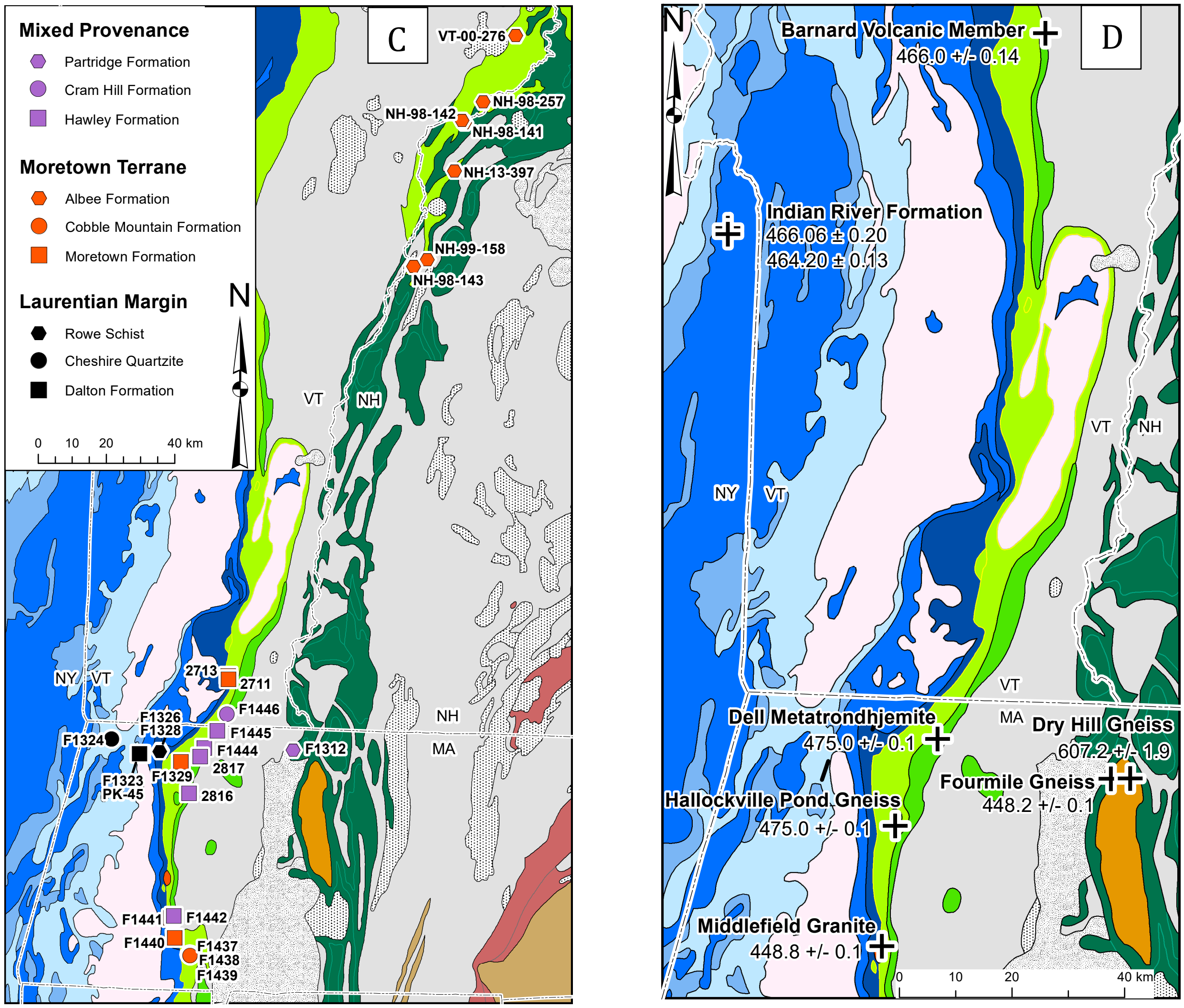

Fig. 1, cont. (D) Location map of samples dated by U-Pb zircon CA-IDTIMS. Units use the same colors and patterns as shown in figure 1B. (E) Schematic diagram of Neoproterozoic to Ordovician rocks involved in the Taconic orogeny of New England. Laurentian deformed margin units based on Zen and other (1983), Doll et al. (1961), and Ratcliffe et al. (2011). Western and Eastern cover sequences stratigraphy is modified from Karabinos (1988). Peri-Gondwanan realm units, and detrital zircon provenance indicators from Macdonald et al. (2014) and this study. Bronson Hill arc ages from Tucker and Robinson (1990) and Moench and Aleinikoff (2003).

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 (Allen et al., 2010; Williams and Hiscott, 1987).

Shelf Carbonate Rocks- Continued tectonic stability of the Laurentian margin to the Early Ordovician is recorded by the extensive Early Paleozoic carbonate platform preserved throughout the Appalachians. Now metamorphosed to dolomitic and calcitic marble, with interbedded quartzite units, these rocks include the Stockbridge Formation in Massachusetts and the Vermont Valley sequence. 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 et al., 1983; Karabinos, 1988; Ratcliffe et al., 2011).

Distal Margin of Laurentian- Outboard of the Laurentian continental shelf, an Ediacaran to Early Ordovician of deeper-water sequence has been interpreted to record deposition on the continental slope and rise (Rowley and 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; Karabinos, 1988; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985).

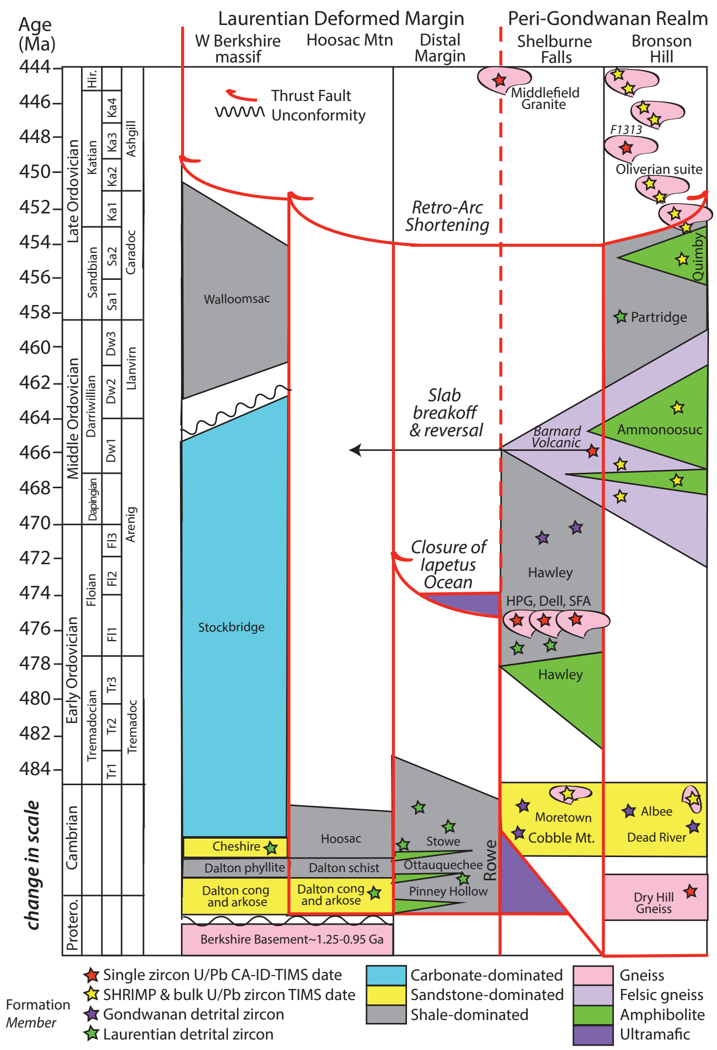

Fig. 2. Time-space diagram of Neoproterozoic to Ordovician rocks involved in the Taconic orogeny in New England. Laurentian deformed margin stratigraphy based on Karabinos (1988), Zen et al. (1983), and Doll et al. (1961). Peri-Gondwanan realm stratigraphy based on Macdonald et al. (2014), Tucker and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

The Rowe Schist is a quartz-rich schist correlated with the Pinney Hollow, Stowe, and Ottauquechee Formations in Vermont by Stanley and Ratcliffe (1985). These rocks may have formed on hyper-extended Laurentian crust, and been separated fom the Laurentian passive margin by the Taconic Seaway (Macdonald et al., 2014; Waldron and van Staal, 2001). Walsh and Aleinikoff (1999) reported a 571 $\pm$ 5 Ma U-Pb zircon age for a meta-felsite from the Pinney 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 et al., 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 et al., 1967).

Gondwanan-Derived 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 et al., 1961; Ratcliffe et al., 2011; Zen et al., 1983), 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 formed either during crustal extension above an Early Ordovician east-dipping subduction zone or above a Late Ordovician to Silurian west-dipping subduction zone (Coish et al., 2011). 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 et al. (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 et al. (2014) is inconsistent with the interpretation that the Moretown Formation formed as an Ordovician forearc deposit (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985).

Ultramafic Lenses- Both the Rowe Schist and Moretown Formation host numerous ultramafic lenses near their contact (Chidester et al., 1967; Ratcliffe et al., 2011; Zen et al., 1983), consistent with the interpretation that this contact is a major suture zone similar to the Birchy Complex in Newfoundland (van Staal et al., 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 et al., 1984). Continuing north across the Canadian border, this contact is marked by the Mont-Orford, Lac-Brompton, Asbestos, and Thetford-Mines ophiolites (Tremblay et al., 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 et al., 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).

Cobble Mountain Formation- 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 et al., 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 et al., 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 quartz, feldspar schist, but the lithology is variable.

The Albee Formation outcrop belt is located in northeastern Vermont (Doll et al., 1961; Ratcliffe et al., 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 pinstripe texture, similar to the Moretown Formation. Correlative rocks occur in adjacent New Hampshire (Lyons et al., 1997), where Moench et al. (1995) mapped them as Dead River Formation, following the convention of Osberg et al. (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 ± 7.8 Ma intrusive tonalitic sill (U-Pb zircon SHRIMP age) east of West Bath, New Hampshire (Rankin et al., 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 et al., 1983). Tucker and Robinson (1990) reported a TIMS upper intercept age of 613 ± 3 Ma, which they interpreted as the eruption age, and a lower intercept age of 289 ± 4 Ma, which they attributed to Alleghenian metamorphism. The Neoproterozoic age of the Dry Hill Gneiss suggests a Gondwanan affinity (Hodgkins, 1985). Aleinikoff et al. (1979), and Wintsch et al. (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 et al. (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

The Hawley Formation is exposed east of and structurally above the Moretown Formation. Equivalent units in Vermont include the Barnard Volcanic, Whetstone Hill, and Cram Hill Members of the Missisquoi Formation of Doll et al., 1961. The Hawley Formation in Massachusetts contains diverse rocks types studied by Jon Kim for his doctoral dissertation. 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, respectively. 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, as suggested by the geochemistry of the Charlemont Mafic Intrusive Suite.

Macdonald et al. (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 et al. (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 et al., 2014).

The Collinsville Formation of the Shelburne Falls Arc- 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 et al., 1983; Rodgers, 1985), which are composed of 475 to 470 Ma arc-related bimodal mafic and felsic plutonic rocks (Karabinos et al., 1998). Karabinos et al. (1998) also dated samples of the Barnard Volcanic Member of the Missisquoi Formation (of Doll et al., 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 et al., 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 et al. (1998) that formed on the Moretown terrane (Macdonald et al., 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.

Arc Rocks in Southwestern Connecticut- 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 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.

The Bronson Hill Arc- East of the Connecticut Valley trough and the Mesozoic Basin, Ordovician meta-igneous rocks are also preserved in structural domes (Thompson et al., 1968; Hibbard et al., 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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (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 et al. (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 et al., 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 et al., 2014), was unknown. Aleinikoff et al. (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 et al., 2016), and Newfoundland (van Staal et al., 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 in Karabinos et al. (2017) fundamental questions remain concerning terrane affinity, and the timing of collision of terranes with the Laurentian margin, and continuity of terranes and boundaries between the New England and Canadian Appalachians.

METHODS

Siliciclastic units and igneous rocks were sampled for U-Pb zircon geochronological studies. 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). The detailed methods used for LA-ICPMS and CA-TIMS dating of zircon can be found in Karabinos et al. (2017).

GEOCHRONOLOGY RESULTS

Detailed descriptions of individual samples can be found in the Appendix following the Road Log.

INTERPRETATIONS OF GEOCHRONOLOGY

Dalton Formation, Cheshire Quartzite, and Rowe Schist- The detrital zircon age spectra found in the Dalton Formation samples (fig. 3) indicate that grains derived locally from the underlying 960 Ma 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 et al., 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 (Aleinikoff et al., 2011; Karabinos et al., 2008; Karabinos and Aleinikoff, 1990; McLelland et al., 2010).

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 et al., 1989), older Mesoproterozoic grains similar in age to ca. 1350 Ma Elzevirian trondhjemitic gneisses in the Green Mountain massif (Ratcliffe et al., 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 and the immaturity of the sedimentary protolith suggest 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), as expected for a mature quartzite. 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 et al., 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 et al., 2009). Macdonald et al. (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 et al., 2011) found in outcrops that Macdonald et al. (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 1300-1400 Ma, consistent with an Amazonian (Strachan et al., 2007) or West African (Bradley et al., 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.

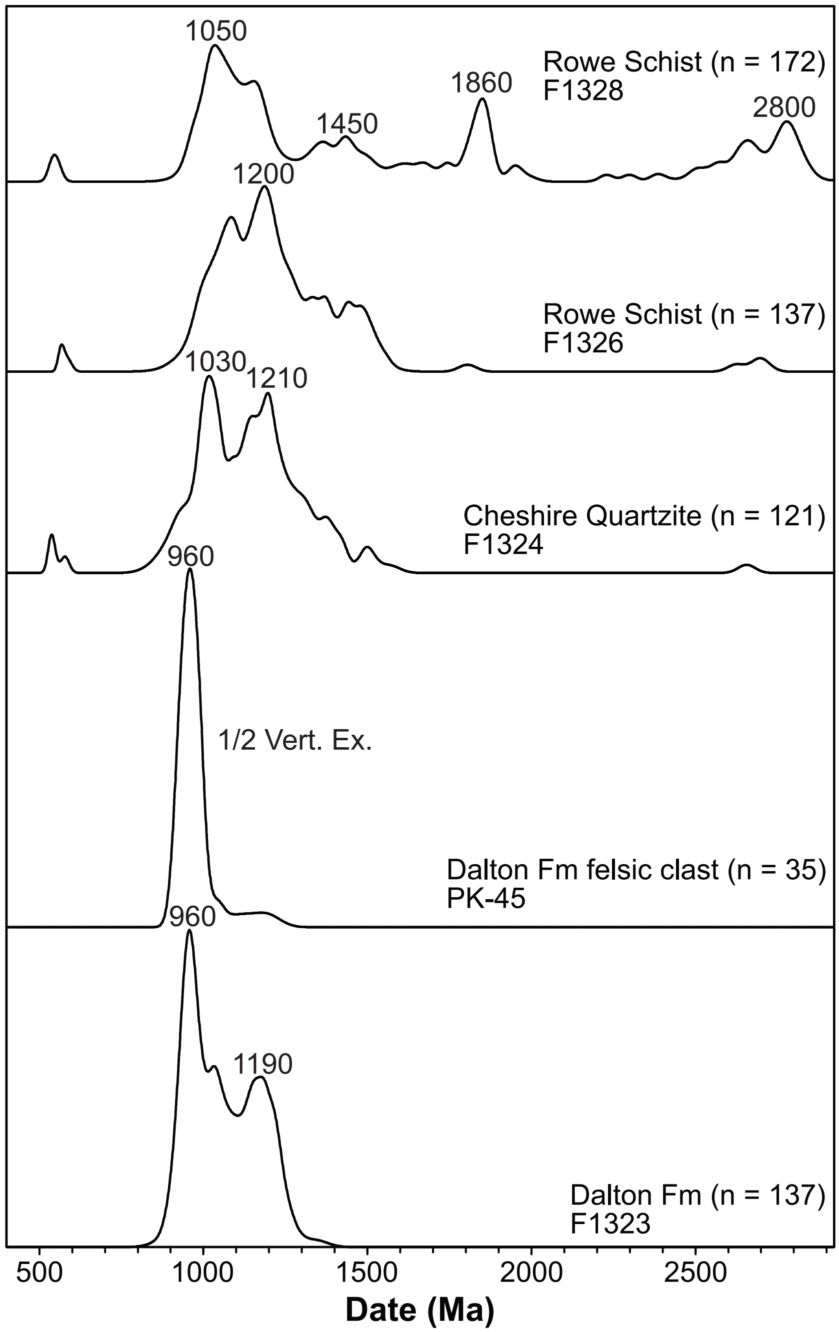

Fig. 3. Detrital zircon normalized probability density plots of samples from Laurentian margin deposits. Locations are shown in figure 1C.

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 et al., 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 et al. (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.

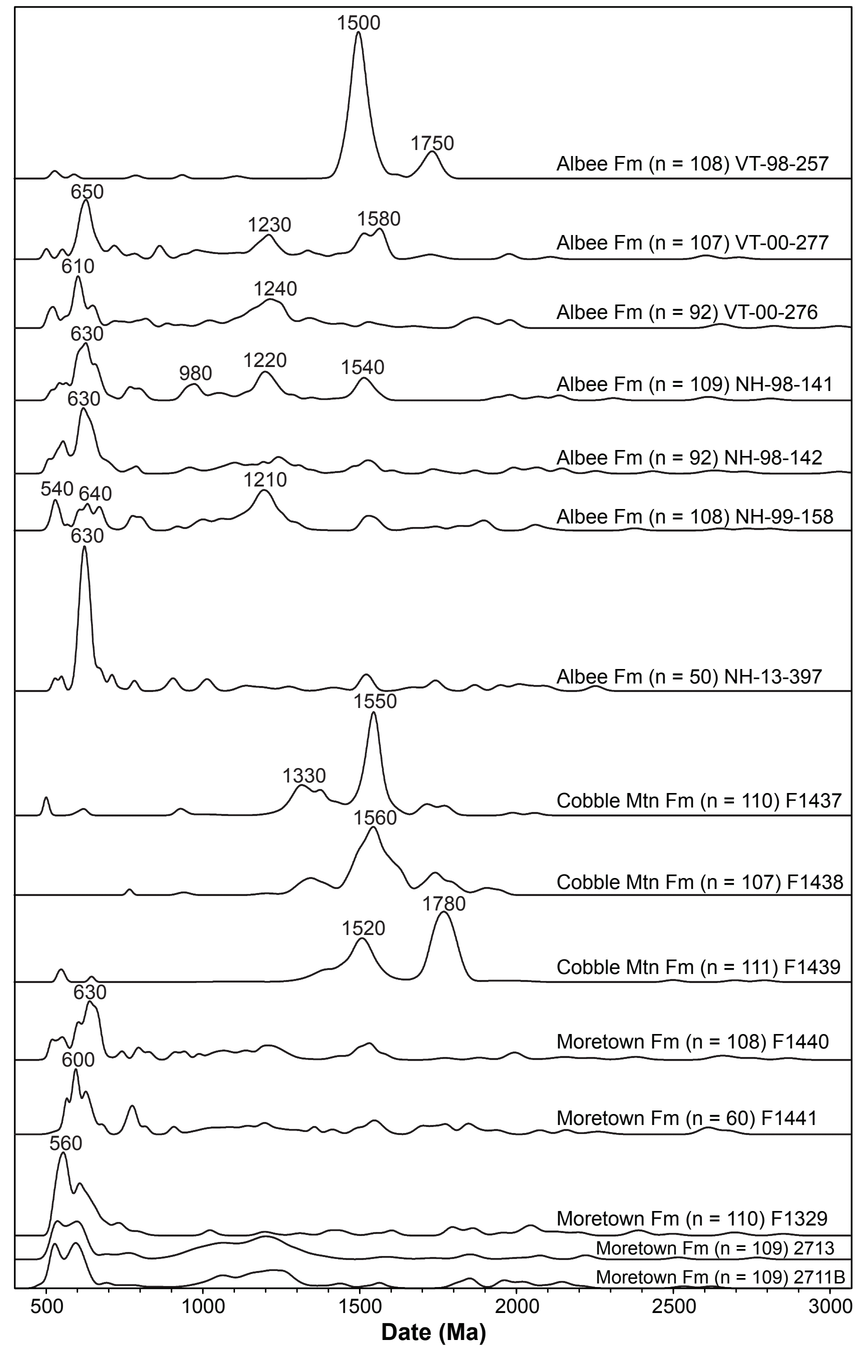

Fig. 4. Detrital zircon normalized probability density plots of samples interpreted to come from units belonging to the Gondwanan-derived Moretown terrane. Locations are shown in figure 1C.

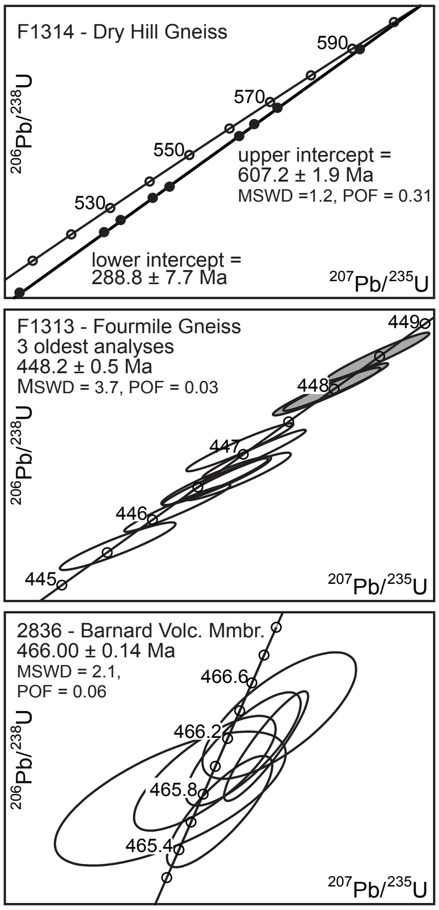

Fig. 5. Concordia plots from single grains and fragments of zircon analyzed by chemical abrasion-thermal ionization mass spectrometry. Locations are shown in figure 1D.

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 et al. (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 et al., 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 et al. (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 et al., 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 et al., 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. A mixed Laurentian-Gondwanan source of detrital zircons in the Partridge Formation is consistent with Bronson Hill magmatism on the eastern trailing edge of the Moretown terrane, but not consistent with magmatism on the western leading edge of Ganderia during its transit through the Iapetus ocean before its Early Silurian collision with Laurentia as proposed by Hibbard et al. (2006).

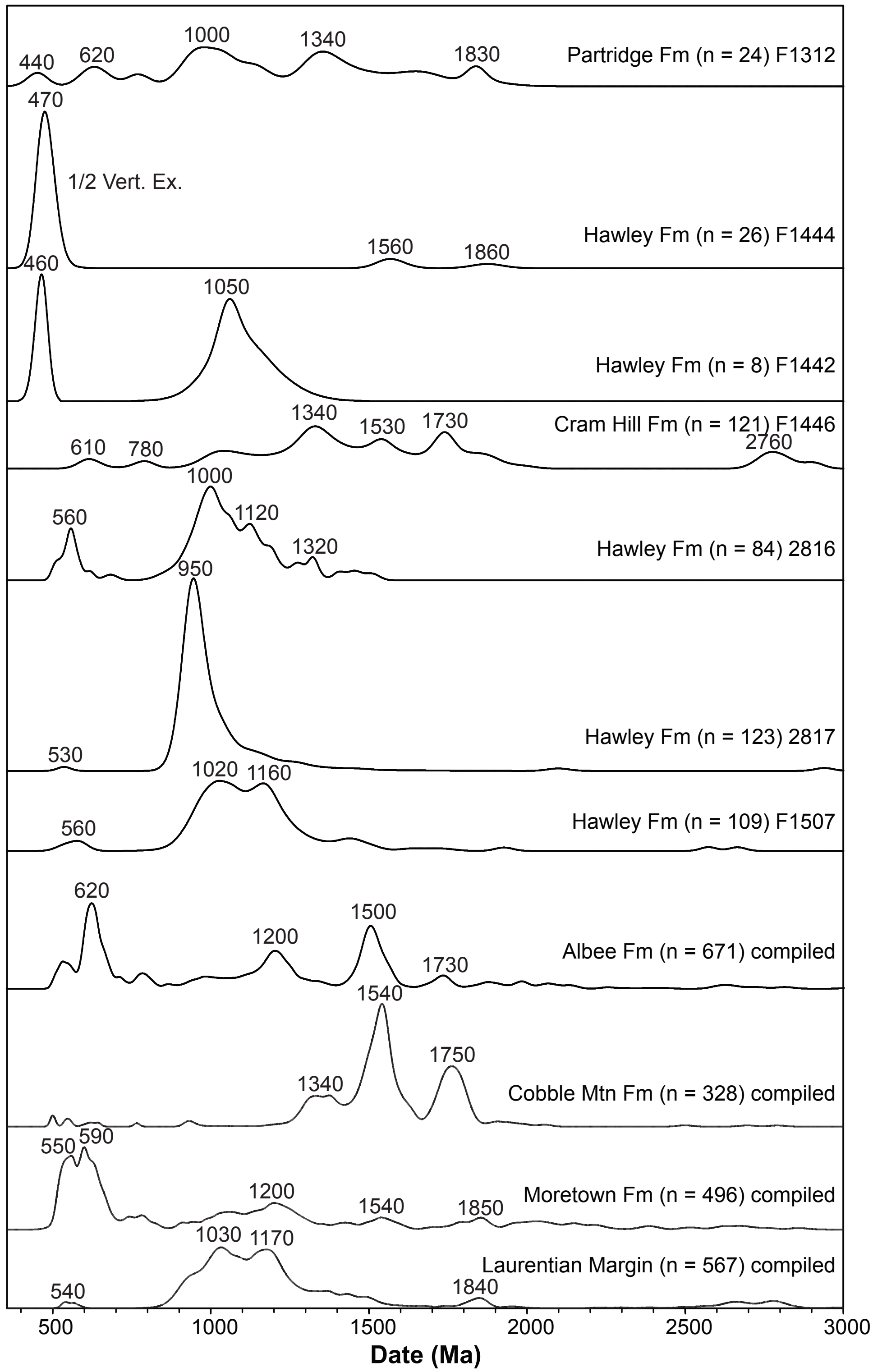

Fig. 6. Detrital zircon normalized probability density plots of samples interpreted as having a mixed Laurentian and Gondwanan provenance. Locations are shown in figure 1C.

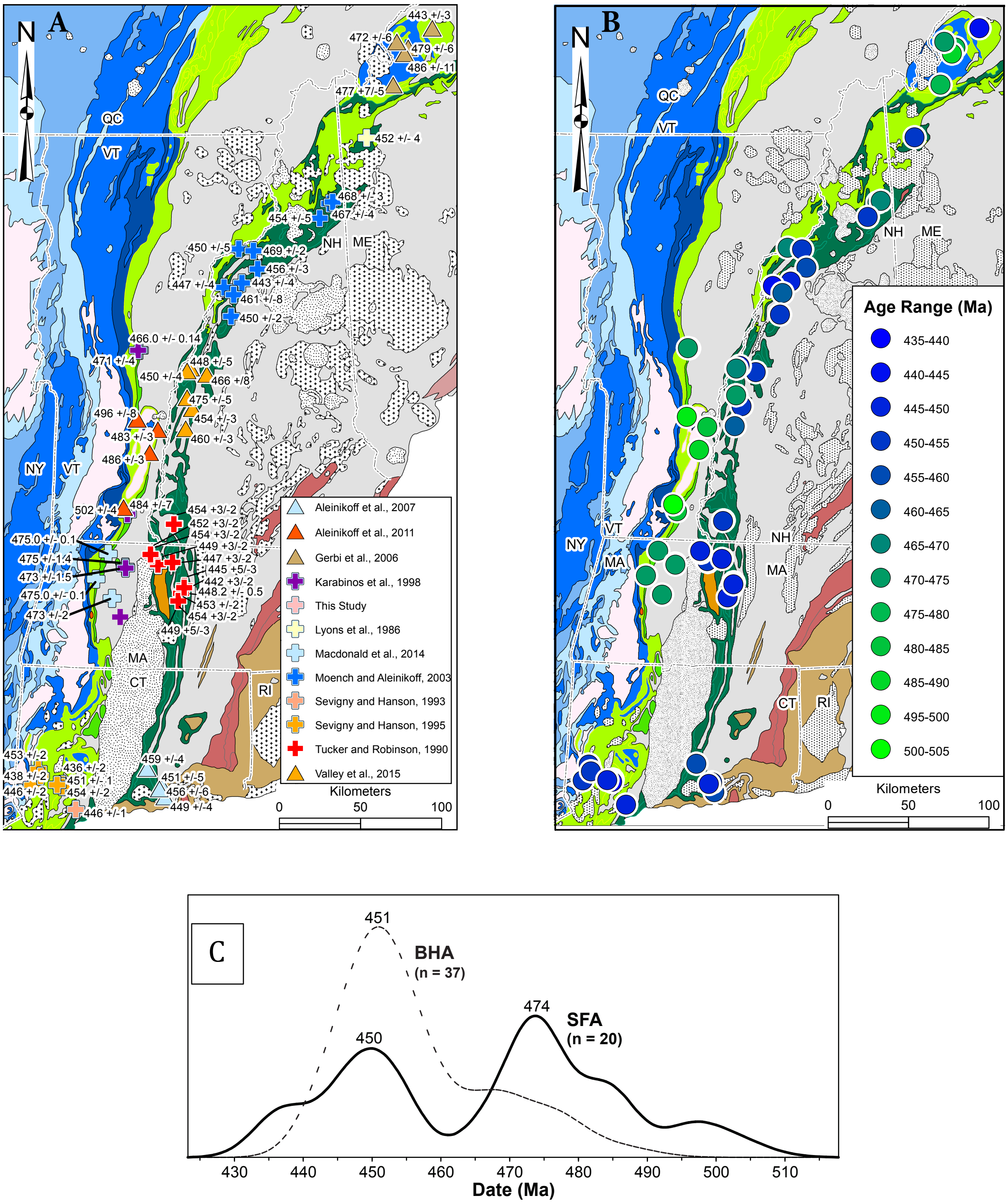

Fig. 7. (A) Tectonic map of New England showing the locations of dated rocks in the Shelburne Falls and Bronson Hill arcs. Triangles are SHRIMP U-Pb zircon ages and pluses are TIMS U-Pb zircon ages. References give data sources. Ages are in Ma. Units use the same colors and patterns as shown in figure 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).

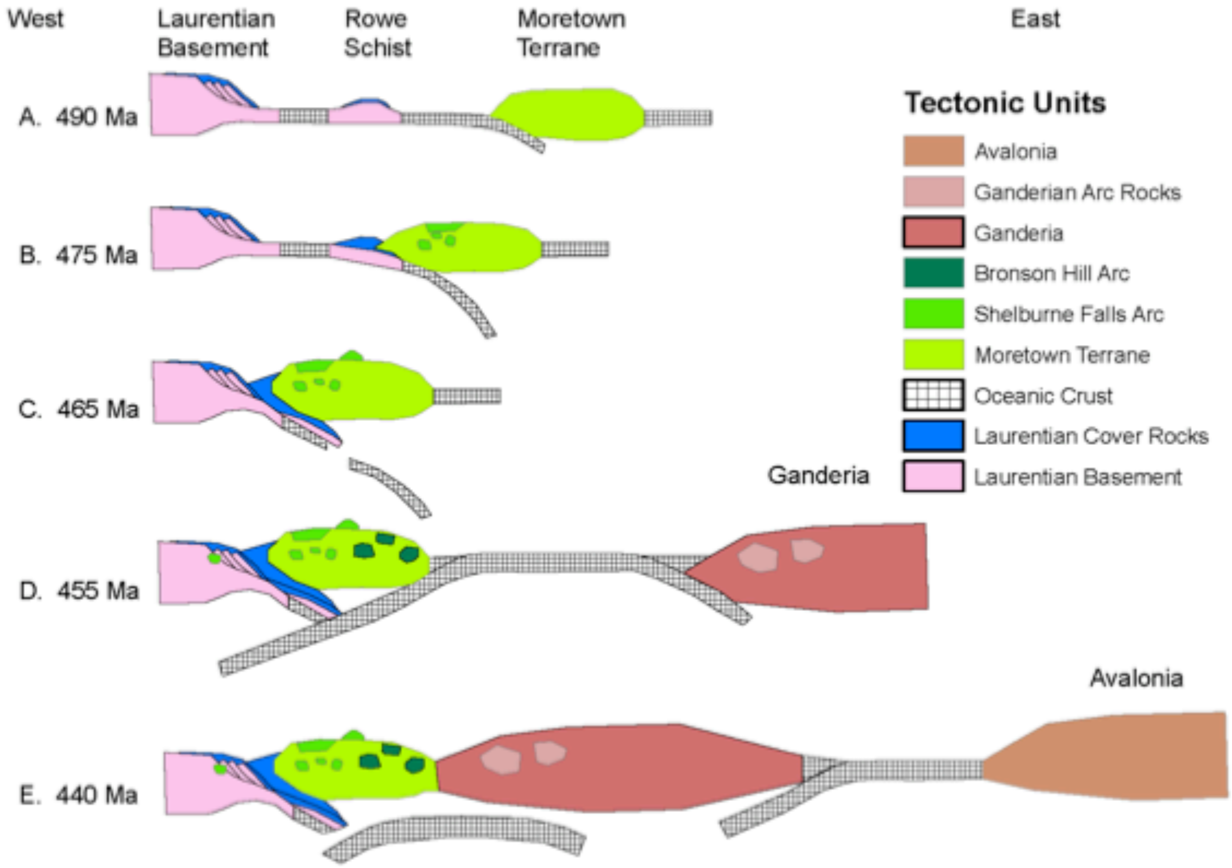

Fig. 8. Schematic cross-sections showing the early Paleozoic tectonic evolution of the New England Appalachians.

DISCUSSSION

The Suture between Laurentia and Gondwanan-derived Terranes

Macdonald et al. (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 et al., 2009). Lenses of amphibolite and altered ultramafic rocks are especially common near the Rowe Schist-Moretown Formation contact (Chidester et al., 1967; Zen, 1983; Ratcliffe et al. 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 et al. (1984). The 505 to 473 Ma $^{40}Ar/^{39}Ar$ metamorphic dates from amphibolites near the suture zone (Laird et al., 1984; Castonguay et al., 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 (Tremblay and

Pinet, 2016; Castonguay et al., 2012; Laird et al., 1984; Whitehead et al., 1996) 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 an Early Ordovician subduction zone had dipped westward under the Laurentian margin.

A critical problem that requires further investigation is that there is no record of Early Ordovician deformation, foreland basin deposits, or air-fall tephras on the Laurentian carbonate platform to the west. As discussed in Macdonald et al. (2017), unconformities within the Early Ordovician carbonate sequence may reflect tectonic activity outboard to the east, but was not dragged down into a subduction zone during this early phase of the Taconic orogeny. Thus, Karabinos et al. (2017) suggested that the collision occurred outboard of the Laurentian passive margin, perhaps east of an intervening Taconic Seaway (fig. 8). It is important to keep in mind that the current thrust geometry and close proximity of the carbonate platform sequence in the footwall and the Taconic thrust sheets and basement massifs in the hanging wall is the likely the result of post-Taconic, Salinic and/or Acadian thrusting (Karabinos et al., 2008; Webb et al., 2018).

Zircon data from the Hawley Formation, which is an integral component of the Shelburne Falls arc, suggest that the Moretown terrane and its active arc were close enough to Laurentia by 475 Ma to receive detritus from the Grenville orogen. 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, 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.

Extent of the Moretown Terrane

Macdonald et al. (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 et al. (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 et al. (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 ± 7.8 Ma age of an intrusive tonalite (Rankin et al., 2013), similar to the Cambrian age constraint placed on the Moretown Formation by felsic intrusive rocks (Aleinikoff et al., 2011; Macdonald et al., 2014).

Both the Moretown and Albee Formations are likely Cambrian in age (Macdonald et al., 2014, Rankin et al., 2013). 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 et al. (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 et al. (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 et al. (2014) demonstrated that the Shelburne Falls and Bronson Hill arcs formed on Gondwanan-derived crust, the Moretown terrane. Hibbard et al. (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 et al., 2007; Karabinos, 2008; Dorais et al., 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 et al. (1999) and Valley et al. (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 et al., 1998, 1999; Moench and Aleinikoff, 2003; Macdonald et al., 2014).

One sample of the Partridge Formation in Massachusetts (figs. 1C, 6) with a limited number of zircon grains (n = 24) contains some Ordovician grains, and appears to have mixed Laurentian and Gondwanan sources. Merschat et al. (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 et al., 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 to 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 et al., 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 et al. (2006) showed the boundary between peri-Laurentian and peri-Gondwanan terranes, the Red Indian Line of Williams et al. (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 et al. (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 et al. (1998) and Macdonald et al. (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 et al., 2006, Dorais et al., 2012; van Staal et al., 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 et al. (2009) and van Staal and Barr (2012), and blurs the distinction between the Taconic and Salinic orogenies. Alternatively, these terranes were not continuous ribbon continents and reflect the collision of two distinct microcontinents.

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 470 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 initiation of west-dipping subduction (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 et al., 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 et al., 1999).

CONCLUSIONS

1. 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.

2. 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.

3. By 475 Ma the Moretown terrane and the Shelburne Falls arc were proximal to Laurentia; meta-sediments in the Hawley Formation, part of the Shelburne Falls arc, were receiving detritus from Laurentia. Collision between the Moretown terrane and distal elements of Laurentia, represented by the Rowe Schist was either in progress or about to begin. This is consistent with numerous $^{40}Ar/^{39}Ar$ cooling ages between 471 and 460

Ma from rocks in the Laurentian rift-drift succession and the Rowe Schist that record cooling from metamorphic temperatures (Tremblay and Pinet, 2016; Castonguay et al., 2012; Laird et al., 1984; Whitehead et al., 1996) after collision of Laurentia and the Moretown terrane.

4. 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).

5. 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.

6. 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.

7. 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.

8. 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.

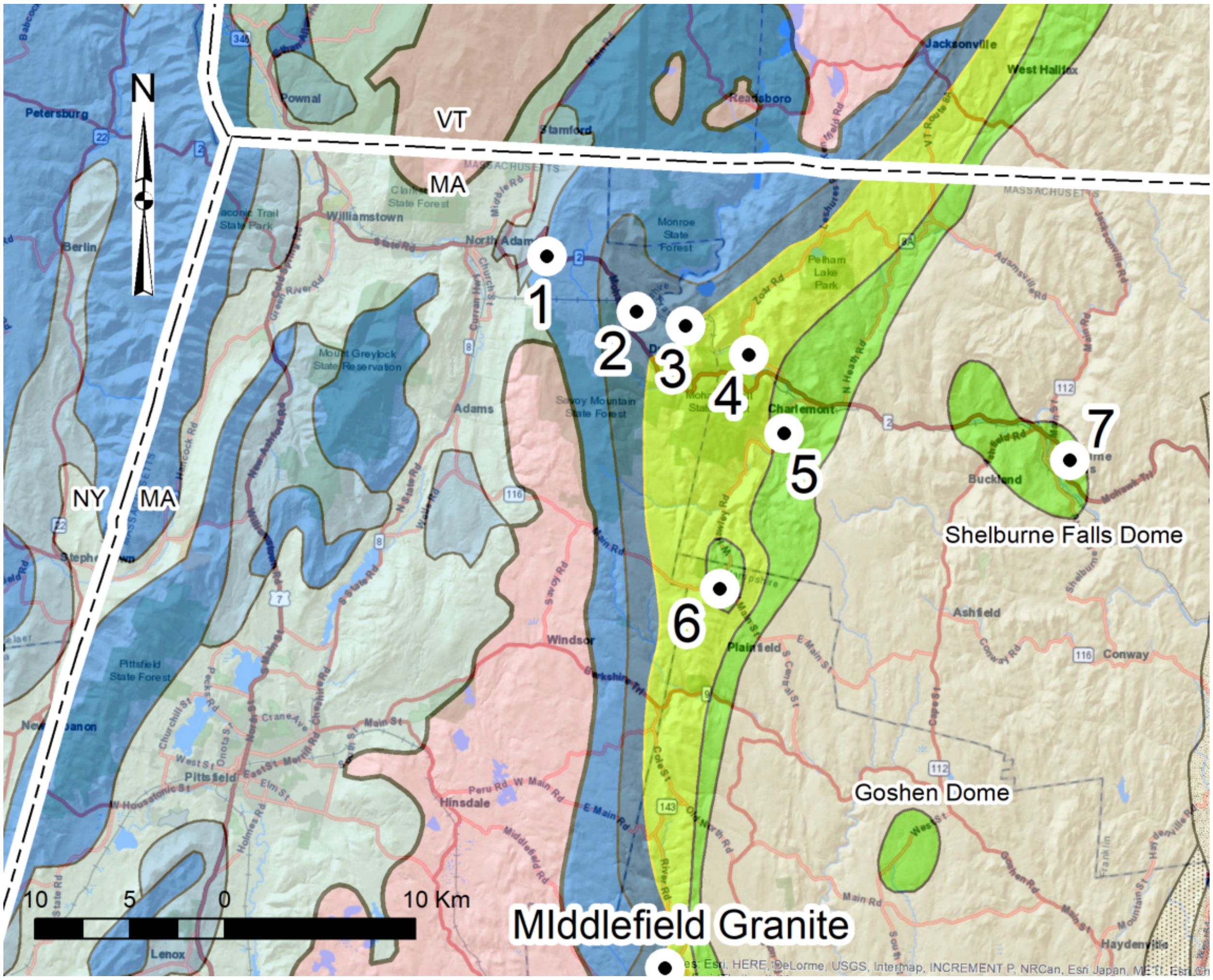

Figure 9. Index map showing field trip stops. See Fig. 1 for legend.

ROAD LOG

Meet on Sunday, October 14, 2018. 9:00 am at the old Wigwam and Western Summit Gift Shop (now closed) on Route 2 east of downtown North Adams and 0.8 miles uphill from the Golden Eagle Restaurant at Hairpin Turn. There is extra parking 100 m east at the trailhead for the Hoosac Range trail. The view to the west includes, from south to north, Mount Greylock, the Taconic Crest, and the southern end of the Green Mountains. Note that it is about two hours by car from Lake George to North Adams.

Miles		Directions
0.0	0.0	The Wigwam and Eastern Summit Gift Shop.

Stop 1- View to west and Hoosac Schist. The gift shop has been closed for a while, but the platform next to it still provides a nice view of Mount Greylock (south), the Taconic Crest (distant ridge), and the southern termination of the Green Mountain massif (north). Across the road from the gift shop is an outcrop of Neoproterozoic to Cambrian Hoosac Schist. It is very similar lithologically to the Greylock Schist on Greylock and the Nassau Formation on the Taconic Crest. They were all deposited as silty mudstones on the continental slope and rise of the Laurentian margin following rifting of Rodinia. Metamorphic grade decreases from our location on Hoosac Summit to the west. Here the Hoosac Schist is a quartz, albite-porphyroblast, muscovite, biotite, garnet schist with lots of quartz veins. The Nassau Formation on the Taconic crest in the distance is a fine-grained phyllite; the Greylock Schist is at an intermediate grade of metamorphism. Small relict garnet crystals can be found in albite porphyroblasts on the eastern most ridges of Mount Greylock. The southern end of the Green Mountain massif is a south-plunging anticline cored by Mesoproterozoic basement unconformably overlain by Neoproterozoic to Cambrian Dalton Formation and Cambrian Cheshire Quartzite. The east-west valley that connects Williamstown and North Adams between the Green Mountains and Mount Greylock must contain a lateral thrust ramp with many kilometers of structural relief because the Taconic sequence rocks of Mount Greylock must have formerly covered the Green Mountains before erosion stripped them away.

Proceed east on Rt. 2.

3.1 3.1 Turn left on Whitcomb Hill Road.

3.3 0.2 Bear right to stay on Whitcomb Hill Road.

4.1 0.8 Outcrop of Rowe Schist on right.

4.3 0.2 Outcrop of Rowe Schist on right.

4.4 0.1 Pull over to right onto shoulder.

Stop 2- Rowe Schist. There is abundant outcrop of Rowe Schist all along Whitcomb Hill Road. This is the best one and it contains a prominent contact between graphitic and non-graphitic schist near the bend in the road. Both contain the same mineral assemblage except for the greater graphite and sulfide content in the rusty-weathering rocks. The Rowe Schist is characterized by alternating graphitic and non-graphitic layers. The graphitic variety tends to be more concentrated in the structurally upper part of the unit close to the contact with the Moretown Formation and near the abundant lens of mafic and ultramafic rocks. The Rowe Schist is a typical pelitic schist with quartz, plagioclase, muscovite, biotite, and garnet. Locally it is more aluminous and contains paragonite (Na-white mica) instead of albit and chloritoid instead of biotite. It also contains a surprisingly large amount of quartz for a sediment that was presumably deposited on the distal Laurentian margin; the quartz-rich layers are best observed on faces perpendicular to the foliation. The two samples of Rowe Schist used for our detrital zircon study came from along this road (Figs. 1C and 3). Both zircon populations are typical of Laurentian-derived sediment with prominent peaks between 1.0 and 1.2 Ga corresponding to the Grenville of North America, and minor Neoproterzoic peaks at approximately 550 Ma, reflecting rift-related magmatism from the breakup of Rodinia.
Note that the boundary between the Rowe Schist and the Moretown Formation is a first-order geophysical feature- the depth to MOHO, as determined by P to S wave conversions, abruptly decreases by 10 to 15 km from west to east approximately below this contact in southern New England (Li et al., 2018).

Continue down Whitcomb Hill Road.

5.4 1.0 Dirt Road on right is Torrey Hill Road. This road leads to the Reed Brook Preserve managed by the Nature Conservancy. A long and winding trail leads uphill to a large ultramafic lens with rare plants. Some large boulders of ultramafic rock are visible in the road a short distance from the paved road.

5.5 0.1 Intersection with River Road. Turn right, south, onto River Road and park in one of the pull outs near the intersection. Walk back toward the intersection and walk across the rickety bridge across the Deerfield River.

After crossing the bridge, continue straight on foot along the dirt road. Go uphill and across the railroad tracks. Turn right and avoid the drive ways to follow Tunnel Road on the far side of the tracks through the woods to get to Stop 3 outcrops. Lots of outcrop of Rowe Schist in woods upslope to left along the road.

Stop 3- Rowe Schist, Mafic and Ultramafic lenses. See map in Figure 10 for details of route.
3A- Rowe Schist. The large outcrop of Rowe Schist next to the road contains abundant graphite and large garnet porphyroblasts. Note the steeply-dipping well-developed foliation and prominent down-dip lineation.
3B- Mafic Schist. The prominent outcrops on the left and right of dirt road are composed of mafic schist and gneiss, likely derived from oceanic crust caught up in the subduction zone between the Moretown terrane and the down-going Laurentian margin rocks.
3C- Highly altered Ultramafic Rocks of the Hoosac Tunnel Soapstone Quarry. The large blocks on the right side of the dirt road are waste from a soapstone quarry and talc mine. Soapstone was quarried between 1885 to 1895. In 1909 an adit was drilled in the quarry to mine talc. The operation did not last long. This fine-grained rock contains talc, actinolite, garnet, antigorite, and calcite. Ultramafic lenses are common in the Rowe Schist and Moretown Formation near their contact, and are probably derived from altered mantle peridotite.

Figure 10. Topographic map showing location of outcrops for Stop 3.

Return to vehicles and continue south on River Road.

6.9	1.4	Outcrop of Moretown Formation.
9.3	2.4	Bear right to stay on River Road.
10.1	0.8	Pull over to left.

Stop 4- Moretown Formation. This enormous outcrop is a convenient place to see the Moretown Formation in good light. Most of the light-colored rock is quartz, plagioclase, muscovite, biotite granofels with a distinctive pin stripe texture. There are some quartz-rich layers, one of which provided one of our many Moretown Formation detrital zircon samples. Dark layers are mafic dikes and sills with diverse geochemistry (Kim and Jacobi, 1996; Karabinos et al., 2017). The Moretown Formation is Cambrian in age (Macdonald et al., 2014; Karabinos et al., 2017). Based on geochemistry, the undated mafic intrusions most likely include Cambrian to Early Ordovician arc rocks, some of which may have formed during back-arc rifting, and Silurian or possibly Devonian rift-related rocks coeval with the initiation of the Connecticut Valley basin. Detrital zircons from the Moretown Formation from northern Vermont to southern Massachusetts show prominent 550 to 650 Ma peaks typical of Gondwanan-derived sediment (Figs. 1C and 4) Macdonald et al., 2014; Karabinos et al., 2017). There is a remarkable lack of Grenville peaks in the zircon populations.

Continue south on River Road.

11.1	1.0	Moretown Formation on left
11.3	0.2	Moretown Formation on left
11.6	0.3	Moretown Formation on left
11.8	0.2	Turn left, east, onto Rt. 2.
13.4	1.6	Turn right, south, onto Rt. 8A.
13.5	0.1	Turn right to stay on Rt. 8A south.
16.4	2.9	Turn left onto Pudding Hollow Road.
16.4	0.0	Turn left onto Middle Road.
16.5	0.1	Park on right before bridge. Proceed on foot along Middle Road across bridge and turn left on pleasant dirt road. Make your way down to the Chickley River to the left. Note that this is private property and that permission is needed to access this outcrop.

Stop 5- Hawley Formation. The mafic gneiss exposed here is one of several common rock types in the Hawley Formation. Jon Kim studied these rocks for his doctoral dissertation and Kim and Jacobi (1996) is an excellent account of the geochemistry of this diverse unit. Structures widely interpreted as pillow basalts are present is some parts of this long exposure. The Hawley Formation is part of the Shelburne Falls arc and its Ordovician age is tightly constrained by a TIMS date of 475 Ma on the intrusive Dell Metatrondhjemite and essentially coeval detrital zircons in metasediments (Fig. 6; Macdonald et al., 2014). At least some of the mafic rocks (Kim and Jacobi, 1996) and perhaps most, if not all, of the metasediments formed during an episode of back-arc rifting. An anoxic environment, consistent with the restricted circulation of a rift basin, is required to explain the highly graphitic schist present in the western and eastern exposures of the Hawley Formation. Notable sulfide and manganese deposits in the Hawley Formation are also consistent with intra-arc rifting/splitting.

Our tectonic model described above is strongly driven by the fact that the detrital zircon populations in the Hawley Formation samples indicate both Laurentian and Gondwanan sources. The Gondwanan source is easy to explain because the Shelburne Falls arc formed on the Moretown terrane. The Laurentian detrital zircons component indicates that by about 475 Ma, the Moretown terrane and the Shelburne Falls arc were close enough to Laurentia to receive detritus from the Grenville rocks so prominent along the Laurentian margin.

Return to vehicles and reverse direction back toward Rt. 8A.

16.6	0.1	Turn right onto Pudding Hollow Road.
16.6	0.0	Turn left onto Rt. 8A south.
22.3	5.7	Hallockville Pond. Lunch stop

Continue south on Rt. 8A

23.3	1.0	Turn right onto Rt. 116 North.
23.4	0.1	Pull over to left in bus turn around circle. Outcrop is on both sides of road but the best exposures are on the north side of Rt. 116.

Stop 6- Hallockville Pond Gneiss. The Hallockville Pond Gneiss is a 475 Ma tonalite (Karabinos and Williamson, 1994; Macdonald et al., 2014) that intruded the Moretown Formation. The intrusive contact is not exposed at this stop, but it is visible nearby on the small hill 0.5 km northwest of the intersection of Hallockville and King Corner Roads in Dubuque State Forest. The arc geochemistry of this pluton (Karabinos et al., 1998) together with the observation that it intruded the Moretown Formation, provides compelling evidence that the Shelburne Falls arc was constructed on the Moretown terrane. The Hallockville Pond Gneiss contains a well-developed foliation that was overprinted by a younger crenulation cleavage. The older fabric, and possibly both, formed during the Taconic orogeny. 20 km to the south the Middlefield Granite at Glendale Falls in Middlefield, MA, is a 447 Ma weakly-foliated granodiorite (Karabinos and Williamson, 1994; Macdonald et al., 2014) that intruded both the Rowe Schist and the Moretown Formation at their contact, but the pluton is not offset at this major terrane boundary. Thus, the suture zone formed before this 447 Ma intrusion. These observations suggest that the strong deformation fabric in the Hallockville Pond Gneiss formed during the Taconic orogeny, and that the Rowe Schist-Moretown Formation fault contact was not greatly modified during the Acadian orogeny.

Reverse direction, and drive easterly on Rt. 116 South.

23.8	0.4	Moretown Formation on left
32.9	9.1	Turn left onto Rt. 112 North and 116 South (?!!?).
34.3	1.4	Straight through intersection to stay on Rt. 112 North.
42.3	8.0	Outcrop of Collinsville Formation on right in arc of road.
42.4	0.1	Turn left onto Rt. 2 East.
42.5	0.1	Outcrop of Collinsville Formation on both sides of road. A sample from this outcrop gave a 475 $\pm$ 1.4 Ma TIMS date (Karabinos et al., 1998).
44.5	2.0	Trailhead for Mahican-Mohawk Trail, alternate way to Stop 7 for those with very low clearance vehicles.
45.0	0.5	Turn right on Wilcox Hollow Road. Dirt road can be rough after severe storms. Use alternate route and hike down Mahican-Mohawk trail if desired.
45.3	0.3	Park without blocking dirt roads. Continue down to power line. Look for small path on right that leads down to the Deerfield River. Long outcrop along the river continues upstream. Pay attention to rising water warnings; this outcrop is just below a hydroelectric dam.

Stop 7- Collinsville Formation in the Shelburne Falls dome. This accessible exposure of the Collinsville Formation includes both tonalite and mafic gneiss. It is great fun to examine and argue about the intrusive relationship between the felsic and mafic rocks. The rocks are strongly foliated, lineated, and folded. The Collinsville Formation makes up the cores of the Shelburne Falls, Goshen, Granville domes. Core rocks from both the Shelburne Falls and Goshen domes are approximately 475 Ma (Karabinos et al., 1998) and surrounded by much younger Devonian metasediments. The contact is not an unconformity, but rather a major extensional shear zone, tops to the south, similar to that described for the Chester dome (Karabinos et al., 2010). Another fascinating feature about this part of the western New England dome belt is the occurrence of potentially ultrahigh-pressure garnet bearing rocks from the Goshen dome just south of the Shelburne Falls dome (Peterman et al., 2016).

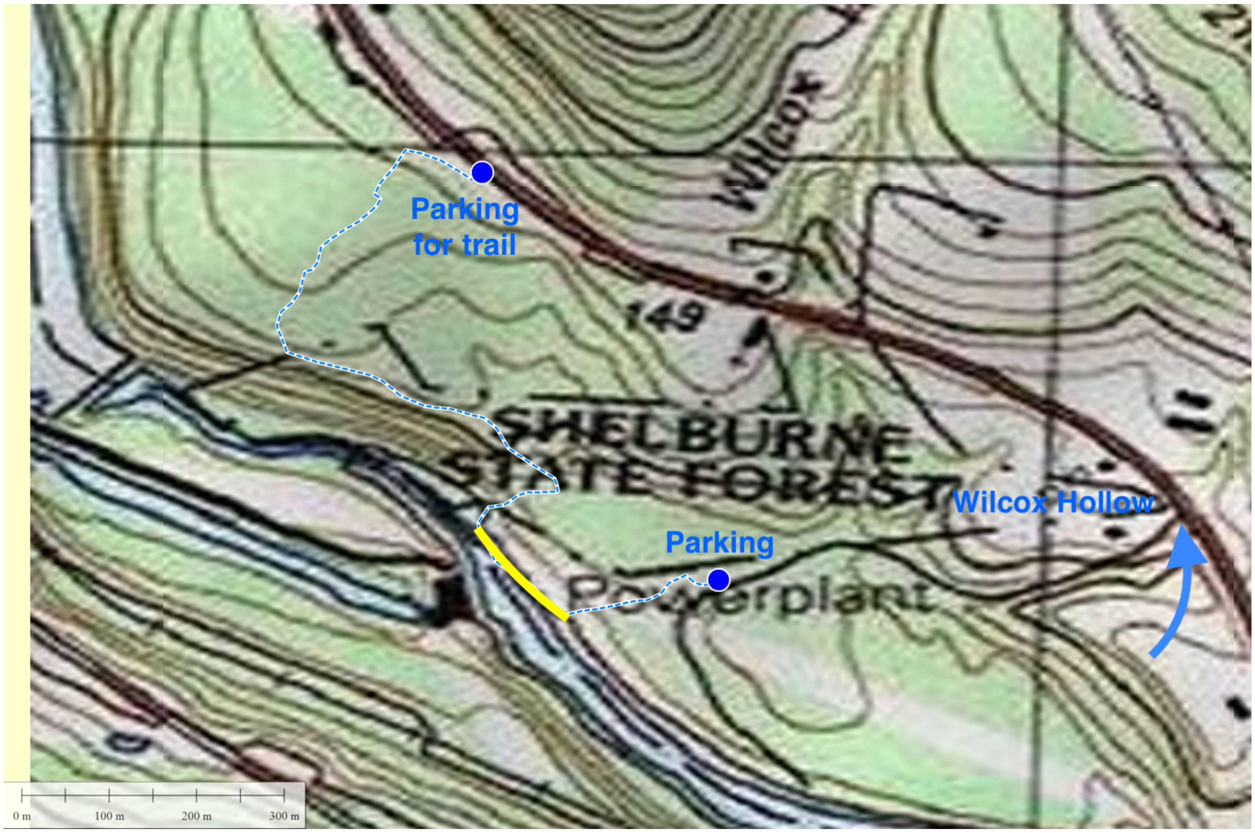

Figure 11. Topographic map showing dirt road to Wilcox Hollow (arrow) and alternative hiking trail down to Deerfield River and outcrop for Stop 7 (yellow line).

END OF TRIP

APPENDIX- 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 (Karabinos and Aleinikoff, 1990, Zen et al., 1983). 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 1200 Ma (fig. 3).

Exotic units

Moretown Formation.-- Macdonald et al. (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 ~640 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).

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 1.31 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) et al. 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 1.55 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 1.75 Ga and another large peak at 1.50 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 1.7 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 620 Ma and other peaks at 1200 Ma and between 1500 and 1600 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 600 Ma and other peaks at 520, 800 and 1200 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 620 Ma and other peaks at 800, 950, 1200 and 1500 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 1200 Ma and other peaks at 530 and 630 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 590-498 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 et al. (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 ~475 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, 1.55, and 1.74 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 between 0.9 and 1.2 Ga. 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 et al., 1961) or Barnard Gneiss (Ratcliffe et al., 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, 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 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, 1.4, and 1.8 Ga. Four <0.9 Ga grains are 452 ± 33, 615 ± 38, 654 ± 40, and 772 ± 36 Ma.

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