THE SHELBURNE FALLS ARC- LOST ARC OF THE TACONIC OROGENY

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ABSTRACT

The Ordovician Taconic orogeny in western New England was typically ascribed to a collision between the Laurentian margin and a magmatic arc identified as the Bronson Hill arc. However, in central Massachusetts and southern New Hampshire, rocks in the Bronson Hill arc are 454 to 442 Ma (Tucker and Robinson, 1990) and, therefore, younger than the onset of Taconic metamorphism in western New England and Quebec, which began by approximately 470 to 460 Ma (Laird and others, 1984; Castonguay and others, 1997). Karabinos and others (1998) used U-Pb zircon ages and geochemistry to document the presence of an older magmatic arc, the Shelburne Falls arc, that formed west of the Bronson Hill arc by approximately 485 to 470 Ma above an east-dipping subduction zone. The Taconic orogeny was the result of the collision between Laurentia and the Shelburne Falls arc beginning at approximately 470 Ma. The younger Bronson Hill arc formed above a west-dipping subduction zone that developed along the eastern edge of the newly accreted terrane after the Taconic orogeny. The Taconic orogeny ended when plate convergence between Laurentia and Iapetus was accommodated by the newly developed west-dipping subduction zone instead of by crustal shortening in the Taconian thrust belt.

INTRODUCTION

The Ordovician Taconic orogeny takes its name from the Taconic Ranges in western New England and eastern New York. Early to Middle Ordovician orogenic activity, now commonly correlated with the Taconic orogeny, was widespread and important in shaping the Appalachians and Caledonides (Pickering and Smith, 1995; MacNiocaill and others, 1997; van Staal and others, 1998). During the past century, the Taconic Ranges have figured prominently in many important debates about how mountains form, and this classic area was one of the first to be explained in terms of plate tectonic theory (Dewey, 1969; Bird and Dewey, 1970). Well-documented field observations in western New England quickly guided geologists to a commonly accepted plate tectonic model in which the Laurentian margin was drawn into an east-dipping subduction zone, eventually colliding with the Bronson Hill arc (e.g. Chappel, 1973; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). This plate tectonic geometry was widely accepted because it successfully accounted for the distribution of rocks interpreted to be remnants of the Laurentian passive margin, the arc complex, and the intervening oceanic lithosphere.

There are, however, several factors that make it difficult to reconstruct the Taconic orogeny in western New England. Not only were Taconic deformation and metamorphism intense but, to further complicate the situation, the eastern part of the Taconic thrust belt was strongly overprinted by the Devonian Acadian orogeny. Thus, accretionary wedge and arc-related rocks in western New England were metamorphosed during two different orogenies and are poorly preserved when compared to similar rocks in the Canadian Appalachians (Williams, 1978). Furthermore, the Bronson Hill arc is separated from the Taconic thrust belt by the Connecticut Valley trough and the Mesozoic Hartford basin (Fig. 1).

In other parts of the Appalachians and Caledonides, where arc terranes are better preserved, a more complete and complicated picture of Ordovician continent-arc interaction has emerged. Multiple arcs and changes in subduction polarity have been documented in Ireland (Dewey and Mange, 1999; Draut and Clift, 2001), Newfoundland (Cawood and others, 1995; MacNiocaill and others, 1997; van Staal and others, 1998), and New Brunswick (van Stall, 1994). These studies suggest that the classic model of a collision between Laurentia and the Bronson Hill arc may be too simple to explain the Ordovician tectonics of the New England Appalachians. In fact, doubt was already cast on this model by Tucker and Robinson (1990), who showed that rocks in the Bronson Hill arc formed after Taconic metamorphism of the Laurentian margin began.

This trip focuses on the eastern part of the Taconic thrust belt, especially on arc-related rocks that Karabinos and others (1998) called the Shelburne Falls arc. These rocks formed at approximately 485 to 470 Ma, and are old enough to have collided with Laurentia during the Taconic orogeny. We will show you exposures that

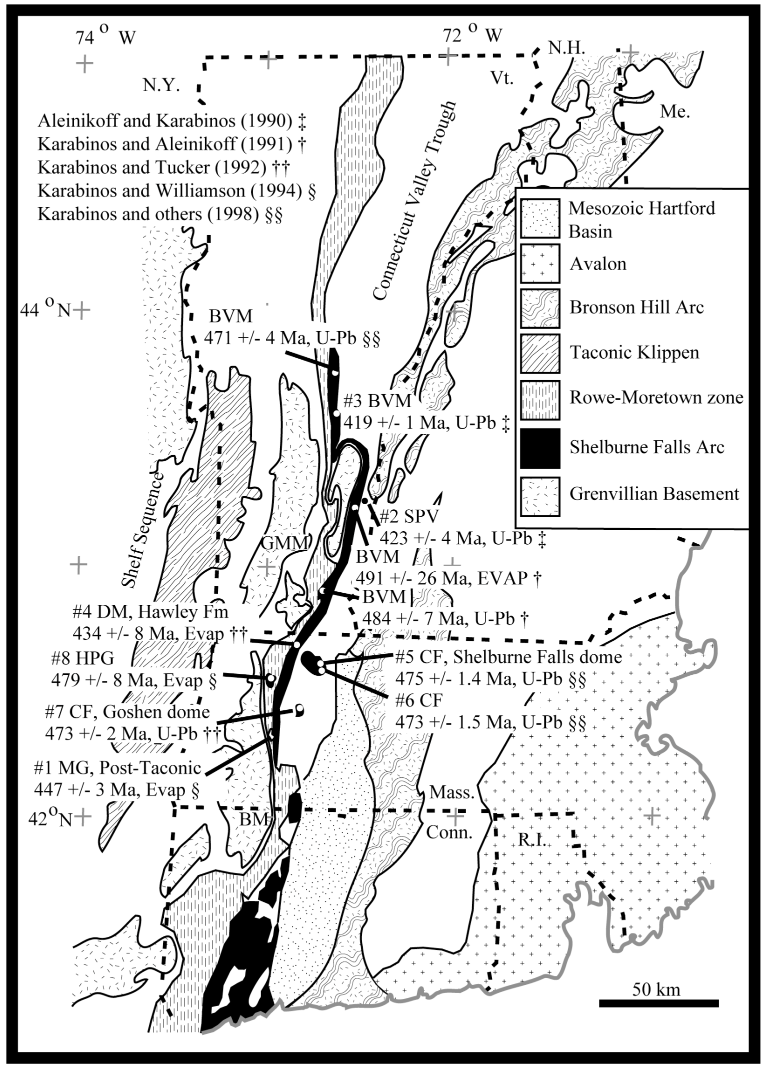

Figure 1. Tectonic map of New England and summary of U-Pb and single-grain evaporation (evap) zircon ages from the Shelburne Falls arc in western New England. Shelburne Falls arc rocks include the Barnard Volcanic Member (BVM), Collinsville Formation (CF), and Hallockville Pond Gneiss (HPG). The post-Taconic Middlefield Granite (MG) indicates that Taconic thrusting ended before ca. 447 +/- 3 Ma. Standing Pond Volcanics- SPV, Dell Metatrondhjemite- DM, Green Mountain massif- GMM, Berkshire massif- BM.

constrain the tectonic setting and timing of the Taconic orogeny, and try to explain why we believe that the Bronson Hill and Shelburne Falls arcs formed above different subduction zones.

GEOLOGIC SETTING

The Taconic klippen are composed of Late Proterozoic to Middle Ordovician slate and phyllite originally deposited as shale and siltstone on the continental slope and rise of the passive Laurentian margin (Fig. 1). The klippen structurally overlie a coeval sequence of clastic and carbonate rocks, which formed on the continental shelf of Laurentia. East of the klippen are the Berkshire and Green Mountain massifs, which are cored by Middle Proterozoic Grenvillian basement. The Rowe Formation in Massachusetts and the Ottauquechee and Stowe Formations in Vermont form the remains of an accretionary wedge of oceanic crust and sediments and the Moretown Formation contains forearc basin deposits (Fig. 1; Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). The Shelburne Falls arc (Fig. 1) is composed of the Barnard Volcanic Member of the Missisquoi Formation in Vermont and the Hawley Formation in Massachusetts. The Collinsville Formation and the Hallockville Pond Gneiss are also part of the Shelburne Falls arc, but they form isolated bodies. The Barnard Volcanic Member, as mapped by Doll and others (1961), is equivalent to the Hawley Formation and, despite its name, contains mafic and felsic plutonic and volcanic rocks intercalated with metasediments. West-directed Taconic thrust faults are common throughout this region.

The Connecticut Valley trough is composed of metasedimentary and metavolcanic rocks of Silurian to Early Devonian age that were deformed during the Acadian orogeny. $^{40}Ar/^{39}Ar$ cooling ages from western Massachusetts and southern Vermont indicate that the Acadian orogeny was underway in this part of New England by 390 to 380 Ma (Laird and others, 1984; Sutter and others, 1985, Hames and others, 1991). The end of intense deformation in western Massachusetts is bracketed by a 376 $\pm$ 4 Ma age (U-Pb zircon) of a highly deformed tonalitic sill (Karabinos and Tucker, 1992) and a 373 $\pm$ 3 Ma age ($^{207}Pb/^{206}Pb$ evaporation) for the post-kinematic Williamsburg Granodiorite (Karabinos and Williamson, 1994). South of Vermont, the Mesozoic Hartford rift basin separates the Bronson Hill arc from the Connecticut Valley trough.

BRIEF HISTORY OF EARLY TACONIC CONTROVERSIES

Stratigraphic vs. structural models for Taconic geology

The existence of large thrust faults with great displacements that carried deep water shales and siltstones of the Taconic sequence (now slates, phyllites, and schists) westward over sandstones and carbonate deposits of the continental shelf (now quartzites and marbles) was hotly contested for many years. Near the turn of the century, Dale (1899) believed that the Taconic sequence shales and siltstones were deposited in the deepest part of a basin and that they were surrounded by coeval carbonate rocks deposited along the shallow margins of the basin. This concept of a stratigraphic approach to explain the complex relationships between the deep water shales and siltstones and the shallow water carbonates was pursued and expanded by Lochman (1956). As mapping in the Taconic Ranges continued, more data led to increasing difficulties for the sedimentological explanation for the juxtaposition of the two sequences. Bucher (1957) of Columbia University developed a complex basin model which relied on alternating periods of shale and carbonate deposition and disconformities to produce the observed relationships.

A structural explanation for the complex relationship between the Taconic sequence rocks and the shelf carbonates was offered by Ruedemann (1909), who is credited with being the first to propose large scale thrusting. Keith (1912) and Prindle and Knopf (1932), greatly influenced by Alpine geology, were also early supporters of the "allochthon" model for the distribution of the carbonate sequence and the overlying slate and phyllite of the Taconic sequence.

In much of the Taconic region, paleontological fossil control is poor and exposure is less than ideal, so it is easy to understand why so much controversy could surround the nature of the contact between the Taconic sequence and the carbonate rocks. To complicate the issue, deep water shales *were* deposited directly on the carbonate bank during the Middle Ordovician (Zen, 1967 and references therein). Geologists now interpret these as flysch deposits eroded from advancing thrust sheets as the continental margin was drawn toward a subduction zone and the carbonate bank was drowned (e.g. Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). Eventually, detailed mapping and paleontological evidence overwhelmed the complex stratigraphic models, and thrust faulting became widely accepted in the Taconic region. Of the many geologists who contributed to our understanding of this region and its complex geology, E-an Zen of the U.S. Geological Survey stands out as one who worked tirelessly to map new areas and to compile work done throughout the region. His structural and stratigraphic compilations had a profound influence on the interpretation shown on the geologic map of Vermont (Doll and others, 1961) and the acceptance, by most geologists, of large-scale thrusting in the Taconic Ranges on the eve of the plate tectonics revolution (e.g. Zen, 1964, 1967).

"Hard-rock" vs. "soft-rock" emplacement and the sequence of thrusting in the Taconic allochthons

Zen helped convince most geologists that large-scale thrusts existed in the Taconic Ranges, but his work fueled other controversies. Zen was a powerful advocate of the "gravity slide" model for emplacement of the Taconic klippen. This view invoked uplift in the region of the Green Mountain and Berkshire massifs, subsidence in the carbonate bank to the west, and subsequent sliding of unlithified deep water deposits off the massifs and downslope to the west over shallow-water carbonates of equivalent age (Fig. 1). This model led to debates over "hard-rock" vs. "soft-rock" emplacement of the Taconic thrust sheets and whether the thrust surfaces dipped toward or away from the transport direction. This debate flourished in the context of the so-called mechanical paradox of large overthrusts (Hubbert and Rubey, 1959).

In some views of the gravity slide model, large blocks of carbonate rocks embedded in black shale were viewed as olistoliths, or large gravity-driven deposits (Rodgers, 1970). An opposing view presented by Rowley and Kidd (1981) and Bosworth and Vollmer (1981) is similar to one offered by Cushing and Ruedemann (1914) that the carbonate blocks are tectonic in origin. Of course, the debate over the tectonic vs. sedimentary origin of melange was not unique to the Taconics.

Another issue that was debated was the sequence of development of thrusts in the Taconic Ranges: are the oldest thrusts located in the west toward the foreland or in the east toward the hinterland? Again, this is an issue that was contested in thrust belts in many places. Zen (1967) argued that the oldest thrusts are located in the west and that the western-most thrust sheets travelled farther than structurally higher and eastern thrust sheets. This argument was largely based on the presence of carbonate slivers along thrust faults separating one package of Taconic sequence rocks from another. Zen (1967, 1972) reasoned that the only way these slivers could have obtained their present position is if rocks of the carbonate bank were exposed at the surface during emplacement of successively younger gravity slides. In other words, the Taconic klippen really were emplaced as klippen not as large thrust sheets later isolated by erosion.

Rowley and Kidd (1981) and Stanley and Ratcliffe (1985) both challenged the gravity slide model and proposed instead that thrusting of fully-lithified rocks in the Taconic Ranges resulted from collision of the passive continental margin of ancient North America with the Bronson Hill arc. Rowley and Kidd (1981) interpreted thrusting in the Taconic Ranges as being similar to foreland fold and thrust belts in which thrusts become progressively younger in the transport direction. Stanley and Ratcliffe (1985), however, were strongly influenced by Zen's interpretation of carbonate slivers along thrusts, and preserved Zen's model of thrusts becoming younger toward the hinterland. One line of evidence that they used was their interpretation that the western-most thrust sheets were emplaced before regional low-grade metamorphism whereas some of the eastern thrusts were active during metamorphism. They implicitly used metamorphism as a time datum to argue that western pre-metamorphic thrusts must be older than eastern syn-metamorphic thrusts. Karabinos (1988) suggested that the deformed Laurentian margin is a crustal-scale duplex that is separated from untransported continental margin rocks by a floor thrust and from rocks of the accretionary wedge by a roof thrust. Karabinos (1988) argued that the carbonate slivers do not provide solid evidence for the younging direction of thrusting and that metamorphism was likely time-transgressive and, therefore, not a reliable time datum.

THE CURRENT TACONIC CONTROVERSY

Which arc collided with Laurentia during the Taconic orogeny?

As described in the introduction, the Taconic orogeny in western New England has classically been attributed to a collision between the Laurentian continental margin and the Bronson Hill arc (Fig. 1). Typically, plate tectonic models portray Laurentian oceanic lithosphere being consumed in an east-dipping subduction zone beneath the Bronson Hill arc (Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). This plate tectonic geometry has been and continues to be very successful in explaining many observations in the orogen, including the pervasive west-directed thrusting in the belt, the distribution of locally preserved high-pressure metamorphism (Laird and others, 1984), the distribution of mafic and ultramafic rocks with oceanic affinity (Stanley and Ratcliffe, 1985; Kim and Jacobi, 1996), and the stratigraphy of the transition from continental shelf to foredeep (Bradley, 1989). The lack of subduction-related intrusives in Proterozoic to Middle Ordovician Laurentian margin rocks further supports this model and is evidence against an Andean-type orogeny, i.e., a west-dipping subduction zone under Laurentia.

Recently, however, geochronological studies in the New England Appalachians raised fundamental questions regarding this commonly-accepted tectonic model. Tucker and Robinson (1990) presented 12 high-precision U-Pb zircon ages ranging from 454 to 442 Ma from the Bronson Hill arc in central Massachusetts and southern New Hampshire. The problem is that the crystallization ages for this part of the Bronson Hill arc are younger than the ca. 470 to 465 Ma $^{40}Ar/^{39}Ar$ Taconic cooling ages for Laurentian margin rocks reported by Laird and others (1984) in Vermont, and by Sutter and others (1985) in Massachusetts. Tucker and Robinson (1990) offered two explantions for this age discrepancy: either the Bronson Hill arc was accreted to an already assembled "Taconia" or there was a significant time lag between subduction and magma generation. Drawing on their work in southern Quebec, Pinet and Tremblay (1995) suggested that the Taconic orogeny was the result of an Oman-type obduction instead of a continent-arc collision.

A solution to this problem that is consistent with the original tectonic model was presented by Karabinos and others (1998), who used geochemical and geochronological data to document the existence of Early Ordovician arc-related rocks in western Massachusetts and southern Vermont (Figs. 1 and 2). These rocks, which Karabinos and Tucker (1992) called the Shelburne Falls arc, formed between 485 and 470 Ma and are thus old enough to account for the Taconic orogeny using the popular east-dipping subduction zone model. Karabinos and others (1998) went on to propose that, following a reversal in subduction polarity, the younger Bronson Hill arc formed above a west-dipping subduction zone that developed along the eastern edge of the newly-accreted terrane at about the same time that the Taconic orogeny ended (Fig. 2). This proposal is consistent with fossil and radiometric evidence that constrains the end of the Taconic orogeny. Melange at the western edge of the thrust belt near Albany, New York, contains graptolites of the *C. spiniferous* zone. Bradley (1989) suggested that these fossils date the final movement of the Taconic thrust sheets. Using the time calibrations of Tucker and McKerrow (1995), this corresponds to about 452 ± 2 Ma, approximately the same time as the oldest arc magmatism in the Bronson Hill arc reported by Tucker and Robinson (1990). Another constraint on when the Taconic orogeny ended was presented by Karabinos and Williamson (1994), who used the $^{207}Pb/^{206}Pb$ evaporation method to obtain a 447 ± 3 Ma zircon age for the post-Taconic Middlefield Granite (Figs. 1, #1, and Fig. 3, STOP 4), located in the hinterland of the Taconic thrust belt.

Karabinos and others (1998) hypothesized that the formation of the new west-dipping subduction zone was directly linked to the end of the Taconic orogeny (Fig. 2) because plate convergence between Laurentia and Iapetus was accommodated by consuming oceanic lithosphere instead of by crustal shortening in the Taconic thrust belt. Thus, understanding how the Bronson Hill arc formed is a critical link to the larger question of how the Taconic orogeny ended.

Ratcliffe and others (1998) and Robinson and others (1998) criticized the model proposed by Karabinos and others (1998) and maintained that rocks in the Shelburne Falls and Bronson Hill arcs are part of the same long-lived arc that formed above a single east-dipping subduction zone. If these geologists are correct, the arc would have formed over an impressive sixty-million-year time interval, from 496 to 436 Ma. This interval is based on the combined age data from arc-related rocks in western New England presented by Sevigny and Hanson (1995), Ratcliffe and others (1997), and Karabinos and others (1998). One argument made by Ratcliffe and others (1998) was that spatial overlap of older and younger arc-related rocks in northern New Hampshire and Connecticut provides evidence against two separate episodes of arc magmatism. Another objection raised by Ratcliffe and others (1998) and Robinson and others (1998) was that the collision between Laurentia and the Bronson Hill arc occurred well after 470 Ma, during the interval 455 to 445 Ma, at approximately the same time that the Bronson Hill arc rocks formed. Because these two issues are critical to our alternative interpretation, we will discuss them in greater detail in the next two sections.

Spatial overlap of older and younger arc-related rocks

In Massachusetts, the intrusive core and mantling strata of the Bronson Hill magmatic arc (Tucker and Robinson, 1990) are separated from the Connecticut Valley trough by the Mesozoic Hartford basin (Fig. 1). Together the Connecticut Valley trough and the Hartford basin obscure the relationship between rocks in the Bronson Hill arc and the Shelburne Falls arc (Fig. 1). In the absence of age data, bimodal meta-igneous rocks and interlayered meta-sedimentary rocks of the Barnard Volcanic member in Vermont and the Hawley and Collinsville Formations in Massachusetts (constituents of the Shelburne Falls arc) were correlated with lithologically similar rocks in the Bronson Hill arc as shown on the state geologic maps of Vermont (Doll and others, 1961) and

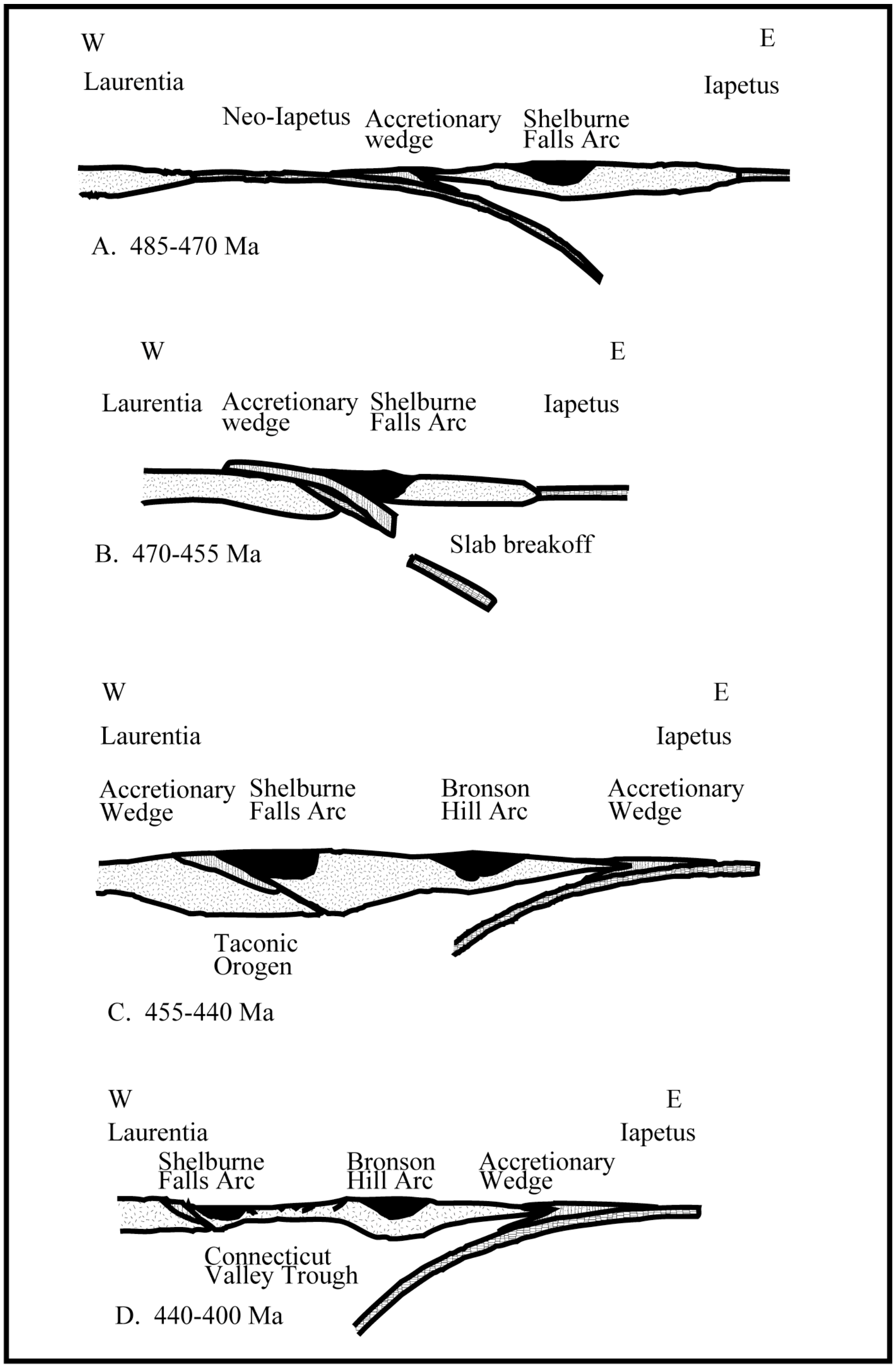

Figure 2. Idealized tectonic model showing the plate tectonic setting of the Laurentian margin from 485 to 400 Ma based on Karabinos and others (1998). A. 485 to 470 Ma- Shelburne Falls arc forms above east-dipping subduction zone, perhaps on a continental fragment rifted from Laurentia. B. 470 to 455 Ma- Crustal shortening during Taconic orogeny. Slab breakoff cuts off supply of magma to Shelburne Falls arc. C. 455 to 440 Ma- Bronson Hill arc magmas form above new west-dipping subduction zone. Taconic orogeny ends when convergence between Laurentia and Iapetus is taken up by subduction of oceanic lithosphere. Collapse of Taconic orogen and unroofing of metamorphic rocks cools rocks below Ar closure temperatures. D. 440 to 400 Ma- Back arc basin forms between Bronson Hill and Shelburne Falls arcs. Connecticut Valley trough and rift-related volcanics form.

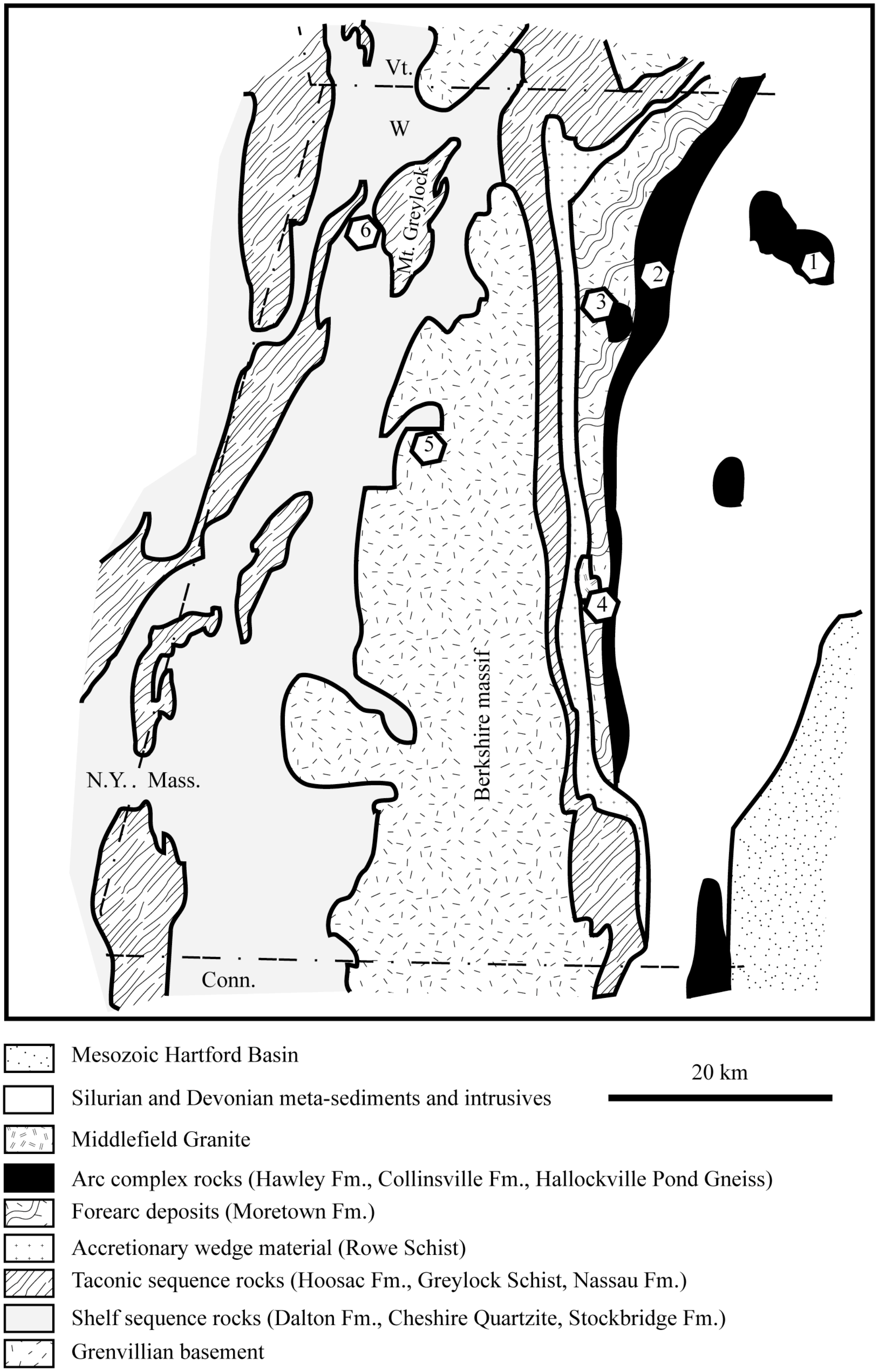

Figure 3. Simplified geologic map of western Massachusetts. Stop numbers shown. Based on Zen et al. (1983). W- Williamstown.

Massachusetts (Zen and others, 1983). Karabinos and others (1998) contrasted their age data from the Shelburne Falls arc with those of Tucker and Robinson (1990) directly across strike to the east from the Bronson Hill arc, and concluded that these geologically reasonable correlations based on lithology were, nonetheless, incorrect. There are, however, two regions to the north and south of the rocks dated by Tucker and Robinson (1990) and Karabinos and others (1998) where there appears to be spatial overlap of the older and younger arc-related rocks.

Aleinikoff and Moench (1992) and Moench and Aleinikoff (in press), working in the northern part of the Bronson Hill arc in New Hampshire, reported a U-Pb zircon age of 469 $\pm$ 1.5 Ma for the Joslin Turn pluton, which they interpreted to be a minimum age for the lower part of the Ammonoosuc Volcanics, as well as a 444 $\pm$ 4 Ma age for the upper part of the Ammonoosuc Volcanics. The close proximity of both older and younger arc-related rocks was interpreted by Ratcliffe and others (1998) as evidence for only one arc. However, Moench and Aleinikoff (in press) now argue that rocks from these two age groups are separated by an unconformity, suggest that the older rocks form a northern extension of the Shelburne Falls arc, and assign the younger rocks to the Quimby Formation of the Bronson Hill arc.

Karabinos and others (1998) showed the Shelburne Falls arc extending south of their study area into western Connecticut because major gneiss domes there are cored by the Collinsville Formation, the same unit they dated in the Shelburne Falls and Goshen domes (Fig. 1). Although the age of the Collinsville Formation is not well established in Connecticut (Craig Dietsch, personal communications), it appears to be older than Bronson Hill arc rocks (454 to 442 Ma) dated by Tucker and Robinson (1990) because it was deformed before it was intruded by the Brookfield plutonic series (453 $\pm$ 3 Ma) and the Newtown gneiss magmatic complex (446 $\pm$ 2 to 436 $\pm$ 2 Ma) dated by Sevigny and Hanson (1995). Thus, it seems reasonable to include the older rocks in the Connecticut gneiss domes in the Shelburne Falls arc despite the existence there of some plutons that are coeval with rocks in the Bronson Hill arc. The important point here is that intrusion of younger plutons into rocks of the Shelburne Falls arc does not preclude the existence of two arcs or the reversal in subduction polarity (Fig. 2) proposed by Karabinos and others (1998), and, in fact, should be expected.

^{40}Ar/^{39}Ar cooling ages and the beginning of the Taconic orogeny

One way to constrain the beginning of the collision between Laurentia and the Shelburne Falls arc is to date metamorphism of rocks from the passive continental margin. In northern Vermont, Laird and others (1984) reported hornblende ^{40}Ar/^{39}Ar cooling ages of 471 $\pm$ 7 Ma from the Pinney Hollow Formation and 471 $\pm$ 6 Ma from the Underhill Formation. Did these rocks cool after initial continent-arc impact or do they record subduction zone metamorphism of oceanic crust and sediments preceding collision? The first alternative seems more likely. Stanley and Ratcliffe (1985) showed thrust slices containing these formations below and west of the Whitcomb Summit thrust, which according to them is the major tectonic boundary that separates Laurentian margin rocks from oceanic rocks above and east of the fault zone. Furthermore, Castonguay and others (1997) reported muscovite ^{40}Ar/^{39}Ar cooling ages of 468 $\pm$ 2 Ma and 462 $\pm$ 2 Ma from rocks in southern Quebec which they identified as belonging to the Laurentian margin.

The situation is murkier in Massachusetts. Sutter and others (1985) reported an ^{40}Ar/^{39}Ar cooling age of 466 $\pm$ 5 Ma from Middle Proterozoic basement rocks of the Berkshire massif in southwestern Massachusetts and took this to be the best estimate for peak Taconic metamorphism. Hames and others (1991) obtained younger ^{40}Ar/^{39}Ar hornblende cooling ages from nearby Middle Proterozoic gneiss (446 $\pm$ 7 Ma) and schist of the Ordovician Walloomsac Formation (443 $\pm$ 3 Ma). They suggested that the 466 $\pm$ 5 Ma age reported by Sutter and others (1985) was anomalously old due to an unresolved component of Proterozoic argon. Their dismissal of the 466 $\pm$ 5 Ma cooling age was not based on a re-analysis of the data presented by Sutter and others (1985). Instead, their argument was that in New York and Vermont the Walloomsac Formation contains fossils that constrain its deposition to between 460 to 455 Ma, and that the metamorphism of the Laurentian margin must be younger than this age. This argument has merit but it does not take into account the time-transgressive nature of metamorphism in a collisional zone. The Walloomsac Formation has long been interpreted as a syn-orogenic flysch deposit (Zen, 1967), and it is likely that metamorphism began in the leading edge of the Laurentian margin to the east well before deposition of the metasediments dated by fossils in New York and western Vermont. Thrusting may have carried already hot thrust sheets over recently deposited sediments, thus providing an advective heat supply for metamorphosing the syn-orogenic flysch (Karabinos, 1988).

To sum up the available evidence, Laird and others (1984) and Castonguay and others (1997) suggested that Taconic metamorphism in the Laurentian margin of western New England started by approximately 470 Ma but

Hames and others (1991) and Ratcliffe and others (1998) argued that metamorphism of these rocks did not occur until 450 to 445 Ma. The distance between the Vermont/Quebec border and western Massachusetts is only about 300 km so it seems unlikely that the 20 to 25 million years difference in age of metamorphism is due to along-strike variations. The resolution of this controversy is important to test competing models for the origin of the Bronson Hill arc and to understand how the Taconic orogeny ended.

Clearly, Karabinos and others (1998) favored the older age data presented by Laird and others (1984) and Castonguay and others (1997) in their interpretation of when metamorphism of the Laurentian margin began. However, there are several reasons to be cautious when using any $^{40}Ar/^{39}Ar$ cooling ages to estimate the time of collision of the Laurentian margin with the arc terrane. By their very nature, $^{40}Ar/^{39}Ar$ cooling ages provide information about the retrograde history of rocks; therefore, they constrain the *end* of metamorphism rather than its beginning. The 450 to 445 Ma $^{40}Ar/^{39}Ar$ cooling ages reported by Hames and others (1991) show that rocks remained at metamorphic temperatures until this time, but they do not constrain when the continental margin entered the subduction zone. In this context, it is important to note that England and Thompson (1984) showed that it is possible for rocks to remain near peak temperatures for tens of millions of years before cooling below the closure temperature of the minerals to be dated.

A possible modern analog to the Taconic orogeny can be found in northern Taiwan where slab breakoff of the east-dipping Eurasian plate was closely followed by the development of a new subduction zone involving the north-dipping Philippine Sea plate (Teng and others, 2000). The flip in subduction polarity, which is currently migrating southward through Taiwan, is linked by Teng and others (2000) to rapid uplift, extensional collapse, and a dramatic reduction in crustal shortening. Using Taiwan as a modern analog, it seems plausible that the 450 to 440 Ma $^{40}Ar/^{39}Ar$ cooling ages, which are so common in western New England (Laird and others, 1984; Sutter and others, 1985; Hames and others, 1991), record rapid cooling of rocks during uplift and denudation following a reversal in subduction polarity rather than the time of continent-arc collision as suggested by Ratcliffe and others (1998).

Why is it important to date the continent-arc collision?

According to studies in the Pacific, arc magmatism ends within several million years after the supply of oceanic lithosphere is cut off by continent-arc collision (Audley-Charles and Harris, 1990; Teng, 1996; Teng and others, 2000; Sajona and others, 2000; Huang and others, 2000). Thus, accurately dating the collision of the Laurentian margin with the advancing arc terrane is critical to test competing tectonic models because the collision necessarily marks the end of the continuous supply of oceanic lithosphere to the subduction zone. Karabinos and others (1998) argued that if the Laurentian margin collided with an arc at approximately 470 Ma, it would be inconceivable that Bronson Hill arc magmas were generated fifteen to thirty million years later above the same east-dipping subduction zone because the supply of oceanic lithosphere would have been cut off. A much more plausible model for the origin of the Bronson Hill arc would be that it formed above a new west-dipping subduction zone east of the Laurentian margin. If it existed, this new west-dipping subduction zone would have accommodated convergence between Laurentia and Iapetus instead of crustal thickening in the Taconic orogen, thus bringing the orogeny to an end (Fig. 2).

TECTONIC IMPLICATIONS

One arc or two?

As noted already, there is widespread agreement that the Taconic orogeny in New England occurred when an arc overrode the Laurentian margin and that rocks included in the Shelburne Falls arc were involved in the collision (Fig. 1; Karabinos and others, 1998; Ratcliffe and others, 1998; Robinson and others, 1998). The current controversy is whether rocks in the Bronson Hill arc formed above the same east-dipping subduction zone as the Shelburne Falls arc (Ratcliffe and others , 1998; Robinson and others, 1998), or above a younger west-dipping subduction zone (Karabinos and others, 1998). How can we test these different models and why is it important to do so?

If collision began before 470 to 460 Ma, the younger rocks in the Bronson Hill arc could not have formed above the same east-dipping subduction zone as the Shelburne Falls arc because the supply of subducting oceanic lithosphere would have been cut off (Audley-Charles and Harris, 1990; Teng, 1996; Teng and others, 2000; Sajona and others, 2000; Huang and others, 2000). On the other hand, if collision did not begin until 455 Ma or later, then there is no need to invoke a second west-dipping subduction zone near the Laurentian margin to account for the

Bronson Hill arc, and the distinction between the Shelburne Falls and Bronson Hill arcs is probably incorrect. Perhaps the best way to estimate when collision began is to date the onset of prograde metamorphism in rocks of undisputed Laurentian affinity. Accurately dating the beginning of metamorphism would allow us to test competing models for the formation of the Bronson Hill arc. This information would also help to address the problem of how the Taconic orogeny ended. A reversal in subduction polarity, as proposed by Karabinos and others (1998), offers a mechanism for transferring plate convergence away from the orogen and is a straightforward way to explain the end of the Taconic orogeny. On the other hand, if the Shelburne Falls and Bronson Hill arcs are really one and the same arc and formed above a single east-dipping subduction zone, then we need a different mechanism for bringing crustal shortening to an end. Better constraints on when the Taconic orogeny began and the origin of arc terranes in western New England will also help to correlate the tectonic history in New England with events in the Canadian Appalachians and the Caledonides in Ireland, where multiple arcs have been identified (Van Staal, 1994, van Staal and others, 1998; Mac Niocaill, 1997; Dewey and Mange, 1999; Draut and Clift, 2001).

Connecticut Valley trough

Testing models for the formation of the Bronson Hill arc will also provide insight into the tectonic framework of the Laurentian margin (i.e. active vs. passive margin) from the Late Ordovician end of the Taconic orogeny through the Early Devonian Acadian orogeny. For example, Karabinos and others (1993) proposed that arc magmatism ended in the Bronson Hill belt at approximately 440 Ma, and was replaced with back-arc rifting in the region between the Shelburne Falls and Bronson Hill arcs for much of the Silurian and Early Devonian. There is geochemical and stratigraphic evidence for such a basin. The Standing Pond Volcanics erupted into a thick sequence of metasediments in the Connecticut Valley trough at approximately 423 $\pm$ 4 Ma (Fig. 1, #2, Aleinikoff and Karabinos, 1990). The back-arc geochemistry of some flows in the Standing Pond Volcanics (Hepburn, 1991) is indistinguishable from that of undated dikes commonly found in the Barnard Volcanic Member in southern Vermont (Stoll, 1994), and the Hawley Formation (Kim and Jacobi, 1996). Although these mafic dikes are undated, there are documented Silurian felsic intrusives within rocks of the Shelburne Falls arc. One is in the Barnard Volcanic Member (Fig. 1, #3, 419 $\pm$ 1 Ma; Aleinikoff and Karabinos, 1990) and the other, the Dell Metatrondhjemite, is in the Hawley Formation (Fig. 1, #4, 434 $\pm$ 8 Ma). It is important to note that some of the mafic dikes in the Hawley Formation in Massachusetts cross-cut the 434 $\pm$ 8 Ma Dell Metatrondhjemite (Kim and Jacobi, 1996). These age constraints suggest that the undated mafic dikes may be coeval with the Standing Pond Volcanics.

Many of the apparently conflicting stratigraphic and structural relationships in the Connecticut Valley trough are readily explained by syn-rifting deposition (Karabinos, 1998). According to this model, the carbonate-rich beds of the Waits River Formation were derived from the Cambrian and Ordovician carbonate bank to the west, whereas the quartz-rich Gile Mountain Formation sediments were derived from the Bronson Hill arc to the east. Syn-depositional faulting along the western border of the trough resulted in a complex contact such that the youngest sediments unconformably overlie Cambrian and Ordovician rocks whereas older basin sediments lie above a low-angle normal fault. Dikes found in the Barnard Volcanic Member west of the Connecticut Valley trough, that share a back-arc basin to extensional type geochemistry with some flows in the Standing Pond Volcanics, were probably feeder dikes to the volcanics, now displaced by low-angle normal faulting.

Acadian orogeny

The question of whether or not a west-dipping subduction zone existed along the Laurentian margin during the Silurian also bears directly on the plate tectonic setting of the Acadian orogeny. Many workers have favored a tectonic model for the Acadian orogeny in which Laurentia and Avalon collided as the intervening ocean basin disappeared into two subduction zones, one under each continent (e.g. McKerrow and Ziegler, 1971; Bradley, 1983). In contrast, other geologists believe that there was no subduction zone under Laurentia just prior to the Acadian orogeny (see Robnison and others (1998) for a thorough discussion of this problem). We believe that the Laurentian margin was active throughout the Silurian and early Devonian, until the Acadian orogeny.

ACKNOWLEDGEMENTS

Karabinos was supported by the donors of The Petroleum Research Fund, administered by the American Chemical Society and National Science Foundation Grant EAR-9117820.

We thank Jarda Dostal and the Nova Scotia Regional X-ray Fluorescence Centre, St. Mary’s University, Halifax, Nova Scotia, for analyses. We acknowledge support from the U.S. Department of Energy Reactor Sharing

Grant No. DE-FG02-95NE38121 and the Massachusetts Institute of Technology Research Reactor personnel for the irradiations used for the instrumental neutron activation analysis trace element analyses.

STOP LOCATIONS AND DESCRIPTIONS

Instead of a traditional road log, we have provided a description of how to reach each stop, including the U.S.G.S. quadrangle in which it is located, along with the UTM coordinates.

This trip will depart from UMASS Lot #62 at 8:00 am. A secondary meeting place will be the "Glacial Potholes" by Mole Hollow Candle Shop in downtown Shelburne Falls at approximately 8:30 am.

Stop 1, Collinsville Formation, plutonic rocks in the core of the Shelburne Falls dome.

This stop is located in the Shelburne Falls 7.5' Quadrangle, Massachusetts, along the Deerfield River in downtown Shelburne Falls, just below the New England Power Company dam. Signs advertise this locality as "Glacial Potholes" and it can be easily reached by the stone steps behind the candle shop. The UTM coordinates are 18 685558 m E and 4719162 m N.

Outcrops below the dam are probably the best exposure of the Collinsville Formation. The comagmatic felsic and mafic gneisses were complexly deformed during the Taconic and Acadian orogenies. The Shelburne Falls dome is surrounded by the Goshen Formation, one of the units in the post-Taconic Connecticut Valley trough, which was only deformed during the Acadian orogeny. These plutonic rocks form the core of the Shelburne Falls dome. Three multigrain fractions from a massive tonalite from this locality (Fig. 1, #5) are slightly discordant, yielding $^{207}Pb/^{206}Pb$ dates that range from 475.8 to 474.5 Ma. A single zircon from this sample is concordant at 474 Ma. The crystallization age of this tonalite is best estimated by the mean of the four $^{207}Pb/^{206}Pb$ dates, 475.4 ± 1.4 Ma. Three fractions from another tonalite sample collected from the southeastern margin of the Shelburne Falls dome (Fig. 1, #6), including one concordant fraction, give a U-Pb upper intercept age of 473.1 ± 1.5 Ma. Karabinos and Tucker (1992) reported a U-Pb lower intercept age of 473 ± 2 Ma from a tonalite collected in the Goshen dome (Fig 1, #7). Two of the three abraded fractions were nearly concordant and one contained a minor inherited component.

Karabinos and others (1998) analyzed 15 felsic to intermediate composition rocks, including 8 dated samples, for major and trace elements by X-ray fluorescence and instrumental neutron activation. These rocks have SiO_2 between 63.2% and 75.2%. Using the Zr/TiO_2 vs. Nb/Y immobile trace element classification system of Winchester and Floyd (1977), these rocks plot in the andesite, dacite, and rhyodacite fields. The samples are enriched in the light rare earth elements (LREE; La-Sm) and have generally flat heavy REE patterns (Tb-Lu). The La_N/Lu_N ratio is between 1.8 and 6.4; La varies from 10x to 83x chondrite. Most samples have a small negative europium anomaly.

The rocks are all subalkaline and plot in the calc-alkaline field on an AFM diagram (Irvine and Baragar, 1971). On geochemical discrimination diagrams for granitic rocks such as Ta vs. Yb and Rb vs. Y+Nb (Pearce and others, 1984), the samples plot in the fields for volcanic arc granite (Fig. 4). Multielement discrimination diagrams also support an arc source for these rocks (Fig. 5). Enrichment in the large ion lithophile elements and depletions in Ta-Nb, P, and Ti, are characteristic of felsic rocks from arc environments (e.g., Condie, 1989; Wilson, 1989). Thus, geochemical evidence from the Collinsville Formation, Hallockville Pond Gneiss (Stop 3), and Barnard Volcanic Member, in Vermont, is consistent with the intermediate to felsic rocks having formed in an arc environment. Geochemical data from mafic rocks in this belt presented by Karabinos and others (1996) are consistent with this conclusion, but they also point to a back-arc basin derivation for some of the mafic rocks. A similar conclusion was reached for parts of the Ordovician Hawley Formation (Stop 2) in Massachusetts by Kim and Jacobi (1996).

Together, the geochemical and geochronological data presented by Karabinos and others (1998) indicate the existence of Early to Middle Ordovician arc rocks that are 15 to 30 million years older than arc-related rocks directly to the east in the Bronson Hill arc (Tucker and Robinson, 1990). Karabinos and others (1998) argued that because Taconic metamorphism began at about 470 Ma, it must have been the Shelburne Falls arc that collided with Laurentia and that the Bronson Hill arc formed above a younger west-dipping subduction zone.

Stop 2, Hawley Formation, relict pillow lavas in the forearc of the Shelburne Falls arc.

This stop is located in the Plainfield 7.5' Quadrangle, Massachusetts, on the east side of the Chickley River, approximately 500 feet north of the intersection of West Hawley Road (Rt. 8A) and Pudding Hollow Road. The UTM coordinates are 18 671215 m E and 4719267 m N.

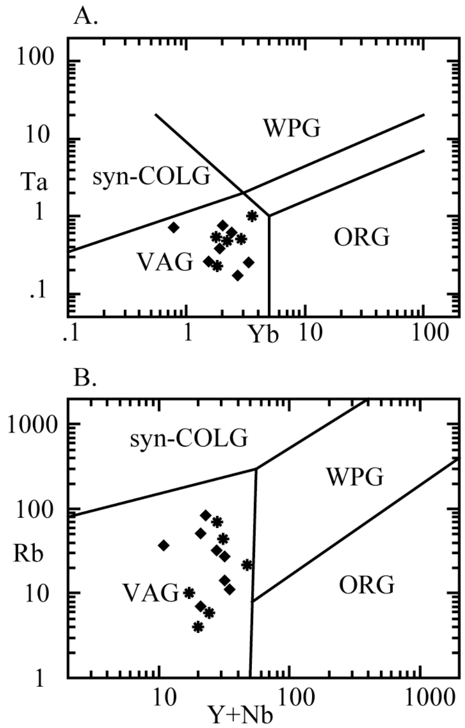

Figure 4. Analyzed samples with SiO2 greater than 63% from the Barnard Volcanic Member, Hallockville Pond Gneiss, and Collinsville Formation plotted on (A) Ta vs. Yb and (B) Rb vs. Y+Nb diagrams after Pearce et al. (1984). All samples plot in volcanic arc granite field. Diamonds are dated samples ranging in age from 465 to 485 Ma. Stars are undated samples. Fields: VAG, volcanic arc granites; syn-COLG, syncollision granites; WPG, within-plate granites; ORG, ocean-ridge granites. From Karabinos and others (1998).

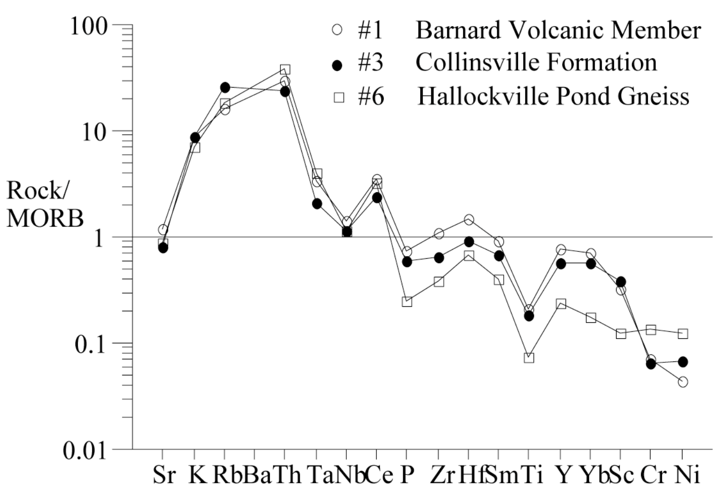

Figure 5. Multielement variation diagram showing one representative dated sample from Barnard Volcanic Member, Hallockville Pond Gneiss, and Collinsville Formation. Enrichment in the large ion lithophile elements and depletion in Ti, P, and Ta-Nb relative to Th and Ce support an arc derivation. Mid-ocean ridge basalt normalization factors are those of Pearce (1983). From Karabinos and others (1998).

The mafic rocks exposed along the Chickley River belong to the Hawley Formation. The bulbous structures have been interpreted by many, including Osberg and others (1971), as relict pillows. Kim and Jacobi (1996) published a detailed geochemical study of the Hawley Formation. They found evidence for island arc tholeiites, mid-ocean ridge basalts, back-arc basin basalts, and boninites in the Hawley Formation. They argued that the presence of boninites indicates a fore-arc setting for the formation.

Karabinos and his students have collected many samples from felsic gneisses in the Hawley Formation in an attempt to date it. Four samples yielded only detrital zircons with Grenvillian ages, but one, the Dell Metatrondhjemite, yielded igneous zircons that gave a 434 $\pm$ 8 Ma $^{207}Pb/^{206}Pb$ evaporation age (Fig. 1, #4). According to Kim and Jacobi (1996) this unit, which has an arc geochemical signature, intruded other subunits of the Hawley Formation. It is important to note that the Charlemont Mafic Intrusive Suite of Kim and Jacobi (1996) intruded all of the other subunits in the eastern part of the Hawley Formation, including the Dell Metatrondhjemite. These intrusives contain plagioclase phenocrysts, commonly have chilled margins, and show back-arc basin geochemical characteristics. They are very similar to dikes in the Barnard Volcanic Member and other units in Vermont, previously described in the section “Tectonic Setting of the Connecticut Valley Trough and the Acadian Orogeny.” Because they intruded the 434 $\pm$ 8 Ma Dell Metatrondhjemite, they must be younger than the Taconic orogeny, and rocks in the Bronson Hill arc, and provide further evidence for back-arc basin rifting during the Silurian.

Stop 3, Hallockville Pond Gneiss, an arc-related pluton in the Moretown Formation.

This stop is located in the Plainfield 7.5’ Quadrangle, Massachusetts, approximately 800 feet west of the intersection of Routes 8A and 116. The UTM coordinates are 18 668778 m E and 4711899 m N.

The Hallockville Pond Gneiss intruded the Moretown Formation of the Rowe-Hawley Belt and contains deformation fabrics comparable in intensity and orientation to those in the surrounding rocks. It intruded before or during the earliest stage of the Taconic orogeny. It is tonalitic in composition and is one of the felsic samples included in the geochemical plots shown in Figures 4 and 5. The surrounding Moretown Formation is typically interpreted as a fore-arc basin deposit (e.g. Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). On the basis of the weighted average of 4 individual grains, the $^{207}Pb/^{206}Pb$ evaporation age of the Hallockville Pond Gneiss is 479 ± 8 Ma (Fig. 1, #8, Karabinos and Williamson, 1994). This age places a lower limit on the timing of the Taconic orogeny and also constrains the undated Moretown Formation to be older than approximately 479 Ma.

Stop 4, Middlefield Granite, a pluton that cross-cuts a Taconic fault and constrains the end of the orogeny.

This stop is located in the Chester 7.5’ Quadrangle, Massachusetts, approximately 1500’ southwest of the intersection of East River Road and Clark Wright Road. The UTM coordinates are 18 667459 m E and 4690665 m N. From the intersection drive up the steep hill on Clark Wright Road and park in the Trustees of the Reservation lot.

The Middlefield Granite intruded the Rowe and Moretown Formations at their contact. The pluton is weakly foliated parallel to the dominant regional schistosity, and most of the 0.5 to 5 m thick layers of Middlefield Granite exposed in the falls are parallel to the strong schistosity in the Moretown Formation. There are, however, xenoliths that contain an older deformation fabric that predates their incorporation into the magma and this fabric is presumably Taconic in age. Hatch and others (1970) also believed that the Middlefield Granite intruded after the Taconic but before the Acadian orogeny. Karabinos and Williamson (1994) reported a $^{207}Pb/^{206}Pb$ single-zircon evaporation age for this pluton of 447 $\pm$ 3 Ma (Fig. 1, # 1, weighted average of 4 grains). The contact between the Rowe and Moretown Formations was interpreted as a Taconic thrust by Stanley and Hatch (1988) and Ratcliffe and others (1992). Thus, Taconic thrusting in this part of the belt must have ended before approximately 447 Ma.

Stop 5, Grenvillian basement of Berkshire massif and the Dalton Formation, an excellent exposure of the profound unconformity.

This stop is located in the Pittsfield East 7.5’ Quadrangle, Massachusetts, approximately three-quarters of a mile north of Grange Hall Road along the Appalachian Trail. The UTM coordinates are 18 651243 m E and 4717638 m N.

After finding the intersection of Grange Hall Road and the Appalachian trail, hike north on the trail for about 15 minutes until a large outcrop looms to the left. This spectacular outcrop contains the contact between the Grenvillian basement rocks of the Berkshire massif and the Dalton Formation and is part of the Day Mountain thrust sheet (Ratcliffe, 1984). Neither unit has been precisely dated, but the Grenvillian basement rocks must be older than 1.1 Ga (age of the

Ottawan phase of the Grenville orogeny), and the Dalton Formation was deposited at approximately the Precambrian-Cambrian boundary. The unconformity is well-exposed in several locations along the outcrop. Note the truncation of gneissic foliation in basement rocks at the contact and the folded contact in some places. Pegmatites record high-grade Grenville metamorphism in the basement rocks which were retrograded during the Taconian orogeny. The cover rocks in the Dalton Formation are at biotite grade. This is also an excellent place to measure strain using the quartzite pebbles in the Dalton Formation.

Stop 6, Stockbridge Formation, thrust fault in marble with a phyllite sliver.

This stop is located in the Cheshire 7.5' Quadrangle, Massachusetts, on the east side of Rt. 7, opposite the rest area, approximately 0.5 miles north of the intersection of Rt. 7 and Mallery Road. The UTM coordinates are 18 644247 m E and 4717638 m N.

At this outcrop folded bedding in the marble is truncated above and below a fault, which is itself folded. A sliver of phyllite approximately 1 m thick is present along the fault. It is very common to find complexly intercalated marble and phyllite in this area.

The numerous outcrops along Rt. 7 in Lanesborough, New Ashford, and Williamstown alternate between marble and phyllite in a complicated pattern. Ratcliffe and others (1993) mapped the marble and graphitic phyllite as Stockbridge and Walloomsac Formations, respectively (shelf sequence and syn-orogenic flysch), and the non-graphitic phyllite as Greylock Schist and Nassau Formation (Taconic sequence rocks). The graphite-rich phyllite and marble along Rt. 7 and on Mount Greylock was correlated with the organic-rich Walloomsac Formation west of the area based solely on the high graphite content of the rocks. There are no fossils in this area, so it is impossible to confirm the Ordovician age assigned to the graphitic phyllite by Ratcliffe and others (1993). Furthermore, the distribution of graphite in phyllite here and on Mount Greylock is extremely erratic. Nemser and Karabinos (1998) suggested that the graphitic phyllite is really part of the Greylock Schist rather than the Walloomsac Formation and that the graphite was precipitated by fluids migrating along fault zones. In support of this interpretation, the Greylock Schist and the metapelitic member of the Walloomsac Formation are lithologically identical and both contain graphite-poor and graphite-rich layers; the Greylock Schist, however, contains fewer graphite-rich layers. Similarly, the Stockbridge Formation and the marble member of the Walloomsac Formation are identical. Graphite occurs as disseminated grains in the matrix and as approx. 1 mm flakes in quartz veins. It is typically concentrated in crenulation cleavage planes. Commonly, rocks contain porphyroblasts with helicitic inclusion trails of graphite but no visible graphite in the matrix. This suggests that graphite was locally dissolved by late fluids and transported out of the rocks. Preliminary carbon isotopic data on graphite suggests that it is biogenic; there is no evidence of substantial fluid mixing of methane- and carbon dioxide-rich fluids to precipitate graphite. The most likely explanation for the high concentration of graphite in some rocks near Mount Greylock is precipitation from carbon-rich fluids as they migrated and cooled along faults.

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