

INTERPRETATION OF AGES OF ARC MAGMATISM, METAMORPHISM, AND COLLISIONAL TECTONICS IN THE TACONIAN OROGEN OF WESTERN NEW ENGLAND

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ABSTRACT. Available geochronologic ages of volcanic and intrusive rocks of the Taconian arc complex of western New England suggest that the Shelburne Falls and Bronson Hill arcs are not temporally or spatially discrete. Arc activity ranges from earliest Ordovician to Silurian. Activity in the Early and Middle Ordovician coincided with outboard accretionary tectonics and metamorphism that was contemporaneous with the older igneous activity in the Shelburne Falls arc and Bronson Hill arcs. Activity at about 455 to 445 Ma coincides with the collisional stage of the Taconian orogeny that affected Caradocian and older rocks of the Laurentian margin. The 455 to 445 Ma range for the collisional stage of Taconian orogeny in western New England is bracketed by biostratigraphic ages of sedimentary rocks formed on the Laurentian margin and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of prograde hornblende formed during Taconian metamorphism. The previous $^{40}\text{Ar}/^{39}\text{Ar}$ age estimate of 465 Ma for this collisional and metamorphic event is now known to be too old because this age violates the age of metasedimentary rocks involved in the collisional tectonics.

Acceptance of the newer $^{40}\text{Ar}/^{39}\text{Ar}$ age estimates of 445 to 450 Ma for Taconian metamorphism during collision establishes the contemporaneity with arc activity in the Bronson Hill arc. Taken together these data support the concept of a long-lived volcanic arc terrane(s) that prograded oceanward. Collision with this time-composite arc terrane(s) in the Caradocian produced the Taconian orogeny rather than the collision of a separate and smaller arc called the "Shelburne Falls arc" by Karabinos and others (1998).

INTRODUCTION

New important geochronologic and geochemical evidence for 485 to 447 Ma arc-related volcanic and intrusive activity within the Rowe-Hawley zone of western Massachusetts and southern Vermont has been presented by Karabinos and others (1998). They assign those rocks to an older Shelburne Falls arc in contradistinction to the Bronson Hill arc that, according to them, has only younger (454–442 Ma) intrusive or volcanic rocks (Tucker and Robinson, 1990). As did Tucker and Robinson, the authors draw attention to the fact that the igneous activity in the Bronson Hill in Massachusetts is too young to be contemporaneous with Taconian dynamothermal metamorphism, which according to their citations began by 470 Ma, as well as too young for the emplacement age of the Taconic allochthons dated by fossils in the overridden autochthon at about 460 to 455 Ma. Karabinos and others then concluded that the collisional mass that caused the Taconian orogeny in western New England was the newly defined Shelburne Falls arc, not the Bronson Hill arc.

As the coauthors of several of the earlier papers cited on the subject (Stanley and Ratcliffe, 1985; Sutter and others, 1985; Ratcliffe and Burton, 1990), we think the conclusions of Karabinos and others (1998) are incorrect and misleading, because they are based on an apparent conflict between Taconian ages of metamorphism and arc volcanism. To be fair, other authors, including Tucker and Robinson (1990) and Pinet and Tremblay (1995), have made the same point as Karabinos and others (1998) for different segments of the Taconide zone of New England and Quebec. Much of the confusion comes from acceptance by most authors of the 460 to 470 Ma estimated of age foreland Taconian metamorphism proposed by Sutter and others (1985). This estimate has been modified to about 445 to 450 Ma (Hames and others, 1991, p. 891 and 904).

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Recognition of this revision (cited in part in Tucker and Robinson, 1990, p. 1417) changes considerably the validity of the arguments of Karabinos and others (1998) and indeed establishes contemporaneity of arc activity with Caradocian collision.

This discussion of the available information pertinent to timing of the Taconian dynamothermal events in western New England can be grouped into three topics:

1. The age range of Taconian metamorphism and interpretation of the $^{40}\text{Ar}/^{39}\text{Ar}$ data;
2. The actual age of plutonism that could uniquely distinguish rocks of the Shelburne Falls arc from other potential arcs; and
3. An analysis of the Shelburne Falls arc as the colliding mass that caused the Taconian orogeny.

AGE OF TACONIAN METAMORPHISM

Stanley and Ratcliffe (1985), Sutter and others (1985), and Hames and others (1991) used their data and that of Laird and others (1984) to suggest that rocks of the Taconian orogen in western New England had been subjected to three metamorphic and deformational events. The oldest (T_1) high-pressure metamorphic event (Laird and others, 1984) occurred during subduction and may be as old as 490 Ma to about 470 Ma (fig. 1). This medium-high to high-pressure metamorphism probably formed outboard of Laurentia prior to final Caradocian emplacement of the Taconic allochthons and was later accreted (Lanphere and Albee, 1974; Laird and others, 1984). All ages greater than 470 Ma of Laird and others (1984) are east of major Taconian thrust faults and occur in allochthonous rocks. Two other metamorphic events, T_2 and T_3 , occurred after emplacement of the allochthons; the final one coinciding with large-scale imbrication, recumbent folding, and translation of the Laurentian Middle Proterozoic crust westward over the allochthon and autochthon in late-Middle to Late Ordovician. This last event marked the end-stage results of collision of Laurentia with an island arc or continental arc and coincided with the peak Barrovian metamorphism of garnet to sillimanite grade in Massachusetts, Connecticut, and New York. $^{40}\text{Ar}/^{39}\text{Ar}$ dating of this T_3 event by Sutter and others (1985) relied on hornblende and biotite collected from mylonitic Middle Proterozoic basement rocks in fault zones of the Berkshire massif that overrode autochthonous rocks as young as the Middle to Late Ordovician Walloomsac Formation. The age of the base of the Walloomsac Formation (fig. 1) is Rocklandian and (or) Kirkfieldian as determined from abundant conodonts of the *Phragmodus undatus* midcontinent zone (see Ratcliffe and others, 1993) and from graptolites of the *Climacograptus bicornis* Subzone (Potter, 1972). K-bentonites from Virginia in the *Phragmodus undatus* zone have U-Pb zircon ages of 453 Ma (Tucker and McKerrow, 1995, p. 375), and we suggest an age of about 453 Ma for the base of the Walloomsac Formation and its correlative, the Ira Formation of Vermont (Ratcliffe and others, in press). Therefore, Taconian metamorphism on the Laurentian plate should be younger than about 453 Ma. Middle Ordovician conodonts (fig. 1) from near Plymouth, Vermont, east of the Green Mountains (Ratcliffe and others, 1997; Ratcliffe and others, in press) suggest that emplacement and metamorphism in the Pinney Hollow Formation is also Caradocian or younger. The oldest $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende age obtained by Sutter and others (1985), however, was 466 ± 5 Ma (sample BM-1). The rock dated contains some relict hornblende texture but was used as the best age of this metamorphism, despite the fact that the range could well violate the absolute age of the Walloomsac Formation. Sutter and others (1985) also determined an age of 446 Ma for more thoroughly recrystallized, mylonitic amphibolite. Recent work on the systematics for argon retention and experimental release in amphibole (Lee and others, 1991; Cumbest and others, 1994) suggests that amphibole concentrates from partially-retrograded assemblages commonly yield high-temperature plateaus that are specious and anomalously old. Therefore, $^{40}\text{Ar}/^{39}\text{Ar}$ plateau or isochron ages for amphibole

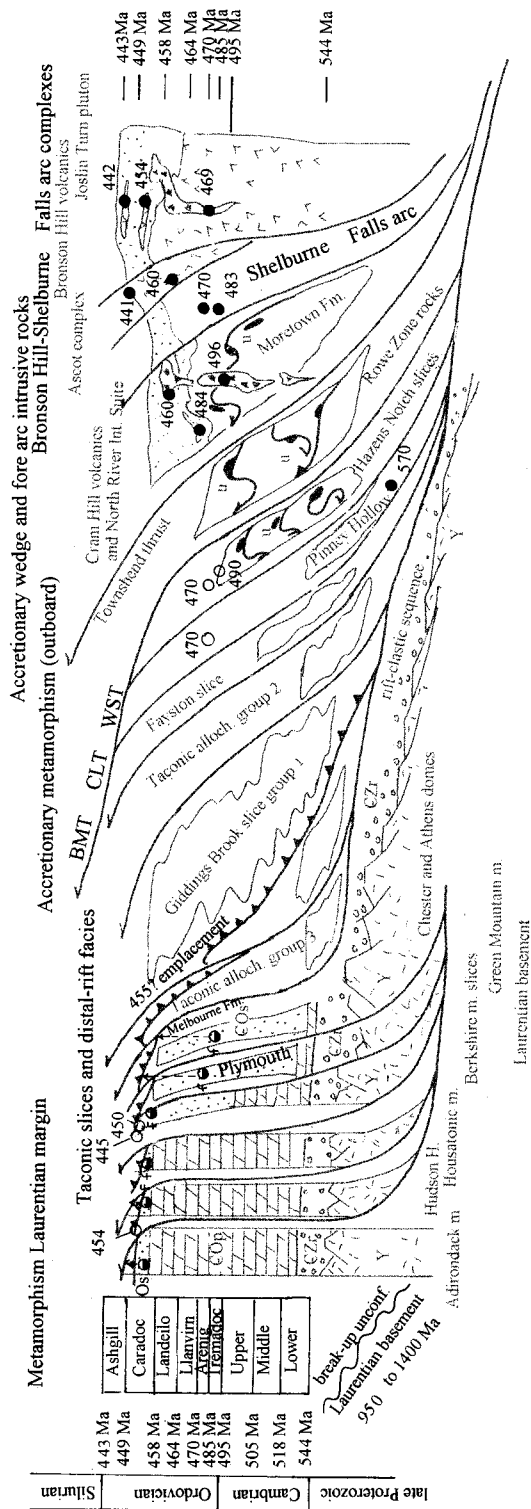


Fig. 1. Schematic diagram showing evolution of the Taconian orogeny in western New England after Stanley and Ratcliffe (1985). Time scale from Tucker and McKerrow (1995) and Bowring and others (1993). Key to symbols and patterns: Os, Middle Ordovician exogeosynclinal pelites of the Ira-Walloomsac Formations and the pelite at Plymouth, Vermont; COs, Cambrian and Ordovician pelites including the Middle Ordovician Melbourne Formation of Quebec (Marquis and Nowlan, 1991); ornamented fault is sole of Giddings Brook slice of Taconic allochthon Filled circle = U-Pb zircon age, half-filled circle = maximum age of Walloomsac, Ira, and Melbourne Formations and of pelite near Plymouth, Vermont (Ratcliffe and others, 1997) as determined from concordants (arrow shows range), open circles are ⁴⁰Ar/³⁹Ar metamorphic ages. BMT, Belvidere Mountain thrust; CLT, Camerons Line thrust; WST, Whitcomb Summitt thrust.

samples that contain extraneous argon (either inherited or unsupported, nonatmospheric argon) should generally be viewed as providing maximum estimates for the timing of argon retention. Hames and others (1991) revised the age estimate for the final Taconian metamorphic thermal peak in the Laurentian plate to approx 450 to 445 Ma (late Caradocian to earliest Ashgillian using the time scale of Tucker and McKerrow, 1995). The revised age was based on their 443 Ma age for a prograde hornblende from the Walloomsac Formation and a 446 Ma age they determined for mylonitic amphibolite from the Housatonic massif, as well as the 446 Ma age of Sutter and others (1985). A U-Pb staurolite age of 454 ± 6 Ma (Lanziratti and Hanson, 1997) from the Walloomsac Formation in the T₃ zone above the Whaley Lake thrust in Dutchess County, New York (Ratcliffe and Burton, 1990) further supports the interpretation of Hames and others. These ages do not violate the approximate absolute age of 455 Ma of the Walloomsac Formation, whereas the range of the older age estimate, 470 to 460 Ma does (Sutter and others, 1985; Ratcliffe and Burton, 1990; Hames and others, 1991, p. 891). The 450 to 445 Ma range for metamorphism is in accord with other data found in Sutter and others (1985), with the data of Laird and others (1984) west of the Underhill thrust, as well as with the Middle Caradocian age of the Walloomsac and Ira Formations. This age also coincides with the time of volcanism in the Ammonoosuc Volcanics of the Bronson Hill arc at 454 to 442 Ma (Tucker and Robinson, 1990). Thus, the available biostratigraphic and isotopic data indicate that volcanism was coeval with the collisional tectonics as expressed in the Laurentian plate. Although the reasons and data for this revision were explicitly defined by Hames and others (1991) and by Ratcliffe and others (1993), it unfortunately appears to have been undetected or disregarded by authors of several recent papers.

AGE OF THE ARC IGNEOUS ROCKS

The second point regards the age range of rocks within the Bronson Hill and Shelburne Falls arcs. Intrusive rocks structurally below the Ammonoosuc Volcanics were dated at 454 to $442^{+3/-2}$ Ma, whereas rhyolite near the top of the Ammonoosuc was dated at 453 ± 2 Ma (Tucker and Robinson, 1990). Their dates indicated that part of the calc-alkaline substrate of the Bronson Hill arc in southern New England is older than the 453 ± 2 Ma intrusives, but that volcanic activity continued to $449^{+3/-2}$ Ma or through the Caradocian in the case of the Partridge Formation. Elsewhere in the Bronson Hill belt of eastern Vermont and adjacent New Hampshire, rocks assigned to the Ammonoosuc Volcanics (fig. 1) are older than the 469 ± 1.5 Ma Joslin Turn pluton (Aleinikoff and Moench, 1992; Rankin, 1996). This date indicates that some volcanic rocks traditionally belonging to the Bronson Hill anticlinorium are older than 454 Ma. The problem is further compounded by the 460 ± 3 to $441^{+7/-12}$ Ma age of rhyolitic rocks of the Ascot complex of Quebec that enters the U.S. Appalachians on the west side of the Connecticut Valley trough (David and Marquis, 1994). This belt could be equated with the Shelburne Falls arc of Karabinos and others (1998) from its position west of the Bronson Hill anticlinorium, but the ages are too young.

U-Pb zircon dates for rocks of the Shelburne Falls arc, as defined by Karabinos and others, range from 487 to 471 Ma. However, the oldest ages used by Karabinos and others now appear to be incorrect. Zircons from a tonalite sill in the Moretown Formation near South Newfane, Vermont that yielded a U/Pb evaporation age of 487 ± 8 Ma and abraded, multi-grain fractions with a lower, discordia intercept age of 484 ± 7 Ma have been revised to an age of 462 ± 6 Ma by John Aleinikoff using U/Pb SHRIMP analysis (see Ratcliffe and others, 1997, for a brief discussion). In Connecticut, arc rocks of the Collinsville Formation were intruded by monzodiorite plutons of the Brookfield Plutonic Suite dated by U-Pb zircon ages, at 453 ± 3 Ma (Sevigny and Hanson, 1995) and by the Newtown Gneiss at 438 ± 2 Ma, suggesting that intrusive ages of the

Shelburne arc as extended into Connecticut (see fig. 1 of Karabinos and others, 1998) are much younger than to the north and agree more closely with ages in the Bronson Hill. Thus, the ages of rocks within the Ascot complex, the Bronson Hill arc, and in the Shelburne Falls arc of Massachusetts and those in Connecticut all overlap in age (fig. 1). Although the westernmost arc rocks (Shelburne Falls arc) are in general older, no consistent geographic grouping by age is possible at this time. To further complicate the problem, four new U-Pb zircon ages of John Aleinikoff from the Barnard Gneiss and Cram Hill Formation in Vermont (fig. 1) range from 496 ± 8 Ma to the above mentioned tonalite at South Newfane dated at 462 ± 6 Ma (Ratcliffe and others, 1997). The new data, as well as the data of Karabinos and others (1998), and other data cited in the above discussion suggest that arc volcanic and intrusive activity covered a period of time from earliest Ordovician (496 ± 8 Ma) to Middle to Late Ordovician (453 Ma). In general, the ages are younger eastward, but all data fit well into the multi-aged, evolving arc complex associated with westward accretion of the progressive Taconian orogeny as proposed by Stanley and Ratcliffe (1985, plate 2 and text). Analysis of the available age data suggest that rocks defined as the "Shelburne Falls arc" do not constitute a temporally distinctive group of rocks.

TACONIAN COLLISION WITH THE SHELBURNE FALLS ARC

The third topic regards the proposition that collision of the Shelburne Falls arc with Laurentia caused the Taconian orogeny. It is clear from the preceding discussion that there is no evidence for collision with an arc in the time period 485 to 471 Ma but much evidence for subduction during an accretionary stage (Stanley and Ratcliffe, 1985). Likewise, the thickness (<1 km to as much as 3 km) of the preserved components of the Shelburne Falls arc, such as the Hawley Formation and Barnard Gneiss, are really insignificant and could not have been the colliding plate that caused the Taconian orogeny. Moreover, many of the rocks, particularly the Hawley Formation, the North River Intrusive Suite (Armstrong, 1994), and Barnard Gneiss, intrude or are interlayered with rocks of the Moretown and Cram Hill Formations and do not constitute a collisional mass separate from the accretionary wedge (Ratcliffe and others, 1997; Armstrong, 1994). These igneous rocks intruded the accretionary wedge probably in a fore-arc setting (Stanley and Ratcliffe, 1985; Kim and Jacobi, 1996) and suffered the effects of Taconian collision and metamorphism. The geochemistry and rock types present in the Shelburne Falls arc suggest an accumulation of oceanic (boninitic) fore-arc and arc rocks (Kim and Jacobi, 1996). The stratigraphy and geologic mapping does not support the existence of the infrastructure for an arc, such as pelagic sediments, oceanic crust, and mature island-arc infrastructure, as pointed out by Stanley and Ratcliffe (1985).

Stanley and Ratcliffe (1985), however, did identify the Bristol Member of the Collinsville Formation as the westward-thinning wedge of amphibolite and gneiss, present largely in the domes of western Connecticut and Massachusetts, and correlated these rocks with the infrastructure of the Bronson Hill anticlinorium. The Bristol thrust at the base of the Collinsville Formation forms the base of the colliding Bronson Hill plate in their interpretation. This wedge of material has the appropriate size and position to form the leading edge of a plate of the approximate scale of an island arc.

The new U-Pb SHRIMP zircon age of John Aleinikoff of 496 ± 8 Ma for trondhjemite of the Barnard Gneiss that intrudes the Moretown Formation near Ludlow, Vermont (Ratcliffe and others, 1997) suggests that the Proctorsville ultramafic belt was incorporated in the Moretown before 496 ± 8 Ma and thus is additional evidence for starting of accretionary tectonics in the earliest Ordovician (fig. 1) as suggested by Stanley and Ratcliffe (1985). Throughout the period from 496 ± 8 to ≈ 445 Ma, tectonic vergence in central Vermont to New York City was westward, including the time period from the emplacement of the Taconic allochthons to the T_3 collisional and dynamother-

mal events. This includes shortening and thrust faulting along the western margin of the Giddings Brook slice of the Taconic allochthon, which must be younger than the Caradocian emplacement of the allochthon as determined by paleontology (Finney, 1986). This observation, coupled with the paucity of arc-related intrusive or volcanic rocks in the Laurentian plate, does not support westward subduction under Laurentia during that time period (Stanley and Ratcliffe, 1985; Sutter and others, 1985; Hames and others, 1991). There are no arc rocks west of the generally agreed upon Taconian suture zone (Cameron's Line in Connecticut or the Whitcomb Summit thrust in Massachusetts and its extensions such as the Belvidere Mountain thrust in Vermont). This point may be one that Karabinos and others (1998) and we agree upon. We differ, however, with the conclusion that the volcanic activity in the Bronson Hill arc at 454 to 442 Ma does not coincide with Taconian orogenesis, because in fact (Hames and others, 1991; Lanziratti and Hanson, 1997) we now know it agrees quite well (Ratcliffe and others, 1993, p. 11–12). We regard the various exposures of arc-related rocks in western New England (Ascot-Weedon Volcanic Complex, Shelburne Falls, and the Bronson Hill arc) not as discrete arc terranes but as a time-composite, tectonically accumulated zones of arc and fore-arc rocks produced by amalgamation before (west of) a colliding mass in the Late Ordovician. It still seems very likely that the volcanism in the Bronson Hill anticlinorium was coeval with the end of eastward subduction.

The igneous rocks of all the above mentioned "arcs" probably are the result of long-continued subduction, perhaps along many complex segments. However, the subduction-related activity at 454 to 442 Ma coincided with excessive crustal shortening, regional metamorphism, and large-scale collisional tectonics in the Laurentian plate (Hames and others, 1991) in Massachusetts, Connecticut, and New York, contrary to the statement of Karabinos and others (1998). On the Laurentian margin, these ages of deformation are younger than about 455 but older than about 445 Ma. The widespread belt of dynamothermal Barrovian metamorphism and large-scale westward synmetamorphic transport, at garnet to sillimanite grade, indicates collisional tectonics under a thickening tectonic cover between Middle and Late Caradocian. All this is consistent with eastward-dipping subduction as late as about 450 Ma. Perhaps the migration of arc volcanism eastward at 454 Ma was induced by lessening of the dip of the subduction zone owing to the buoyancy of the subducted Laurentian margin. Following collision at about 454 to 445 Ma subduction polarity and volcanism may have switched, but the effect of this never extended into the Laurentian plate west of the Taconian suture.

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