Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburne Falls arc

Paul Karabinos
Department of Geology, Williams College, Williamstown, Massachusetts 01267
Scott D. Samson
Department of Earth Sciences, Syracuse University, Syracuse, New York 13244
J. Christopher Hepburn
Department of Geology and Geophysics, Boston College, Chestnut Hill, Massachusetts 02167
Heather M. Stoll
Department of Geosciences, Princeton University, Princeton, New Jersey 08544

ABSTRACT

Tectonic models of the Ordovician Taconian orogeny in western New England usually invoke 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 and therefore younger than much of the Taconian deformation and metamorphism in western New England and eastern New York, which began by 470 Ma. U-Pb and single-grain evaporation zircon ages combined with geochemical analyses reveal the presence of an older magmatic arc, the Shelburne Falls arc, that formed west of the Bronson Hill arc at 485 to 470 Ma. The Shelburne Falls arc formed above an east-dipping subduction zone by the Early Ordovician. The Taconian orogeny was the result of the collision between Laurentia and the Shelburne Falls arc beginning ca. 475 to 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 during the final stages of and subsequent to the Taconian orogeny. The Taconian 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. The tectonic history of the New England Appalachians is inconsistent with a Middle Ordovician collision between Laurentia and the proto-Andean margin of Gondwana.

INTRODUCTION

Plate tectonic models typically explain the Ordovician Taconian orogeny in western New England as a collision between the Laurentian continental margin and the Bronson Hill arc (e.g., Rowley and Kidd, 1981; Stanley and Ratcliffe, 1985). However, doubt was cast on this model when 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. Because Taconian metamorphism and deformation began before 470 Ma (e.g., Laird et al., 1984), rocks in the Bronson Hill arc dated by Tucker and Robinson (1990) could not have formed before collision with Laurentia as would be predicted from the plate tectonic model.

Tucker and Robinson (1990) suggested that the Bronson Hill arc may have been accreted to an already assembled “Taconia” or that the age data reflect a significant time lag between subduction and magma generation. A third explanation proposed by Pinet and Tremblay (1995) for southern Quebec explained the Taconian orogeny as the result of an Oman-type obduction instead of a continent-arc collision.

We present new geochronological and geochemical data documenting the existence of an older arc, called the Shelburne Falls arc by Karabinos and Tucker (1992), preserved west of the Bronson Hill arc (Fig. 1). We suggest that (1) the Taconian orogeny was the result of collision between Laurentia and the Shelburne Falls arc, (2) the Taconian orogeny ended in the Late Ordovician when a west-dipping subduction zone formed east of the newly accreted Shelburne Falls arc; and (3) the Bronson Hill arc formed above this post-Taconian subduction zone near the Laurentian margin.

GEOLOGIC SETTING

The Taconic klippen are composed of Late Proterozoic to Middle Ordovician rocks orginally deposited on the continental slope and rise of Laurentia, east of the basement-cored Berkshire and Green Mountain massifs (Fig. 1). 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 Vocanic Member, as mapped by Doll et al. (1961), is equivalent to the Hawley Formation and, despite its name, contains mafic and felsic plutonic and volcanic rocks intercalated with metasediments. West-directed Taconian thrust faults are common throughout this region.

The Connecticut Valley trough (metasedimentary and metavolcanic rocks of Silurian to Early Devonian age that were deformed during the Acadian orogeny) and a Mesozoic rift basin separate the Shelburne Falls arc from the Bronson Hill arc to the east and obscure the relationship between the two.

GEOCHRONOLOGY

New U-Pb zircon analyses performed at Syracuse University followed methods described by Samson (1995), except that all Pb isotopic ratios were measured with a Daly detector in ion-counting mode. Single-grain zircon

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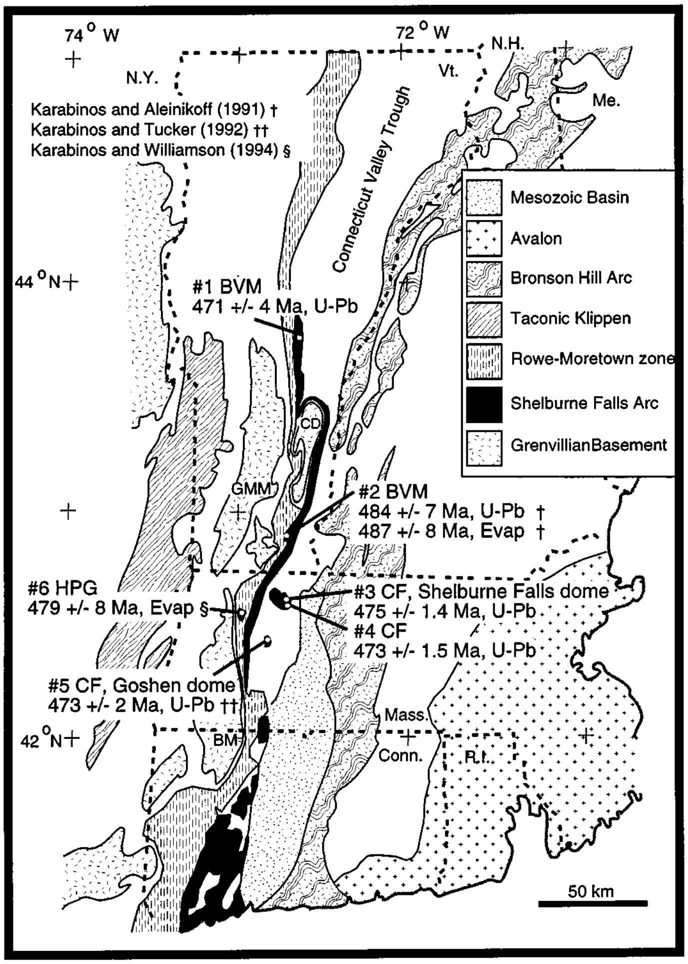

Figure 1. Tectonic map of New England and summary of U-Pb and single-grain evaporation (evap) zircon ages from Shelburne Falls arc in western New England. Shelburne Falls arc rocks: Barnard Volcanic Member (BVM), Collinsville Formation (CF), and Hallockville Pond Gneiss (HPG), GMM is Green Mountain massif; BM is Berkshire massif; CD is Chester dome.

evaporation analyses performed at Brown University used methods originally outlined by Kober (1986). Tables 1 and 2 contain complete data and additional analytical details.[1]

Four abraded fractions from a sample of the Barnard Volcanic Member from the type section in Barnard, Vermont (Fig. 1, #1), produce a well-defined discordia with a U-Pb upper intercept age of 471.4 ± 3.7 Ma (Fig. 2A). Using six abraded fractions to construct a discordia, a U-Pb lower intercept age of 484 ± 7 Ma was reported by Karabinos and Aleinikoff (1991) for a felsic gneiss from the Barnard Volcanic Member from South Newfane, Vermont (Fig. 1, #2). This sample also gave a $^{207}Pb/^{206}Pb$ evaporation age of 487 ± 8 Ma based on the weighted average of three single zircon grains.

Three multigrain fractions from a massive tonalite interlayered with mafic schist from Shelburne Falls in the Shelburne Falls dome (Fig. 1, #3) are slightly discordant, yielding $^{207}Pb/^{206}Pb$ dates that range from 474.5 to 475.8 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 (Fig. 2B). Three fractions from another tonalite sample collected from the southeastern margin of the Shelburne Falls dome (Fig. 1, #4), including one concordant fraction, give a U-Pb upper intercept age of 473.1 ± 1.5 Ma (Fig. 2C). $^{207}Pb/^{206}Pb$ zircon evaporation ages for three other tonalites within the Shelburne Falls dome (not shown in Fig. 1) are 458 ± 17 Ma, 468 ± 10 Ma, and 485 ± 4 Ma. Although these ages are less precise than the U-Pb ages reported here, they are consistent with our U-Pb data and provide further support for Early Ordovician magmatism. 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, #5). Two of the three abraded fractions were nearly concordant and one contained a minor inherited component.

The Hallockville Pond Gneiss is a tonalite that intruded the Moretown Formation in Massachusetts (Fig. 1, #6). On the basis of the weighted average of 4 grains (Karabinos and Williamson, 1994), the $^{207}Pb/^{206}Pb$ evaporation age of this unit is 479 ± 8 Ma.

GEOCHEMISTRY

We analyzed 58 samples for major and trace elements by X-ray fluorescence and instrumental neutron activation analysis at the Nova Scotia Regional X-ray Fluorescence Centre, St. Mary's University, and the Department of Geology and Geophysics, Boston College, respectively. Here we present only the results from the 15 felsic to intermediate composition rocks analyzed, including 8 dated samples. 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 varyies 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 et al., 1984), the samples plot in the fields for volcanic arc granite (Fig. 3). Multielement discrimination diagrams also support an arc source for these rocks (Fig. 4). 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 Barnard Volcanic Member, Hallockville Pond Gneiss, and Collinsville Formation 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 et al. (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 in Massachusetts by Kim and Jacobi (1996). The geochemical and geochronological data indicate the existence of an Early to Middle Ordovician arc (Shelburne Falls arc) in western New England.

TECTONIC MODEL

Tectonic models of the Taconian orogeny in western New England must account for the predominantly west directed thrusting in the belt, relict high-pressure metamorphism (Laird et al., 1984), and the juxtaposition of rocks interpreted as preserving an arc and a deformed passive continental margin separated by the narrow vestige of an accretionary wedge. The commonly accepted model involving collision of the Laurentian margin with the Bronson Hill arc explained the above features, but there are several problems with this model. (1) No definitive evidence exists that rocks in the Bronson Hill arc underwent Taconian deformation or metamorphism. (2) $^{40}Ar/^{39}Ar$ cooling ages from Laurentian margin rocks related to Taconian metamorphism in southern Quebec, Vermont, and western Massachusetts range in age from 470 to 460 Ma (Laird et al., 1984; Sutter et al., 1985; Hames and Hodges, 1993; Castonguay et al., 1997) and are 15 to 30 m.y. older than arc-related rocks dated by Tucker and Robinson (1990) in the Bronson Hill arc. (3) The age of emplacement of the Giddings Brook thrust sheet in the Taconic Range in Vermont is constrained by the presence of *Orthograptus truncatus* in flysch below the thrust (Zen, 1967) to have

[1]GSA Data Repository item 9823, U-Pb and evaporation data tables, is available upon request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

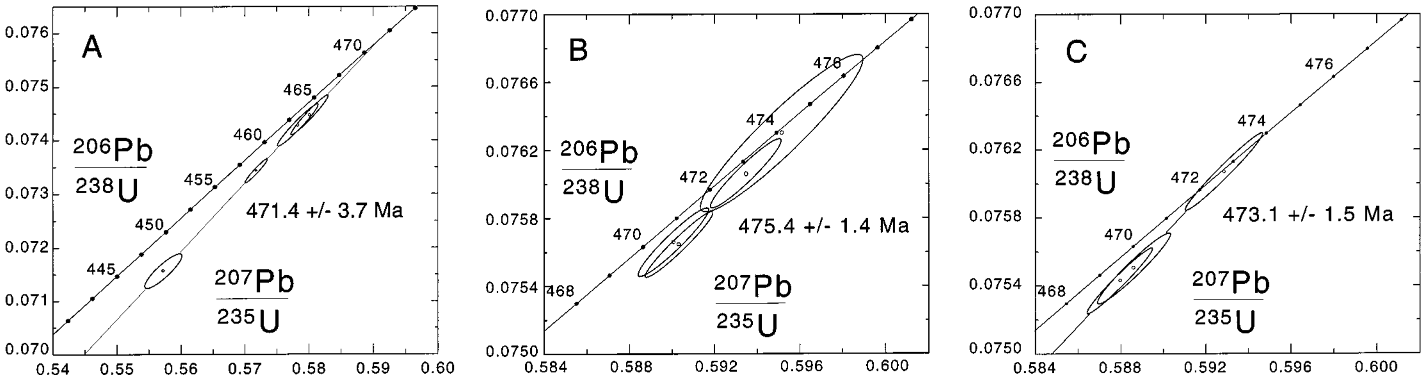

Figure 2. Concordia plots of age data from (A) sample #1, Barnard Volcanic Member, Barnard, Vermont, (B) sample #3, and (C) sample #4, both from the Collinsville Formation, Shelburne Falls, Massachusetts. Sample locations shown in Figure 1; U-Pb data presented in Table 1 (see footnote 1).

taken place during late Trenton time. Thus, thrusting in the western part of the Taconian thrust belt occurred ca. 460 to 455 Ma. (4) The Middlefield Granite in Middlefield, Massachusetts, intruded the Moretown Formation and the Rowe Schist at their contact, which was interpreted as a Taconian thrust by Stanley and Hatch (1988), but the pluton is not offset at the contact. Therefore, the 447 ± 3 Ma zircon evaporation age of the Middlefield Granite (Karabinos and Williamson, 1994) indicates that Taconian thrusting in the eastern part of the thrust belt ended before or possibly during formation of the Bronson Hill arc.

We propose that the Taconian orogeny in western New England records the collision of the Laurentian margin with the Shelburne Falls arc (Fig. 5A). Although basement to the Shelburne Falls arc is not exposed, ubiquitous inheritance in zircon strongly suggests that it was built on continental crust. In Figure 5A, we use part of the model of McKerrow et al. (1991), who suggested that a continental fragment was rifted from Laurentia and separated from it by a narrow ocean basin, Neo-Iapetus. We suggest that magma generated from an east-dipping subduction zone under this continental fragment produced the Shelburne Falls arc in Early Ordovician time. Closure of Neo-Iapetus led to collision and the Taconian orogeny.

Rodgers (1981) suggested that a west-dipping subduction zone existed east of the Bronson Hill arc from the Late Ordovician to Early Devonian on the basis of similarities between metasedimentary rocks east of the Bronson Hill arc and modern accretionary prisms; we endorse this proposal. We suggest that by ca. 454 Ma, the oldest age from arc-related rocks reported by Tucker and Robinson (1990), a west-dipping subduction zone developed and the Bronson Hill arc began to form above it east of the newly accreted Shelburne Falls arc on or near the Laurentian margin (Fig. 5B). Crustal shortening in the Taconian thrust belt, which accommodated plate convergence during the orogeny, probably ended after this west-dipping subduction zone developed. Thus, formation of the Bronson Hill arc may have been part of a process that ended the Taconian orogeny.

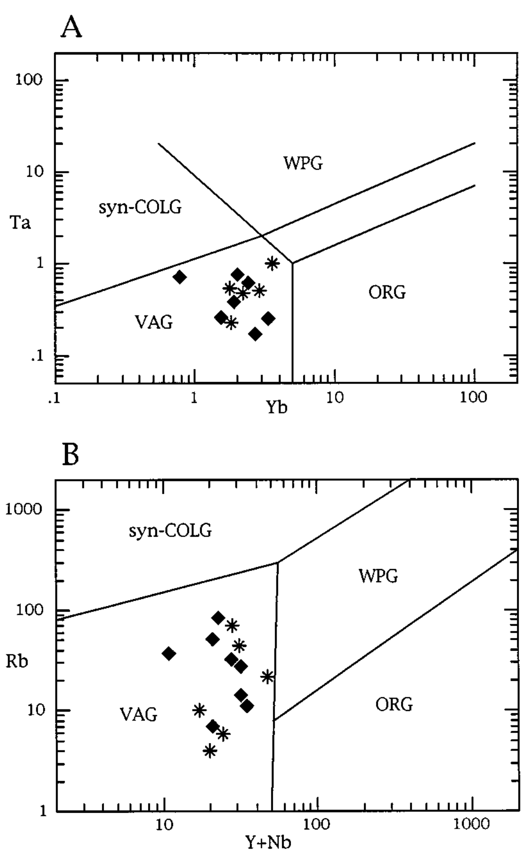

Figure 3. Analyzed samples with SiO_2 greater than 63% from the Barnard Volcanic Member, Hallockville Pond Gneiss, and Collinsville Formation plotted on (A) Ta vs. Yb and (B) Rb vs. Y+Nb diagrams after Pearce et al. (1984). All samples plot in volcanic arc granite field. Diamonds are dated samples ranging in age from 465 to 485 Ma. Stars are undated samples. Fields: VAG, volcanic arc granites; syn-COLG, syn-collision granites; WPG, within-plate granites; ORG, ocean-ridge granites.

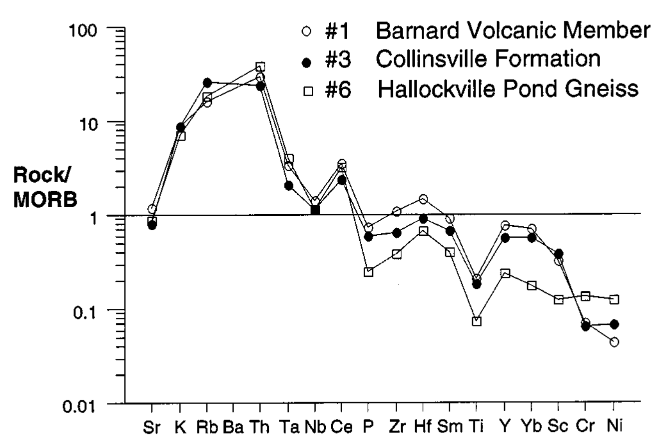

Figure 4. Multi-element variation diagram showing one representative dated sample from Barnard Volcanic Member, Hallockville Pond Gneiss, and Collinsville Formation. Enrichment in large ion lithophile elements and depletion in Ti, P, and Ta-Nb relative to Th and Ce support an arc derivation. Mid-ocean-ridge basalt normalization factors are those of Pearce (1983).

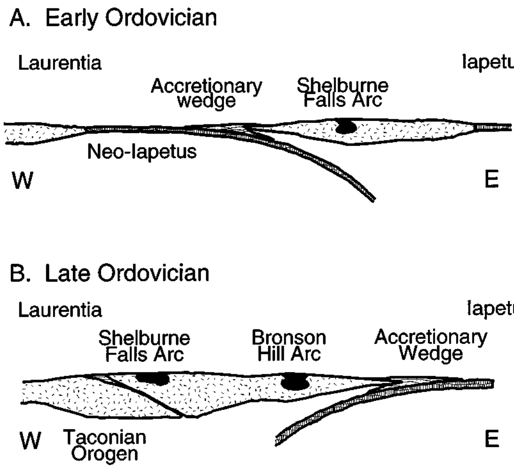

Figure 5. Tectonic model illustrated in cross sections at approximately the latitude of the Massachusetts border with Vermont and New Hampshire. East and west references are based on present geographic coordinates.

The more complicated Ordovician tectonic history of the New England Appalachians proposed here is inconsistent with the suggestion of Dalziel et al. (1994), that the Taconian orogeny resulted from a continent-continent collision between Laurentia and the proto-Andean margin of Gondwana. The New England segment of the Taconian orogen lacks evidence for a continent-continent collision such as thick clastic wedges and S-type granites. However, our model is consistent with recent advances in the Canadian Appalachians by Tremblay (1992), van Staal (1994), van der Pluijm et al. (1995), and Mac Niocaill et al. (1997), who showed that the Laurentian margin was active throughout the Ordovician and Silurian and that multiple arcs are preserved between Laurentia and Avalonia.

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