both directions, we find more interconnected, sheetlike sand bodies. Whatever the cause, the distribution of stacking is not like that predicted by the LAB models.

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Taconian orogeny in the New England Appalachians: Collision between Laurentia and the Shelburn Falls arc: Comment and Reply

COMMENT

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Karabinos et al. (1998) presented 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. 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 to 442 Ma) intrusive or volcanic rocks (Tucker and Robinson, 1990). As did Tucker and Robinson, Karabinos et al. drew 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 et al. 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 et al., 1985; Ratcliffe and Burton, 1990; Hames et al., 1991), we believe that the Karabinos et al. paper is misleading, chiefly because it relies on an apparent conflict between Taconian ages of metamorphism and arc volcanism to substantiate what we consider is an erroneous, but thought-provoking, conclusion.

Metamorphism of the Laurentian margin must be younger than the Middle Ordovician age of the Walloomsac and Ira Formations based on graptolites of the *C. Bicornis* subzone (Potter, 1972) and conodonts of the *Phragmodus undatus* mid-continent zone (see Ratcliffe et al., 1993). The age of the latter zone is given by a U-Pb zircon date of 453 Ma (Tucker and McKerrow, 1995, p. 375). This age is approximately the same as the age of volcanic activity in the Bronson Hill arc of 454 to 442 Ma (Tucker and Robinson, 1990) and is in accord with $^{40}Ar/^{39}Ar$ ages of hornblende from rocks truly of the Laurentian margin in New England (both from the Walloomsac Formation and thoroughly recrystallized hornblende from the Berkshire and Housatonic massifs) that are ca. 445 Ma (Hames et al., 1991). We fail to see how these and other discussions could have been overlooked by Karabinos et al. (1998) when they concluded that initial collision of the Shelburne arc with the Laurentian margin occurred between 475 and 470 Ma.

We also do not agree that the ages of rocks of the Shelburne Falls arc as defined by Karabinos et al. (1998) are uniquely different from rocks of the Bronson Hill arc, because the ages overlap. Ages of arc rocks in the Vermont part of the Shelburne Falls arc range between 496 ± 8 to 462 ± 6 Ma (Ratcliffe et al., 1997). In central Vermont the Ammonoosac Volcanics are older than 469 ± 1.5 Ma (Aleinikoff and Moench, 1992; Rankin, 1996) and in the Connecticut part of the Shelburne Falls arc as shown by Karabinos et al., intrusive rocks dated at 453 ± 3 to 438 ± 2 Ma (Sevigny and Hanson, 1995) intrude the Collinsville Formation. It appears that rock ages of the Shelburne Falls arc are not uniquely different from ages of rocks from the Bronson Hill arc.

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REPLY

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Ratcliffe et al. raise two issues central to the tectonics of the Taconian orogeny: the location and age of arc-related igneous rocks and the time of impact between Laurentia and the colliding arc. We presented evidence for arc-related igneous activity in western Massachusetts and southern Vermont ranging from 485 to 470 Ma, not 485 to 447 Ma as stated by Ratcliffe et al. The 447 ± 3 Ma age we cited is for a post-Taconian, within-plate granitic pluton that we used to constrain the age of Taconian deformation in western Massachusetts (Karabinos and Williamson, 1994). We contrasted our results with the younger ages of arc-related rocks (454 to 442 Ma) presented by Tucker and Robinson (1990) from central Massachusetts and southern New Hampshire directly across strike from our study area. We then went on to suggest that the older rocks formed above an east-dipping subduction zone preceding the Taconian orogeny (Shelburne Falls arc) and that the younger rocks formed above a west-dipping subduction zone after the orogeny (Bronson Hill arc). Space limitations prevented us from discussing all of the age data bearing on our model, leading Ratcliffe et al. to express some concerns about regions north and south of our study area.

First, Aleinikoff and Moench (1992), working in the northern part of the Bronson Hill arc, reported a U-Pb zircon age of 469 ± 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 ± 4 Ma age for the upper part of the Ammonoosuc Volcanics. The close proximity of both older and younger arc-related rocks is interpreted by Ratcliffe et al. as evidence for only one arc. However, Moench and Aleinikoff (1998, personal commun.) now believe 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. Second, we showed the Shelburne Falls arc extending southward into western Connecticut because major gneiss domes there have at their cores the same unit we dated in the Shelburne Falls and Goshen domes, the Collinsville Formation. Although the age of the Collinsville Formation is not well established in Connecticut, it must be older than Bronson Hill arc rocks dated by Tucker and Robinson (1990), because it was deformed and later intruded by the Brookfield plutonic series (453 ± 3 Ma) and the Newtown gneiss magmatic complex (446 ± 2 to 436 ± 2 Ma) (Sevigny and Hanson, 1995). Thus, it is logical to include 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.

Intrusion of younger plutons into rocks of the Shelburne Falls arc does not preclude the existence of an older arc or the reversal in subduction polarity that we proposed. A much more important problem is the time of collision of the arc with the Laurentian margin. This event marks the end of subduction of oceanic lithosphere and, therefore, of arc magma generation in the east-dipping subduction zone that brought the arc and Laurentia together. The best way to estimate when this collision occurred is to constrain the age of metamorphism of Laurentian margin rocks.

Ratcliffe et al. assert that metamorphism of the Laurentian margin must be younger than the 453 Ma age of the Walloomsac Formation in the western part of the Taconian thrust belt. We argue that metamorphism is time transgressive and older in the eastern part of the Taconian orogen than in the western part. The important question in this context is not when metamorphism of Laurentian rocks ended but rather when it began.

Laird et al. (1984) reported hornblende $^{40}Ar/^{39}Ar$ cooling ages of 471 ± 7 Ma from the Pinney Hollow Formation and 471 ± 6 Ma from the Underhill Formation in northern Vermont. 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. Further, Castonguay et al. (1997) reported muscovite $^{40}Ar/^{39}Ar$ cooling ages of 468 ± 2 and 462 ± 2 Ma from rocks in southern Quebec which they explicitly identified as belonging to the Laurentian margin. These studies indicate that metamorphism of Laurentian margin rocks began before ca. 470 Ma.

Our tectonic model explains existing data better than the model advocated by Ratcliffe et al. in which one very long-lived arc formed continuously above an east-dipping subduction zone for 60 m.y. (496 to 436 Ma)—i.e., before, during, and after the Taconian orogeny. Deformation and metamorphism of the Laurentian margin began by ca. 470 Ma, leading us to conclude that the oceanic lithosphere separating Laurentia and the colliding arc was completely subducted at this time. The Taconian orogeny reflects crustal convergence between Laurentia and this arc, which we identified as the Shelburne Falls arc. Renewed subduction of oceanic lithosphere is needed, however, to account for arc magmas formed from ca. 455 to 440 Ma. We maintain that the most straightforward way to explain the younger arc-related rocks is to propose a west-dipping subduction zone beneath the Laurentian margin, then buttressed by the newly accreted arc terrane. Such a subduction zone could have produced the Late Ordovician magmas in the Bronson Hill arc (coeval with cooling of metamorphic rocks to the west) and accommodated postorogenic plate convergence between Laurentia and Iapetus. This proposed subduction zone is also consistent with evidence for Silurian back-arc rifting in the Connecticut Valley trough (Hepburn, 1991) and models of the Acadian orogeny (e.g., Bradley, 1983).

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