Forum

Does the arc-accretion model adequately explain the Paleoproterozoic evolution of southern Laurentia: An expanded interpretation: COMMENT AND REPLY

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Assembly of lithosphere in southern Laurentia is best interpreted to have taken place along a long-lived (1.8–1.0 Ga) active margin via subduction-accretion processes broadly analogous to present-day convergence between Australia and Indonesia (Karlstrom and Bowring, 1988; Karlstrom et al., 2001, Jessup et al., 2005). Bickford and Hill (2007) challenge this model, and view the Yavapai province to be underlain by older crust and to be the product of continental rifting. This is reminiscent of the arc versus rift debates for Archean greenstone belts in the 1980s. We argue that the four main points in the Bickford and Hill paper are consistent with the arc-accretion model (Bowring and Karlstrom, 1990; Whitmeyer and Karlstrom, 2007).

1) Older Crust: Evidence for older crust and detritus is expected in an accretionary orogen. The Indonesian region is a modern analog involving assembly of a complex collage of terranes onto an older continent. This region has older crustal fragments on which younger island arcs are constructed (e.g., Sumatra but not Java), tectonic imbrication is common, and older detritus can be transported thousands of kilometers in arc-trench systems (Hamilton, 1979). Similarly, in the Proterozoic of the southwestern United States, Nd, Pb, and Hf isotopic data indicate localized older (pre-1.8 Ga) crust. The best-characterized older crust is an isolated exposure of 1.84 Ga Elves Chasm granodiorite, on which part of the 1.75–1.72 Ga arc was built (Hawkins et al., 1996). Bickford and Hill focused on volumetrically minor inherited zircon cores (1.85 Ga, and some Archean) in 1.77 Ga igneous rocks in Colorado and speculated that "Trans-Hudson–Penokean crust, or fragments thereof, underlies much of southern Laurentia" (p. 169). However, without documentation of the extent, age, and tectonic affinities of older crustal components, we caution against assuming that all 1.84 Ga rocks or inherited grains are genetically related, or even originated in the same orogen.

2) Bimodal Volcanism: The assertion that a bimodal (mafic/felsic) composition of volcanic rocks uniquely indicates continental rift zones is overly simplistic. Our studies of the Yavapai province suggest that the 1.8–1.7 Ga metavolcanic rocks are dominantly basaltic to basaltic andesite. Rhyolite-rhyodacite is present, but is volumetrically minor, as is true in oceanic arcs such as Krakatowa and Tonga. Metasedimentary rocks are dominantly greywacke turbidites. Most of the volcanic rocks are contemporaneous with calc-alkaline granitoids. The complete volcanic-plutonic-turbidite associations have no modern analogs in continental rift zones, but are typical of arcs.

3) Ophiolites and Accretionary Complexes: Ophiolites, mélanges, and accretionary prisms have low preservation potential in any orogen, and their rarity in the Southwest is not a surprise given the 10–25-km-deep levels of exposure. In addition to the Grand Canyon accretionary complex (Karlstrom and Williams, 2006) and the 1.73 Ga Payson ophiolite (Dann, 1997), there are numerous other examples of ultramafic rocks, pillow basalts, and chert that have been interpreted as some combination of dismembered ophiolite, tectonic mélange, and other oceanic terranes (e.g., Eisele and Isachsen, 2001; Swift and Force, 2001; Tyson et al., 2002; Cavosie and Selverstone, 2003). These occurrences must be incorporated into any alternate tectonic model (c.f. Bickford and Hill's Fig. 3).

4) Extension and Transpression: Indonesia and other modern analogs have complex stress regimes and networks of linked subduction-transform–spreading ridges (Hamilton, 1979). However, intra-arc and backarc extension, slab roll-back in forearc basins, and transpressive pull-apart basins are distinct from continental rifts. In the Southwest, transcurrent shear zones are present (Bergh and Karlstrom, 1992), but structural studies suggest early crustal thickening via thrust stacking, followed by progressive horizontal shortening by folding, resulting in mainly dip-slip stretching lineations. We know of no data that support their model that major transcurrent shear zones "caused crustal extension and initiation of bimodal volcanism" (Bickford and Hill, 2007, p. 169).

In summary, Bickford and Hill highlight the need for continued efforts to decipher the accretionary history of southern Laurentia, but they offer no new data that require a different or expanded model.

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We were delighted to learn that Karlstrom et al. (2007) had written a Comment on our recent article in *Geology*; one of our major purposes was to stir debate on the origin of the extensive Paleoproterozoic crust of the southwestern United States. This Reply is intended not so much as a point-by-point defense of our earlier arguments, but as a further attempt to promote debate and study of this question.

Karlstrom et al. state that we have challenged the arc-accretion model for the Yavapai Province and "view the Yavapai province to be underlain by older crust and to be the product of continental rifting." Although we suggested that older crust, perhaps as enclaves, must be present and have contributed to the formation of ca. 1750 Ma rocks, we did not rule out the accretion of arcs, but rather suggested that there must have been other operative processes as well. That is why the words "an expanded interpretation" were included in our title. Is it possible that southern Laurentia was a "metacraton" (a region of heterogeneous crust that was variably affected by tectonic events) during the Paleoproterozoic (e.g., Abdelsalam et al., 2002; Liegeois et al., 2003)?

With regard to the involvement of older crust, Karlstrom et al. cite the fact that the Indonesian region is a modern analog involving the assembly of a complex collage of terranes, including older crust, onto an older continent. If this model applies to the Southwest United States, key questions remain: what older crust, and where did it come from? Although "where did it come from?" may be a tough question, "what older crust?" is something that can be determined. We are impressed with the fact that, where studied, inherited zircons are mostly ~1840–1870 Ma, while some others are ca. 2500 Ma, suggesting to us that Trans-Hudson–Penokean crust is present. And, in the Grand Canyon, the Elves Chasm pluton has been dated at 1840 Ma, a solid Trans-Hudson age (Hawkins et al., 1996).

Karlstrom et al. also challenge, as overly simplistic, our observation that much of the Paleoproterozoic crust of the Southwest is strongly bimodal, and likely related to continental rifting. Whereas Karlstrom et al. state that their studies of the Yavapai province "suggest that the 1.8–1.7 Ga metavolcanic rocks are dominantly basaltic to basaltic andesite" and that "rhyolite-rhyodacite is present but volumetrically minor," we note that this is certainly not the case in central Colorado where high-silica rhyolite makes up ~40 percent of exposed metavolcanic rocks, and the rest is tholeiitic basalt (e.g., Boardman and Condie, 1986; Bickford and Boardman, 1984), nor is it evidently true in much of New Mexico, where Robertson et al. (1993) described a 1.765–1.72 Ga basalt-dominated bimodal suite that includes rhyolite, but no andesite. Further, Mazatzal age terranes (ca. 1660–1600 Ma) in both Arizona and New Mexico are described as including voluminous assemblages of rhyolite (e.g., Robertson et al., 1993, and references therein). More to the point, where does all this rhyolite come from if it is not derived from remelting of preexisting crust? We are not aware of juvenile island arcs in which this volume of rhyolite is present.

We accept the suggestion of Karlstrom et al. that accretionary complexes and ophiolites may not be preserved at the crustal levels currently exposed in much of the Southwest. However, in central Colorado, where Paleoproterozoic rocks are in upper greenschist to lower amphibolite facies, pillowed basalts and basaltic breccias are beautifully preserved. Indeed, near Salida there is a thick section of basaltic lapillistone that even preserves cross-bedding (Boardman, 1986). To our knowledge, however, there are no preserved ophiolites or accretionary complexes in this region.

Finally, with regard to crustal extension and initiation of bimodal volcanism, our suggestion was part of a proposed model (a "tentative scenario", as we put it) to stimulate discussion and further research. We think our proposed model is testable through (1) sensitive high-resolution ion microprobe (SHRIMP) dating of inherited components in zircons to determine the age and distribution of older crust; (2) study of the chemistry, particularly the isotopic chemistry, of the extensive bimodal volcanic suites by Sm-Nd whole-rock methods and Hf isotopic methods in zircons; and (3) further structural and geochronological studies of exposed shear zones.

We again wish to express our pleasure that our article has stimulated discussion in *Geology*, and we encourage others interested in this aspect of the crustal evolution of Laurentia to write additional comments.

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