Forum

Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time: Comment and Reply

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I agree with my friend Bob Stern that the onset of actualistic plate tectonics is an unsolved problem, and that the answer must ultimately come from geological evidence and not from model calculations. There are simply too many unknown factors (e.g., eclogitization, oceanic crustal delamination) that could have affected lithospheric buoyancy in the early Earth.

There are, however, diagnostic products of subduction not considered by Stern (2005). Arc magmatism is genetically linked to lithospheric subduction and is distinctive in type and distribution. Arc magmatism occurred throughout the Proterozoic and Archean (Hoffman, 1989). The example I am most familiar with is the Great Bear magmatic zone (1875–1845 Ma) in the northwest of the Canadian Shield. This linear 1000-km-long by 100-km-wide zone was originally interpreted as a magmatic arc related to east-dipping subduction on the basis of petrology, petrochemistry, geochronology, aeromagnetics, and tectonic setting (Hildebrand et al., 1987; Hoffman, 1987). Deep seismic reflection profiling later revealed east-dipping mantle reflections at a depth of ~100 km beneath the zone, which "almost certainly represent a subduction surface associated with arc development" (Cook et al., 1999, p. 1). They are among the strongest mantle reflections of any age. Equally significant is the tectonic setting of the magmatic arc, which initiated ≤7 m.y. after the collision of an exotic island arc with a west-facing passive continental margin (Hoffman, 1980; Hildebrand et al., 1987; Bowring and Grotzinger, 1992; Gandhi and van Breemen, 2005). It shows that the Andean-type magmatic arc developed as a consequence of arc-continent collision and subduction polarity reversal. This process, presently underway in Taiwan (Suppe, 1984), has long been recognized as the fundamental means through which passive margins become active margins (McKenzie, 1969, their Fig. 13). The Great Bear magmatic zone is just one of countless former magmatic arcs indicating lithospheric subduction long before the Neoproterozoic. Moreover, Archean boninites (Kerrich et al., 1998), boninitic komatiites (Parman et al., 2003), and ultrahigh-pressure crustal xenoliths (Schulze et al., 2003) indicate that subduction began much earlier.

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REPLY: doi: 10.1130/G23026.1

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I thank Paul Hoffman for his comments about my paper "Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time," and appreciate the opportunity this provides for continuing the discussion. Hoffman and I agree that the question of when plate tectonics (PT) began is an unsolved problem, one that will be answered by examining Earth's geologic record. Hoffman does not object to my paper's linchpin argument that the excess density of oceanic lithosphere sinking in subduction zones powers plate motions, nor to the corollary that subduction—ergo, modern-style PT—could not have begun until oceanic lithosphere became denser than underlying asthenosphere. I take this as tacit approval of the paper's central geophilosophical tenet, that it is the density of oceanic lithosphere—and the evolution of this through time—that has determined Earth's tectonic style. This requires rejection of the idea that plates moved faster in the Archean than they do now because the Earth was hotter and thus convected faster. Nor does Hoffman object to 1) the importance placed on the evidence of PT, or to 2) the conclusion that these only occur or become common from Neoproterozoic time onward. Hoffman and I differ about whether or not this indicates that PT began in Neoproterozoic time, partly because he argues that there are other diagnostic products of subduction that I did not consider, which indicate an earlier start to PT. Hoffman specifically refers to arc magmatism, using as an example the 1875–1845 Ma Great Bear magmatic zone in NW Canada; its association with underlying dipping mantle reflectors, etc. This is a strong argument—one that I specifically acknowledge—that something very similar to modern PT occurred at that time: "Some ophiolites were

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generated and emplaced ca. 2.0–1.95 Ga, but ophiolites are uncommon in the rest of the Paleoproterozoic and Mesoproterozoic record. Paleoproterozoic ophiolites may represent a short-lived or aborted episode of subduction tectonics…" (Stern, 2005, p. 558). These observations are similar to the evidence that Hamilton (2003) used to argue that plate tectonics began in Paleoproterozoic time.

It should be emphasized that I focused on when the modern episode of plate tectonics began, and why such an onset is expected to have happened later rather than earlier in Earth history; I offered no insights about what happened before PT onset in Neoproterozoic time. Hoffman's comment focuses on pre-Neoproterozoic tectonics, so it is clear we have different perspectives on the same problem. For that reason, it may be useful to consider more generally the full range of possible scenarios. One is that PT began very early in Earth history, perhaps during Hadean time (>4.0 Ga; Harrison et al., 2005), and has continued without interruption. Another possibility is that PT began relatively late in Earth history—similar to what Hamilton (2003) and I conclude—and the previous tectonic style was fundamentally different. A final possibility is that the Earth has a more complex thermal history than we have yet imagined. It could be that something like modern PT started early—perhaps during Archean or Paleoproterozoic time—and then stopped. The Paleoproterozoic episode may have been an early, short-lived episode in which PT began but failed after a few hundred million years because the oceanic lithosphere was not quite dense enough to continue to subduct.

To resolve this controversy, we need to agree on the criteria that constitutes convincing geologic evidence of PT. I explicitly identified three criteria, while Hoffman identifies others, principally arc magmatism. In his comment, Hoffman states "Arc magmatism occurred throughout the Proterozoic and Archean," but arc magmatism is much more of an interpretation 'in the eye of the beholder' than are ophiolites, blueschists, and UHP terranes. Modern arc magmas have distinctive geochemical characteristics (Stern, 2002), but there should be other ways to cause (non-PT) wet melting of the mantle on a watery planet like Earth. We should be careful not to over-interpret the tectonic significance of igneous rocks and deformation, especially when there are other, more compelling arguments for the operation of PT. We know that Venus and Mars do not have PT, yet there is evidence for igneous activity and deformation. Similarly, the pre-PT Earth would have experienced a lot of magmatic and tectonic activity. Perhaps the pre-PT Earth was dominated by deformation and magmatism associated with delamination of the lower crust and mantle lithosphere (Jull and Kelemen, 2001; Anderson, 2005; Bédard, 2006).

It will not be easy to recognize the igneous and tectonic fingerprints of a pre-PT world. We may make some real progress in this discussion if we think broadly about what ancillary effects the start of PT would have on the Earth system and look for this evidence as well. A tectonic revolution of this magnitude should have an effect on the climate (Snowball Earth) and perhaps on Earth's moment of inertia and rotational behavior (True Polar Wander). What else would be affected?

This may be the most important reason that my study and this discussion are useful; the controversy may stimulate a much-needed effort to address a related set of fundamental, unresolved questions about Earth history: when did plate/subduction tectonics begin, what was the earlier tectonic style, and how was the transition accomplished? Without this inquiry into such fundamental questions about our planet's evolution, our understanding of the Earth system is woefully incomplete.

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