ABSTRACT
Geodynamic models for supercontinent assembly, whereby the dispersing continental fragments of a supercontinent break up and migrate from geoid highs to reassemble at geoid lows, fail to account for the amalgamation of Pangea. Such models would predict that the oceans created by continental breakup in the early Paleozoic (e.g., Iapetus, Rheic) would have continued to expand as the continents migrated toward sites of mantle downwelling in the paleo-Pacific, reassembling an extroverted supercontinent as this ocean closed. Instead, Pangea assembled as a result of the closure of the younger Iapetus and Rheic Oceans. Geodynamic linkages between these three oceans preserved in the rock record suggest that the reversal in continental motion may have coincided with the Ordovician emergence of a superplume that produced a geoid high in the paleo-Pacific. If so, the top-down geodynamics used to account for the breakup and dispersal of a supercontinent at ca. 600–540 Ma may have been overpowered by bottom-up geodynamics during the amalgamation of Pangea.

Keywords: Pangea, geodynamics, supercontinents, Appalachian orogen, Terra Australis orogen.
In the early Paleozoic, Laurentia and Gondwana were surrounded by the paleo-Pacific Ocean, vestiges of which are preserved in the Terra Australis orogen, which extends from eastern Australia and Tasmania into New Zealand, the Transantarctic Mountains, southern Africa, and South America (Fig. 1; Cawood, 2005). Subduction along this margin began at ca. 580 Ma (Cawood and Buchan, 2007) and continued until the end of the Paleozoic, by which time the orogen was distributed along the periphery of Pangea. The orogen is interpreted to have formed by accretionary processes without the involvement of major continental collisions. Its evolution is best documented in the Adelaide, New England, and Lachlan fold belts of eastern Australia (Collins, 2002; Gray and Foster, 2004). The most complete record of continental-margin evolution is preserved in the Adelaide fold belt, where Neoproterozoic to Cambrian passive-margin sedimentary successions occur in a series of rift-sag basins. Abundant early Paleozoic volcanic complexes and intra-oceanic sequences are preserved in the New England fold belt, and the 700-km-wide Lachlan fold belt is dominated by 520–480 Ma oceanic volcanic rocks overlain by a blanket of sediments analogous to the modern Bengal fan. Between 440 and 400 Ma, intra-oceanic arc and basin development recorded in these belts by sedimentary and mafic volcanic rocks is interpreted to reflect the retreat of the subducted slab during episodes of upper-plate extension and basaltic magmatism, and transient flat subduction attributed to the arrival of buoyant oceanic plateaus (Collins, 2002).

Intra-oceanic subduction in the paleo-Pacific Ocean was clearly well established ~80 m.y. before subduction commenced in the Iapetus Ocean (Cawood and Buchan, 2007) and before the Rheic Ocean opened. According to conventional geodynamic models, slab-pull forces associated with this subduction should have resulted in the migration of the dispersing continents toward the paleo-Pacific subduction zones, as was the case when the Iapetus Ocean opened. However, this motion reversed itself when subduction commenced in the relatively newly formed Iapetus and Rheic Oceans between Laurentia, Baltica, and Gondwana. During the
assembly of Pangea, therefore, subduction was not only initiated within the new interior oceans, but the rates of subduction of this relatively young Paleozoic lithosphere must also have overpowered those of the already well established subduction zones within the exterior (paleo-Pacific) ocean. Thus, rather than forming by extroversion, as most geodynamic models would predict, the formation of Pangea was actually achieved by introversion (see Fig. 2).

**GEODYNAMIC SCENARIO**

A key problem that needs to be addressed in resolving this conundrum is the geodynamic scenario that facilitated the initiation of subduction in the Iapetus and Rheic Oceans and generated sufficient slab pull to drive the dispersing continental fragments toward the Pangea configuration. Subduction initiation is controversial, although it is generally accepted that initiation at passive margins is mechanically difficult because of the flexural rigidity of the oceanic lithosphere (Cloetingh et al., 1989). No simple modern analogues for such a process have been documented. On the other hand, Stern and Bloomer (1992) and Stern (2004) showed that intra-oceanic subduction initiation along the Azores-Bonin-Mariana arc system occurred along a transform system where younger, less dense oceanic lithosphere was in contact with older, denser lithosphere. This was followed by rapid trench retreat and voluminous mafic (including boninitic) magmatism as the older lithosphere subducted beneath the younger, and it is consistent with geodynamic models that show subduction initiation followed by rapid back-arc extension (Gurnis et al., 2004). A modern analogue for this process may be occurring along the Atlantic margin beneath Gibraltar, where subduction initiation of the Atlantic has been documented at the eastern end of the Azores-Gibraltar transform fault (Gutscher et al., 2002).

Within the Iapetan realm, such a scenario would have existed in the early Paleozoic along boundaries been the young Iapetus and old paleo-Pacific oceanic lithosphere (see Figs. 2B and 2C). Such boundaries are a requirement of supercontinent breakup. The high angle between these boundaries and the Iapetus ocean ridge suggests that they had a strong strike-slip component and, hence, were likely sites for transform faults to nucleate. The age of the paleo-Pacific oceanic lithosphere adjacent to these transform faults may never be known, but it is almost certain to have been older than the adjoining interior (Iapetus) oceanic lithosphere. The age and density contrast between them, and therefore the most favorable conditions for subduction initiation, would have been most pronounced when the Iapetus Ocean was young. We view this to be the most favorable geodynamic scenario for the origin of the arc-related oceanic complexes that were respectively obducted onto the margins of Laurentia and Baltica during the ca. 500–480 Ma Taconic and Grampian orogenies (see van Staal et al., 1998). The implication of this interpretation is that these mafic arc-related complexes were formed from the subduction of paleo-Pacific, rather than Iapetan, lithosphere in a manner analogous to the Scotia arc and the Mesozoic-Cenozoic “capture” of the subduction zones around the Caribbean plate within the Atlantic realm (e.g., Pindell et al., 2006). The evolution of the Iapetan–paleo-Pacific plate boundaries would have depended on a number of factors, including the spreading rate at the Iapetan ridge, the drift of the dispersing continents, and the rate of rollback of the subduction zone. However, the presence of boninites and mafic sheeted dikes in Iapetan ophiolitic complexes (e.g., Béard et al., 1998) indicates that forearc extension, and hence slab rollback, occurred. The strike of an arc produced in this fashion would have been oriented at a high angle to the Iapetan ocean ridge, and this geometry would have facilitated its subsequent obduction (see Suhr and Cawood, 1993). However, as pointed out by Gurnis et al. (2004), subduction zones initiated in this manner cannot pull the large overriding plates toward them, and so cannot be considered a mechanism that began the assembly of Pangea.

Global reconstructions (e.g., Scotese, 1997; Stampfl i and Borel, 2002) imply that assembly of Pangea began after the closure of the Iapetus Ocean. They also imply that the rate of subduction of Rheic Ocean lithosphere exceeded subduction rates in the paleo–Pacific Ocean despite the fact that subducted Rheic oceanic lithosphere was a maximum of 60 m.y. old, and that subduction zones were already well established in the paleo–Pacific Ocean.

Although the causes are hotly debated, a geodynamic linkage between tectonic events in the Rheic and paleo–Pacific Oceans is suggested by the dramatic change in tectonic environment of paleo-Pacific subduction zones between 440 Ma and 420 Ma, best documented in the Lachlan fold belt of eastern Australia (e.g., Gray and Foster, 2004), the time at which the Iapetus Ocean was closing and subduction within the Rheic Ocean was commencing.

Proxy records for oceanic lithosphere evolution are also consistent with this linkage. Rapid sea-level rise in the Cambrian and Early Ordovician (e.g., Hallam, 1992), generally attributed to the development of relatively young, elevated Iapetan oceanic lithosphere, gave way to a drop in sea level from the Late Ordovician to the Carboniferous, implying that the average age of the oceanic lithosphere increased during the middle to late Paleozoic. This trend is compatible with preferential subduction of relatively young Rheic Ocean lithosphere over older paleo-Pacific oceanic lithosphere. Similarly, compared to the early Paleozoic, the lower initial 87Sr/86Sr value deduced for ocean waters in the late Paleozoic (e.g., Veizer et al., 1999) implies an increase in the rate of seafl oor spreading. Taken together, the sea-level and Sr isotope data suggest that any increased seafl oor spreading in the paleo–Pacific Ocean during Pangea assembly was compensated, not by subduction of old paleo-Pacific lithosphere, but by subduction of newer Rheic Ocean lithosphere.

Top-down geodynamic models adequately account for the early Paleozoic dispersal of continents, but they cannot account for the middle to late Paleozoic introversion that resulted in the amalgamation of Pangea. This conundrum suggests that top-down geodynamic forces can be overridden by other forces. Assuming that continents migrate from geoid highs to geoid lows, the reversal of their movement in the middle Paleozoic implies that the geoid lows became geoid highs. The mechanisms for this are unclear. However, one possibility is that the descent of subducted slabs in the paleo–Pacific Ocean to the core-mantle boundary thermally insulated that boundary, leading to the ponding of hot mantle material that built up and rose toward the surface as a superplume (Zhong and Gurnis, 1997; Condie, 1998; Tan et al., 2002). Such an event would result in a geoid high and enhanced seafl oor spreading in the paleo–Pacific Ocean that could have been responsible for the reversal in the direction of motion of the continents. In this scenario, “top-down” tectonics of the early Paleozoic gave way to “bottom-up” tectonics in the late Paleozoic. An Ordovician superplume has been proposed by Condie (2004) to account for the period’s high sea levels, high paleotemperatures, abundant black shales, and strong biological activity.

**CONCLUSIONS**

The amalgamation of Pangea cannot be explained by top-down geodynamic models. If these principles are applied to an Early Ordovician world, they would not generate Pangea in the correct configuration. Instead, the geologic record implies that the rates of subduction in the relatively new interior oceans (e.g., the Iapetus and Rheic Oceans) exceeded those in the exterior paleo–Pacific Ocean. Geodynamic linkages between subduction in the interior and exterior oceans are implied by dramatic changes in the style of subduction in the paleo-Pacific that coincide with the onset of subduction in the Rheic Ocean. Assuming continents migrate from geoid highs to geoid lows, then the reversal in continental motions that led to the formation of Pangea may have coincided with the emergence of a geoid high in the paleo–Pacific during the Ordovician.
We tentatively suggest that this may reflect the formation of a superplume, for which there is independent, supporting evidence in the rock record. If so, the preferential destruction of interior oceans, required to produce introverted supercontinents such as Pangea, may occur when top-down tectonics give way to bottom-up tectonics.

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