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A comparison of the evolution of arc complexes in Paleozoic interior and peripheral orogens: Speculations on geodynamic correlations

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ABSTRACT

We discuss the potential geodynamic connections between Paleozoic arc development along the flanks of the interior (e.g. the Iapetus and Rheic) oceans and the exterior Paleopacific Ocean. Paleozoic arcs in the Iapetus and Rheic oceanic realms are preserved in the Appalachian–Caledonide and Variscan orogens, and in the Paleopacific Ocean realm they are preserved in the Terra Australis Orogen. Potential geodynamic connections are suggested by paleocontinental reconstructions showing Cambrian–Early Ordovician contraction of the exterior ocean as the interior oceans expanded, and subsequent Paleozoic expansion of the exterior oceans while the interior oceans contracted. Subduction initiated in the eastern segment of Iapetus at ca. 515 Ma and Early to Middle Ordovician orogenesis along the flanks of this ocean is highlighted by arc–continent collisions and ophiolite obductions. Over a similar time interval, subduction and orogenesis took place in the exterior ocean and included formation of the Macquarie arc in the Tasmanides of Eastern Australia and the Famatina arc and correlatives in the periphery of the proto-Andean margin of Gondwana. Major changes in the style of subduction (from retreating to advancing) in interior oceans occurred during the Silurian, following accretion of the peri-Gondwanan terranes and Baltica, and closure of the northeastern segment of Iapetus. During the same time interval, subduction in the Paleopacific Ocean was predominantly in a retreating mode, although intermittent episodes of contraction closed major marginal basins. In addition, however, there were major disturbances in the Earth tectonic systems during the Ordovician, including an unprecedented rise in marine life diversity, as well as significant fluctuations in sea level, atmospheric CO_2, and $^{87}Sr/^{86}Sr$ and ^{13}C in marine strata carbonates. Stable and radiogenic isotopic data provide evidence for the addition of abundant mantle-derived magma, fluids and large mineral deposits that have a significant mantle-derived component. When considered together, the coeval, profound changes in the style of tectonic activity and the disturbances recorded in Earth Systems are consistent with the emergence of a superplume during the Ordovician. We speculate that the emergence of a superplume triggered by slab avalanche events within the Iapetus and Paleopacific oceans was associated with the establishment of a new geoid high within the Paleopacific regime, the closure of the interior Rheic Ocean and the amalgamation of Laurussia and Gondwana, which was a key event in the Late Carboniferous amalgamation of Pangea.

1. Introduction

In the classical Wilson cycle, oceanic crust generated during supercontinent breakup (the “interior ocean”) is consumed during subsequent amalgamation so that the supercontinent turns “inside in” (introversion, Murphy and Nance, 2003). Alternatively, following supercontinent breakup, the exterior margins of the dispersing continental fragments collide during reassembly so that the supercontinent turns “outside in” (extroversion). Irrespective of whether a supercontinent forms by introversion or extroversion, orogenic activity attending the assembly and amalgamation of a supercontinent typically occurs by subduction-related then collisional orogenesis, with the resulting orogenic belts occurring in the interior of the supercontinent, known as interior orogens (Murphy and Nance, 1991). Elimination of subduction zones between the colliding blocks results in their relocation to the periphery of the supercontinent, resulting in peripheral orogens (Murphy and Nance, 1991), a general term to describe all types of activity along the periphery of supercontinents, including orogenesis due to subduction and accretionary processes (e.g. Cawood and Buchan, 2005).

The final breakup of the supercontinent Rodinia between 650 and 540 Ma is a manifestation of fundamental changes to global plate

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motions during the Late Neoproterozoic (Fig. 1a,b; Dalziel, 1997; Hoffman et al., 1998; Murphy et al., 2004; Cawood, 2005; Meert and Lieberman, 2008; Pisarevsky et al., 2008). New oceanic lithosphere developed between the diverging plates leading to the development of interior oceans, (e.g. the Iapetus Ocean, Murphy and Nance, 2003). At about the same time (Early Cambrian), Gondwana became completely amalgamated (e.g. Collins and Pisarevsky, 2005; Collins, 2006) and subduction commenced in the exterior (paleo-Pacific) ocean, evidence of which is preserved in the 18,000 km long Terra Australis orogen (Fig. 1b; TAO, Cawood, 2005).

By the end of the Early Cambrian (ca. 515 Ma), subduction had commenced in the interior Iapetus Ocean (Fig. 1b; van Staal et al., 1998, 2007, 2009) along both of its margins. Although punctuated by obduction of oceanic lithosphere and several episodes of terrane accretion, subduction continued more-or-less continuously in the interior oceans throughout the remainder of the Paleozoic, culminating in Late Paleozoic terminal collision and the amalgamation of Pangea. Similarly, the TAO preserves evidence of subduction adjacent to the flanks of the exterior paleo-Pacific ocean. Beginning locally at ca. 580 Ma, subduction was established along the entire length of the TAO by 550 Ma and continued until ca. 230 Ma (e.g. Fig. 1b–g; Cawood, 2005; Cawood and Buchan, 2007).

Although there are abundant recent data documenting the evolution of arcs in the interior and exterior oceans, there is no comprehensive overview that compares their respective evolutions and investigates potential geodynamic connections. Paleocontinental reconstructions (e.g. Scotese, 2001, 2004; Stampfli and Borel, 2002; Winchester et al., 2002) suggest the possibility of geodynamic connections in that the exterior ocean contracts as the interior oceans expand in the Early Paleozoic, whereas the interior oceans contract as the exterior ocean expands in the Late Paleozoic. In this paper we compare the evolution of arcs in interior and exterior oceans and assess potential geodynamic connections. The challenges and caveats associated with this approach have been outlined by Lister et al. (2001). Nevertheless, our purpose is to generate a broader discussion of the globally widespread Early Paleozoic arc magmatism, which seems to have been mainly peri-cratonic in nature, in which events in the interior and exterior oceans are investigated as part of a global tectonic system.

2. Arc development in the Iapetus oceanic tract

A combination of lithostratigraphic, geochronologic and paleomagnetic data indicate that the Iapetus Ocean opened in stages. Laurentia separated from Baltica between ca. 600 and 570 Ma, and from West Gondwana not later than ca. 570 Ma (Cawood et al., 2001; Cawood and Pisarevsky, 2006; McCausland et al., 2007). Separation of microcontinents from the Laurentian margin at ca. 540–535 Ma (e.g. Meert et al., 1998; Cawood et al., 2001) happened along the full length of the margin (e.g. Chew et al., 2010) and resulted in development of the Humber Zone passive margin and the Taconic seaway, which extends ca. 2000 km along the Laurentian margin (Hibbard et al., 2007b). These microcontinental ribbons are known as the Dashwoods terrane in the northern Appalachians (Fig. 1b; Waldron and van Staal, 2001) and the Precordillera in the southernmost Appalachians (Thomas and Astini, 1996, 1999).

By the late Early Cambrian (ca. 515 Ma), subduction of the Iapetus oceanic tract had initiated along both the Laurentian and Gondwanan margins producing western Pacific-type arc–back arc systems (Figs. 1b and 2; van Staal et al., 1998). Preserved ophiolitic complexes along both margins typically exhibit supra-subduction zone geochemical affinities (Jenner and Swinden 1993; Swinden et al., 1997; Bédard et al. 1998; Lissenberg et al., 2005; Zagorevski et al., 2006). The Ordovician to Devonian evolution of the Laurentian margin was first dominated by accretion of peri-Laurentian followed by peri-Gondwanan terranes (Fig. 3) which include Carolinia and Ganderia (which have been correlated, e.g. Hibbard et al., 2007b), Avalonia and Meguma. Accretion of the peri-Gondwanan terranes is in many ways analogous to the Mesozoic–Cenozoic transfer of the Cimmerian terranes from of Gondwana to Asia (e.g. Stampfli and Borel, 2002). However, the record of these accretionary events is overprinted, to varying degrees, by Devonian and Carboniferous orogenesis after Iapetus had finally closed in the Late Silurian and by terminal late Paleozoic Alleghenian collision between Laurussia and Gondwana. In the northern Appalachians, closure of the Iapetus Ocean was followed by northwestward-directed subduction of Rheic oceanic lithosphere beneath Laurentia (Murphy et al., 2011; van Staal et al., 2009), but in the southern Appalachians, the polarity of Rheic subduction is more contentious (Hibbard et al., 2010).

Outboard of the Dashwoods terrane, Iapetan subduction was initially directed oceanward leading first to collision between the peri-Laurentian ribbon, such as Dashwoods, and an outboard 515–500 Ma ensimatic arc (Fig. 2; van Staal et al., 1998; 2007; Hibbard et al., 2007a,b). This collision was generally followed by re-accretion of the now composite and magmatically active Dashwoods ribbon continent (e.g. Notre Dame arc on Dashwoods) to Laurentia (Waldron and van Staal, 2001). These events are collectively assigned to the mainly Early to Middle Ordovician Taconic orogeny, which preserves evidence for partial obduction of the intervening oceanic material of the Taconic seaway between Dashwoods and the Laurentian margin (Williams, 1979; Dewey et al., 1983; Searle and Stevens, 1984; van Staal et al., 1998, 2007, 2009; Waldron and van Staal, 2001). Following the Taconic orogeny, subduction was solely directed northwestward (i.e. beneath the Laurentian margin) until closure of the Iapetus Ocean by the late Silurian (Fig. 3).

The Precordillera terrane, on the other hand, has a very different history. Instead of re-accreting to Laurentia, it converged upon the proto-Andean margin of Gondwana (Thomas and Astini, 1996, 1999). The absence of an ensimatic late Early–Middle Cambrian arc in this segment of Iapetus apparently allowed uninterrupted travel of the Precordillera terrane to the active Gondwanan margin.

In the northern Appalachians, Late Early Cambrian (ca. 515 Ma) subduction occurred beneath the Ganderian portion of the Amazonian margin of Gondwana (van Staal et al., 1996). Ganderia (van Staal et al., 1998; Hibbard et al., 2007b) is characterized by early Paleozoic passive-margin clastic sedimentary rocks and related arc–backarc sequences such as the Penobscot arc and associated back arc basin, which was floored by oceanic lithosphere (Zagorevski et al., 2007, 2010). Extension induced by slab-rollback probably was responsible for Ganderia's rifting and departure from the Amazonian margin of Gondwana at ca. 505 Ma (Schulz et al., 2007). Early Ordovician (485–480 Ma) closure of the Penobscot backarc basin, while still being in the vicinity of Gondwana, led to a short-lived re-assembly of Ganderia into one coherent terrane, which was the principal cause of the Penobscot orogeny in the northern Appalachians. Shortly thereafter (ca. 475 Ma), Ganderia was split-up again due to Middle Ordovician backarc spreading, which led to formation of the Popelogan–Victoria arc, the Tetagouche-Exploits backarc basin and the trailing Gander margin (van Staal, 1994; van Staal et al., 1996, 1998; Zagorevski et al., 2007, 2010). The Penobscot orogenic event may have been more complex in the British Isles and may even have led to oblique accretion of Avalonia and Ganderia (Valverde-Vaquero et al., 2006) in the Caledonides. The Penobscot orogeny is absent in the southern Appalachians, principally because Carolinia, the leading edge of the peri-Gondwanan terranes, was consistently positioned in a lower plate setting during its drift towards Laurentia (Hibbard, 2000). The Penobscot orogeny overlaps in time with the early stages of the Taconic orogeny, but paleocontinental reconstructions based on multiple lines of evidence (e.g. Cocks and Torsvik, 2002; Stampfli and Borel, 2002) for the Cambrian–Ordovician show that they were 3000–4000 km apart, and hence, not directly related.

Following the Penobscot and Taconic orogenies, the remaining Iapetus oceanic tract in the northern Appalachians and British