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A magma-poor rift model for the Cordilleran margin of western North America

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ABSTRACT

The Cordilleran margin of western North America has an uncertain rift evolution that includes >300 m.y. of lithospheric extension, breakup, and syn- to post-breakup magmatism. Here I use the Newfoundland-Iberia rift system as a modern analogue to evaluate Cordilleran margin development and propose a magma-poor rift model for western North America. After polyphase Tonian–Ediacaran rifting, early Cambrian breakup resulted in a base-level fall and generation of the basal Sauk I megasequence boundary. A lower to middle Cambrian breakup succession developed over this lithospheric breakup surface and from bottom to top consists of lowstand, transgressive, and highstand systems tract deposits. Lower Cambrian volcanic strata are recognized in proximal breakup successions and predicted to be more voluminous in outboard regions with hyperextended crust and exhumed mantle. Off-axis, post-breakup volcanic strata were generated during the release of in-plane tensile stresses and focusing of extension toward the nascent plate boundary. These findings suggest that ancient magma-poor rift assemblages, including those affected by later convergent tectonism, can preserve their original stratigraphic attributes and be successfully identified in the geological record.

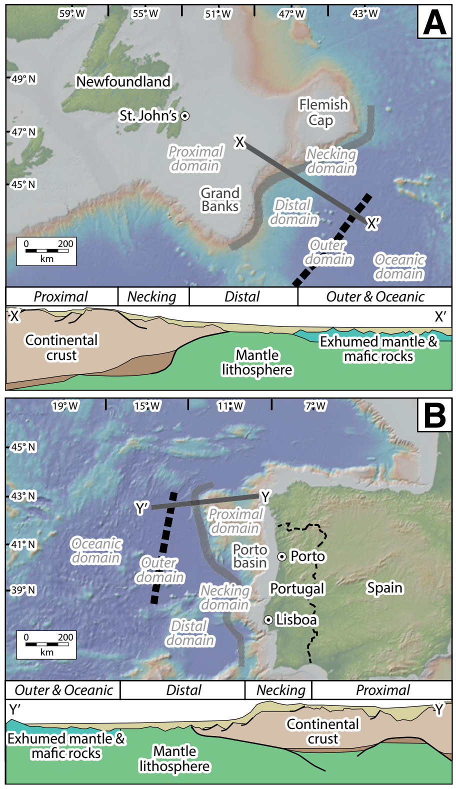

Figure 1. Continental margin maps, schematic cross-sections, and architectural elements after Péron-Pinvidic et al. (2013). Solid gray line shows necking domain; dashed black line shows outer domain. A: Newfoundland margin. B: Iberia margin.

INTRODUCTION

There is growing consensus for two end-members of rifted continental margins: (1) magma-rich or volcanic rifted margins, which result from the upwelling of anomalously hot mantle, coeval rupturing of continental and mantle lithosphere, and subsequent eruption of flood basalts; and (2) magma-poor or non-volcanic rifted margins, which are the sites of extreme thinning, rupture of continental lithosphere before that of mantle lithosphere, and limited synrift magmatism (e.g., Franke, 2013; Doré and Lundin, 2015). The Newfoundland-Iberia conjugate margins (Figs. 1A, 1B) are type examples of magma-poor rifting, in part based on the recognition of hyperextended crust and continental mantle blocks in deep-water regions of the North Atlantic Ocean (e.g., Tucholke et al., 2007). These and other architectural elements preserve the evidence for depth-dependent extension and exhumation along magma-poor margins (e.g., Huismans and Beaumont, 2014). North Atlantic rift scenarios further predict the deposition of breakup successions during breakup-related uplift (Soares et al., 2012) and off-axis, post-breakup magmatism across the embryonic plate boundary (Jagoutz et al., 2007).

In this article, I compile observations from the modern Newfoundland-Iberia rift system to propose a magma-poor rift model for the Neoproterozoic–early Paleozoic Cordilleran margin of western North America (Figs. 2, 3). As in the Newfoundland-Iberia rift system, I argue here that Cordilleran rift evolution included (1) depth-dependent extension with lithospheric thinning and exhumation; (2) deposition of breakup succession strata; and (3) off-axis, post-breakup volcanism. The presented model illustrates the utility of stratigraphic analysis in magma-poor margin identification, especially for rift systems affected by later convergent tectonics and terrane accretion.

SUMMARY OF NEWFOUNDLAND-IBERIA RIFT EVOLUTION

Triassic–Early Cretaceous Stretching and Thinning

A major outcome of magma-poor rift research has been the recognition of proximal, necking, distal, outer, and oceanic domains (Figs. 1A, 1B) that record the progressive localization of rifting toward the area of eventual breakup (Péron-Pinvidic et al., 2013). Triassic–Early Cretaceous proximal domain basins along Portugal and Newfoundland formed during moderate crustal stretching and contain syntectonic strata that are as young as Oxfordian–Berriasian (ca. 161–140 Ma) and Kimmeridgian–Valanginian (ca. 155–138 Ma), respectively (Fig. 4A; Péron-Pinvidic et al., 2013). The necking domain is a region of highly thinned crust, such as the continental slope at the edge of the Grand Banks (Fig. 1A), and characterized by faulting that affects the upper crust and lower crust–upper mantle. Along the Portuguese margin, tilted Tithonian (ca. 151–145 Ma) rocks of the necking domain were overlapped by syntectonic Berriasian to Aptian (ca. 145–112 Ma) strata (e.g., Péron-Pinvidic et al., 2013).

Early to Mid-Cretaceous Hyperextension and Mantle Exhumation

The distal and outer domains evolved during the advanced phases of rift development. Hyperextended continental crust and serpentinized mantle within the North Atlantic distal domains were likely exhumed along Valanginian (ca. 138 Ma) to Aptian-Albian (ca. 112 Ma) low-angle normal faults (Fig. 4A; Péron-Pinvidic et al., 2013). The outer domains comprise narrow corridors of exhumed mantle and mafic

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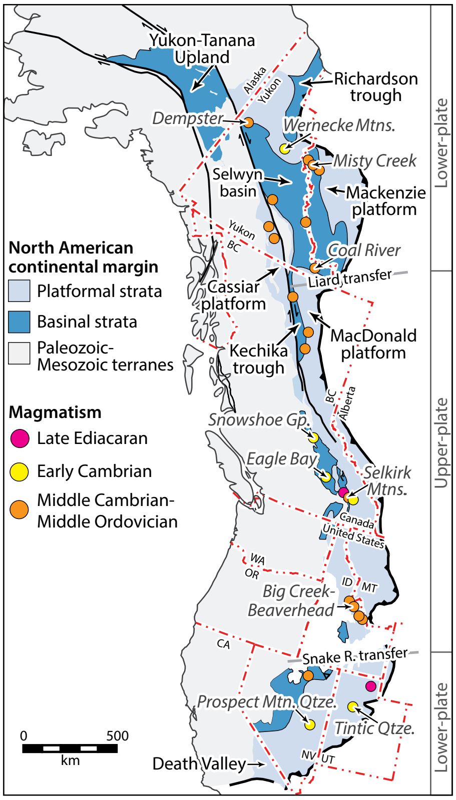

Figure 2. Ediacaran–early Paleozoic magmatic rocks and basins of the North American Cordillera adapted from Colpron and Nelson (2009) and Lund (2008). Lower- and upper-plate divisions are from Lund (2008). References for Cordilleran magmatism are provided in the GSA Data Repository[1]. Gp.—Group; R.—river, Mtns.—Mountain, Qtze.—Quartzite.

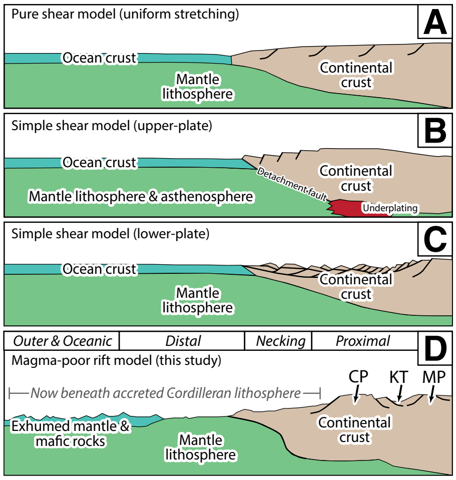

Figure 3. Rift models for the Cordilleran margin. A: Pure shear extension (e.g., Bond et al., 1985). B: Simple shear extension along an upper-plate margin (Lund, 2008). C: Simple shear extension along a lower-plate margin (Lund, 2008). D: Magma-poor rift model (this study) with elements in the Canadian Cordillera. CP—Cassiar platform, KT—Kechika trough, MP—MacDonald platform.

rocks (e.g., Ocean Drilling Program Site 1070; Tucholke et al., 2007), which juxtapose inboard elements with oceanic domain units that define the continent-ocean boundary.

Early to Mid-Cretaceous Magmatism and Breakup Successions

The transition from hyperextension-exhumation to Aptian–Albian lithospheric breakup was coincident with magmatism that spanned the proximal to outer domains (Fig. 4A). Magmatic activity was most voluminous in the outer domain, where it triggered the separation of Newfoundland-Iberia and onset of seafloor spreading (Bronner et al., 2011). Off-axis magmatism continued into the Cenomanian (ca. 96 Ma) and reflects low-degree decompressional melting during the release of in-plane tensile stresses and focusing of extension toward the nascent plate boundary (Jagoutz et al., 2007). A plume-related origin was rejected by Jagoutz et al. (2007) based on the small magmatic volume and isotopic composition of rocks on either side of the Mid-Atlantic Ridge.

The Newfoundland-Iberia margins contain breakup successions (Fig. 4A; breakup sequences of Soares et al., 2012) that record the transition from breakup tectonism to thermal subsidence. Soares et al. (2012) reported that the inner proximal Porto Basin (Fig. 1B) has an Albian to Cenomanian (ca. 112–95 Ma) breakup succession with four units that are each ~200 m thick: (1) a basal, progradational unit above the Aptian-Albian unconformity that resulted from a base-level fall; (2) a transgressive unit capped by a maximum flooding surface; (3) an aggradational to progradational unit; and (4) a transgressive unit that signals thermal subsidence. Post-Albian mafic sills are observed within the Newfoundland breakup succession (Soares et al., 2012).

SUMMARY OF CORDILLERAN RIFT EVOLUTION

Tonian–Ediacaran Stretching and Thinning

Continental extension along western Laurentia began by 820 Ma; however, two younger rift phases are recognized in the North American Cordillera (Yonkee et al., 2014). The early phase involved the moderate stretching of initially thick, strong lithosphere and deposition of Tonian–Cryogenian (780–650 Ma) volcanic rocks and nonmarine to marine strata (e.g., Yonkee et al., 2014). Strike-slip deformation likely affected some parts of western Laurentia during the early phase (Strauss et al., 2015). Following a period of thermal subsidence, a later rift phase affected thinner, weaker lithosphere and is recorded by Ediacaran (610–540 Ma) volcanic rocks (Fig. 2) and nonmarine to marine strata that are associated with breakup (e.g., Colpron et al., 2002).

Cordilleran rift models have called for homogeneous pure shear (e.g., Bond et al., 1985) or heterogeneous (Christie-Blick and Levy, 1989) simple shear extension that leads to upper- and lower-plate margins (e.g., Lund, 2008) to explain Tonian–Ediacaran deformation (Figs. 2, 3A–3C). Yonkee et al. (2014) recently proposed a depth-dependent model with lithospheric thinning and necking, and concluded that Cordilleran margin development is akin to North Atlantic rift evolution. This hypothesis is consistent with the geophysical results of Hayward (2015), who suggested that hyperextended Laurentian basement and exhumed mantle exist beneath the accreted terranes of western Canada.

Early Cambrian Sedimentation and Magmatism

Lower to middle Cambrian strata of the Sauk I megasequence have been important for dating Cordilleran passive margin development. In the Canadian Rocky Mountains, Terreneuvian to Cambrian Stage 3 shelf strata of the Hamill Group presumably document the timing of postrift thermal subsidence (e.g., Bond et al., 1985). Coeval strata of the western United States, such as the Wood Canyon Formation and Zabriskie Quartzite (Death Valley, California) and Brigham Group (Utah and Idaho), similarly mark the onset of passive margin sedimentation (Yonkee et al., 2014). Mafic volcanic units record ca. 535–520 Ma magmatism along the Cordilleran margin during Sauk I deposition (Fig. 2; Stewart, 1972). Middle to upper Cambrian carbonate strata (Sauk II, III megasequences) cover these clastic and volcanic rock successions (e.g., Colpron et al., 2002).

Lower Paleozoic facies belts along western Laurentia initiated during the Cambrian Period. In Canada, the Mackenzie and MacDonald platforms passed westward into the Selwyn basin, Kechika trough, and Richardson trough (Fig. 2). Platform-to-basin transitions varied from fault controlled to interfingered and gradual (Cecile et al., 1997). The Cassiar platform (Fig. 2) and other highs imply that thick crust was located outboard of the deep-water troughs, similar to the Flemish Cap along Newfoundland (Fig. 1A).

Middle Cambrian–Middle Ordovician Magmatism

Post–early Cambrian magmatism is an enigmatic feature of the Cordilleran passive margin. Field studies in western Canada have long recognized middle Cambrian to Middle Ordovician volcanic piles associated with normal faults and exhalative ore horizons (Fig. 2; e.g., Cecile et al., 1997). Coeval alkaline rocks are also observed in central Idaho and Nevada (Fig. 2; Lund, 2008).

[1]GSA Data Repository item 2017381, references corresponding to magmatic ages in Figure 2, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

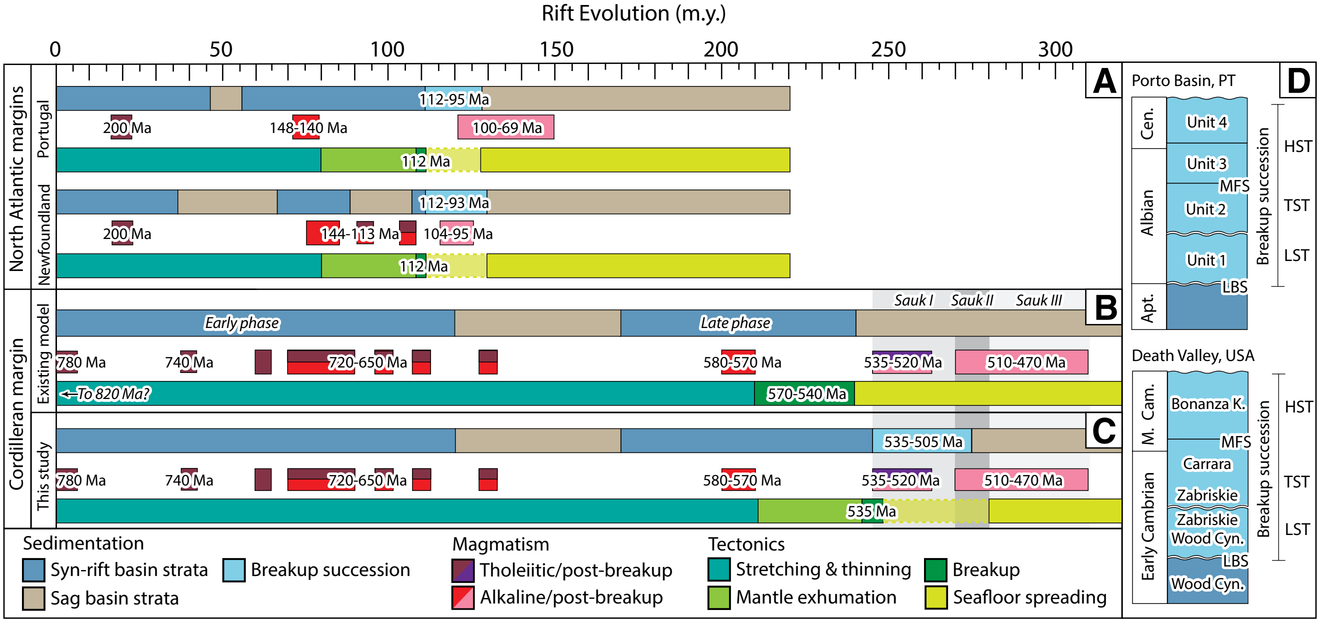

Figure 4. A: Magma-poor rift model for the North Atlantic margins (Péron-Pinvidic et al., 2013 and references therein). B: Existing rift models for the Cordilleran margin (Lund, 2008 and references therein). C: Magma-poor rift model for the Cordilleran margin (this study). D: Breakup successions of the Porto Basin (Soares et al., 2012) and Death Valley (California) (this study, based on Keller et al., 2012). Apt.—Aptian, Cen.—Cenomanian, Cyn.—Canyon, HST—highstand systems tract, LBS—lithospheric breakup surface, LST—lowstand systems tract, MFS—maximum flooding surface, PT—Portugal, TST—transgressive systems tract.

Post–early Cambrian magmatism may be the result of upwelling asthenosphere and underplating near the Liard and Snake River transfer zones (Figs. 2, 3B; e.g., Lund, 2008).

MAGMA-POOR RIFT MODEL FOR THE CORDILLERAN MARGIN

A magma-poor rift model for the Cordilleran margin is shown in Figures 3D and 4C. Tonian-Ediacaran extension was linked to polyphase thinning (Yonkee et al., 2014) within the proximal domain and analogous to Triassic-Cretaceous deformation in the Grand Banks and Iberia. Although the duration of Neoproterozoic extension was greater than that along Newfoundland-Iberia (Fig. 4A–C), it is comparable with the Carboniferous–Paleocene evolution of the magma-poor, East Greenland–Mid-Norwegian rift system (e.g., Péron-Pinvidic et al., 2013). Distal exposures of the Cordilleran rift margin, including exhumed mantle, are predicted beneath the accreted terranes that underlie western North America (Figs. 2, 3D; Hayward, 2015).

A lower to middle Cambrian breakup succession in the Cordilleran proximal domain, analogous to that of the Porto Basin (Fig. 4D), documents the transition from lithospheric breakup to thermal subsidence. An early Fortunian (ca. 535 Ma) sequence boundary at the base of the Sauk I megasequence (Sauk α supersequence; Keller et al., 2012) represents the lithospheric breakup surface along western Laurentia. This sequence boundary likely corresponds to a base-level fall (Soares et al., 2012). The uppermost breakup succession correlates with the Sauk II megasequence (Fig. 4C). An example of the early Fortunian–Cambrian Stage 5 (ca. 535–505 Ma) breakup succession in Death Valley (Fig. 4D; Keller et al., 2012) includes (1) middle to upper Wood Canyon Formation and Zabriskie Quartzite strata (~400 m) that compose a lowstand systems tract; (2) upper Zabriskie Quartzite and Carrara Formation strata (~450 m) that compose a transgressive systems tract capped by a maximum flooding surface; and (3) lower Bonanza King Formation strata (~250 m) that compose a highstand systems tract capped by a sequence boundary. Analogous histories are proposed for the Prospect Mountain Quartzite–Pioche Formation–Howell Limestone (Utah and Nevada), Camelback Mountain Quartzite–Gibson Jack Formation–Elkhead Limestone (Idaho), Hamill Group–Donald Formation (British Columbia), and Backbone Ranges–Vampire–Sekwi formation successions (Yukon).

Off-axis, syn- to post-breakup magmatism is a defining feature of the Newfoundland-Iberia system and therefore lower Paleozoic igneous rocks along the Cordilleran margin are consistent with a magma-poor rift origin. Lower Cambrian volcanic strata of the proximal domain (Fig. 2) are volumetrically limited and their overall relationship to breakup remains speculative. However, based on North Atlantic analogues (Bronner et al., 2011), it is predicted that coeval magmatism in outboard regions was more voluminous and triggered final lithospheric breakup.

Post–lower Cambrian volcanic strata were generated after the onset of seafloor spreading, equivalent to the Albian–Cenomanian magmatic evolution of the Newfoundland margin. The youngest post-breakup lavas and related rift grabens are located in northwestern Canada (Early to Middle Ordovician; Cecile et al., 1997). Some hypotheses for this tectonism include (1) enhanced mantle upwelling along the Liard transfer zone and subsidiary lineaments; (2) northward propagation of spreading, analogous to North Atlantic rift evolution (Bronner et al., 2011); and (3) spreading rate differences (slow versus fast) between northern and southern segments of the ridge system.

GLOBAL IMPLICATIONS

Hyperextended crust and exhumed mantle blocks are hallmark features of modern magma-poor margins, but these distal elements may be poorly preserved in ancient rift systems that have been affected by later convergent tectonism and terrane accretion. The presented model for western North America therefore demonstrates the value of ancient proximal domain rocks in magma-poor rift margin identification, especially proximal breakup successions and syn- to post-breakup volcanic strata that may have a higher preservation potential in orogenic belts. It is predicted that proximal domain stratigraphy can facilitate the identification of other ancient magma-poor margins and provide new testable hypotheses for continental margin evolution around the globe.

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