Geometry of the Neoproterozoic and Paleozoic rift margin of western Laurentia: Implications for mineral deposit settings

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ABSTRACT

The U.S. and Canadian Cordilleran miogeocline evolved during several phases of Cryogenian–Devonian intracontinental rifting that formed the western margin of Laurentia. Recent field and dating studies across central Idaho and northern Nevada result in identification of two segments of the rift margin. Resulting interpretations of rift geometry in the northern U.S. Cordillera are compatible with interpretations of northwest-striking asymmetric extensional segments subdivided by northeast-striking transform and transfer segments. The new interpretation permits integration of miogeoclinal segments along the length of the western North American Cordillera. For the U.S. Cordillera, miogeoclinal segments include the St. Mary–Moyie transform, eastern Washington–eastern Idaho upper-plate margin, Snake River transfer, Nevada-Utah lower-plate margin, and Mina transfer. The rift is orthogonal to most older basement domains, but the location of the transform-transfer zones suggests control of them by basement domain boundaries. The zigzag geometry of reentrants and promontories along the rift is paralleled by salients and recesses in younger thrust belts and by segmentation of younger extensional domains. Likewise, transform-transfer zones localized subsequent transcurrent structures and igneous activity. Sediment-hosted mineral deposits trace the same zigzag geometry along the margin.

Sedimentary exhalative (sedex) Zn-Pb-Ag ± Au and barite mineral deposits formed in continental-slope rocks during the Late Devonian–Mississippian and to a lesser degree, during the Cambrian–Early Ordovician. Such deposits formed during episodes of renewed extension along miogeoclinal segments. Carbonate-hosted Mississippi Valley–type (MVT) Zn-Pb deposits formed in structurally reactivated continental shelf rocks during the Late Devonian–Mississippian and Mesozoic due to reactivation of preexisting structures. The distribution and abundance of sedex and MVT deposits are controlled by the polarity and kinematics of the rift segment. Locally, discrete mineral belts parallel secondary structures such as rotated crustal blocks at depth that produced sedimentary subbasins and conduits for hydrothermal fluids. Where the miogeocline was overprinted by Mesozoic and Cenozoic deformation and magmatism, igneous rock–related mineral deposits are common.

Keywords: U.S. and Canadian Cordilleran miogeocline, Laurentia, Neoproterozoic–Paleozoic rift, sediment-hosted mineral deposits, sedimentary exhalative, Mississippi Valley type.

INTRODUCTION

Along the Canadian and U.S. Cordillera, Cryogenian–Devonian intracontinental rifting formed the western (present coordinates) margin of Laurentia (Fig. 1). Geochronologic data indicate that rifting began in the Cryogenian and accelerated in the Ediacaran to Cambrian (Stewart, 1972; Bond and Kominz, 1984; Thompson et al., 1987; Ross, 1991; Colpron et al., 2002). Stratigraphic data indicate that there was significant younger Late Cambrian–Early Ordovician and Late Devonian extension (Thompson et al., 1987; Turner et al., 1989; Pyle and Barnes, 2003; Emsbo et al., 2006). These data document a prolonged episodic rift and basin-subsidence history for the western Laurentian margin, resulting in successive stacked passive-margin sequences (Thompson et al., 1987; Turner et al., 1989; Ross, 1991; Lund and Cheney, 2008; Pyle and Barnes, 2003).

With the exception of very complicated areas in southeastern California and Idaho to northeastern Washington, the western edge of the Laurentian continent is well defined by combinations of lithofacies, fossil community (Stewart, 1980; Stevens, 1981; Cecile et al., 1997), and isotopic data (Armstrong et al., 1977; Armstrong, 1988; Elison et al., 1990; Wright and Wooden, 1991; Tosdal et al., 2000). Although subsequent complicated contractional, transcurrent, and extensional events affected western Laurentia, palinspastic reconstructions (not incorporated into Figs. 1–4) indicate that the present map expression (as far as it is known) reflects the original configuration (Stewart and Poole, 1974; Stevens, 1981; Abbott et al., 1986; Levy and Christie-Blick, 1989). Thus where well documented, the present general trace of the Cordilleran miogeocline (Stewart, 1972; Aitken, 1993; Speed, 1994; Sears and Price, 2003) forms sinuous mapped traces that persisted through geologic time despite subsequent deformation (Aitken and Long, 1978; Stevens, 1981; Oldow, 1984; Thompson et al., 1987).

For the eastern margin of Laurentia, Thomas (1983) demonstrated that embayments and promontories (terminology as defined by Rankin, 1976; Marshak, 2004; Thomas, 2006) were original extensional and transform (or transfer) segments of that sinuous Neoproterozoic rift margin. Similar arguments for the origin of margin segments were made for the Cordilleran margin in Canada (Hansen et al., 1993; Cecile et al., 1997) and for Nevada (Tosdal et al., 2000). However, there was no rift model linking the entire Cordilleran margin because identification of rift segments was lacking along other parts of the U.S. Cordillera.

It is widely recognized that rift-related continental margin sedimentary rocks are the preferred location for Paleozoic sedimentary exhalative (sedex) deposits and Paleozoic and younger Mississippi Valley–type (MVT) deposits (Albers, 1983; Dawson et al., 1991; Goodfellow et al., 1995; Leach et al., 2005). In the northern Canadian Cordillera, localities of such sediment-hosted mineral deposits of the paired

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Mackenzie Platform–Selwyn Basin and Ketchika Trough–MacDonald Platform (plus the paired Nasina Basin–Cassiar Platform, part of the former that was translated northward) have been related to the Cordilleran rift geometry (Nelson, 1991; MacIntyre, 1991; Goodfellow et al., 1993). In northern Nevada, most Paleozoic sedex, Mesozoic and Paleogene pluton-related, and Eocene Carlin-type and Neogene epithermal mineral deposits are hosted in (or underlain by) platform-margin, slope, and basin sedimentary rocks and, further, are in linear arrays interpreted to be related to basement structures that originated during the rifting along western Laurentia (Hofstra and Cline, 2000; Tosdal et al., 2000; Crafford and Grauch, 2002; Grauch et al., 2003; Cline et al., 2005; Emsbo et al., 2006). Because of the lack of integration of individual rift segments into a miogeoclinal model, mineral deposits in each segment have largely been investigated independently of those in other segments.

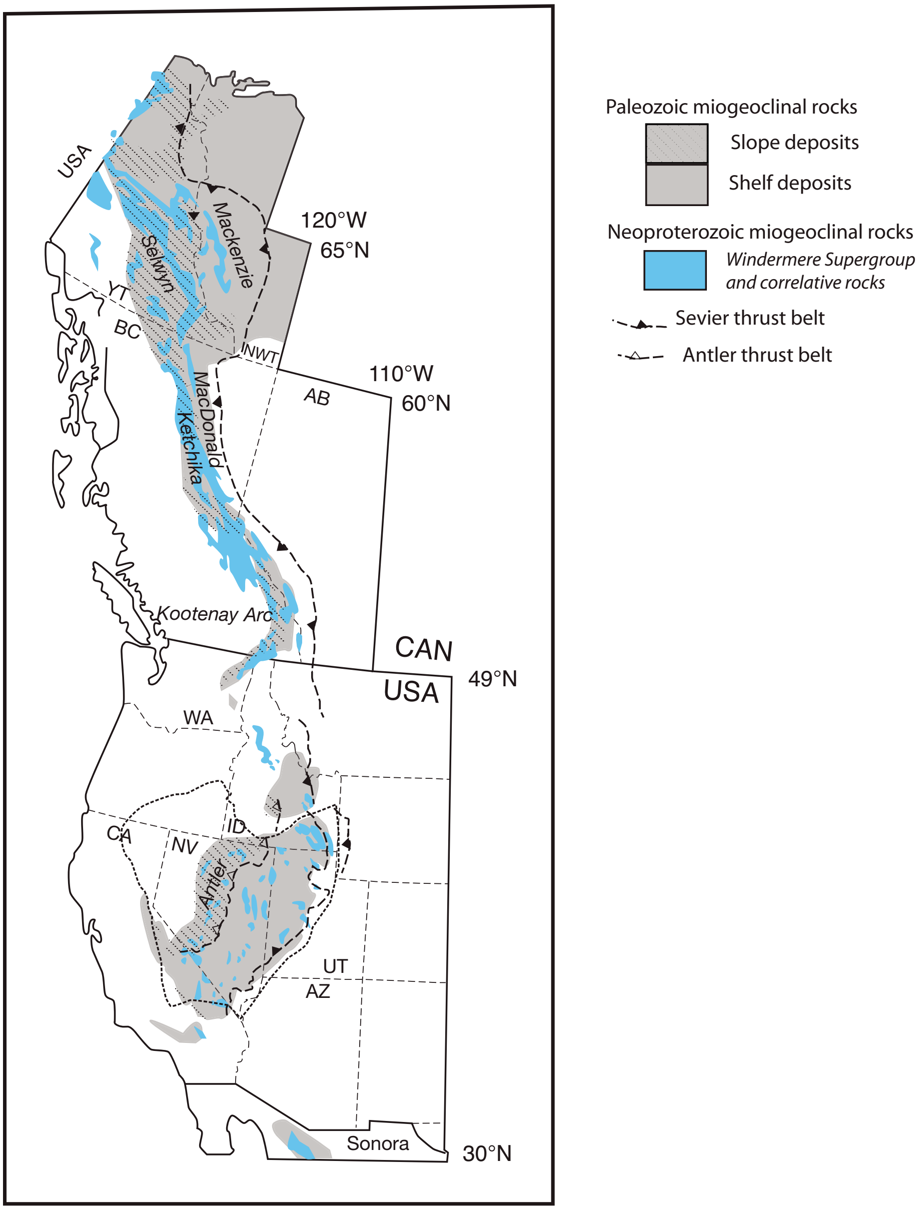

Figure 1. Regional map of the U.S. and Canadian Cordillera showing exposure belts for Neoproterozoic rocks and shelf and slope facies belts for Paleozoic sedimentary rocks. Dotted line shows area of the Great Basin, southern U.S. Cordillera. Not palinspastically restored, reflects present position after contractional movement along most of the margin, transcurrent northward translations of slices along the Canadian margin, and differential extension in the different segments (compiled from Stewart and Suczek, 1977; Stewart, 1991; Ehman and Clark, 1985; Turner et al., 1989; Poole et al., 1992, 2005; Ross et al., 1995; Cecile et al., 1997; Price and Sears, 2000; and Lund et al., 2003).

Cordilleran-wide evaluation of mineral deposit occurrence data in conjunction with rift-segment interpretation adds another aspect to understanding the geometry and polarity of the rift as well as understanding the subsequent structural reactivations. Conversely, mineral deposit investigations in the rift context may result in identification of relationships (1) between commodities and specific rift polarity, and (2) between commodities or size of deposit and individual segment history.

This study is based on field studies in central Idaho and northern Nevada and integration of that new data for the northern U.S. Cordillera with the more comprehensively studied and interpreted rift and miogeoclinal segments in the Canadian and southern U.S. Cordillera. The objectives of this paper are to (1) identify and interpret the rift geometry for the U.S. Cordilleran miogeoclinal segments, (2) combine rift-geometry interpretations for the Canadian and U.S. Cordillera, and (3) integrate the interpreted rift geometry with Paleozoic sediment-hosted mineral deposits along the length of the Cordilleran miogeocline as well as with younger deposits in segments that underwent subsequent episodes of deformation and magmatism.

CONTINENTAL CRUST RIFT MODELS

Common models for continental rifts include an element of asymmetry. Asymmetric extension results in opposing upper-plate and lower-plate margins (Fig. 2), each with distinct characteristics (Lister et al., 1986). Margins that form along the lower plate of such an asymmetric extensional system are characterized by marked thinning of continental crust, manifested by subsidence across a broad continental shelf margin and by rotated crustal blocks. In contrast, upper-plate margins are characterized by limited crustal thinning, manifested by relatively narrow continental shelf margins, development of proximal continental drainage divides (or arches), alkalic magmatism, and down-to-the-basin normal faults (Lister et al., 1986, 1991; Wernicke, 1985; Etheridge et al., 1990; Thomas, 1993, 2006). Along a single margin, extensional asymmetry may reverse across transfer zones and, likewise, offsets between two same-asymmetry segments may occur across transform zones (Lister et al., 1986). Such transfer or transform zones are characterized by abrupt changes in crustal thickness and in sedimentary facies that are parallel to the transverse zones rather than to the rift zones (Thomas, 1993). Different segment types can be discriminated by polarity, kinematics, and dip of the bounding structure (Lister et al., 1986, 1991; Wernicke, 1985; Etheridge et al., 1990; Thomas, 1993, 2006). The original geometry of a segment controls differences in basement character (thinning and structural fabric), amount of subsidence, and the type and thickness of fill deposited in the developing sedimentary basin (Etheridge et al., 1990; Thomas, 1993). Some aspects of these extensional systems are reactivated by subsequent continental-scale deformation, and these systems may exhibit inheritance from preexisting geologic trends or structures (Thomas, 2006).

During the long span of time for which extension is documented along the western margin of Laurentia (following section), changes in extension direction may be expected. In this paper, no direct evidence for direction of extension is presented. Rather, general orthogonal extension relative to the trace of the rift and parallel facies belts is assumed, even though transtension may be equally likely. Additionally, changes in polarity may occur along a segment during subsequent extensional events, which would significantly complicate the resultant structure.

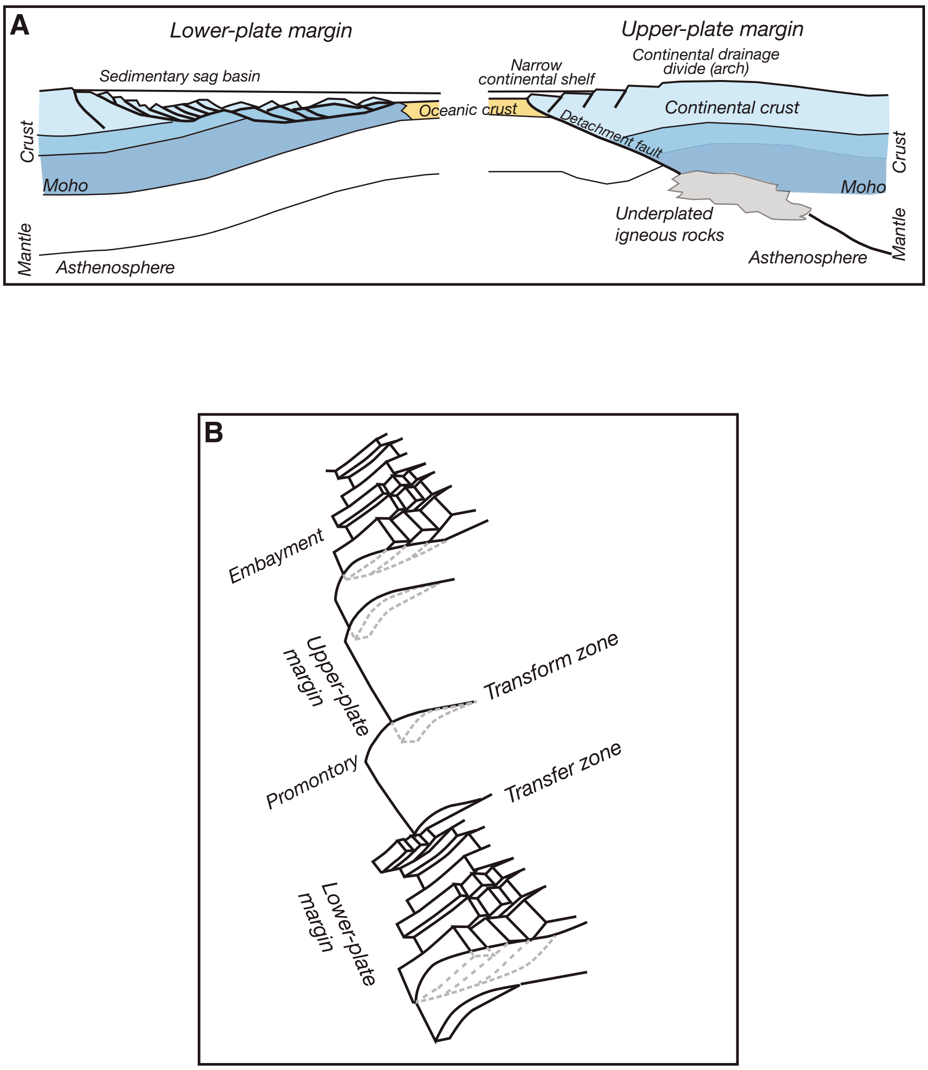

Figure 2. Models for asymmetric rift systems. (A) Schematic cross-section view of structures in asymmetric extension (modified from Lister et al., 1986). (B) Schematic block diagram illustrating asymmetric extension for segments along the Cordilleran margin of Laurentia (after Thomas, 1993).

MIOGEOCLINAL TRENDS

Widely separated Cryogenian mafic magmatic events ca. 780 Ma in the northern Canadian Cordillera (Jefferson and Parrish, 1989; Heaman et al., 1992; LeCheminant and Heaman, 1994) and sporadic events from 750 to 723 Ma in northern Canada, British Columbia, and the Grand Canyon region of Arizona (Parrish and Scammell, 1988; Roots and Parrish, 1988; McDonough and Parrish, 1991; Heaman et al., 1992; Karlstrom et al., 2000) represent regionally restricted extension (Roots and Parrish, 1988; Sears, 1990; Ross, 1991; Rainbird et al., 1996; Timmons et al., 2001) at about the time of breakup of Rodinia (Meert and Torsvik, 2003). However, sediments deposited in these basins are generally not within the confines of the miogeocline and the basins were not interconnected (Timmons et al., 2001), so these deposits are not herein considered to be part of the miogeocline.

The onset of major continental extension along Cordilleran-wide interconnected depositional basins was marked by alkalic igneous rocks (Fig. 3) and coarse detritus, including glacial diamictite, that are part of or correlated with the Windermere Supergroup of the central Cordillera (Crittenden et al., 1972, 1983; Gabrielse, 1972; Stewart, 1972; Eisbacher, 1985; Christie-Blick and Levy, 1989; Aitken, 1991; Link et al., 1993; Miller, 1994; Prave, 1999; Lund et al., 2003). This period of extension began ca. 709–685 Ma and continued until ca. 650 Ma (Ferri et al., 1999; Lund et al., 2003; Fanning and Link, 2004; Lund, 2004; Pigage and Mortensen, 2004). The early rift-related deposits were succeeded by subsidence-phase rocks, including (1) interglacial carbonaceous shale and carbonate rocks, (2) a younger glacial-interglacial cycle, and (3) thick Ediacaran sandstones (Ross, 1991; Link et al., 1993; Rainbird et al., 1996; Lund et al., 2003). Together, these deposits have been considered a Windermere miogeocline (Ross, 1991).

Extension increased at 570 Ma and was associated with rift-related volcanism (Fig. 3; Colpron et al., 2002). Related subsidence accelerated from Early Cambrian to Early Silurian time, as shown by facies compilations (Cecile, 1982; Turner et al., 1989; Gabrielse and Yorath, 1991; Stevens, 1991; Poole et al., 1992; Price and Sears, 2000; Pyle and Barnes, 2003) and subsidence calculations (Bond and Kominz, 1984; Levy and Christie-Blick, 1991).

Sedimentation patterns established in the Neoproterozoic were further developed within the same depositional basins to form the Paleozoic miogeocline (Fig. 1). However, the tectonic setting of the Cryogenian to Early Cambrian extensional events (with respect to what was being rifted and which event constituted continental separation) is debated (Meert and Torsvik, 2003).

Short-lived but important rejuvenation of extension occurred in the Devonian–Mississippian, accompanied by magmatic activity (Fig. 3) and a possible change in extension direction (Turner et al., 1989; Stevens, 1991; Root, 2001; Pyle and Barnes, 2003). This younger event has been related to backarc extension during slab rollback (Nelson et al., 2006). Influx of mineralizing basinal brines through the continental margin sedimentary rocks at this time resulted in formation of sedex deposits containing Zn-Pb, Ba, or Au (Turner and Otto, 1995; Root, 2001; Nelson et al., 2002; Emsbo et al., 2006).

These late Ediacaran to Devonian rocks are the classic Cordilleran miogeocline. Depositional facies can be reconstructed for both Neoproterozoic and Paleozoic rocks along the Canadian and U.S. portions of the miogeocline (Fig. 1), with stratigraphic thickening progressing westward across the continental shelf and slope and into a deeper basin (Stewart, 1980; Turner et al., 1989; Ross, 1991; Stevens, 1991; Poole et al., 1992; Cecile et al., 1997; Price and Sears, 2000). The prominent gap in information for the northern U.S. Cordillera (demonstrated by those previous compilations) is in a region that was overprinted by successive overlapping orogenic belts. However, Neoproterozoic–early Paleozoic rocks have recently been documented across that region, primarily by application of mapping and dating techniques (Lund et al., 2003; Lund, 2004).

In the Canadian Cordillera, Neoproterozoic–middle Paleozoic shelf and slope deposits are northwest striking and southwest deepening. As illustrated in Figure 1, the paired Selwyn Basin and Mackenzie Platform form a broad depositional basin in the Yukon Territory. They are succeeded to the south by a markedly narrower system formed by the Ketchika Trough and the MacDonald Platform (and the Nasina Basin and Cassiar Platform, which were translated to the north by transcurrent faulting, making the Selwyn Basin appear broader and the Ketchika Trough narrower) (Cecile, 1982; Gabrielse and Yorath, 1991; Ross, 1991; Cecile et al., 1997). This British Columbian segment is further subdivided, especially north and south of the MacDonald–Hay River fault (Great Slave shear zone in the basement), wherein the facies belts in the southern part are narrower than to the north (Cecile et al., 1997).

From southern Alberta to northeastern Washington, the trace of Neoproterozoic–middle Paleozoic shelf and slope facies forms an arcuate belt (the Kootenay Arc) and, at the international boundary, these facies belts are northeast striking, northwest facing, and narrow (Miller, 1994; Price and Sears, 2000). Along the eastern Washington to eastern Idaho segment, exposures of the Neoproterozoic Windermere Supergroup (Lund et al., 2003) and of primarily slope facies Paleozoic rocks (Scholten, 1957; Armstrong, 1975; Ruppel, 1986) indicate that the original miogeocline was northwest striking and relatively narrow.

The Snake River Plain is coincident with an ~400-km-long change in trend of the facies belts from north-central Nevada to southeastern Idaho (Stewart and Suczek, 1977). Paleozoic facies data indicate a narrow zone of Cambrian to Devonian slope facies rocks striking northeast between southeastern Idaho and north-central Nevada and deepening to the northwest (Stewart, 1980). Along the same trend, Neoproterozoic carbonate and volcaniclastic rocks of north-central Nevada (Stevens, 1981; Ehman

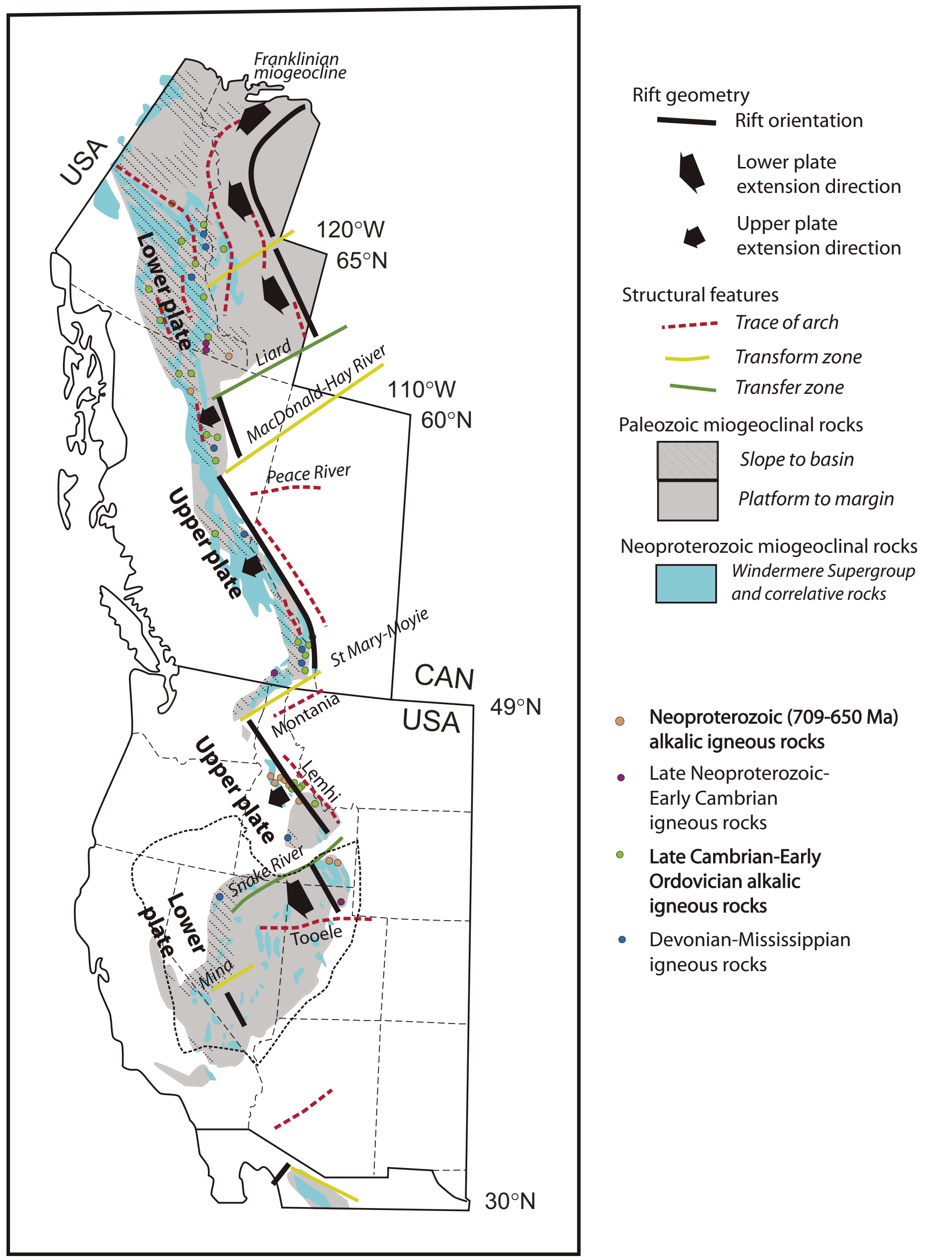

Figure 3. Regional map showing sedimentary basins forming the miogeocline (as in Fig. 1) and schematic interpretation of rift segments, transfer and transform zones, and arches of the U.S. and Canadian Cordillera. Canadian interpretation after Cecile et al. (1997).

and Clark, 1985, 1990; Little, 1987) investigated for this study indicate a similar, narrow, northeast-striking belt of slope rocks. This northeast-striking deviation of facies belts has been portrayed as an offset caused by tearing of Sevier thrust faults along a proposed Snake River fault (Poole et al., 1992) or the Wells fault (Thorman, 1970). However, a change in facies belt trends of this magnitude only along the south side of the Snake River Plain is difficult to explain by tear faulting. Retrodeformation of the Wells fault showed that the shape of the facies belt was original (Stevens, 1981). Additionally, isotopic data from plutonic rocks in northern Nevada and southern Idaho document a northeast-striking zone of progressive northwestward thinning of the continental crust in the area of the Snake River Plain (Tosdal et al., 2000).

Across western Utah and central Nevada in the Great Basin, north-northwest–striking Paleozoic miogeoclinal facies belts are broad and the depositional basin deepened to the west (Stewart, 1980). Likewise for Cryogenian and Ediacaran rocks correlative with the middle and upper Windermere Supergroup, sandstones of the paleoshelf dominate in Utah (Christie-Blick and Levy, 1989), whereas carbonate and shale of the paleoslope dominate in east-central Nevada (Misch and Hazzard, 1962). These Neoproterozoic rocks indicate that the basin deepened to the west (Stewart, 1980; Christie-Blick and Levy, 1989). Isotopic data from plutonic rocks across the Great Basin document that continental crust thins progressively westward toward a northwest-striking continental edge in central Nevada (Tosdal et al., 2000).

In southwestern Nevada, the Paleozoic shelf-slope facies belts change trend from north-northwest striking to northeast striking in the Mina deflection (Wetterauer, 1977; Tosdal et al., 2000). Although this zone is complicated by younger structures associated with the Walker Lane fault zone, it is suggested to be an original feature of the Laurentian margin (Oldow, 1984; Stewart, 1988b; Saleeby et al., 1994; Tosdal et al., 2000).

To the southwest, exposures of both Neoproterozoic and Paleozoic miogeoclinal strata of southeastern California exhibit similar facies belts that are oriented northwest. The facies belts are difficult to reconstruct because of offset by the Walker Lane fault zone, possibly by the San Andreas fault system, and possibly by the Mojave-Sonora megashear (Stevens et al., 1992; Stewart, 2005). The connections between the southeastern California miogeoclinal rocks and those in Sonora are unclear because of the faulting and lack of exposure. In Sonora, miogeoclinal strata strike east-northeast with shelf and slope deposits facing south-southeast along the Gulf of Mexico margin, ultimately connecting with Neoproterozoic–early Paleozoic rift structures along the Appalachian margin of Laurentia (Poole et al., 2005). The many young structural offsets in southern California probably obscure a right-angle junction (part of a triple junction?) between miogeoclinal rocks that formed along a Cordilleran rift system and those that formed along the Gulf of Mexico and Appalachian system.

The original margin geometry was overprinted and modified by post-rift tectonic activity in the form of thrust, extensional, and transcurrent faulting. However, palinspastic reconstructions of different segments of the Cordillera (Stewart and Poole, 1974; Stevens, 1981; Abbott et al., 1986; Levy and Christie-Blick, 1989) result in a recognizable, although modified, zigzag shape of the margin. For example, (1) dextral shear along the St. Mary–Moyie zone during Mesozoic contraction may have exaggerated this transform segment, (2) the Great Basin has undergone both thrust transport and moderate to extreme extension, possibly not changing the geometry significantly, and (3) the Nasina Basin and Cassiar Platform are segments of the Ketchika Trough and MacDonald Platform that were transported north along the Tintina fault system, widening the segment to the north and narrowing the segment to the south (Stewart, 1972; Aitken, 1993; Speed, 1994; Sears and Price, 2003). Parts of the margin in British Columbia and Washington-eastern Idaho are not easily reconstructed because of the amount of overprint by magmatic belts and deformation. Reconstruction of the original width of the eastern Washington–eastern Idaho segment comes from the facies belts at the southeastern end of this segment, where stratigraphic belts are best documented (Turner and Otto, 1988; Link et al., 2001). Those palinspastic restorations suggest that the present expression of the miogeocline displayed in the figures is essentially similar to the original geometry of the rift margin.

EXTENSIONAL SETTING OF MARGIN SEGMENTS

A general model for Neoproterozoic–Paleozoic rift geometry around Laurentia presented by Speed (1994) features a rift triple junction in present northwestern Mexico. In that model, both eastern and western Laurentian margins are defined by schematic northeast-striking rift and northwest-striking transform segments (generally northwest-southeast–directed extension). That model did not account for north-south–directed rifting in Arctic Canada and was not tied to segment-specific stratigraphic or structural data for the Cordillera. A recently proposed model for rifting of Siberian and Laurentian cratonic masses, based on offsets of geologic elements, accounts for the geometry of broad miogeoclinal segments and identifies the location of specific rift segments, but is also based on northwest-southeast extension (Sears and Price, 2003). Another proposed depiction with northwest-southeast extension shows a northwest-striking transform from northeastern Washington to southeastern Idaho that was interpreted to have formed during diachronous extension along adjacent rift segments in Canada and the Great Basin (Dickinson, 2006). However, in none of these schematic models of rift geometry were orientations of miogeoclinal facies trends or rift interpretations for the Canadian Cordillera taken into account.

The previous geometric solutions that require generalized northwest-southeast continental separation (generally U.S. Cordillera–centric models) are perpendicular to the extensional segments proposed for the Canadian Cordillera. Models for rifting in the Canadian Cordillera are defined on the basis of stratigraphic, structural, and geochemical evidence. Differences in three-dimensional geometry of individual segments (including sedimentation patterns, basement thickness, and relative timing of extension) were attributed to asymmetric extension along rift segments (Hansen et al., 1993; Cecile et al., 1997). Herein, criteria used to interpret the Canadian segments by Cecile et al. (1997) and Hansen et al. (1993) are applied to the Cordilleran margin from south-central British Columbia to southern California (with an emphasis on central Idaho to northern Nevada).

In the Canadian Cordillera, asymmetric extension formed three major margin segments (Fig. 3). As described by Cecile et al. (1997), these are: (1) a northwest-striking, lower-plate extensional margin in the Yukon Territory associated with broad thick miogeoclinal sedimentary packages of the Selwyn Basin and Mackenzie Platform; (2) a northwest-striking, upper-plate extensional margin in British Columbia (Ketchika Trough and MacDonald Platform) associated with early Paleozoic alkalic magmatic rocks, parallel arch systems, and relatively narrower miogeoclinal deposits (Fig. 2); and (3) a northeast-striking transfer zone along the Liard line that linked the adjacent segments (1 and 2 above) of opposite polarity.

Southward (Fig. 3), a northeast-striking, thick, Cryogenian–Paleozoic sedimentary succession was deposited northwest of the down-to-the-northwest St. Mary–Moyie basin-bounding fault system (Norris and Price, 1966; Lis and Price, 1976; Price and Sears, 2000). Paired to the southeast was the recurrently emergent Montania arch (Deiss, 1941; Lis and

Price, 1976; Benvenuto and Price, 1979; Bush, 1991; Price and Sears, 2000). This structural system controlled the miogeoclinal segment in northeastern Washington and British Columbia. Although the St. Mary–Moyie zone was complexly reactivated by dextral transcurrent motion during Mesozoic tectonism (Larson and Price, 2006), the stratigraphic and structural features across it suggest that this segment acted as a transform between the upper-plate extensional margin in the southern Canadian Cordillera and an upper-plate margin in Washington-Idaho (Fig. 2B) during Cryogenian–Devonian rifting.

From eastern Washington to eastern Idaho, data come mostly from east-central and south-central Idaho. There, relatively thin Cryogenian–Ordovician miogeoclinal sedimentary successions form narrow northwest-striking facies belts (Sloss, 1950, 1954; Scholten, 1957; Stewart, 1972; Armstrong, 1975; Turner and Otto, 1988; Lund et al., 2003). Parallel to, but inboard of, the miogeoclinal facies are the Neoproterozoic–Devonian Lemhi Arch (Sloss, 1954; Ruppel, 1986) and an aligned belt of Cryogenian and Late Cambrian–Early Ordovician alkalic to calc-alkaline plutonic suites (Evans and Zartman, 1988; Lund, 2004). These are related manifestations of recurrently active, Cryogenian–Late Cambrian, continental arch and extensional magmatic systems, respectively. Across central Idaho southwest of the miogeoclinal and alkalic igneous belts, aeromagnetic and isotopic data indicate that Laurentian basement is present and extended, but not offset (Armstrong et al., 1977; Sims et al., 2005). These features suggest that the Idaho segment of the western Laurentian margin was related to a northwest-striking rift segment with northeast-southwest extension. The parallel features in this segment, including the continental arch (Lemhi), repeatedly reactivated alkalic igneous belt (Lund, 2004), and narrow Paleozoic facies belts (Turner and Otto, 1995), suggest that it formed as an upper-plate extensional margin. The Lemhi Arch was a continental drainage divide and the aligned plutonic suites and volcanic rocks are manifestations of a reactivated basement fault on an upper-plate, thinned-to-the-southwest, continental margin.

Near the Idaho boundary with Nevada and parallel to the northeast-striking Snake River Plain is a tract of lower Paleozoic facies changes, with relatively deeper water strata toward the northwest (Poole et al., 1977, 1992; Stewart, 1980; Stevens, 1981, 1991; Little, 1987; Miller et al., 1991). The isotopically defined edge of the Precambrian continental margin (Speed, 1982; Elison et al., 1990) parallels the facies trend. Poole et al. (1977, 1992) inferred a northeast-striking, recurrently reactivated Mesozoic Snake River fault system (obscured by Neogene Snake River Plain volcanic rocks) that offset many regional-scale late Paleozoic and younger stratigraphic and tectonic features. This northeast-striking zone is also interpreted to be a more fundamental feature including (1) basement structures of unspecified origin that controlled northeast-striking sedimentary facies (Stevens, 1981; Coats and Riva, 1983), (2) a northeast-striking, right-lateral offset in the Laurentian margin (Tosdal et al., 2000), or (3) the boundary of an embayment in the Laurentian margin (Little, 1987). Taken together, the stratigraphic, structural, and isotopic data indicate that, in its rift context, the Snake River Plain is underlain by a multiply reactivated structural zone fundamentally caused by a Neoproterozoic–middle Paleozoic, northeast-striking transfer zone (left-lateral relative motion) between the opposite polarity rift segments in central Idaho and the Great Basin.

Across the Great Basin of eastern Nevada and western Utah, Neoproterozoic–Devonian geologic features are characterized by the great width and thickness of north-striking miogeoclinal facies belts of the carbonate platform shelf and the Antler allochthon slope and basin (Stewart, 1980, 1991; Turner et al., 1989; Poole et al., 1992; Cook, 2005; Crafford, 2008). This segment is also characterized by minor episodes of alkalic magmatism (Turner et al., 1989), underlying zones of both extended and intact Laurentian basement, and the presence of probable rotated crustal fault blocks at depth (Tosdal et al., 2000; Crafford and Grauch, 2002) that were reactivated during the Devonian (Emsbo et al., 1999; Morrow and Sandberg, 2008). These features indicate that the Nevada-Utah segment of the miogeocline was created along a lower-plate, north-striking, rift segment.

In southwestern Nevada, there is a relatively short, northeast-striking segment (Mina deflection) of miogeoclinal facies (Stewart, 1980, 1991; Poole et al., 1992) that follows the edge of continental crust, based on isotopic data from plutonic rocks (Tosdal et al., 2000). Although broken and translated by faults of the Walker Lane, the Mina deflection was interpreted to be a promontory along the original Laurentian margin (Stewart, 1972, 1980, 1991; Oldow, 1984; Saleeby et al., 1994; Tosdal et al., 2000) and was probably a transfer zone. Southwest of the Mina deflection, many Mesozoic and younger transcurrent faults offset miogeoclinal rocks that originally trended northward and, if reconstructed, would form a narrower belt than the miogeoclinal segment across central Nevada and Utah to the north (Stevens et al., 1992). This southeastern California–southern Nevada segment was an extensional segment, but there is too much subsequent structural disruption to determine much about its original geometry.

There are two proposed scenarios for the connection between the western Laurentian rift system and the eastern system as manifested by segments of the rift system in Sonora, northern Mexico: (1) offset by the younger San Andreas fault system and Mojave-Sonora megashear (Stevens et al., 1992; Stewart, 1988a, 2005), or (2) poorly preserved continuity with Sonoran segments that formed part of the eastern Laurentian margin along northeast-striking rift and northwest-striking transform segments (Speed, 1994; Poole et al., 2005). Resolution of geometry through this area is critically important because the change in extension orientations between northeast-southwest, as proposed for the Cordilleran margin (as presented herein and Hansen et al., 1993; Cecile et al., 1997), and northwest-southeast, as proposed for the Atlantic margin (Thomas, 2006), occurred here.

Taken together, the structural and stratigraphic data from the northern Canadian (Cecile et al., 1997) through the U.S. Cordillera indicate that northwest-striking segments were rift segments and northeast-striking segments were the transfer and transform zones, as shown in Figure 3. The corner between the west-facing Cordilleran miogeocline and the north-facing Franklinian miogeocline of the Canadian Arctic is interpreted to form a fundamental junction of rift systems (Cecile et al., 1997; Sears, 2001). Likewise, a predicted corner between miogeoclinal trends in southeastern California and those in Sonora, although severely disrupted by younger structures (cf. Poole et al., 2005; Stewart, 1988a, 2005), probably represents the major junction between the Cordilleran and Atlantic rift systems.

INFLUENCE OF PREEXISTING STRUCTURES ON INHERITANCE

Preexisting Archean–Paleoproterozoic basement domains or Paleoproterozoic–Mesoproterozoic structures may influence rift geometry and provide conduits for magmatic and hydrothermal activity relating to mineral deposits. The core of Laurentia is composed of Archean and Paleoproterozoic domains that were assembled in the Paleoproterozoic (Hoffman, 1988; Ross et al., 1991; Karlstrom et al., 2002; Sims et al., 2005; Foster et al., 2006). Across that Paleoproterozoic continental mass, isolated Mesoproterozoic basins were created in localized rifting events (Link et al., 1993; Price and Sears, 2000; Ross et al., 2001). Because the location of the pre-Rodinian western margin of Laurentia is unknown and the continental masses or microcontinents that were present west of Laurentia are debated (cf. Meert and Torsvik, 2003; Sears and Price, 2003), the structural elements and fabric of western Laurentian Precambrian basement are the most valuable available sources of information for evaluating inheritance.

Current maps of Precambrian basement domains in western Laurentia show dominantly north- and northeast-striking domain boundaries (Ross et al., 2001; Karlstrom et al., 2002; Sims et al., 2005; Foster et al., 2006) that are oblique or orthogonal to the trace of the Neoproterozoic–Paleozoic miogeocline. These orthogonal trends between basement domains and the future Cordilleran margin are also depicted in models matching basement domains between western Laurentia and other continental masses (Karlstrom et al., 1999; Sears and Price, 2003). Thus, in general, the Neoproterozoic–Paleozoic rift system of the Cordilleran margin cut across preexisting domains and their boundaries.

However, subsequent to assembly of Laurentia, Mesoproterozoic basins, such as the Belt Basin, were localized along northwest-striking, early Mesoproterozoic extensional faults (Price and Sears, 2000; Timmons et al., 2001; Sims et al., 2005). Some of these early Mesoproterozoic structures are generally parallel to the succeeding Neoproterozoic–Paleozoic rift segments (i.e., Mesoproterozoic structures related to the southern margin of the Belt Basin are parallel to the Neoproterozoic–Paleozoic eastern Washington–eastern Idaho rift segment) and may have influenced location, orientation, and evolution of the younger rift segments.

In contrast to the rift segments, the transform and transfer zones exhibit evidence of influence by basement structures. The Liard line overlies a preexisting basement structure (Cecile et al., 1997) that also controlled the northern margin of a Mesoproterozoic basin (e.g., Muskwa basin, Ross et al., 2001). The St. Mary–Moyie zone is superposed over the Vulcan Low, a Paleoproterozoic domain boundary or suture (Ross et al., 1991). It was previously interpreted that the Vulcan Low was reactivated by Neoproterozoic–Paleozoic block faulting and by Mesozoic deformation within the St. Mary–Moyie fault system (Price and Sears, 2000; Sears and Price, 2003). As part of the Cordilleran rift margin, the St. Mary–Moyie transfer was an early reactivation of the Vulcan Low.

There are interpretations that the covered west-striking suture between the Wyoming and Mojave Provinces (Cheyenne Belt) controlled the change in orientation of the Laurentian margin from Nevada into the Snake River Plain (Tosdal et al., 2000), herein named the Snake River transfer. The trace of the west-striking basement suture is identified by isotopic and geophysical techniques (Tosdal et al., 2000; Premo et al., 2005; Rodriguez and Williams, 2008). Recent geophysical data show that this major basement structure changes from west striking (across Wyoming to north-central Nevada) through north striking (in north-central Nevada) and northeast striking (along the south side of the Snake River Plain, Rodriguez and Williams, 2008). The orientation and location of the Cheyenne Belt (west-striking across northern Utah and Nevada) make it unlikely that it controls any major aspect of the Cordilleran rift margin. However, the combination of isotopic and geophysical data (Premo et al., 2005; Rodriguez and Williams, 2008) with the facies data (above) suggests that the Cheyenne Belt extends into northeastern Nevada and is cut off by the Snake River transfer zone. A more geometrically appealing explanation for basement structure influencing position of the Snake River transfer is that the northwestern margin of the Wyoming Province, along the southern boundary (Madison mylonite) of the Great Falls tectonic zone (Karlstrom et al., 2002; Sims et al., 2005), underlies the Snake River Plain. The position of the Snake River transfer (previous section), as predicted by facies and structural data, indicates that structures along the disrupted northwestern edge of the Wyoming Province probably controlled the location of the Snake River transfer.

The Mina deflection in southwestern Nevada is along the trend of the northwestern edge of the Paleoproterozoic Mojave Province as shown by Tosdal et al. (2000, 2003). This correspondence in location suggests that the Mina transfer formed along that preexisting basement domain boundary.

Thus, although the general trend of the rift system and the individual extensional segments cut orthogonally across most preexisting basement domains of the assembled Laurentian continent, the transform and transfer zones may have been significantly influenced by post-assembly Proterozoic structures. This suggests that any control on mineral deposits exerted by underlying older basement (in terms of source composition or structural system) would mainly be in conjunction with transform-transfer zones or locally where an extensional segment intersects a specific basement structure.

INFLUENCE OF THE RIFT SYSTEM ON YOUNGER DEFORMATION AND MAGMATISM

The zigzag geometry of embayments and promontories along the rifted Cordilleran margin is paralleled by salients and recesses in thrust belts (nomenclature as used by Rankin, 1976; Marshak, 2004; Thomas, 2006). The Mississippian Antler orogen (Fig. 1) extends northward through most of Nevada and wraps around the promontory in north-central Nevada. Farther north, it strikes northeast across southern Idaho and wraps northwestward back into central Idaho (where inundated by plutonic rocks).

Thrust faults of the Mesozoic Cordilleran thrust system also parallel the western Laurentian margin (Fig. 1). A broad thrust belt extends east across the Selwyn Basin and Mackenzie Platform (forming a salient), whereas to the south, the belt steps west along the Liard line (forming a recess) such that the thrust belt in British Columbia and Alberta parallels the strike of the miogeoclinal margin but forms a narrower system than the thrust system north of the Liard line. This thrust fault geometry has been suggested to reflect the preexisting geometry of the miogeocline (Norris, 1972; Aitken and Long, 1978; Thompson et al., 1987; Mair et al., 2006). In southern British Columbia, the Kootenay Arc is defined by parallel miogeoclinal trends and deformation features that curve southward from the southern Canadian Cordillera into the St. Mary–Moyie zone and project southwestward into northeastern Washington (Yates, 1970). In the St. Mary–Moyie transfer, complex Mesozoic east-directed dextral translation and thrust faulting reactivated Neoproterozoic–Paleozoic abrupt facies changes and the underlying basement Vulcan Low structure (Larson and Price, 2006). The foreland fold-and-thrust belt in southwestern Montana and southeastern Idaho strikes northwest, paralleling the miogeoclinal margin in central Idaho, and was inferred to be an artifact of margin geometry (Beutner, 1977). The Mesozoic thrust system in Utah and Nevada parallels the shape of the margin and rocks of the broad miogeocline were transported eastward. Thus, both late Paleozoic and Mesozoic Cordilleran thrust systems are molded to the earlier zigzag rift margin. With respect to the preexisting continental margin, these examples show that the geometry of subsequent contractional systems constitutes "a best-fit curve around that framework" (Thomas, 1977, p. 1270; Oldow, 1984).

In general, the control of contractional geometry was due to inversion of the miogeoclinal sedimentary basins. The Cryogenian–Devonian rift-related normal faults in the unexposed basement rocks at depth along different margin segments were inverted during younger (late Paleozoic and Mesozoic) thick-skinned contractional deformations forming structural culminations at different scales (cf. Crafford and Grauch, 2002; Muntean et al., 2007; Mair et al., 2006). As a corollary, the relatively narrow rift margins, which formed as upper-plate margins, are more intensely overprinted by magmatic activity; these are the southern Canadian Cordillera segment and the eastern Washington to eastern Idaho segment. Perhaps the more abrupt changes in basement thickness (in comparison to the broad transition zones across the Selwyn and Great Basins) affected the style of hinterland deformation during contraction and subsequent crustal relaxation. The mineral deposit character is also different in these different polarity margins (see following section).

The transform and transfer zones are particularly notable for displaying evidence of repeated reactivation. In addition, the promontories at the ends of these structures in northeastern Washington and north-central Nevada were sites of repeated overlapping events where kinematics are complicated by intersecting rift structures. The St. Mary–Moyie transform and the promontory at the southwest end in northeastern Washington are the sites of overlapping structural systems, including Jurassic contractional structures, Cretaceous contractional tear and thrust faults, and segmentation of Tertiary extensional domains (Yates, 1970; Ross et al., 1991; Price and Sears, 2000; Larson and Price; 2006). Structures near the promontory in north-central Nevada (west end of the Snake River transfer) record Paleozoic and Mesozoic thrust and transcurrent faulting, and contrasting extensional domains (Coats and Riva, 1983; Little, 1987). The Snake River transfer was reactivated as a zone of tear systems during Mississippian Antler and Cretaceous Sevier orogenies. It was also reactivated as a bounding structure defining different Tertiary extensional domains between the Great Basin and northern Rocky Mountains that underwent different amounts of diachronous extension. Subsequently, magmas associated with the Yellowstone hotspot were erupted progressively northeastward along this zone. New geophysical data indicate that the Yellowstone hotspot plume dips moderately northwest and that, as the continental crust moves over the plume, only the top of the plume is located under the Snake River Plain (Yuan and Dueker, 2005; Waite et al., 2006). This suggests that the top of the plume has preferentially occupied the structural weakness along the much older Snake River transfer. The combined structural and plume data indicate that the Snake River transfer zone is a long-lived structural element showing evidence of repeated activity during different types of crustal deformation.

INFLUENCE OF THE RIFT SYSTEM ON COEVAL AND YOUNGER MINERAL DEPOSITS

Sediment-hosted (sedex and MVT) mineral deposits are well documented in intracontinental rift-margin basins (Goodfellow et al., 1993; Leach et al., 2005), but their position with respect to rift versus transform settings or rift asymmetry is less well documented. Relationships between the deposits and their respective tectonic settings bear further study to evaluate the influence of internal (subsidiary) basin facies and structure, pulses of extension, and circulation of brines on relative mineral deposit size and metals present. For all of the rift segments where sedimentary facies are mapped (not available for segments severely overprinted by hinterland crustal thickening and magmatism, extension-related magmatism, or hotspot magmatism), the sedex deposits are in the belt of continental slope facies rocks, whereas MVT deposit occurrences are along an inboard belt in platform margin rocks that were deformed by younger tectonic reactivations (Fig. 4; Table 1).

Mackenzie Platform–Selwyn Basin

In the northern Canadian Cordillera, the broad lower-plate rift system that formed the Mackenzie Platform and Selwyn Basin is locus for sediment-hosted deposits whose distribution relates to their original paleogeographic position on the Neoproterozoic–Paleozoic continental margin (Nelson et al., 2002). In particular, the association of three types of Devonian–Mississippian sediment-hosted deposits across the shelf to the slope and basin setting (east to west) is evidence of complicated Devonian–Mississippian tectonics along the Canadian margin (Nelson et al., 2006).

Cambrian–Early Ordovician, Early Silurian, and Late Devonian–Mississippian sedimentary exhalative (sedex) Zn-Pb-Ag(±Ba) and Late Devonian–Mississippian sedex barite deposits are in slope rocks (MacIntyre, 1991; Goodfellow et al., 1993). Several Au-bearing Cambrian–Ordovician sedex (Zn-Pb-Ag-Au ± Ba) deposits are located along the western edge of the slope rocks. At a later interval, Late Devonian–Mississippian Au-bearing sedex (Zn-Pb-Ag-Au-Ba) deposits are associated with same-age sedex barite deposits in slope rocks both on the western edge and in the center of the Selwyn Basin (MacIntyre, 1991).

Carbonate-hosted MVT Zn-Pb deposits formed in the Late Devonian–Mississippian and are hosted dominantly in Silurian–Devonian carbonate platform rocks at the western edge of the shelf (MacIntyre, 1991; Nelson, 1991; Goodfellow et al., 1993; Nelson et al., 2002). A northeast-striking zone with potential for concealed MVT deposits is present in Devonian carbonate shelf rocks that overstep the Liard transfer zone, northwest of the MacDonald–Hay River fault (Nelson et al., 2002).

Within the regional deposit-type zones, many mineral deposits are along discrete mineral belts that parallel the facies belts (Fig. 4). Discrete belts of Cambrian–Ordovician sedex deposits were localized by rotated crustal blocks at depth. Such blocks formed as a result of extension and crustal thinning such as in the lower-plate system modeled for asymmetric extension shown in Figure 2B. The rotated crustal blocks resulted in restricted depositional basins and structures that provided pathways for basinal brines (MacIntyre, 1991; Goodfellow et al., 1993). Extensional reactivation of those earlier rift structures by Devonian–Mississippian slab rollback resulted in discrete belts containing Devonian–Mississippian sedex and MVT deposits (Nelson et al., 2002).

British Columbia

South of the Liard line in the upper-plate rift segment along the northern British Columbian Cordillera, the originally narrow facies belts were further narrowed by northward dextral transcurrent faulting of the Nasina Trough and Cassiar Platform relative to the autochthonous Ketchika Trough and MacDonald Platform. When the northward translation is restored (Abbott et al., 1986), mineral deposit types are grouped in narrow, closely neighboring belts that are significantly narrower than those in the basin to the north. Cambrian–Ordovician sedex Pb-Zn-Ag and Late Devonian–Mississippian sedex Pb-Zn-Ag-Ba deposits are hosted in continental slope and margin shales (MacIntyre, 1991; Nelson, 1991; Goodfellow et al., 1993; Paradis et al., 1998; Nelson et al., 2002). MVT Zn-Pb deposits are hosted in Silurian–Devonian rocks of the continental shelf-edge carbonate platform and are dated as Late Devonian–Mississippian age (Nelson, 1991; Goodfellow et al., 1993; Nelson et al., 2002).

There is a gap in sediment-hosted deposit occurrences along the central British Columbian Cordillera (Fig. 4), perhaps due to tectonic complexity and erosion (Nelson, 1991). There, Mesozoic and Cenozoic igneous rock–related replacement and vein deposits are located along the miogeocline (Fig. 5). In southern British Columbia (northern Kootenay Arc; Table 1), pericratonic rocks host both Cambrian and Devonian–Mississippian VMS deposits (Höy, 1991; Nelson et al., 2002). Continental slope rocks of the Kootenay terrane and Shuswap Complex include Early Cambrian carbonate-hosted sedex Pb-Zn-Ag deposits that are not generally associated with barite (MacIntyre, 1991; Nelson, 1991). To the east, a belt of MVT deposits hosted in Early Cambrian slope-shelf transition rocks may have formed in the Cretaceous (Nelson, 1991; Symons et al., 1998).

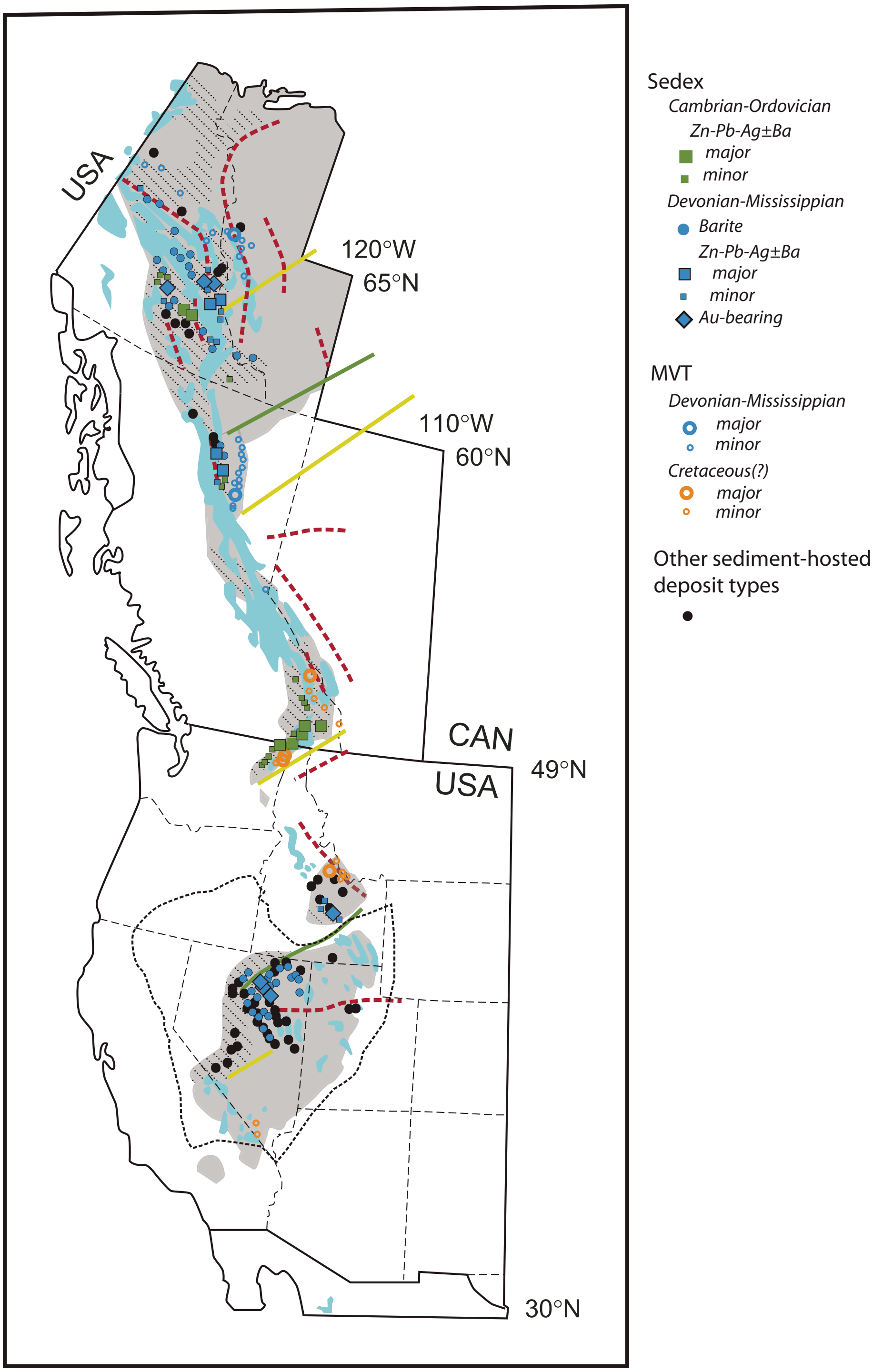

Figure 4. Mineral deposit belts and types that may be related to formation or reactivation of the rift-related and miogeoclinal segments along the western margin of Laurentia (see Figs. 1 and 3 for patterns). Sedex—sedimentary exhalative; MVT—Mississippi Valley type. Deposit localities and types compiled from Huntting (1956); Weissenborn et al. (1970); Brady (1984); MacIntyre (1991); Nelson (1991); Goodfellow et al. (1993); Vikre (2000); Nelson et al. (2002); Emsbo et al. (2006); and Klein and Sims (2007).

This south end of the British Columbia segment, near the juncture with the St. Mary–Moyie transform (Fig. 4), contains many significant sediment-hosted sedex and MVT deposits (Leach et al., 2005). Although more narrowly distributed, these deposits are the result of processes similar to those that produced the deposits in basins to the north.

St. Mary–Moyie Transform Zone

Cambrian–Ordovician rocks, which were deposited in a narrow basin along the St. Mary–Moyie transform zone, host both sedex and MVT deposits in closely aligned belts (Fig. 4; Table 1). A western belt in extreme southern British Columbia and extending southwest into northeastern Washington includes Cambrian–Ordovician carbonate-hosted sedex Pb-Zn-Ag deposits (MacIntyre, 1991; Nelson, 1991) in continental slope facies rocks (Greenman et al., 1977; Bush, 1991). In northeastern Washington, a narrow northeast-striking Cambrian–Ordovician slope-shelf transitional limestone (Greenman et al., 1977; Bush, 1991) hosts MVT deposits that are the predominant mineral deposits in the northeast-striking facies belts. These include the rich MVT Zn-Pb deposits of the Metaline mining district (McConnel and Anderson, 1968; Weissenborn et al., 1970; Brown and Ahmed, 1986; St. Marie and Kesler, 2000; McClung et al., 2001). The age of MVT mineralization has not been determined. The slope-shelf transitional facies also hosts bedded (sedex) barite deposits (Moen, 1964).

The same trend localized Cenozoic (possibly Eocene) epithermal low-sulfidation Au-Ag and skarn deposits hosted in the Cambrian–Ordovician and younger rocks (Huntting, 1956; Brown and Ahmed, 1986).

Eastern Washington–Eastern Idaho

From eastern Washington to central Idaho, only scattered Neoproterozoic–middle Paleozoic sedimentary rocks are exposed because of younger cover rocks and numerous Mesozoic and Cenozoic plutons. There is a corresponding gap in sediment-hosted mineral deposits in the same zone (Fig. 4). Farther southeast in central Idaho, Cambrian–Devonian slope and shelf rocks are preserved and sediment-hosted mineral deposits are present.

In south-central Idaho, a northwest-striking mineral belt is hosted by Devonian basinal to continental slope (outer continental margin) rocks (the "black shale mineral belt") in a northern extension of the Roberts Mountains allochthon (Turner and Otto, 1988, 1995). The belt contains Devonian sedex Zn-Pb-Ag deposits with only

TABLE 1. COMPILATION OF SEDIMENT-HOSTED MINERAL DEPOSIT TYPES, THEIR AGES, AND THEIR HOST ROCKS FOR SEGMENTS OF THE CANADIAN AND U.S. CORDILLERAN MIOGEOCLINE

Basin		Deposit type	Age of deposit	Age of MVT host
Yukon	Selwyn	Sedex Zn-Pb-Ag(±Ba)	Ꞓ–eO, eS, lD–M	
		Sedex Zn-Pb-Ag-Au(±Ba)	Ꞓ–O	
		Sedex Ba	lD–M	
		Sedex Au w/ sedex Ba	lD–M	
	Mackenzie	MVT	lD–M	S–D
British Columbia	Ketchika	Sedex Pb-Zn-Ag	Ꞓ–O	
		Sedex Pb-Zn-Ag-Ba	lD–M	
	MacDonald	MVT	lD–M	S–D
	Northern Kootenay Arc	Sedex Pb-Zn-Ag (no Ba)	eꞒ (carbonate)	
		MVT	K	eꞒ
St. Mary–Moyie		Sedex Pb-Zn-Ag	Ꞓ–O (carbonate)	
		Sedex Ba	Ꞓ–O	
		MVT Zn-Pb	?	Ꞓ–O
Eastern Washington–southeastern Idaho		Sedex Zn-Pb-A	D	
		Sedex Zn-Pb-Ag-Au	m-lD	
		MVT Zn-Pb-Ag	Mz-Cz	D–M
		Replacement Zn-Pb-Ag±Au±Ba	Mz-Cz	
Snake River		Sedex Ba	D	
		Replacement Ba-Ag-Zn-Pb	Mz-Cz	M–P
Utah–Nevada		Sedex Ba	O, D	
		Sedex Au	D	
Southeast Californian–southern Nevada		MVT	?	M
		Replacement Pb-Zn-Ag	K	Z–M

Note: Sources of data are in text and caption for Figure 4. Sedex—sedimentary exhalative; MVT—Mississippi Valley type; Z—Neoproterozoic; Ꞓ—Cambrian; eꞒ—Early Cambrian; eS—Early Silurian; S—Silurian; eO—Early Ordovician; O—Ordovician; D—Devonian; m-lD—Middle to Late Devonian; lD—Late Devonian; M—Mississippian; Mz-Cz—Mesozoic–Cenozoic; K—Cretaceous; P—Pennsylvania; ?—unknown.

minor barite and Middle to Late Devonian sedex Zn-Pb-Ag-Au deposits (Albers, 1983; Hall, 1985; Turner, 1992; Turner and Otto, 1995). It also contains Cretaceous or Eocene Zn-Pb-Ag ± Au ± Ba replacement and vein deposits (Hall, 1985; Hobbs, 1985; Burton and Link, 1995; Mahoney, 1995; Turner and Otto, 1995; Winkler et al., 1995), and some of the associated host structures and fluid pathways are inferred to have originated during Late Devonian–Early Mississippian Antler-age deformation (Turner and Otto, 1988, 1995).

In east-central Idaho, a parallel, northwest-striking belt of Devonian–Mississippian continental shelf carbonate rocks hosts Zn-Pb-Ag mineralization in MVT deposits that may be Cretaceous or Eocene (Skipp et al., 1983; Hobbs, 1985) as well as in similar age replacement and vein deposits (Albers, 1983; Skipp et al., 1983; Hobbs, 1985; Ruppel and Lopez, 1988).

In south-central Idaho, isotopic data reveal parallel northwest-striking crustal zones having transitional continental crust on the southwest and Precambrian crust on the northeast (Sanford and Wooden, 1995). The crustal zones are paralleled by northwest-striking facies and mineral belts, demonstrating the influence of the underlying older northwest-trending rift system on subsequent events.

To the north in central Idaho, where Cretaceous (Idaho batholith) and Eocene (Challis volcanic-plutonic) rocks are predominant and the only recognized miogeoclinal rocks are discontinuous Neoproterozoic exposures in roof pendants (Lund et al., 2003), there are no known sedex or MVT deposits. However, there are many base and precious metal mineral deposits within Cretaceous and Eocene igneous rocks. Region-wide studies of mineral-deposit occurrences (disregarding Mesoproterozoic sediment-hosted and Coeur d'Alene deposits) in western Montana and central and northern Idaho show that although many important igneous-rock related mineral deposits are along the mostly unexposed, broad, northeast-striking Paleoproterozoic Great Falls tectonic zone in the basement (O'Neill and Lopez, 1985; Klein, 2004; O'Neill et al., 2007; Klein and Sims, 2007), there are also many additional epigenetic deposit occurrences that extend northwest across central Idaho (Albers, 1983; Klein, 2004; Klein and Sims, 2007) along the projected northwest trend of the Laurentian margin (Fig. 5). Similar age and composition igneous rocks to the north and northeast of the trend of the miogeocline are mostly barren. The pluton-related and volcanic-hosted deposit types in the trend of the miogeocline include polymetallic vein ± W; replacement Pb-Ag ± Ba; distal disseminated Au; and epithermal Au, Hg, and Sb deposits (Kiilsgaard et al., 1986; Ruppel and Lopez, 1988; Klein, 2004). Northwest-striking linear aeromagnetic anomalies [North America Magnetic Anomaly Group (NAMAG), 2002] correlate with several of the northwest-striking central Idaho mineral belts. The aeromagnetic anomalies are inferred to reflect basement faults in extended continental basement (Sims et al., 2005), possibly normal fault–related crustal blocks at depth within the Neoproterozoic and Paleozoic upper-plate rift margin. Such structures may have influenced deposition of Neoproterozoic–middle

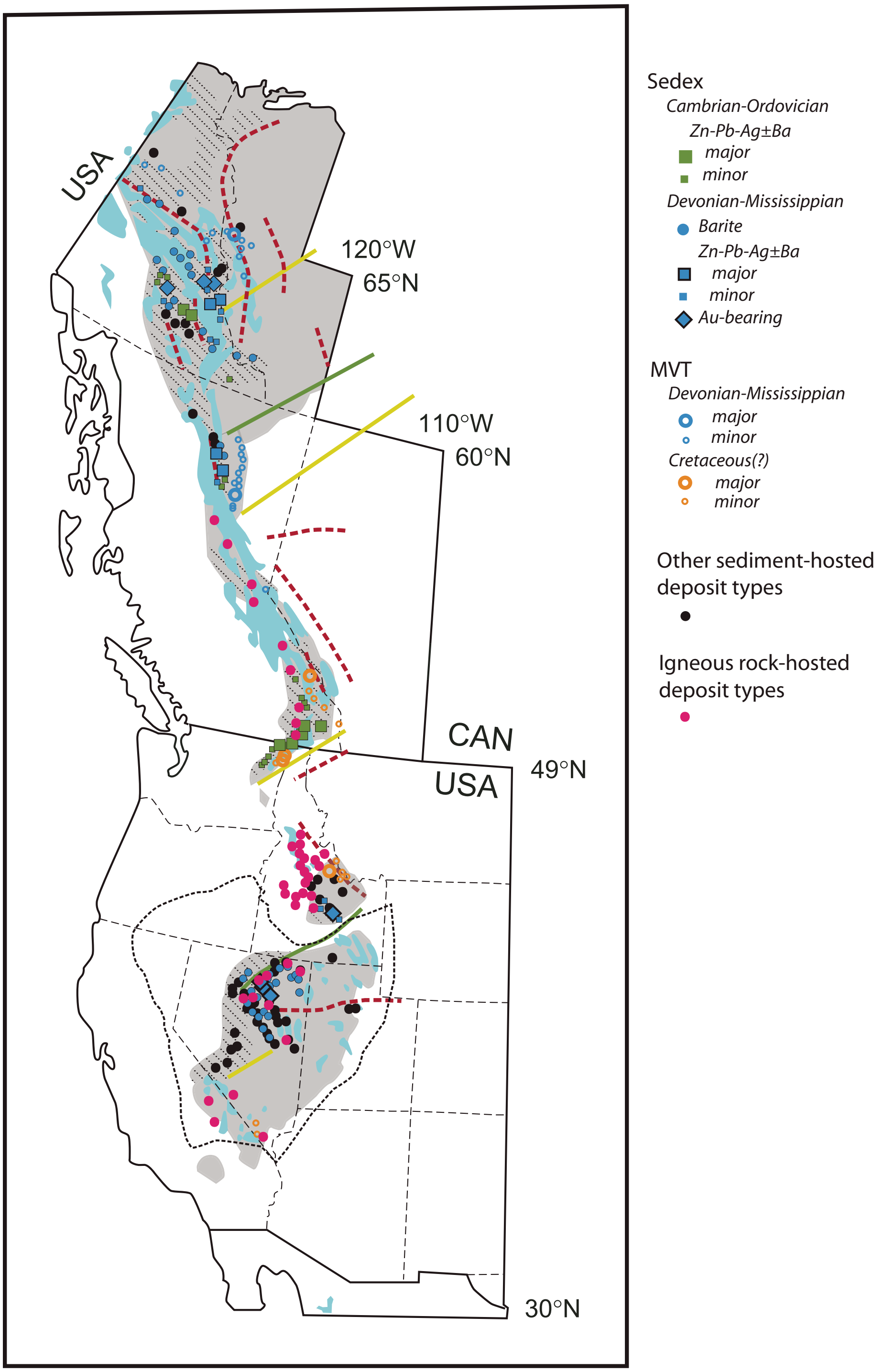

Figure 5. Mineral deposit belts and types, including magmatic rock–related deposits that are within the trend of the U.S. and Canadian Cordilleran miogeocline. Sedex—sedimentary exhalative; MVT—Mississippi Valley type. (See Figs. 1 and 3 for patterns; Fig. 4 for sources.)

Paleozoic sedimentary rocks (of the many different facies seen in south-central Idaho; e.g., Hobbs and Hays, 1990) and may have been the locus for subsequent structural, magmatic, and hydrothermal activity. In the southern part of these mineral deposit belts, lead isotopic data indicate remobilization from Precambrian basement and from Devonian syngenetic sources (Sanford and Wooden, 1995).

Snake River Zone

There are few exposed or studied mineral deposits related to miogeoclinal rocks in the limited exposure of pre-Neogene rocks near the Snake River Plain. Early Paleozoic rocks are mostly not exposed at the surface. However, along the south margin of the Snake River Plain, northeast-striking Devonian–Pennsylvanian slope facies rocks provide evidence of the Snake River transfer zone as well as incompletely studied mineral deposits. The general trend of bedded barite deposits in slope facies rocks of the Roberts Mountains allochthon bends northeast in northern Nevada (Albers, 1983) into the Snake River transfer zone. The most important deposits are disseminated Au with minor Hg, As, and Sb that may be classified as hot spring–type (low sulfidation epithermal) deposits of Cretaceous–Miocene age (Brady, 1984). Most of the reported occurrences are small Ba-Ag-Zn-Pb replacement and polymetallic vein deposits in Pennsylvanian rocks that probably also formed in the Cretaceous–Miocene (Brady, 1984).

Great Basin

Zones of Sn and Sb mineralization and Pb-Zn replacement mineralization are distributed across the miogeoclinal shelf carbonate rocks in eastern Nevada and central Utah (Albers, 1983; Vikre, 2000). In central Nevada, continental slope strata of the Roberts Mountains allochthon, which formed along the western side of the broad lower-plate margin of the Nevada-Utah segment, host a north-striking belt of Devonian and some Ordovician sedex (bedded) barite deposits (Albers, 1983; Papke, 1984; Poole et al., 1992; Koski and Hein, 2003). In this continental slope setting, the major sedex barite deposits are associated with few sedex Pb-Zn occurrences (Turner, 1992). In contrast, the parautochthonous Silurian–Devonian platform-margin to slope sedimentary rocks (Cook, 2005), which underlie the Roberts Mountains allochthon, host Devonian sedex Au deposits with associated Zn, Pb, Ag, Ba, W, and Sb mineralization (Emsbo et al., 1999; Emsbo, 2000). These deposits formed during renewed rifting in the Devonian that was superposed on the outer edge of the platform margin (Emsbo, 2000). Large areas of Cambrian and Devonian–Mississippian platform-margin rocks in north-central Nevada show evidence of basinal brine circulation in zebra dolomite that is associated with the Devonian sedex Au and Ba deposits (Diehl et al., 2005).

Overprinted on the Paleozoic sediment-hosted mineral deposits in these broad facies belts are the rich mineral deposit belts of north-central Nevada. Mesozoic–Neogene mineral deposits, including Jurassic–Oligocene porphyry, mid-Eocene Carlin Au, and Neogene epithermal deposit types, extend along the northwest-striking Carlin and Battle Mountain–Eureka trends (Hofstra and Cline, 2000; Wallace et al., 2004; Cline et al., 2005; Emsbo et al., 2006). Two shorter discrete northeast-striking mineral deposit trends (Getchell trend and Jerritt Canyon district) are located at the north ends of the larger northwest-striking mineral trends (Hofstra and Cline, 2000; Emsbo et al., 2006), where the facies belts and structures swing to the northeast into the Snake River transfer. The long time span of mineral deposit formation and great variety of deposit types in these two general orientations indicate multiple mineralization episodes and reactivated structural conduits (Hofstra and Cline, 2000; Emsbo et al., 2003, 2006; Cline et al., 2005).

Many Mesozoic–Neogene mineral deposits are suggested to be preferentially located in continental slope-platform margin rocks (Cook, 2005) in windows beneath or directly in front of overthrust continental slope to basin rocks of the Roberts Mountain allochthon (Roberts et al., 1958; Stewart, 1980; Hofstra and Cline, 2000; Cline et al., 2005; Cook, 2005). The host rocks were deposited in subbasins above deep crustal structures that were secondary features of this segment of the Cordilleran rift margin (Tosdal et al., 2000; Crafford and Grauch, 2002). The subbasin-controlling structures formed as rotated crustal blocks during northeast-southwest Neoproterozoic–early Paleozoic extension, were reactivated during renewed Devonian extension events forming pathways for mineralizing basinal brines (Hofstra and Cline, 2000; Cline et al., 2005; Emsbo et al., 2006), and were inverted during contractional deformation in the Mesozoic, further opening pathways for younger mineralizing systems (Emsbo et al., 2006; Muntean et al., 2007). Structures in the mineral belts were reactivated again during initiation of the Yellowstone hotspot (Ponce and Glen, 2002), but the main Miocene rift faults may have been influenced by northeast-striking Neoproterozoic and Paleozoic structures. The various deposit types of different ages in the Carlin, Battle Mountain–Eureka, Getchell, and Jerritt Canyon trends indicate that their distribution was controlled by the much earlier rift structures.

Southeastern California and Southern Nevada

In southwestern and southern Nevada, MVT deposits are hosted in Mississippian platform carbonate rocks overlying a Cryogenian–Devonian shelf succession (Stewart, 1980; Vikre, 2001; Church et al., 2005). Along this miogeoclinal segment, the platform carbonate rocks display evidence for movement of basinal brines associated with formation of sedex and MVT deposits (Diehl et al., 2005). However, sedex Pb-Zn and barite deposits are uncommon (Albers, 1983; Papke, 1984). In contrast, Cretaceous pluton-related replacement Pb-Zn-Ag and skarn deposits are widespread in Cryogenian–Mississippian miogeoclinal rocks of southeastern California (Albers, 1983; Vikre, 2000; Church et al., 2005). The amount of transcurrent faulting in this zone makes it difficult to be specific about the facies and depositional setting of rocks that host the mineral deposits; however, it is significant that the sedimentary and structural conditions were similar to those of other margin segments.

CONCLUSIONS

The geometry of the Cryogenian–Devonian rift margin of western Laurentia, which formed the Cordilleran miogeocline, can be reconstructed by linking new interpretations for the northern U.S. Cordillera with previous interpretations from Canada and central Nevada. The rifting formed a systematic zigzag pattern of northwest-striking extensional segments alternating with northeast-striking transcurrent segments. As with the Canadian margin, individual segments of the miogeocline from southern British Columbia to southeastern California are characterized using structural, stratigraphic, and geometric data. Evaluation of these characteristics indicates that extensional segments developed as independent domains of asymmetric extension separated by transform or transfer zones. The setting of segments of the U.S. Cordilleran margin include the southern British Columbia–northeastern Washington St. Mary–Moyie transform, the eastern Washington–eastern Idaho upper-plate margin, the southern Idaho–north-central Nevada Snake River transfer zone, the Utah-Nevada Great Basin lower-plate margin, and the southwestern Nevada Mina transfer zone. Several discrete, widely distributed extension events along the margin are recognized by mafic and/or alkalic magmatism and increased subsidence. These events occurred in the Cryogenian (from ca. 709–685 Ma continuing until, or with a separate event, ca. 650 Ma), late Ediacaran–Early Cambrian, Late Cambrian–Early Ordovician, and Devonian. Although widespread along the margin, the present data are not sufficient to determine whether these events were completely synchronous or equivalent along the length of the margin in terms of amount of extension or resultant subsidence. However, widespread evidence suggests correspondence of increased sedimentation, magmatism, and mineralizing events at these times.

Extensional (northwest-striking) rift segments generally cut orthogonally across basement domain boundaries, exhibiting little influence by preexisting fabrics. However, transform and transfer zones are preferentially located along preexisting basement domain boundaries, suggesting basement control. During subsequent tectonic activity that affected the rift margin, deformation overlapped and paralleled the rift-derived geometry of the margin, with structures wrapping around promontories and into embayments. This resulted in reactivation of primary and secondary rift structures and localized magmatic activity particularly along upper-plate margins, and provided repeatedly open conduits for hydrothermal fluids. Transform and transfer zones were commonly reactivated as zones of transcurrent faulting, acting as accommodation zones for diachronous and/or differing amounts of tectonic displacement (contractional and extensional).

Sedimentary rocks deposited in the rift segments contain sediment-hosted mineral deposits that are associated with specific stratigraphic setting and extensional history. In the context of broad lower-plate margins (Yukon and Great Basin), sedex Zn-Pb-Ag-Au and barite deposits are in broad zones that correspond to the width of continental slope rocks; likewise, carbonate-hosted MVT Zn-Pb deposits are broadly located across the wide zone of shelf rocks. A similar correlation exists along the narrower upper-plate margins (British Columbia and central Idaho), where these two general mineral deposit types occupy the correspondingly narrower facies belts. Transform and transfer zones also host similar deposit types, but in even more narrowly constrained shelf and slope facies rocks; in the St. Mary–Moyie transfer, the sedex deposits are carbonate hosted rather than siliciclastic hosted. Discrete, rift-parallel mineral belts are superposed on the general pattern of occurrences. These are genetically related to secondary rift structures such as rotated crustal blocks that formed as the crust thinned. Such crustal blocks localized restricted basins during sedimentation and provided critical long-lived fluid pathways for formation of syngenetic and epigenetic mineral deposits. Although extension models predict there will be more rotated crustal blocks along lower-plate margin segments, rotated blocks or major normal faults, which are inferred from discrete sedex and MVT belts, are also present along upper-plate segments.

Parts of the upper-plate rift segments in central British Columbia and central Idaho were intensely overprinted by Mesozoic hinterland deformation and both Mesozoic and Cenozoic magmatism that largely destroyed evidence of Paleozoic sediment-hosted mineral deposits. However, abundant igneous rock–related mineral deposits are preferentially located along the trend of the miogeocline in comparison with barren plutons of the same age outside of the miogeoclinal trend. In addition, these deposits are located along discrete mineral deposit belts that may reflect rift structures at depth.

Present information does not show a link between Cryogenian or Early Cambrian extension events and sedex deposits. However, Late Cambrian–Early Ordovician and Devonian–Mississippian ages of increased extension are closely correlated with ages of sedex deposits. Late Devonian–Mississippian MVT deposits are related to extension or contraction in different rift segments.

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