# Asymmetric rift interpretation of the western North American margin

Vicki L. Hansen
John W. Goodge
Myra Keep
Douglas H. Oliver
Department of Geological Sciences, Southern Methodist University, Dallas, Texas 75275

**ABSTRACT**

**Geologic evidence shows that the Neoproterozoic rift margin of western North America formed as a set of asymmetric detachments, leading to alternating upper- and lower-plate domains distinguishable by the width and gradient of the continental margin, thickness of overlying strata, uplift-subsidence history, relative structural complexity, and presence or absence of exposed lower-crustal rocks. The gradient of the cratonal margin is a key feature related to the transition between continental and oceanic crust; upper-plate margins are marked by steep gradients, whereas lower-plate margins have gentle gradients. In the Canadian Cordillera, the gradient across this transition changes coherently along the margin, from shallow, to steep, to shallow, in turn from north to south. The sinuosity of the Cretaceous-Tertiary thrust-belt front, the distribution of basement exposures, and patterns of miogeoclinal deposition may therefore be inherited from the original asymmetric Neoproterozoic rift geometry.**

## INTRODUCTION

The configuration of the western rifted margin of North America in space and time is of continuing great interest. Since the observations of Stewart (1972), geologists have focused in particular on the timing and duration of rifting (Silver, 1978; Zartman et al., 1982; Bond and Kominz, 1984; Bond et al., 1984; Hoy, 1989; Heamon and Grotzinger, 1992) and identification of the craton(s) that form the conjugate margin to North America (Sears and Price, 1978; Bell and Jefferson, 1987; Moores, 1991; Dalziel, 1991). In addition, the geometry and kinematics of rifting are poorly understood, largely due to the subsequent Phanerozoic tectonic history.

We propose that this Neoproterozoic margin formed as a set of oppositely asymmetric detachments as hypothesized by Bally (1981), leading to alternating thick upper-plate segments and thin, extended lower-plate segments along the length of the margin. Several key features of the modern Canadian Cordillera, some long recognized, reflect underlying control by initial rift geometry. First, the curvature and variable width of the Cretaceous-Tertiary thrust belt indicate primary inflections along the margin. Second, the only exposures of proven Precambrian basement lie west of relatively wide parts of the thrust belt. Third, Cambrian isopachs, reflecting the magnitude and expanse of marine transgressions, vary along the margin. Here, we expand on a theme, considered by earlier workers, that the formation of some or all of these features is controlled at least in part by the geometry of basement structures (e.g., Aitken and Long, 1978; Park et al., 1989; Cook et al., 1991).

## PASSIVE-MARGIN MODELS

Most models for continental rifting are based either on pure-shear (McKenzie, 1978) or simple-shear (Bally, 1981; Wernicke and Burchfiel, 1982; Lister et al., 1986) mechanisms. Pure shear leads to symmetric rifting with minimal along-strike structural changes, whereas simple shear predicts asymmetric rifting and important along-strike changes in the nature of the margin. An asymmetric-rifting model (Bally, 1981) suggests that rifted margins may be composed of alternating upper- and lower-plate segments (Fig. 1). Upper-plate segments, characterized by thick continental crust with narrow continental shelves and thin sedimentary sequences, are structurally simple, dominated by weakly rotational normal faults; the lower crust is not exhumed. Conversely, lower-plate margins consist of extended continental crust with broad shelves overlain by thick sedimentary sequences. The basement to sediment crustal section is structurally thinned by rotational listric faults, tilt blocks, and half grabens, resulting in tectonic exhumation of lower crust. Lower-plate margins undergo rapid uplift followed by pronounced subsidence; subsidence is greater than in upper-plate margins due to isostatic compensation resulting from more severe crustal thinning, mantle replacement of crust, and greater mean lithospheric density. Broad marine encroachments will occur over areas of tectonically induced subsidence following extension. In contrast, upper-plate margins will largely remain compensated.

Upper- and lower-plate margins are therefore distinguishable on the basis of the width and gradient of the continent-ocean transition, thickness of sedimentary strata, uplift-subsidence history, structural complexity, and the presence or absence of exposed lower-crustal rocks. We can use these criteria to help establish the primary configuration of the Neoproterozoic Cordilleran rift margin.

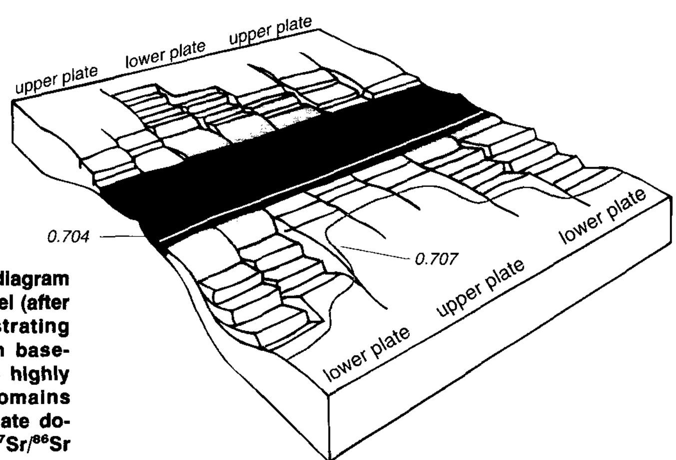


**Figure 1. Simplified block diagram of asymmetric rifting model (after Lister et al., 1986) illustrating along-strike contrasts in basement structures between highly extended lower-plate domains and more intact upper-plate domains. Predicted initial $^{87}Sr/^{86}Sr$ isopleths (light gray lines) illustrate inferred variations in surface and crustal gradients along drift-stage margin.**

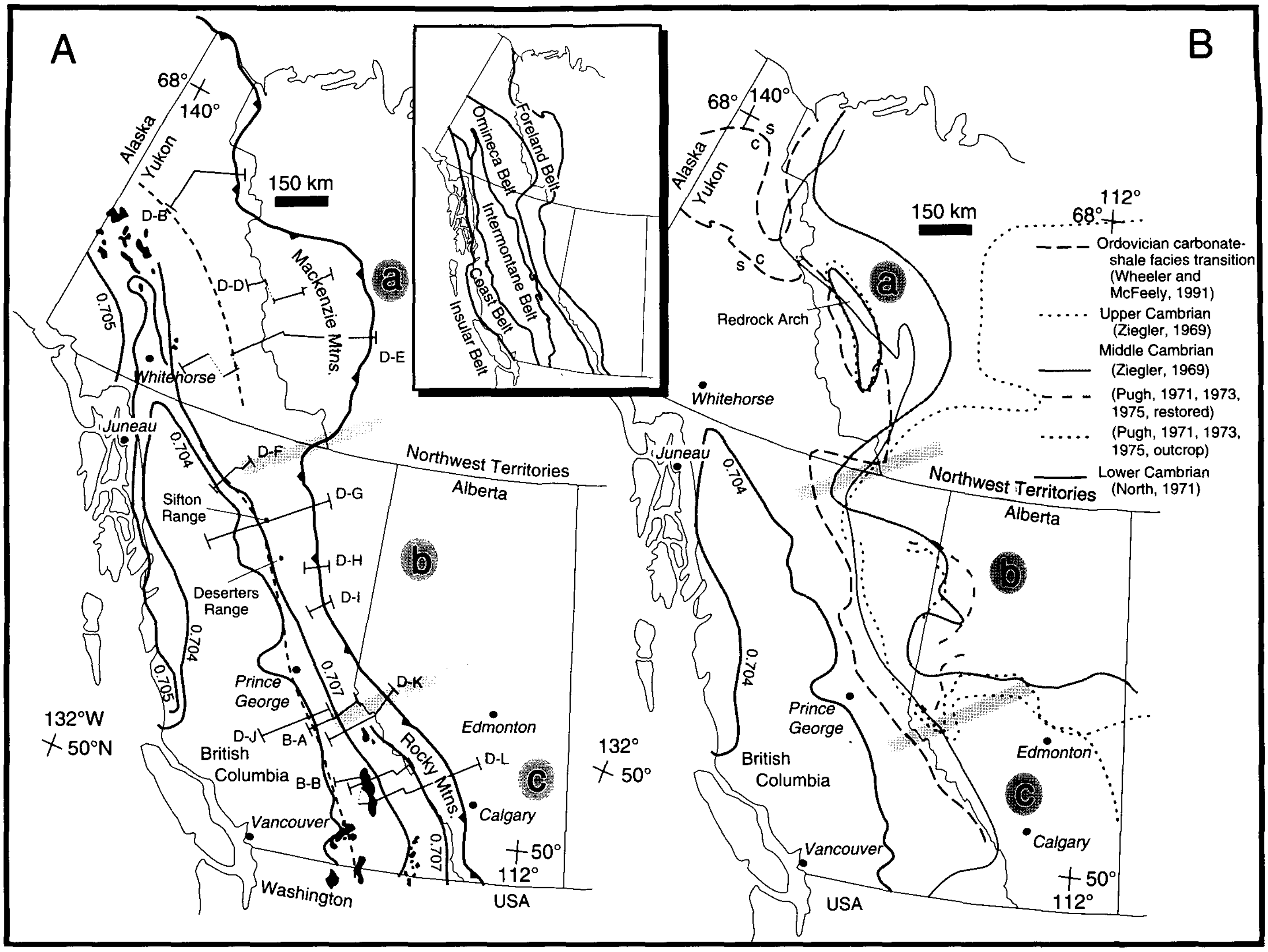


**Figure 2. Maps of Canadian Cordillera showing principal Precambrian to Cambrian geologic features used to delineate lower (a, c) and upper (b) plate asymmetric rift domains. Inset shows relation to present tectonic belts (Wheeler and McFeely, 1991). A: Map showing eastern limit of Cretaceous-Tertiary thrust-belt (barbed line), isopleths of initial $^{87}Sr/^{86}Sr$ (gray lines; Armstrong, 1988), Precambrian crystalline basement exposure (black areas; Parrish, 1991), locations of restored crustal cross sections (B-A and B-B from Brown et al., 1986; D-B to D-L from Gabrielse, 1991, Fig. 17.1), and eastern limit of inferred oceanic crust (dashed line; see text). B: Map showing Lower, Middle, and Upper Cambrian zero isopachs, and Ordovician carbonate-shale facies transition (c and s). Middle Cambrian isopachs of Pugh (1971, 1973, 1975) show present-day outcrop of shoreline facies and restored position of this isopach compensating for postdepositional erosion.**

## CONTINENT TO OCEAN TRANSITION ACROSS THE MARGIN

We evaluate variations in the ocean-continent crustal gradient across the early Paleozoic margin by compiling published Sr isotopic compositions of Mesozoic plutons, the extent of Cambrian near-shore sedimentary facies, restored crustal-scale cross-sections, and the distribution of exposed crystalline basement (Fig. 2). Although there is evidence for episodic extension and/or rifting as old as 1200 Ma, we focus on early Paleozoic relations to assess the character of the well-established rift margin.

Sr isotopic data from Mesozoic plutons (Armstrong, 1988) allow characterization of the crustal type from which they were derived; initial $^{87}Sr/^{86}Sr$ ratios $\leq 0.704$ indicate underlying oceanic crust, and ratios $\geq 0.707$ reflect continental crust. Spatial variation in these $^{87}Sr/^{86}Sr$ isopleths imply changes in gradient across the ocean-continent transition (Fig. 2A). From north to south, the spacing between isopleths changes from broad to narrow to broad, inferring, in turn, shallow, steep, and shallow gradients in passing from continental to oceanic crust.

The gradient across the continent-ocean transition is also reflected in isopachs of Cambrian sedimentary rocks and their pattern of onlap onto the craton. Isopachs for Lower, Middle, and Upper Cambrian strata show a general trend of shallow-steep-shallow gradients across the continental margin (Fig. 2B), suggesting an initial configuration of embayment-salient-embayment from north to south. These gradients become more pronounced with time. Restoration of Cambrian isopachs using restored crustal cross sections (Gabrielse, 1991, Fig. 17.1) results in <35 km net displacement and indicates that the isopachs are not far from their original pre-Cretaceous position. Therefore, inflections in the margin do not appear to be artifacts of foreland deformation. Paleomagnetic data and facies relations in the Mackenzie belt lead to similar conclusions (Aitken and Long, 1978; Park et al., 1989).

Migration of the Lower, Middle, and Upper Cambrian zero isopachs track relative movement of the shoreline during differential subsidence along the Cordilleran margin. Time-transgressive cratonward onlap was most pronounced within the embayment segments. However, erosion may have subsequently modified the isopachs (Fig. 2B), a factor we are unable to evaluate.

The coincidence in gradient variations along the margin as defined by isotopic and sedimentologic data is most pronounced between the 0.704 Sr-isotope isopleth and the Lower Cambrian zero isopach (i.e., the full transition from oceanic to continental crust). Similar variations can be noted between the 0.704 Sr-isotope isopleth and the shallow-water–deep-water facies transitions (Fig. 2B). Therefore, variations in the continental-margin gradient appear to be real and have existed from at least the Early Cambrian. Restored crustal cross sections that extend west of the thrust belts of the Rocky-Mackenzie mountains (Brown et al., 1986; Gabrielse, 1991, Fig. 17.1) allow qualitative delineation of the easternmost permissible oceanic crust (Fig. 2A). This limit is based on inferred basement type beneath Proterozoic and lower Paleozoic supracrustal sequences and on the restored position of such features as the carbonate-shale transition. In the central and southern Rocky Mountains this delineation is nearly coincident with the Sr isotope 0.704 isopleth, affirming the presence of a steep continent-ocean transition. Farther north, this line is not well constrained, yet it indicates that transitional crust may extend west of the Mackenzie thrust belt.

On the basis of these observations, we differentiate three principal upper- and lower-plate domains, a, b and c, along the Canadian Cordillera (Fig. 2). Lower-plate domains (a and c) are defined by inferred shallow surface gradients, exposures of crystalline basement, and thick, extensive Cambrian sequences, whereas the upper-plate domain (b) is marked by steep inferred surface gradients, absence of intact crystalline basement, and thin, areally restricted Cambrian sediments. The central upper-plate margin is marked by a broad salient of basement arches, as manifested in the sedimentary record, whereas the lower-plate domains show evidence of transgressions in isopach embayments and increased sediment thickness.

Exposures of Precambrian crystalline basement are located far to the west of the Cretaceous-Tertiary deformation front on the lower-plate margins in southern British Columbia and central Yukon (Fig. 2A). These exposures coincide with shallow gradients and are the expected result of severe extension of continental lithosphere during rifting. The Redrock arch (Fig. 2B) is within a lower-plate domain and may represent a continental ribbon resulting from differential extension. In central British Columbia, in our designated upper-plate domain (Fig. 2A), exposures of crystalline basement—the 1.85 and 0.73 Ga orthogneisses from the Sifton and Deserters ranges, respectively (Evenchick et al., 1984)—are not predicted by our hypothesis. These exposures are along the northern Rocky Mountain trench and display structural features that indicate Mesozoic-Cenozoic strike-slip displacement (Evenchick et al., 1984; Parrish, 1991); therefore, they may not represent intact crust. Rocks of the Sifton range, for example, may have formed initially within a lower-plate rift position and were subsequently transferred to their present upper-plate position by southeastward displacement in mid-Cretaceous time, consistent with temporal and kinematic relations documented in the Sifton orthogneiss (Evenchick et al., 1984).

Basement arches, defined by Cambrian isopach data, occupy our upper-plate domain. Paleocurrent indicators (Pugh, 1973) indicate that sediment was shed radially from these highs to the southeast and the northeast. Although sedimentary overlap obscures the original extent of the arches, we propose that the highs reflect a minimum extent of the underlying upper-plate crystalline basement.

We propose that many of the geologic complexities of the Canadian Cordillera result from shortening of an initial asymmetric rift margin. For example, major Cordilleran thrust belts are formed in sections of the margin characterized by a thick Proterozoic and Paleozoic sedimentary veneer (Bally et al., 1966; Price, 1981; Gabrielse, 1991). These areas underwent extensive sediment deposition, and they correlate with our lower-plate margin where subsidence and marine encroachment are most extensive. In addition to this lithologic control on structural development, many of the low-angle structures related to original rifting in lower-plate domains may have been reactivated as thrusts during contraction of the margin (e.g., Struik, 1988).

## DISCUSSION

Basement control on Neoproterozoic and Phanerozoic tectonics of the North American Cordillera has been suggested by others. The Mackenzie arc is a primary feature of the margin (Aitken and Long, 1978; Park et al., 1989), and basement control accounts for the distribution of Belt Group sedimentary facies (Winston, 1986). Burchfiel and Davis (1972) recognized the relation between miogeocline thickness and the style of thrust-belt contraction, and Cook et al. (1991) suggested that basement ramps controlled later thrust-fault geometry. Rankin (1976) proposed similar ideas about initial rift patterns controlling later tectonic development of the Appalachians.

The idea of basement control on Phanerozoic tectonics is, therefore, not new. However, our proposal that the basement of the western margin comprises both upper- and lower-plate domains formed during asymmetric rifting explains along-strike changes in basement distribution, sedimentation history, and thermal and structural evolution that are not easily reconciled with symmetric rifting. Symmetric rift domains may be offset along transform faults; however, there would be no along-strike changes in continental margin gradient. One major problem with our hypothesis is the lack of constraints on the amount and timing of displacement on Triassic and younger strike-slip systems, any of which may have affected one or more of the geologic features we have used. Cambrian near-shore facies are not affected by strike slip, because they lie east of the northern Rocky Mountain trench, but parts of the Sr-isotope 0.707 and 0.704 isopleths may be displaced, the 0.707 isopleth moving farther west in Yukon. The magnitude of left-lateral displacement along the margin during Triassic-Jurassic time may be greater than Cretaceous right-lateral displacement, resulting in net left slip along the margin (Engebretson et al., 1985). If right slip balances left slip, the present positions of the eastern limit of oceanic crust, and the 0.704 and 0.707 isopleths, may be essentially correct. Even in the case of net left slip along the Cordillera, the relations among the data sets by which we defined upper- and lower-plate rift margins would be largely unchanged. As discussed above, however, there is evidence that Jurassic and younger strike-slip faults have modified parts of the margin (e.g., Sifton Range gneisses).

Along-strike stratigraphic and isotopic data (Lochman-Balk, 1971, 1972; Armstrong et al., 1977; Kistler and Peterman, 1978) are consistent with the continuation of our proposed upper- and lower-plate domains into the U.S. Cordillera, although they are obscured by Basin and Range extension and Columbia Plateau and Snake River Plain volcanism. For example, the Montana-Idaho, Colorado-Kansas, and Bliss embayments may represent lower-plate domains, and the Uinta and Defiance arches may mark upper-plate salients. Despite significant Cenozoic extension across the Great Basin, there is a wide gap between the Sr-isotope 0.704 and 0.706 isopleths across Nevada that may represent extended crust corresponding to the Colorado-Kansas embayment. A rift geometry proposed by

Kistler and Peterman (1978, Fig. 6) is perhaps ahead of its time in anticipating an asymmetric rift model.

The principles of asymmetric rifting may also be applied to the long-standing problem of *what* rifted away from North America. Eastern Australia has been suggested as the conjugate margin to the Canadian part of western Laurentia (Bell and Jefferson, 1987; Moores, 1991; Dalziel, 1991; Young, 1992; Ross et al., 1992). If this correlation is correct, evidence of a corresponding system of alternating upper- and lower-plate segments may exist in the eastern Australian margin, perhaps contained in the Neoproterozoic-Cambrian sedimentary record.

## CONCLUSIONS

Geologic evidence indicates that the Neoproterozoic margin of western North America formed as a set of oppositely asymmetric detachments, leading to alternating upper- and lower-plate domains distinguishable on the basis of the width and gradient of the resulting continental margin, thickness of overlying strata, uplift-subsidence history, structural complexity, and presence or absence of exposed lower-crustal rocks. The sinuosity of the thrust-belt deformation front, the distribution of basement exposures, the patterns of miogeoclinal deposition, and other features of the Canadian Cordillera may thus be inherited from the original Neoproterozoic rift geometry, and, although a large amount of crust has been subsequently added to the cratonal margin by magmatic and accretionary mechanisms, there does not appear to be significant modification of the underlying primary Neoproterozoic rift margin as a result of subsequent tectonism.

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