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## ABSTRACT

**We propose that the Andes Cordillera formed by a "collision" between the trenchward-moving South American plate and the Nazca slab and subslab mantle. Resistance to trenchward motion, in the form of horizontal compressive normal stress, deforms South America's leading edge. The advancing continent also perturbs the subslab mantle flow field as mantle is displaced. This flow field, detected via shear-wave splitting, includes trench-parallel flow away from a central stagnation point and corner flow around the northern and southern ends of the continent. The corresponding spatial variation in applied stress accounts for the large-scale characteristics of Andean deformation: buckling at the stagnation point (maximum normal stress) forming the Central Andes and Bolivian orocline, and corner flow associated with the eastward motion of the Caribbean and Scotia plates. The high stresses required to form and maintain the Andes imply that South America's trenchward motion is primarily driven by deep mantle flow coupled to its base; no other driving force of sufficient magnitude is available. Similarities between North and South American plate motion history and large-scale Cordillera structure indicate that the western North American Laramide Rockies formed in a similar manner and that the North American plate is also driven westward by deep mantle flow. We infer that Atlantic spreading itself is similarly driven. By contrast, slab rollback in a closing ocean basin opens marginal basins at convergent margins, as in the western Pacific. We suggest that there is a causal link between the opening and closing of ocean basins and the formation of cordilleras and marginal basins. Cordillera formation occurs at the leading continental margin during the spreading phase of the Wilson cycle, whereas marginal basins form during the closing phase.**


## INTRODUCTION

The formation of the Andes, and in particular the Bolivian orocline and Altiplano plateau of the Central Andes, is paradoxical: Morphologically, the Andes resemble collisional mountain belts like Tibet, but they formed at a convergent, not collisional, margin. Tibetan-style collisional orogens are the culmination of the classical Wilson cycle of continental breakup and aggregation, but the Wilson cycle does not explain formation of cordilleras in a convergent environment. Convergence alone cannot produce the Andes: the western Pacific is rimmed by convergent margins without attendant Andean-style chains. We infer that South America is "colliding" with the Nazca slab and subslab mantle. The continent's westward motion generates compressive stresses that deform its western (leading) edge in a characteristic manner. South America's westward motion must be driven by deep mantle flow coupled to the continent's base, and probably Atlantic spreading in general is driven in a similar manner. Thus, we infer a causal link between the opening of ocean basins and cordillera formation, and between closing ocean basins and marginal basin formation. Cordillera and marginal basin formation are interim consequences of the Wilson cycle.

## MANTLE ANISOTROPY AND TRENCH-PARALLEL MANTLE FLOW

Our model is motivated by observations of seismic anisotropy beneath the Nazca plate. Seismic anisotropy delineates the flow field of the Earth's upper mantle via strain-induced lattice preferred orientation of mantle minerals (Nicolas and Christensen, 1987; Mainprice and Silver, 1993): shear-wave splitting is a manifestation of seismic anisotropy. We examined the mantle flow field associated with subduction by analyzing shear-wave splitting beneath the Nazca slab (Russo and Silver, 1994). The splitting we observed was not consistent with the two-dimensional slab-entrained flow field expected from plate-driven models of mantle flow (e.g., Hager and O'Connell, 1979). Instead, we resolved a component of horizontal trench-parallel flow beneath the Nazca slab. Thus, mantle flow beneath the slab is largely decoupled from the slab itself, and we postulate that trench-parallel mantle flow is a response to the combined effects of the retrograde (Pacificward) motion of the Nazca slab (Elsasser, 1971; Garfunkel et al., 1986) and the rapid westward motion of South America over the past 50 m.y. (Pardo-Casas and Molnar, 1987; Gripp and Gordon, 1990). The westward-moving continent-slab system displaces the subslab mantle, giving rise to northward-directed flow beneath northern South America, southward-directed flow beneath southern South America, corner flow around the continent's northern and southern tips, and a central stagnation point (Fig. 1). The lateral flow and its driving pressure gradient have predictable consequences that we observe: geoid and topographic highs over the proposed stagnation point (Russo and Silver, 1994).

Perhaps the most important consequence of South America's westward motion is the corresponding deformation of western South America. The resulting compressive stresses transmitted to the continent produce the cordillera itself; in addition, the along-trench variations in stress, which reach a maximum at the stagnation point, yield observable variations in cordillera structure. In fact, the greatest horizontal shortening (Isacks, 1988) and vertical thickening (James, 1971; Isacks, 1988) of the plate margin occurs in the central Andes at the Bolivian orocline (18°S), where the Andes achieve their greatest height and width, culminating in the upraised mass of the Altiplano plateau. Crustal thickness and the elevation and width of the Andean chain decrease with a marked along-strike gradient both north and south of the Bolivian orocline–Altiplano region. Late Cenozoic crustal shortening exhibits a similar gradient from a maximum at the central Andes (Mégard, 1984; Sheffels, 1990; Allmendinger et al., 1983, 1990; Baby et al., 1992). The mountain chain bends sharply, forming a 120° angle from a northwest trend in southern Peru to a south-southwest trend in northern Chile (Fig. 2). Isacks (1988) proposed that the curvature of the Andean belt is a result of oroclinal bending, wherein gradients in the horizontal shortening of the Andes result in the buckling of the mountain chain, analogous to fold production by inhomogeneous simple shear. Thus, the maximum shortening in the central Andes indents the leading edge of South America the greatest amount, and shortening decreases both north and south of this central point, yielding a curved belt.

Andean paleomagnetic rotations are consistent with Isacks's oroclinal bending model (e.g., MacFadden et al., 1995). Rock units north of the Bolivian orocline are rotated counterclockwise (maximum around 20°W

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**Figure 1. Trench-parallel mantle flow model beneath Nazca slab (after Russo and Silver, 1994). Flow is driven by westward retrograde motion of Nazca slab (red arrows) and westward motion of South America (black arrows). Because fast shear-wave directions, and hence mantle flow directions, are trench parallel, we posit a barrier to mantle flow regardless of whether slab penetrates into lower mantle. Mantle flows from high-pressure region coincident with central Andes (stagnation point) toward regions of lower pressure beneath the Caribbean and Scotia Sea plates (orange arrows). Vertical exaggeration 3.3:1.**

of N), but units south of the bend are rotated clockwise. Because the paleomagnetic rotations approximately parallel the coastline, we infer that the continent edge was only mildly curved and trended approximately north-south before oroclinal bending. We interpret the fact that Cretaceous through Miocene rocks are rotated similar amounts to indicate that the units were all rotated at the same time in the late Cenozoic during formation of the Bolivian orocline.

The onset of intense central Andean deformation coincided with the formation of the orocline at about 25–30 Ma (Sempere et al., 1990). If, as we propose, establishment of a continent-scale trench-parallel mantle flow field is fundamental to the formation of the orocline, then such flow must have been active by the late Cenozoic. Consistent with this notion is the onset of eastward relative translation of the Caribbean plate, as indicated by the onset of eastward spreading in the Cayman Trough between 30 and 20 Ma (Rosencrantz, 1995), and the onset of eastward motion of the Scotia Sea plate, inferred from the opening of the Drake Passage, at about 30 Ma (Cunningham, 1993). The eastward motions of both plates could be driven by corner flow around northern and southern South America (Alvarez, 1982; Russo and Silver, 1994; Russo et al., 1996). The onset of trench-parallel mantle flow at or just before 30 Ma is probably related to increased westward velocity of South America relative to the hotspots at this time (O'Connor and Duncan, 1990).

It is commonly assumed that interplate shear stress at subduction zones, rather than horizontal normal stress, gives rise to deformation of the overriding plate. However, this does not appear to be the case along western South America, because shear coupling cannot be related easily to the observed along-strike variations in deformation. Strong coupling is associated with high convergence velocity and young shallowly dipping slabs. Yet, for South America, convergence velocity is essentially identical along the entire length of the Andes, and the most intensely deformed central Andes are adjacent to the oldest and most steeply dipping slab. Nor is it likely that paleogeography plays a dominant role, because there is no strong correlation between the deformation gradients in the Andes and the presence of accreted terranes and/or regions of previous tectonism. The Central Andes, inferred to sit atop the overridden and downwarped Brazilian shield (James and Snoke, 1994), is the most deformed Andean zone. Regions to the south, above accreted terranes (Ramos, 1988), which might be expected to have a less competent, thinner lower crust and upper mantle lithosphere, are much less deformed.

## COMPARISON TO TECTONICS OF NORTH AMERICA

Like South America, North America has had a long history of relatively fast westward motion (Engebretson et al., 1985), and we might expect it to have deformed similarly to South America. Long-noted gross correspondences between the North American Laramide and Sevier deformations (see Allmendinger, 1992, and references therein) and Andean deformation are remarkable (Fig. 2). The overall eastward convex shape of the Laramide-Sevier orogen along its inboard (eastern) boundary is similar to that of the Bolivian orocline: the chain undergoes a bend from a southern leg with north-south trend to a northern leg with northwest trend in the Wyoming–South Dakota border region, forming a 120° angle. The width of the deformed region is greatest here, coincident with the maximum shortening and thickening of the orogen (Hamilton, 1988a), and is similar to the width and thickening of

**Figure 2. Comparison of topography of South American Altiplano (left) and North American Rockies (right). Figures are same scale. Red lines indicate approximate loci of inboard deformation front. Note similarity of shape of both orogens, which we attribute to oroclinal bending induced by trench-parallel mantle flow pressure buckling leading edges of both continents during late Cenozoic (Andes) and Laramide orogeny (North America).**

the Altiplano at the Bolivian orocline. Other correspondences (Jordan and Allmendinger, 1986) include structural similarities between inboard basement uplifts (Sierras Pampeanas in South America and Laramide foreland basement uplifts in North America) and thin-skinned deformed belts (Sevier in North America and Precordillera and Subandean in South America). Evidence of intermontane basins with internal drainage (Miller et al., 1992) and of dual vergence belts encompassing little-deformed enclaves (Speed et al., 1988) indicates that crustal structure was similar to that of the Altiplano and that elevations in the Nevada portion of the Sevier belt were 6 to 7 km, comparable to those in the Altiplano.

## CORDILLERAS, MARGINAL BASINS, AND DRIVING FORCES

Cordilleras are not generally found at convergent continental margins but are unique to the eastern Pacific. Along the western Pacific rim, overlying Eurasia is only moderately deformed where it is in compression (Japan), or it is in extension (Hamilton, 1988b). The east Eurasian plate edge is a series of marginal basins (Sea of Okhotsk, Japan Sea, Yellow Sea, South China basin). Uyeda and Kanamori (1979) explained the contrast between eastern and western Pacific margins by noting a difference between the trenchward velocities of overriding continents and the natural retrograde velocities of the slabs in the eastern and western Pacific. Where trench lines are moving away from the continent, tensional stresses are generated behind the trench, as in the western Pacific. If the continent moves toward the trench, then the continent collides with the slab and subslab mantle, as in the eastern Pacific. In this context, consideration of driving forces is instructive. Marginal basin formation is driven by the sinking of a slab into the mantle under its own weight, inducing retrograde motion (Elsasser, 1971; Garfunkel et al., 1986; Kincaid and Olson, 1987), and for a stationary (or retreating) continent, tensional stresses behind the trench. The existence of a cordillera requires a driving force capable of producing both trenchward motion of the continental plate (3 cm/yr; Gripp and Gordon, 1990), and trench-normal compressional stresses sufficient to create and maintain cordillera deformation. Dynamic analysis of the South American plate is straightforward because of the relative simplicity of the plate's boundaries and the near absence of slab-pull and/or slab-resistance forces that appear to dominate the torque balance of Pacific basin plates (Forsyth and Uyeda, 1975). Meijer and Wortel (1992) showed that ridge push is the largest force acting on the South American plate, other than an unquantifiable basal drag; however, their calculated ridge push force yields a total stress on the plate boundary of only 200 bar. Calculations by Molnar and Lyon-Caen (1988) and Meijer (1995) indicate that a stress of 500 bar is required merely to maintain the Altiplano plateau against gravitational spreading, and the stress necessary to form such a feature in the first place is probably about 1–2 kbar (England and Houseman, 1986). Ridge push is not by itself capable of even maintaining, let alone forming, the Andes. Therefore, another force is necessary to drive South America and form the Andes. We suggest on this basis that the South American plate is coupled to (and driven by) deep mantle flow, perhaps via entrainment of its thick cratonic regions (Jordan, 1981). Meijer and Wortel's analysis admits this possibility. Supporting evidence for this inferred coupling comes from analysis of the global shear-wave splitting data set (Silver, 1996), which is not consistent with a subcontinental decoupling zone. In addition, tomographic images of eastern Brazil upper mantle reveal the presence of the remnant Tristan plume head (VanDecar et al., 1995) preserved in its pristine location spanning almost the entire upper mantle, indicative that most of the upper mantle beneath eastern South America has moved with the plate. We conclude that the motion and deformation of South America are probably the clearest demonstrations of deep mantle flow as a plate driving force.

The above analysis is easily extended to encompass North American plate motion. The motion histories of North and South America, comparable present-day plate velocities, and the existence of western Cordillera are all evidence of a single mechanism, deep mantle flow, driving both plates. Deep mantle flow of sufficient scale to drive motions throughout the western Atlantic probably is responsible for Atlantic spreading itself. Thus, Atlantic ocean spreading, which is unrelated to subduction, seems to be fundamentally different from Pacific spreading, which is probably driven or aided by subduction-related forces (i.e., slab pull).

## CORDILLERAS, MARGINAL BASINS, AND THE WILSON CYCLE

Cordillera formation, Atlantic Ocean spreading, and deep mantle flow can all be linked through the Wilson cycle (Fig. 3). Cordillera formation requires rapid trenchward motion of an overriding continental plate. Breakup of a continent with convergent margins during the spreading phase of the Wilson cycle increases the trenchward velocity of one of the rifted continental fragments with attendant cordillera formation at its margin. Continental breakup and ocean spreading, at least in the Atlantic spreading phase of the Wilson cycle, are driven by large-scale deep mantle flow: hence, the gross parallelism and similar approximately pole-to-pole lengths of the American Cordilleras and the Mid-Atlantic Ridge. The closing of an ocean basin will also affect continental margins, because subducted slabs draw away from continents through slab rollback at convergent margins, thus forming marginal basins. Ocean opening and cordillera formation, and ocean closing and marginal basin formation, may therefore each be temporally linked. The initiation of cordillera formation in North America and later South America appears to be contemporaneous with the initiation of spreading in the North and South Atlantic, respectively (Coney and Evenchick, 1994). Thus, cordillera and marginal basin formation can be

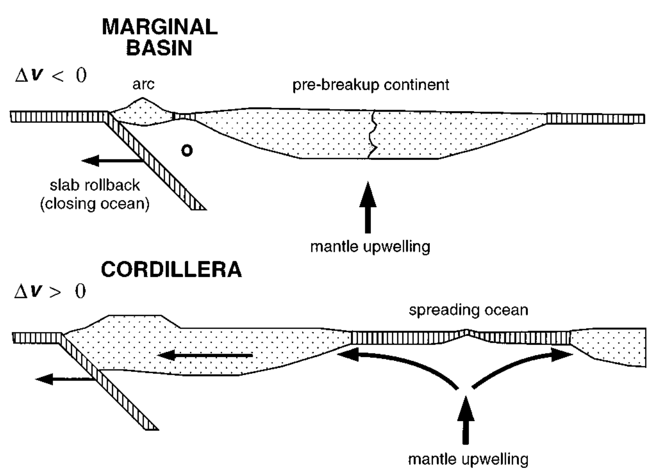


**Figure 3. Schematic of proposed relation between opening and closing of ocean basins (Wilson cycle) and cordillera and marginal basin formation. Top: Pre-breakup subduction at active convergent margin; slab rollback of closing ocean basin to left (not shown) opens marginal basin. Rollback velocity of slab ($V_r$) is greater than trenchward velocity of continent ($V_c$) and hence $\Delta v = V_c - V_r < 0$. Bottom: Spreading begins, driven by active mantle upwelling. Westward velocity of continent now greater than rollback of slab ($\Delta v > 0$), marginal basin closes, and cordillera forms as slab and subslab mantle collide with continent.**

seen as complementary interim processes of the classical Wilson cycle. Cordilleras, like continental collisional orogens, are natural consequences of the Wilson cycle: the opening and closing of ocean basins.

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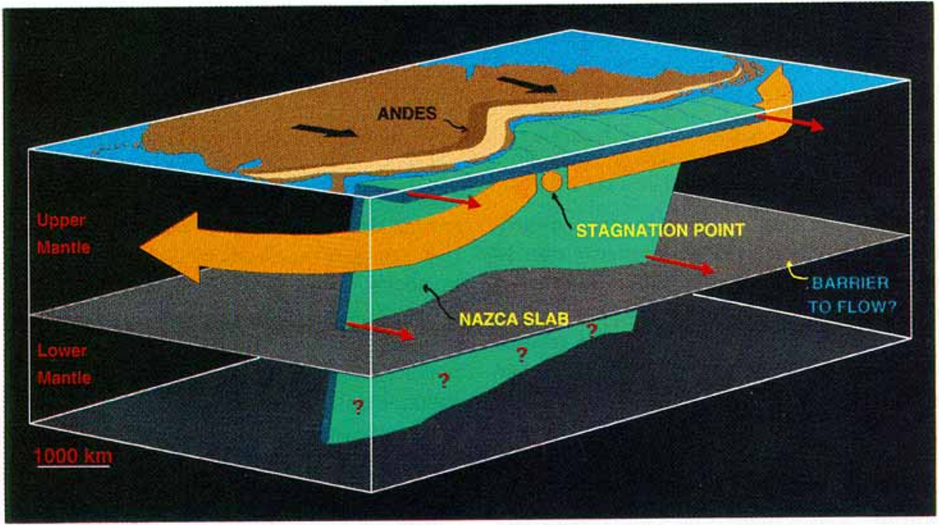
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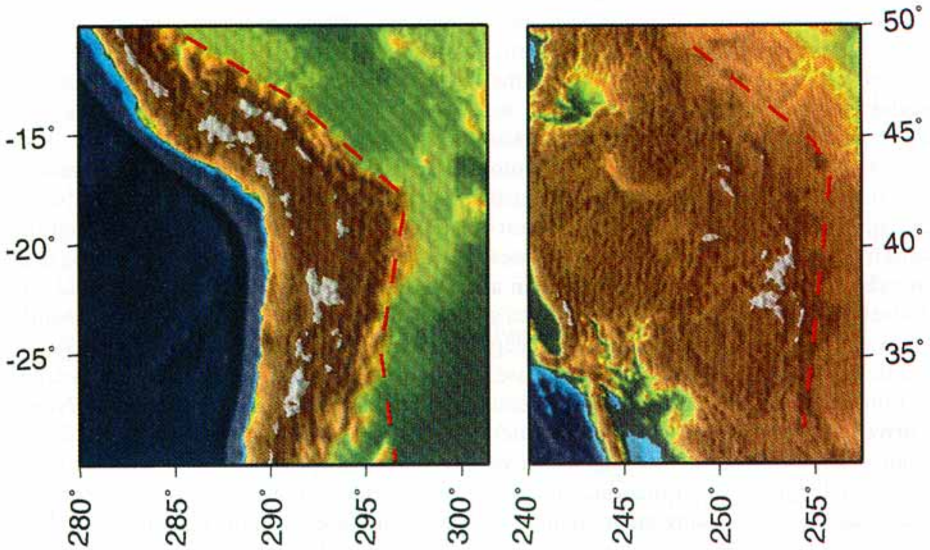

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