The Laramide Orogeny: What Were the Driving Forces?

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Abstract

The Laramide orogeny is the Late Cretaceous to Paleocene (80 to 55 Ma) orogenic event that gave rise to the Laramide block uplifts in the United States, the Rocky Mountain fold-and-thrust belt in Canada and the United States, and the Sierra Madre Oriental fold-and-thrust belt in east-central Mexico. The Laramide orogeny is believed to post-date the Jurassic and late Early Cretaceous accretion of the terranes that make up much of the North American Cordillera, precluding a collisional origin for Laramide orogenesis. Instead, the deformation belt along much of its length likely developed 700–1500 km inboard of the nearest convergent margin. The purpose of this paper is to show, through a review of proposed mechanisms for producing this inboard deformation (retroarc thrusting, "orogenic float" tectonics, flat-slab subduction and Cordilleran transpressional collision), that the processes responsible for orogeny remain enigmatic.

Introduction

THE LARAMIDE OROGENY is the Late Cretaceous to Paleocene (80 to 55 Ma) orogenic event that gave rise to the Laramide block uplifts in the United States, as well as the Rocky Mountain fold-and-thrust belt in Canada and the United States, and the Sierra Madre Oriental fold-and-thrust belt in east-central Mexico (Fig. 1). The Laramide orogeny is believed to post-date the Jurassic and late Early Cretaceous accretion of the terranes that make up much of the North American Cordillera (e.g., Dickinson and Snyder, 1978; Monger et al., 1982; Monger and Nokleberg, 1996; Dickinson and Lawton, 2001); a collisional origin for Laramide orogenesis has therefore been ruled out. Thus, along much of its length, the deformation belt is thought to have developed 700–1500 km inboard of the nearest convergent margin. The purpose of this paper is to illustrate, through the review of proposed mechanisms for producing this inboard deformation, that the processes responsible for orogeny remain enigmatic. Proposed mechanisms reviewed here are retroarc thrusting, "orogenic float" tectonics, flat-slab subduction, and Cordilleran transpressional collision.

Retroarc Thrusting

Retroarc thrusting, during which thrust faulting is antithetic with respect to subduction at the plate margin, has been suggested for backthrusting of the Cordillera onto the adjacent continental interior (e.g., Price, 1981; Fig. 2) due to strong regional compressive stresses. The zone of backthrusting represents a locus of continuing relative motion between the Cordillera and the continental interior; its location may be controlled by inherited weaknesses in the lithosphere produced by a craton-rifted margin boundary or by thermal weakening during an earlier plutonic/metamorphic episode (e.g., Omineca Belt in Canada). In this model, the rate of western advancement of the North American plate exceeds the rate of slab rollback in the subducting oceanic plate, and the continent essentially "collides" with the oceanic slab due to its inability to actively override the slab. A similar mechanism has been proposed for Andean deformation (Russo and Silver, 1996). This mechanism has the advantage of being of continental-scale; along-strike variations in deformational style may be produced by variations in crustal heterogeneity.

The retroarc thrusting model requires that stress, attributable to the upper-plate versus lower-plate collision at the subduction interface, was transmitted across the entire Cordillera without causing significant deformation within the internal portions of the orogen. This requires that: (1) the differential stress attributable to collision be small enough in order to avoid failure and shortening proximal to the subduction zone: and (2) that the highly faulted accretionary complex that comprises the central portion of the Cordillera consists of a coherent,

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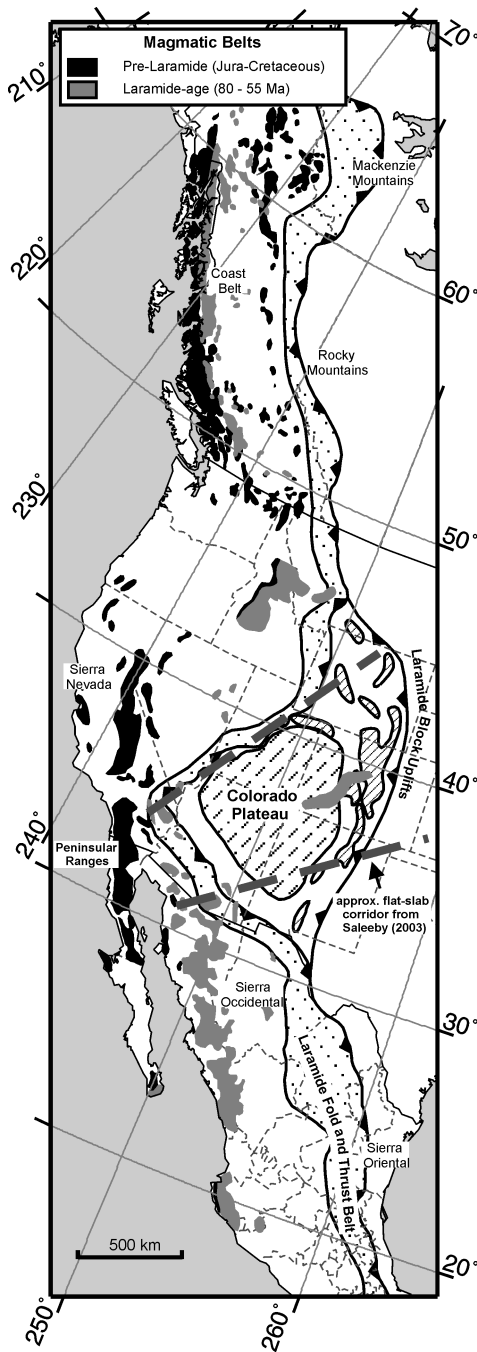[1]Corresponding author; email: englishj@uvic.ca

FIG. 1. Map showing areas of pre-Laramide and Laramide magmatism, the extent of the Laramide thin-skinned fold-and-thrust belt and thick-skinned block uplifts, and the approximate location of the Laramide flat slab according to Saleeby (2003). Cenozoic extension has not been restored in this figure.
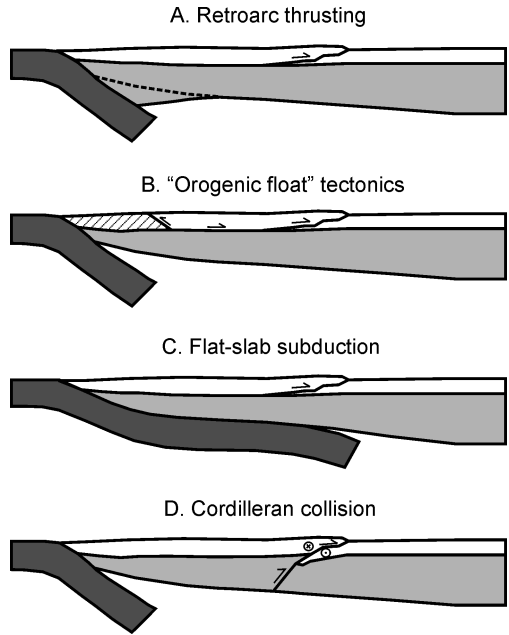

FIG. 2. Schematic diagrams illustrating the various models that have been proposed for producing the inboard deformation belts of the Laramide orogeny.

strong block despite the presence of numerous older crustal-scale faults. It is also not apparent in this model how the shortening was accommodated in the mantle lithosphere.

"Orogenic Float" Tectonics

The addition of "orogenic float" (Oldow et al., 1990) at the convergent margin may have driven far-field strain in the foreland region of the Cordillera. In this model, faults in the foreland are linked to a collision zone at the plate boundary by a major through-going deep-crustal basal detachment, so that the entire crustal section "floats" on its underlying lithosphere (Fig. 2). In convergent margins characterized by large-scale terrane collision and accretion, the addition of mass (i.e., terranes) above the basal detachment exerts a horizontal normal compressive stress on the continental crust and drives deformation in the foreland. There is no contraction within the Cordilleran mantle lithosphere, and a lithospheric root is not developed; the mantle formerly attached to the accreted terranes must be removed by subduction. This concept has been used to relate current deformation in the Mackenzie

Mountains of northern Canada to collision of the Yakutat block in southeastern Alaska (Mazzotti and Hyndman, 2002). There are, however, no known terrane accretion events coeval with Laramide orogeny. In Canada, inboard terranes within the central part of the orogen (e.g., Quesnellia and Stikinia) are stitched to pericratonic crust of presumed North American affinity by Jurassic plutons, whereas the outboard terranes (e.g., Wrangellia) are stitched to the inboard terranes by mid-Cretaceous and possibly older plutons. The Eocene accretion of the Crescent terrane outboard of Wrangellia post-dates Laramide orogeny and was responsible for nearby deformation, including buckling of Wrangellia and the formation of a fold-and-thrust belt (Johnston and Acton, 2003). Therefore, there was no driving force present to apply a horizontal compressive stress above the proposed deep-crustal basal detachment, and this model can be effectively ruled out for the Laramide orogeny.

Flat-Slab Subduction

In the flat-slab subduction model for Laramide deformation (e.g., Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Bird, 1988), the oceanic slab subducting along the western margin of the continent remained in contact with the upper plate for a distance of > 700 km inboard of the trench (Fig. 2). Flat-slab subduction is postulated to have formed in response to the subduction of the Kula-Farallon spreading center, or in response to the subduction of a buoyant oceanic plateau (e.g., Livaccari et al., 1981; Murphy et al., 2003; Saleeby, 2003). Stress coupling of the upper plate with the flat slab could have transmitted stresses eastward and caused basement-cored block uplifts in the foreland of the U.S. Cordillera (e.g. Dickinson and Snyder, 1978; Bird, 1988). Deformation is inferred to have developed above the zone along which the subducting slab eventually steepened and descended into the deep mantle. Basement-cored uplifts in Wyoming, Colorado, and New Mexico are comparable to structures in the Sierra Pampeanas in Argentina (Jordan and Allmendinger, 1996), where deformation has been linked to a period of flat-slab subduction (Kay and Abbruzzi, 1996). However, the development of a magmatic arc within 300 km of the trench in Canada and Mexico during Laramide time refutes the existence of flat-slab subduction in these regions (Fig. 1; English et al., 2003). Therefore, if we accept that the Laramide orogeny in the United States is the product of flat slab subduction, then the coeval fold-and-thrust belt formation to the north in Canada, and to the south in Mexico, must be attributed to some other process. While possible, it is not clear why such disparate regions should all have synchronously undergone contractional deformation if the processes responsible for shortening differed along the length of the orogen.

Cordilleran Transpressional Collision

Paleomagnetic studies of Cretaceous layered sedimentary and volcanic rocks within the Cordilleran orogen have been interpreted to show that much of the Canadian Cordillera originated 2000–3000 km to the south relative to autochthonous North America (e.g., Irving et al., 1996; Wynne et al., 1998; Enkin et al., 2002). Timing constraints indicate that northward translation must have occurred between 85 and 55 Ma, coeval with the duration of Laramide orogenesis. Therefore, it is possible that Laramide orogenesis occurred in response to a dextral transpressional collision between a northward migrating ribbon continent and autochthonous North America (Johnston, 2001). Northern pinning and buckling of this ribbon continent is proposed to have led to the formation of the Alaskan oroclines during collision with North America in Laramide time. In this model, the Rocky Mountain fold-and-thrust belt may have been produced by offscraping of passive margin sediments during subduction of the North American plate beneath the northward migrating ribbon continent (Fig. 2). However, foreland basin formation and extensive westerly derived sedimentation on the North American craton from at least Early Cretaceous time (e.g. Stott, 1993), and the absence of an inner Late Cretaceous arc magmatic belt, cast doubt on the existence of an intervening oceanic basin between the Cordillera and the continental interior during Late Cretaceous–Paleocene time.

Discussion

Jarrard (1986) proposed that four variables (convergence rate, slab age, intermediate slab dip–average dip to 100 km, and absolute motion of the upper plate) determine the strain regime of the overriding plate at a convergent margin. Convergence rate and slab age affect the strain regime by changing the level of coupling between the plates. For example, an increased convergence rate increases

the horizontal compressive stress applied to the upper plate, whereas an increase in slab age may reduce this stress due to increased gravitational pull on an older slab. Intermediate slab dip may affect the strain regime of the upper plate by changing the surface area over which coupling occurs at the plate boundary.

If the convergence rate, intermediate slab dip, or slab age were important factors for driving Laramide deformation, then orogenesis was ultimately driven by the subducting oceanic slab. Plate reconstruction models indicate that the Kula and Farallon oceanic plates, separated by a spreading center, were subducting beneath western North America during Laramide time (e.g., Engebretson et al., 1985; Kelley, 1993), although the location of the Kula–Farallon–North America triple junction during Laramide time remains a matter of much debate (e.g., Breitsprecher et al., 2003). It is, therefore, likely that the age of the subducting slab varied significantly along strike. The convergence rate is estimated to have been high during Laramide time (average trench-normal component of 10–15 cm/yr for the Farallon and North American plates, and somewhat less for the Kula–North American plates). However, given that Laramide-age deformation occurred along the entire length of North America regardless of which plate was subducting beneath it, it seems unlikely that slab age or convergence rate were the principal driving force of orogenesis. It is possible that a ~100 km eastward migration of arc magmatic belts in western Canada and Mexico during Laramide time (e.g., van der Heyden, 1992; Friedman and Armstrong, 1995; Fig. 1) may reflect a shallowing of the subducting slab, and hence enhanced coupling across the plate boundary. However, it is not apparent why this increased horizontal compressive stress would be transferred up to 1000 km inboard to drive foreland deformation. Nor does it explain why slab shallowing should simultaneously occur along the length of the continent spanning two subducting plates. Flat-slab subduction beneath the southwestern U.S. Cordillera may have locally influenced the structural style and location of orogenesis in this region. This may be analogous to the modern Andes where variations in subduction angle have been interpreted to exert a significant influence on the anatomy of the orogen; one significant difference is that the Laramide deformation belt along the entire length of the North American Cordillera lies at great distances (700–1500 km) from the current plate margin. Thus, post-

Laramide extension alone cannot account for the inboard location of this orogenic belt.

Alternatively, the absolute motion of the overriding plate may have been important for driving Laramide orogenesis (as in the retroarc thrusting model). The high rate of western advancement of the North American plate must have been driven by ridge-push from the Atlantic spreading-center or by basal drag caused by mantle convection. Basal drag is not considered to be an important factor in driving plate motions (e.g. Stüwe, 2002); this model, therefore, requires that horizontal normal compressive stresses applied by ridge-push from the mid-Atlantic spreading center must have been sufficient to drive Laramide orogenesis. However, it is not apparent why ridge-push would only have driven orogenesis during the Laramide, as spreading rates were not anomalously high during this time. Although Africa and North America began to separate at ~180 Ma, the main phase of drift between Eurasia and North America did not occur until ~80 Ma; separation varied from 5.0 to 4.0 cm/yr until 53 Ma, and then dropped off to ~2 cm/yr (Pitman and Talwani, 1972). It remains a possibility that pre-Laramide and Laramide-age spreading rates in the North Atlantic were sufficient to culminate in a greater ridge-push force on the North American continent during Laramide time. Subsequent slowing of the spreading rates during the Eocene may have resulted in a decline in the ridge-push force and absolute motion of the North American continent.

None of the proposed mechanisms for driving Laramide orogenesis satisfactorily explain the geometry, timing, or extent of this inboard, continental-scale orogeny. In addition to our assessment of available models for Laramide orogenesis, we offer three major questions that require resolution.

1. Are the paleomagnetic data implying northward translation correct, and if so, how expansive was the Cordilleran entity that underwent > 2000 km of northward translation during Laramide time? Existing data suggest that much of the Alaskan and Canadian Cordillera underwent northward translation, but the extension of this Cordilleran entity into the United States Cordillera is currently unconstrained.

2. What was the relationship between northward translation, dextral transpression, and fold-and-thrust belt formation? Does the fold-and-thrust belt represent the product of a collisional event following closure of an intervening ocean basin, or does the fold and thrust belt root into an oblique dextral

transpressional system that assisted in accommodating northward translation? Attributing Laramide orogeny to collision with a northward-translating ribbon continent leaves unexplained the presence of pre–Late Cretaceous westerly-derived molasse deposited on North America.

3. Why did the Laramide strain zone form so far inboard (~1000 km) of the inferred plate boundary along the entire length of the continent?

Acknowledgments

REFERENCES

Bird, P., 1988, Formation of the Rocky Mountains, western United States: A continuum computer model: Science, v. 239, p. 1501–1507.

Breitsprecher, K., Thorkelson, D. J., Groome, W. G., and Dostal, J., 2003, Geochemical confirmation of the Kula-Farallon slab window beneath the Pacific Northwest in Eocene time: Geology, v. 31, p. 351–354.

Coney, P. J., and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Dickinson, W. R., and Lawton, T. F., 2001, Carboniferous to Cretaceous assembly and fragmentation of Mexico: Geological Society of America Bulletin, v. 113, p. 1142–1160.

Dickinson, W. R., and Snyder, W. S., 1978, Plate tectonics of the Laramide Orogeny, *in* Matthews, V., ed., Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 355–366.

Engebretson, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper, 59 p.

English, J. M., Johnston, S. T., and Wang, K., 2003, Thermal modelling of the Laramide orogeny: Testing the flat-slab subduction hypothesis: Earth and Planetary Science Letters, v. 214, p. 619–632.

Enkin, R. J., Mahoney, J. B., Baker, J., Kiessling, M., and Haugerud, R. A., 2002, Syntectonic remagnetizations in the southern Methow block: Resolving large displacements in the southern Canadian Cordillera: Tectonics, v. 21 [10.1029/2001TC001294].

Friedman, R. M., and Armstrong, R. L., 1995, Jurassic and Cretaceous geochronology of the southern Coast Belt, British Columbia, 49° to 51°N, *in* Miller, D. M., and Busby, C., eds., Jurassic magmatism and tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 95–139.

Irving, E., Wynne, P. J., Thorkelson, D. J., and Schiarizza, P., 1996, Large (1000–4000 km) northward movements of tectonic domains in the northern Cordillera, 83 to 45 Ma: Journal of Geophysical Research, v. 101, p. 17,901–17,916.

Jarrard, R. D., 1986, Relations among subduction parameters: Reviews of Geophysics, v. 24, p. 217–284.

Johnston, S. T., 2001, The great Alaskan terrane wreck: Reconciliation of paleomagnetic and geological data in the northern Cordillera: Earth and Planetary Science Letters, v. 193, p. 259–272.

Johnston, S. T., and Acton, S., 2003, The Eocene southern Vancouver Island orocline—a response to seamount accretion and the cause of fold and thrust belt and extensional basin formation: Tectonophysics, v. 365, p. 165–183.

Jordan, T. E., and Allmendinger, R. W., 1986, The Sierras Pampeanas of Argentina: A modern analogue of Rocky Mountain foreland deformation: American Journal of Science, v. 286, p. 737–764.

Kay, S. M., and Abbruzzi, J. M., 1996, Magmatic evidence for Neogene lithospheric evolution of the central Andean "flat-slab" between 30°S and 32°S: Tectonophysics, v. 259, p. 15–28.

Kelley, K., 1993, Relative motions between North America and oceanic plates of the Pacific basin during the past 130 million years: Unpubl. M.Sc. thesis, Western Washington University, 89 p.

Livaccari, R. F., Burke, K., and Sengor, A. M. C., 1981, Was the Laramide orogeny related to subduction of an oceanic plateau?: Nature, v. 289, p. 276–278.

Mazzotti, S., and Hyndman, R. D., 2002, Yakutat collision and strain transfer across the northern Canadian Cordillera: Geology, v. 30, p. 495–498.

Monger, J. W. H., and Nokleberg, W. H., 1996, Evolution of the northern North American Cordillera: Generation, fragmentation, displacement, and accretion of successive North American plate margin arcs, *in* Geology and ore deposits of the American Cordillera: Reno, NV, Geological Society of Nevada, p. 1133–1152.

Monger, J. W. H., Price, R. A., and Tempelman-Kluit, D. J., 1982, Tectonic accretion and the origin of the two major metamorphic and plutonic welts in the Canadian Cordillera: Geology, v. 10, p. 70–75.

Murphy, J. B., Hynes, A. J., Johnston, S. T., and Keppie, J. D., 2003, Reconstructing the ancestral Yellowstone plume from accreted seamounts and its relationship to flat-slab subduction: Tectonophysics, v. 365, p. 185–194.

Oldow, J. S., Bally, A. W., and Ave' Lallemant, H. G., 1990, Transpression, orogenic float, and lithospheric balance: Geology, v. 18, p. 991–994.

Pitman, W. C., and Talwani, M., 1972, Sea-floor spreading in the North Atlantic: Geological Society of America Bulletin, v. 83, p. 619–646.

Price, R. A., 1981, The Cordillera foreland thrust and fold belt in the southern Canadian Rocky Mountains, *in* McClay, K., ed., Thrust and nappe tectonics: Geological Society of London Special Publication 9, p. 427–448.

Russo, R. M., and Silver, P. G., 1996, Cordillera formation, mantle dynamics, and the Wilson cycle: Geology, v. 24, p. 511–514.

Saleeby, J., 2003, Segmentation of the Laramide slab—evidence from the southern Sierra Nevada region: Geolgical Society of America Bulletin, v. 115, p. 655–668.

Stott, D. F., 1993, Evolution of Cretaceous foredeeps: A comparative analysis along the length of the Canadian Rocky Mountains, *in* Caldwell, W. G. E., and Kauffman, E. G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, p. 131–150.

Stüwe, K., 2002, Geodynamics of the lithosphere: An introduction: Berlin, Germany and New York, NY, Springer-Verlag, 463 p.

van der Heyden, P., 1992, A Middle Jurassic to Early Tertiary Andean-Sierran arc model for the Coast Belt of British Columbia: Tectonics, v. 11, p. 82–97.

Wessel, P., and Smith, W. H. F., 1995, New version of the Generic Mapping Tools released: EOS (Transactions of the American Geophysical Union, v. F359.

Wynne, P. J., Enkin, R. J., Baker, J., Johnston, S. T., and Hart, C. J. R., 1998, The big flush—paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera: Canadian Journal of Earth Sciences, v. 35, p. 657–671.