Location, location, location: The variable lifespan of the Laramide orogeny

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ABSTRACT

The Laramide orogeny had a spatially variable lifespan, which we explain using a geodynamic model that incorporates onset and demise of flat-slab subduction. Laramide shortening and attendant uplift began in southeast California (USA) at ca. 90 Ma, swept to the northeast to arrive in the Black Hills of South Dakota (USA) at ca. 60 Ma, and concluded in South Dakota within ~10 m.y. During subsequent slab rollback, the areal extent of Laramide deformation decreased as the eastern edge of active deformation retreated to the southwest rapidly from ca. 55 to 45 Ma and more slowly from ca. 45 to 40 Ma, with deformation ultimately ceasing in the southwestern part of the orogen at ca. 30 Ma. Geodynamic modeling of this process suggests that changes in the strength of the North America plate and densification of the Farallon plate played important roles in controlling the areal extent of the Laramide orogen and hence the lifespan of the orogenic event at any particular location in western North America.

INTRODUCTION

The Laramide orogeny most generally refers to basement-involved deformation and intermontane basin development that took place in the Rocky Mountain region (western United States) between ca. 80 and 40 Ma (e.g., Bird, 1998; Saleeby, 2003; DeCelles, 2004; English and Johnston, 2004; Yonkee and Weil, 2015). Deformation produced uplifts within a formerly extensive foreland basin that developed adjacent to thin-skinned thrust sheets of the Sevier orogenic belt (Armstrong, 1968). Laramide foreland disruption was a largely amagmatic event that affected a broad region between southern Montana (USA) and northern Mexico (Dickinson and Snyder, 1978). Time-equivalent shortening in central Mexico was accompanied by arc magmatism and diverse structural styles including ramp-flat thrusting and large-scale buckle folding (Guzman and de Cserna, 1963); coeval deformation in Canada was thin-skinned (Bally et al., 1966). The mechanism for the distinctive basement-involved deformation that characterized the classic Laramide province constitutes a geodynamic conundrum that geoscientists have struggled to explain for more than 100 years.

OBSERVATIONS

To understand the temporal variability of the Laramide orogeny at a regional scale, we compiled observations relevant to the evolution of marine sedimentation, magmatism, deformation, and surface elevation across the Laramide region and beyond. Figure 1 shows the distribution of igneous rock, estimates of the time of the transition from marine to nonmarine sedimentation, estimates of the time of initiation and cessation of Laramide-style deformation, the estimated time of attainment of maximum surface elevation, and the inferred timing of transit of the thickest part of the conjugate Shatsky Rise (CSR) beneath the region during subduction of the Farallon (FA) plate (see the GSA Data Repository[1]). The locations have been restored from their modern-day positions to the approximate locations they occupied at ca. 25 Ma. We note a substantial northeast shift of magmatic age north of a line from northern California through Idaho and into Montana (Fig. 1A) relative to magmatic ages south of this line. It is likely that this shift in magmatic activity is due to the presence of an embayment in the margin of western North America (Yonkee and Weil, 2015; Schmandt and Humphreys, 2011), a holdover from the development of a Proterozoic transfer zone (Lund, 2008). The lack of Cretaceous arc magmatism in Oregon and Washington reflects the ca. 50 Ma accretion to North America of the Siletzia terrane, a large igneous province or plateau (Fig. 1A; Wells et al., 2014). The boundary we note in Laramide magmatism is coincident with variations revealed by body-wave tomography of the western United States (Schmandt and Humphreys, 2010), suggesting a tear in the Laramide slab (Humphreys, 2009; Schmandt and Humphreys, 2010; Colgan et al., 2011). Based on these observations and because

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[1]GSA Data Repository item 2017058, sources of data and details of methods used, is available online at www.geosociety.org/datarepository/2017 or on request from editing@geosociety.org.

our boundary passes through the northwest edge of the classic Laramide province (DeCelles, 2004), we designate this line as the northwest margin of the region we consider below.

Figure 1B shows the age of the various phenomena listed above versus distance along a line of projection, A-A′ (Fig. 1A), which has a bearing of 045 and passes through the middle of the classic Laramide province (DeCelles, 2004). This approach compresses the spatial complexity of a continent-scale orogen onto a single line that may not be the best choice for all points portrayed, but we conclude that the synoptic utility of the diagram outweighs the shortcomings of the approach. For details of our methods and sources of data, see the Data Repository.

Estimates of the age of the youngest marine strata in the study area reveal a northeastward migration of the shoreline during the interval 100–60 Ma (Fig. 1B). This distribution of marine strata in space and time could be explained if the surface of the continent sloped from a high in the southwest to low in the northeast *and* sea level was falling, but the long-term eustatic curve indicates that sea level was essentially unchanged during this time interval (Haq, 2014). Therefore, a regional tectonic cause is needed to explain the distribution of marine rocks.

The eastward-then-westward sweep of magmatism across western North America (Fig. 1B) has been interpreted as a consequence of progressive shallowing of the subducting Farallon plate in the Late Cretaceous and Paleogene followed by slab break-off or slab rollback in the Eocene and Oligocene (Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Saleeby, 2003; Liu et al., 2010). The presence of a buoyant oceanic plateau (the CSR) within the Farallon plate has been suggested as an important contributing factor in the decrease of the plate's subduction angle (e.g., Liu et al., 2010; Heller and Liu, 2016). Along our line of projection, a close temporal correspondence exists between the passage of the thickest part of the CSR and the initiation of Laramide-style deformation, and the youngest marine sedimentation (Fig. 1B).

In addition, close spatial-temporal correspondence exists between cessation of Laramide shortening and age of attainment of maximum

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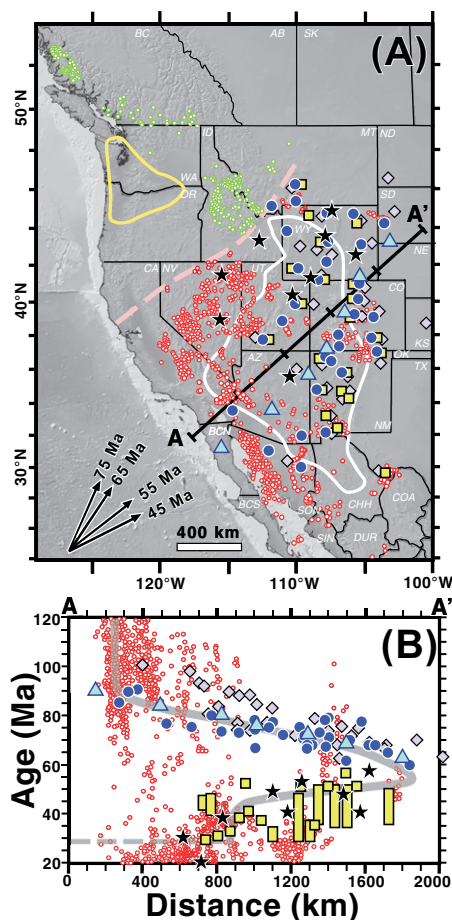
Figure 1. A: Map of western North America indicating locations of magmatic rocks (red circles between 120 and 20 Ma; green circles between 120 and 40 Ma), sites at which estimates have been made for age of youngest marine deposits (lavender diamonds), sites of estimates for timing of initiation and cessation of Laramide shortening (blue circles and yellow squares, respectively), sites at which estimates have been made for timing of attainment of maximum surface elevation (black stars), and projected trajectory of thickest part of CSR beneath North America (blue triangles). All points have been restored to their positions at ca. 25 Ma. White line indicates extent of Laramide province of DeCelles (2004). Black arrows in lower left indicate approximate relative convergence direction between Farallon and North America plates at times noted. Yellow line indicates approximate extent of Siletzia terrane (Schmandt and Humphreys, 2011; Wells et al., 2014). Pink dashed line marks discontinuity in mantle tomography (Schmandt and Humphreys, 2010) and Laramide magmatism. B: Projection of data south of pink dashed line in A, using same symbols as in A, showing temporal distribution of magmatism, uplift, and deformation along line A-A'. For deformation cessation estimates, yellow rectangles indicate stratigraphic uncertainty. Gray line shows evolution of easternmost interaction of Farallon and North America plates from our thermal-mechanical model (Fig. 2). See Data Repository (see footnote 1) for sources of data and details of palinspastic restoration and geodynamic modeling.

surface elevation (Fig. 1B); in the study area, these events are oldest in the northeast and become younger to the southwest, contrary to the trend for the initiation of Laramide deformation. The temporal trends for the initiation and cessation of shortening indicate that the lifespan of the Laramide orogeny varied systematically with distance from the trench, with deformation persisting for as long as 60 m.y. (from the Turonian to the Oligocene) in parts of California, Arizona (USA), and Sonora (Mexico), but occurring for perhaps <10 m.y. of the Paleocene in eastern Wyoming and South Dakota.

A GEODYNAMIC MODEL

Following the hypothesis that Laramide shortening was a consequence of the traction between the base of the North America (NA) plate and the top of the Farallon plate (e.g., Yonkee and Weil, 2015; Heller and Liu, 2016), we suggest that the southwestward migration of the inboard deformational edge (Fig. 1B) was a consequence of a narrowing of the zone of FA–NA lithospheric interaction by progressive rollback of the Farallon plate from northeast to southwest beginning at ca. 55 Ma and continuing into the Oligocene. To investigate the possibility of slab rollback after shallow subduction as much as 1900 km inboard of the trench, we developed a geodynamic model following the work of Liu and Currie (2016). The two-dimensional model calculates the coupled thermal-mechanical evolution of a subduction zone in which the geometry of the oceanic plate evolves dynamically in response to applied boundary velocities and internal buoyancy forces. Initially, an oceanic plateau (the CSR), with a crustal thickness of 24 km, enters the trench at 90 Ma (Liu et al., 2010). As the thick oceanic crust is less dense than mantle, it is able to buoyantly deflect the slab to a subhorizontal trajectory. This is aided by break-off of the dense slab downdip of the plateau and the westward motion of the continental plate (Liu and Currie, 2016).

From ca. 80 to ca. 60 Ma, the slab flattens at ~150 km depth, and the tip of the slab moves relative to stable North America at a rate of 6–7 cm/yr, consistent with magmatism and deformation patterns (Fig. 1B). During flattening, the upper part of the oceanic plateau crust is sheared and accreted to the base of the continental mantle lithosphere. At ca. 55 Ma, the tip of flat slab segment is ~1900 km from the continental margin.

The duration and spatial extent of the flat-slab geometry depend primarily on the density of the oceanic plateau crust. Slab flattening requires that the basaltic oceanic plateau crust remains metastable and therefore buoyant with respect to the mantle (van Hunen et al., 2002; Liu and Currie, 2016). This may be due to the oceanic plateau crust being water poor, which would kinetically delay the metamorphic phase change to eclogite (Hacker, 1996). Sinking of

the flat slab then coincides with an increase in plateau density via eclogitization. In the model, progressive plateau eclogitization is imposed from 58 to 48 Ma to match geological observations of the timing of cessation of deformation (Fig. 1B). Sinking also depends on the strength of the continental mantle lithosphere. The continental mantle lithosphere may weaken during flat-slab subduction due to the infiltration of hydrous fluids released from the oceanic plate. The primary source of fluids is likely dehydration reactions within the oceanic mantle lithosphere (Currie and Beaumont, 2011); additional fluids would be released during crustal eclogitization. We simulate this by gradually weakening the continental mantle lithosphere closest to the margin from 75 Ma until 50 Ma. With the combination of eclogitic densification of the Farallon lithosphere and hydration weakening of the NA lithosphere, the flat slab decouples from the continent and sinks as subduction continues.

DISCUSSION

The results of this lithospheric model compare favorably with observations of surface geologic phenomena. The limit of easternmost FA-NA interaction tracks both the northeastward migration of the Laramide deformation front and shoreline from ca. 90 to ca. 60 Ma and the southwestward retreat of the eastern deformational edge from ca. 60 to ca. 40 Ma (Fig. 1B). The excellent correspondence between our model and the surface observations breaks down somewhat after 40 Ma: the slab stops rolling back at ~900 km along A-A' but deformation continues to the southwest until ca. 30 Ma (Fig. 1B). We suggest that deformation from 40 to 30 Ma in the southwest part of the Laramide province was due to continued but more-conventional ocean-continent convergence that persisted until the subduction of the Pacific (PA)-FA ridge and the establishment of a new type of plate boundary at the edge of North America at ca. 29 Ma (dotted line in Fig. 1B; see Atwater, 1970).

As the modeled slab rolls back and steepens, it breaks into smaller fragments (Fig. 2). This may explain small-scale mantle velocity anomalies, which have been interpreted as small pieces of Farallon plate lithosphere (Sigloch et al., 2008). Removal of the slab brings hot asthenosphere into contact with the base of the continent, which could trigger asthenospheric- and lithospheric-derived magmatism that would migrate with the foundering slab. In addition, the region of thinned continental mantle lithosphere affected by mechanical erosion and hydration-induced weakening from the flat slab persists following slab removal. This is consistent with the observation of a step in the thickness of the continental lithosphere at ~1800 km along our line of projection (Yuan and Romanawicz, 2010). Conversely, our model is at odds with suggestions
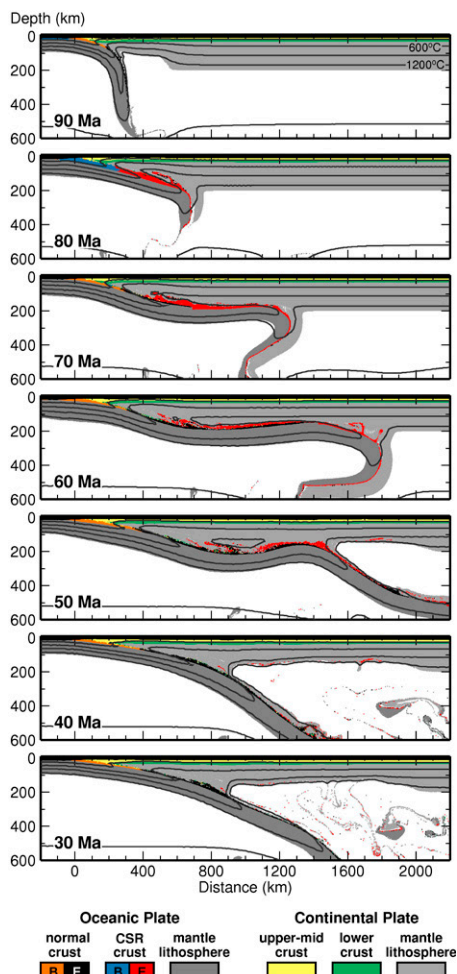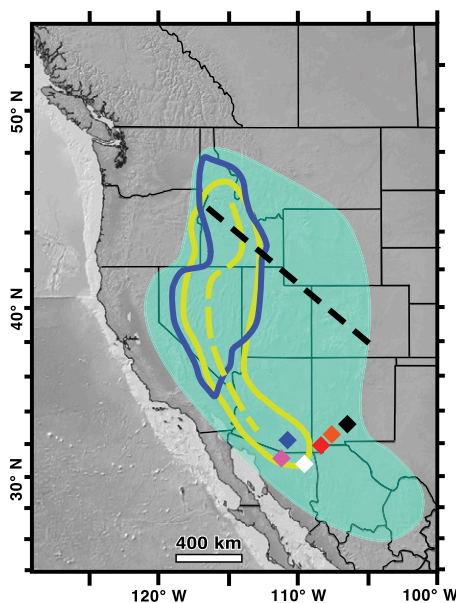
Figure 2. Two-dimensional finite-element model showing coupled thermal-mechanical evolution of Farallon–North America plate convergence. CSR—Conjugate Shatsky Rise; B—basalt; E—eclogite. Black lines are isotherms at 300 °C intervals. See Data Repository (see footnote 1) for details of model construction and animation.

Figure 3. Comparison of various interpretations and data to our proposed Laramide orogenic plateau (western North America) at ca. 50 Ma (green area). Blue line shows our interpretation of maximum extent of "Nevadaplano" based on our reading of DeCelles (2004); it encompasses erosional highland (greater Nevadaplano) of Henry et al. (2012), which is based on distribution and characteristics of paleovalleys and ages of rocks deposited in them; yellow dashed line indicates approximate drainage divide at 50 Ma (Henry et al., 2012). Shown are locations of intermontane basins in Arizona and New Mexico (USA) (Clinkscales and Lawton, 2014): white diamond—Cocóspera Formation (Turonian); pink diamond—Escalante Formation; blue diamond—Fort Crittenden Formation (Campanian); red diamond—Ringbone Formation (Campanian); orange diamond—Lobo Formation (Paleocene–Eocene); black diamond—Love Ranch Formation (Eocene). Black dashed line shows approximate location at ca. 75 Ma of deformation front, which constituted a hypothesized topographic barrier between dinosaur clades in southern Utah (USA) and Alberta (Canada) (Gates et al., 2012).

that western North America has been fundamentally shaped by steep subduction, including a period of west-directed subduction (e.g., Hildebrand, 2009; Sigloch and Mihalynuk, 2013).

Data similar to those discussed here, and other observations, have led workers to suggest that a broad plateau—the Nevadaplano—existed completely (DeCelles, 2004) or mostly (Henry et al., 2012) on the north side of line A-A′ in Figure 1 (Fig. 3). Much less is known about the evolution of the surface of the region to the south of A-A′ than to the north; however, the data compiled here suggest that the deformation history on either side of this line is broadly similar. Therefore, we suggest it is reasonable to assume that surface uplift of the southern Rockies tracked deformation in a similar fashion to the northern Rockies and that the orogenic plateau, produced as a consequence of crustal shortening, extended further south than is commonly inferred, perhaps

as far south as Sonora and west Texas (Fig. 3). The area of our proposed Laramide orogenic plateau is slightly larger than the combination of the Nevadaplano province and the Laramide province of DeCelles (2004). The distribution of synorogenic Laramide deposits south of the Colorado Plateau (Fig. 3) is consistent with development of high elevations attendant upon Laramide shortening. Coarse-grained deposits were deposited in isolated intermontane Laramide basins in Sonora, southeast Arizona, and southwest New Mexico in Late Cretaceous and Paleogene time (Clinkscales and Lawton, 2014). Boulder conglomerates composed of locally derived clasts indicate that these units were surrounded by evolving mountain ranges, perhaps at elevations higher than now. Dinosaur evolution suggests topographic isolation

due to local surface uplift between southern Alberta (Canada) and southern Utah by ca. 75 Ma (Gates et al., 2012), consistent with the arrival of the deformation front in Utah at about this time (Figs. 1B and 3). Mammalian evolution in the western United States suggests that a high-standing plateau existed by mid- to late Eocene time (Eronen et al., 2015). The shape of modern river profiles (Roberts et al., 2012), the age distribution of zircons in Cenomanian and Paleocene deposits in the Gulf Coast (southeastern United States) (Blum and Pecha, 2014), and thermochronology from the Grand Canyon (Arizona; Flowers et al., 2008; Flowers and Farley, 2012) are all consistent with uplift of the southern Rockies between 80 and 50 Ma.

On the basis of the ages of samples from which elevation estimates have been obtained, Chamberlain et al. (2012, p. 321) suggested that the region from southern Alberta and British Columbia (Canada) to Nevada and Utah underwent "southward encroachment of an Eocene plateau." Our analysis of geologic surface observables (also including surface elevation data [n = 9], but in addition, data relevant to crustal deformation [n = 53], the location of the Laramide shoreline [n = 29], and the locus of magmatism from 120 to 20 Ma [n = 800]) and lithospheric modeling of the subsurface suggests that this plateau extended further to the southeast into Texas and northern Mexico and that the encroachment of the plateau was initially from the southwest to northeast from 90 to 60 Ma and then later from the northeast to the southwest from 55 to 30 Ma. Thermochronology (House et al., 1998), stable isotopes (Cassel et al, 2009), and the distribution of paleovalleys (Henry et al., 2012) suggest that a high-standing Sierra Nevada (eastern California) was the western boundary of this orogenic plateau by at least the late Paleocene.

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