Hydrodynamic mechanism for the Laramide orogeny

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ABSTRACT

The widespread presumption that the Farallon plate subducted along the base of North American lithosphere under most of the western United States and ~1000 km inboard from the trench has dominated tectonic studies of this region, but a number of variations of this concept exist due to differences in interpretation of some aspects of this orogeny. We contend that five main characteristics are central to the Laramide orogeny and must be explained by any successful hypothesis: thick-skinned tectonism, shutdown and/or landward migration of arc magmatism, localized deep foreland subsidence, deformation landward of the relatively undeformed Colorado Plateau, and spatially limited syntectonic magmatism. We detail how the first two elements can be well explained by a broad flat slab, the others less so. We introduce an alternative hypothesis composed of five particular processes: (1) a more limited segment of shallowly subducting slab is created by viscous coupling between the slab and the Archean continental keel of the Wyoming craton, leaving some asthenosphere above most of the slab; (2) dynamic pressures from this coupling localize subsidence at the edge of the Archean Wyoming craton; (3) foreland shortening occurs after the subsidence of the region decreases gravitational potential energy, increasing deviatoric stresses in lithosphere beneath the basin with no change to boundary stresses near the subduction zone or changes to basal shear stress; (4) shear between the slab and overriding continent induces a secondary convective system aligned parallel to relative plate motion, producing the Colorado Mineral Belt above upwelling aligned along the convection cell; (5) the development of this convective system interrupts the flow of fresh asthenosphere into the arc region farther west, cutting off magmatism even in segments of the arc not over the shallowly dipping slab.

INTRODUCTION

The Late Cretaceous to early Tertiary Laramide orogeny that affected much of southwestern North America was not only a major mountain building event, but also coincided with major shifts in the distribution of both igneous activity and sedimentary depocenters. Despite the critical role the Laramide orogeny played in the geologic evolution of western North America, its origin remains enigmatic (e.g., English and Johnston, 2004). This orogeny is particularly difficult to place in a conventional plate tectonic framework, largely because it involved the development of basement-cored mountain belts in the interior of the western United States, ~1000 km inboard of the convergent plate margin that defined the western edge of the continent at the time. What were the forces acting on the continental lithosphere and in what tectonic setting were they generated?

Current tectonic models of the Laramide orogeny are based largely on the observation that magmatism ceased along the western margin of southwest North America in Late Cretaceous time, but then apparently migrated inland through the early Tertiary in concert with the development of the basement cored mountain ranges. Earlier workers suggested that the inland spread in magmatism and crustal deformation were ultimately the product of a Late Cretaceous to early Tertiary shallowing in the angle of subduction of oceanic lithosphere beneath the North American continent (Coney and Reynolds, 1977; Lipman et al., 1971; Snyder et al., 1976). Despite some notable subsequent attacks (Mutschler et al., 1987; Livaccari, 1991; Maxson and Tikoff, 1996), the "flat-slab" model has survived over the past 30 years, even if the relationship between slab angle and the distribution and style of crustal deformation, magmatism, and sedimentation remains unclear. However, geologic evidence from the southwestern United States obtained over the past few decades has suggested that Late Cretaceous to early Tertiary low-angle subduction and attendant subduction erosion only affected only a narrow (~200 km) swath of oceanic lithosphere underthrusting present-day southern California (Barth and Schneiderman, 1996; Saleeby, 2003). If so, why was the shallowly subducting lithosphere so restricted spatially, and how could such narrow "flat-slab" produce the array of geologic features generally attributed to the Laramide orogeny throughout western North America?

To address these issues we explore in this paper the possibility that the Laramide orogeny in the western U.S. was a response to the interaction between subducting oceanic lithosphere and the thick continental lithosphere of the Archean Wyoming craton. We integrate age and compositional information for Late Cretaceous and early Tertiary igneous rocks and sedimentary successions with numerical modeling of the subcontinental mantle to demonstrate that an essentially hydrodynamic model of slab–continental lithosphere interaction can account much of what is currently known about the geologic evolution of the Laramide orogeny.

BACKGROUND

The Laramide orogeny encompasses the early Tertiary creation of basement-cored thrust-bounded uplifts in the western United States; for our purposes we exclude coeval but dominantly thin-skinned deformation to the north and south. Very limited magmatism occurred within this orogen, principally along a linear trend across Colorado, the Colorado Mineral Belt (COMB). The region most strongly affected by Laramide-age deformation can be split into two distinct subregions. The Southern Rocky Mountains in Colorado and New Mexico are built from Paleoproterozoic basement terranes that were strongly deformed in the late Paleozoic Ancestral Rockies orogeny. The uplifts in Wyoming and adjacent areas to the north disturbed Archean crust that had lain virtually undeformed since the middle Proterozoic. The Laramide uplifts extend well into North America, more

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than 1000 km inland from the continental margin volcanic arc active prior to the Laramide orogeny and more than 500 km inland from the eastern edge of the thin-skinned fold-and-thrust belt of the Sevier orogen active prior to the Laramide orogeny (e.g., Burchfiel et al., 1992; DeCelles, 2004; Burchfiel and Davis, 1975) (Fig. 1). This eastward shift is most dramatic in the southern part of the Laramide orogen, where basement involved thrusts first appear at the surface 500 km east of the easternmost thrusts of the thin-skinned Sevier orogen, leaving a more mildly deformed Colorado Plateau to separate the Southern Rocky Mountains from the thrusts of central Utah.

The main episode of deformation started in the Maastrichtian (66–75 Ma), usually dated by the appearance of local basins and locally derived clastic rocks, the disappearance of marine sedimentary facies (e.g., Dickinson et al., 1988), and the initiation of igneous activity within the continental interior (Cunningham et al., 1994; Mutschler et al., 1987). This must be regarded as a minimum age; there are suggestions that some Laramide uplifts were influencing sedimentary depositional patterns by 76–80 Ma (Cather, 2004; DeCelles, 2004; Guiseppe and Heller, 1998). Deformation continued until ca. 30–45 Ma (e.g., Dickinson et al., 1988; Gries, 1983; Bird, 1998; Cross, 1986). Although there are differences between different workers in inferred slip azimuths and timing on individual structures (e.g., Bird, 1998; Gries, 1983; Johnson and Anderson, 2009), the overall orientation of shortening across the orogen is northeast-southwest (Bird, 1998; Erslev, 1993). Total shortening estimates have ranged from 43 to 120 km across the Wyoming part of the orogen (Bird, 1998; Chapin and Cather, 1983).

Several events outside the Laramide orogen or prior to it could be relevant to understanding the cause of this event. Most notably, igneous activity in the long-lived volcanic arc along the western margin of the United States was shut off from north of southern Arizona and New Mexico to near the Canadian border in the Late Cretaceous (Armstrong and Ward, 1991; Chen and Moore, 1982) (Fig. 2). Arc magmatism continued outside this gap; within this 1200-km-wide gap, magmatism was limited principally to the COMB prior to ca. 60 Ma (Figs. 2D, 2E). We agree with earlier workers that melt generation that led to the COMB likely took place in the upper mantle (Lipman et al., 1971; Mutschler et al., 1987; Snyder et al., 1976), although we recognize that radiogenic isotope data from "calc-alkaline" Laramide intrusive igneous rocks in the COMB require a large lower crustal component in these rocks (Simmons and Hedge, 1978; Stein and Crock, 1990). We base this assertion on new chemical and isotopic data from remnants of Laramide-age basaltic lavas flows and from mafic clasts in Laramide volcaniclastic units in Colorado that confirm that COMB magmatism was ultimately related to a mantle melting event (Bailley, 2010). Published age determinations consist exclusively of relatively low precision mineral or whole-rock K-Ar, or fission track apatite and/or zircon, ages that have complications associated with reheating by younger magmatism or postemplacement hydrothermal activity (Cunningham et al., 1994). Thus available geochronology cannot distinguish between synchronous Laramide magmatism across much of the COMB or some time-transgressive pattern (Mutschler et al., 1987).

Deformation in the Sevier fold-and-thrust belt also seems to have waned in this time, especially in southern Nevada and nearby Utah, where thrusting appears to have halted by 87–81 Ma, prior to the start of Laramide tectonism (Barth et al., 2004; Burchfiel and Davis, 1977), and in the Maria fold and thrust belt of southeastern California and western Arizona, which shortened until 85 Ma (Barth et al., 2004; Boettcher et al., 2002; Karlstrom et al., 1993) and possibly until 70 Ma on the Mule Mountains thrust (Tosdal, 1990; Tosdal and Stone, 1994). Farther north, shortening continued on frontal thrusts through most of the Laramide (DeCelles, 2004; DeCelles and Coogan, 2006), ceasing and then reversing into extensional faulting toward the close of the Laramide (Constenius, 1996).

Exhumation of deep crustal rocks and surface normal faulting has been documented in the latest Cretaceous in the Sevier hinterland (Wells and Hoisch, 2008; Druschke et al., 2009a, b; Hodges and Walker, 1992; Wells et al., 1990). The timing of shortening in central Arizona is less certain. Considerable evidence of major early-Late Cretaceous shortening exists (e.g., Krantz, 1989), but whether later deformation is contractional and/or extensional remains unclear (e.g., Livaccari, 1991).

Much of the Rocky Mountain foreland that underwent Laramide shortening had subsided substantially immediately prior to shortening, accumulating more than 2 km of Late Cretaceous sediments, but sedimentary cover around this region indicates that this subsidence was not caused by surface loading as in the foredeep to the west (Bird, 1984; Cross, 1986; Cross and Pilger, 1978b; Liu and Nummedal, 2004). This subsidence occurred within a much broader zone of less intense subsidence, the Western Interior Seaway, which has often been linked to shallowing subduction under all of western North America (Burgess et al., 1997; Mitrovica et al., 1989; Pang and Nummedal, 1995 [Fig. 2]).

EXISTING HYPOTHESES

Three main processes have been hypothesized to contribute to the Laramide orogeny: collision with an exotic terrane (Maxson and Tikoff, 1996; Silver and Smith, 1983; Hildebrand, 2009), collapse of the hinterland of the Sevier orogen (Livaccari, 1991), and shallow subduction of oceanic lithosphere (e.g., Bird, 1984; Dickinson and Snyder, 1978). The first two ideas have significant problems that have led them to be marginalized. Collision requires stresses to be greater at the margin than the continental interior unless stresses can be focused; yet little if any contractional deformation was produced in the Great Valley–Sierra Nevada–Southern Nevada region in this time frame (Barth et al., 2004; Burchfiel and Davis, 1977; Unruh et al., 2007). Absence of significant deformation requires either greater lithospheric strength than in the continental interior or increased gravitational potential energy to offset the compressional stresses. Neither condition has been demonstrated across the entire distance from trench to foreland, although increased potential energy might occur in parts of the Sevier hinterland (Livaccari, 1991; Wells and Hoisch, 2008). Additional difficulties arise in trying to synchronize the timing of arc shutoffs with the presumed migration of the colliding Insular superterrane, especially in light of Late Cretaceous intrusive igneous rock ages acquired after publication of Maxson and Tikoff (1996) in the Mojave Desert and Penninsular Ranges by Barth et al. (2004) and Moniz et al. (2007) (after Maxson and Tikoff, 1996) and the north-to-south younging of emplacement of underthrust oceanic assemblages (Rand, Pelona, and Orocopia Schists; Grove et al., 2003).

The collapse process essentially requires that the Sevier hinterland rise up enough that stresses in the hinterland are extensional. This allows the region to undergo highly compressive horizontal stresses from the plate margin without contraction; if the hinterland has risen through foundering of mantle lithosphere (e.g., Wells and Hoisch, 2008), then overall horizontal stresses might be higher than prior to uplift. This process requires the Colorado Plateau to be stronger than the Wyoming craton, a presumption discussed more below. It also fails to explain the shutdown in frontal thrusts in southern Nevada at a location presumably subject to the greatest increase in compressional stress. The collapse hypothesis as envisioned by Livaccari (1991) decouples Laramide shortening from changes in arc magmatism, which requires the changes in the distribution of magmatism to be an irrelevant coincidence. Wells and Hoisch's (2008) vision of this process integrates it with a

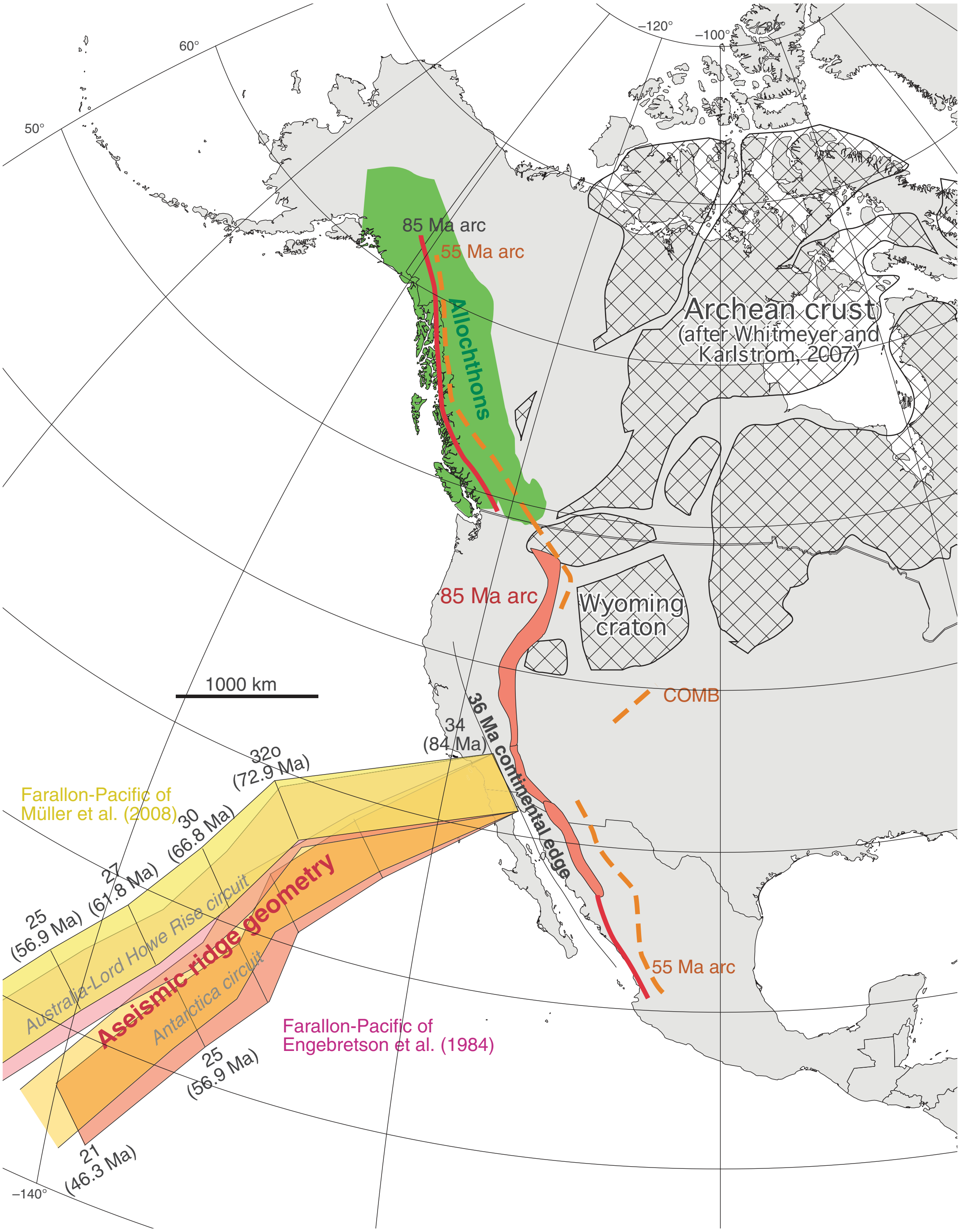


Figure 1. Map of North America showing locations of Archean cratons (Whitmeyer and Karlstrom, 2007), major allochthonous terranes, Precambrian basement exposures of the Rocky Mountain region (Grose, 1972), Colorado Mineral Belt (COMB), and pre-Laramide arc in western North America [NAVDAT (North American volcanic and intrusive rock database, www.navdat.org); Walker et al., 2006] and Canada (Gehrels et al., 2009). Eocene arc in Canada is from Gehrels et al. (2009) and U.S. and northernmost Mexico data are from NAVDAT. Central Mexico is sketched to reflect migration shown by Damon et al. (1981) over all northern Mexico and eastward motion of arc shown by Henry et al. (2003) in Sinaloa. Allochthonous rocks were probably farther south before and during the Laramide orogeny and would have increased the distance from the trench to possible Archean lithosphere in Montana and Alberta (e.g., Butler et al., 2001; Saleeby, 1992). Four possible swaths of ocean floor to be subducted under the continental edge where the Pelona, Rand, and Orocopia Schists are exposed are shown at their position at 84 Ma, with the time at which that seafloor reaches the trench marked along each swath. The four swaths combine two North America–Pacific plate circuit reconstructions and two Farallon-Pacific reconstructions (Doubrovine and Tarduno, 2008); these give an approximate sense of uncertainty in plate reconstructions. The extent of a swath would roughly correspond to the oceanic plateau needed to have driven shallow subduction through the Laramide, were that the cause of narrow, long-lived, flat-slab subduction.

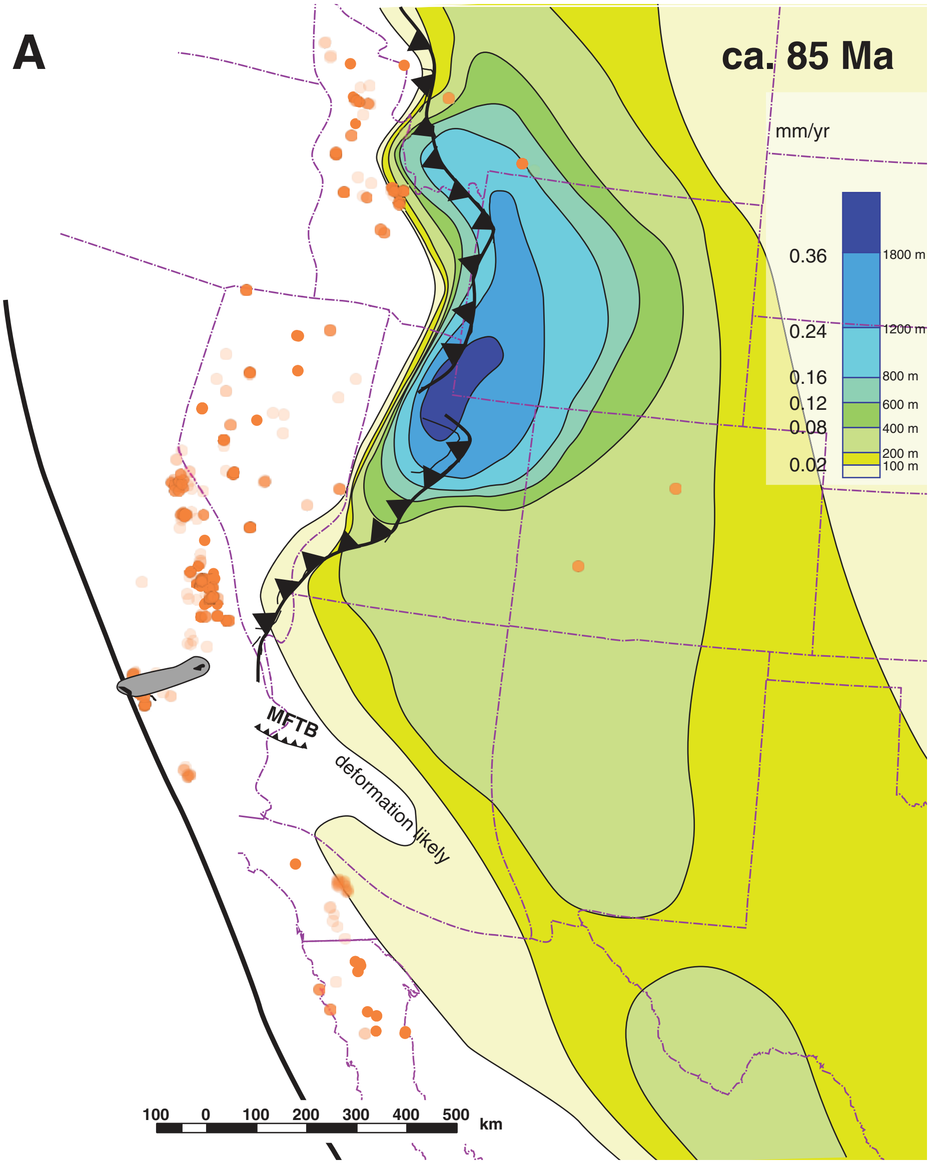
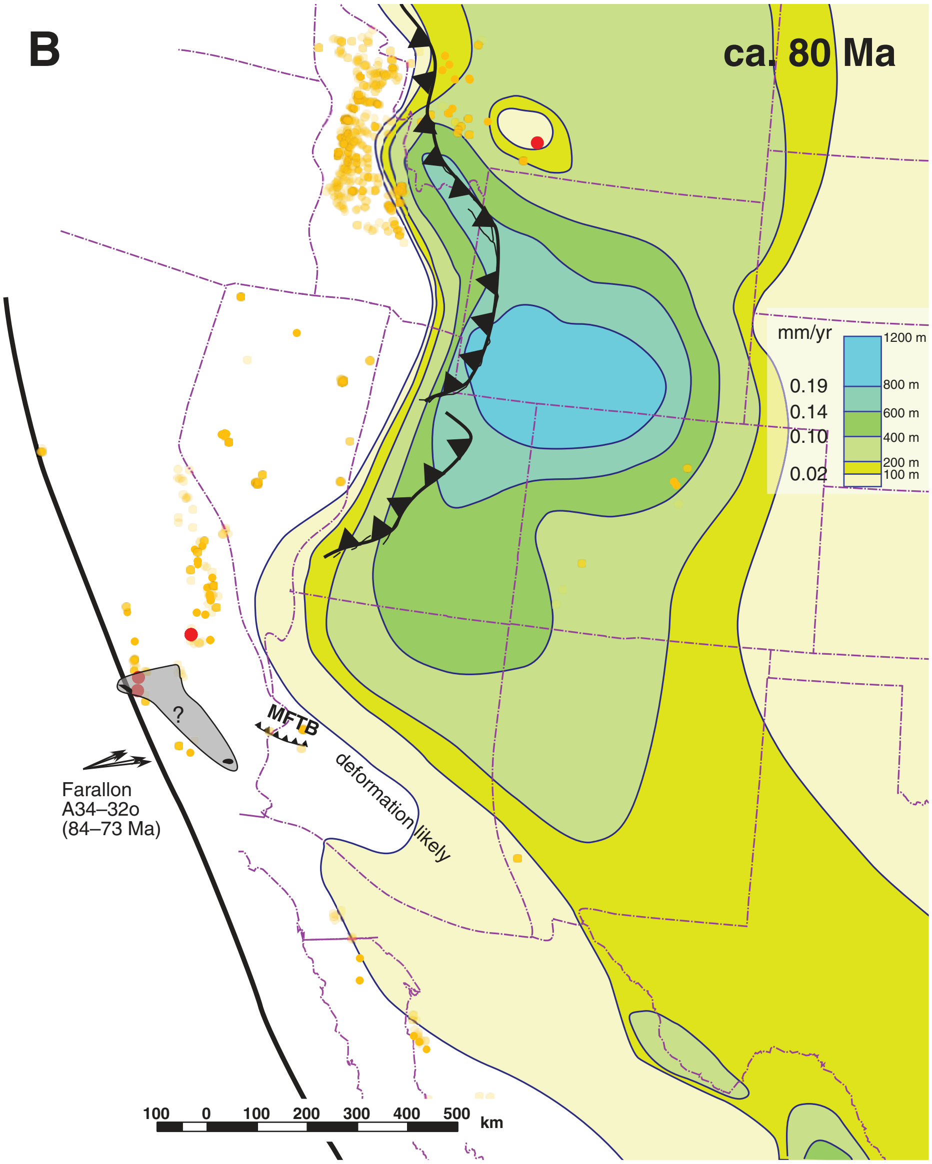


Figure 2 (*on this and following four pages*). Time-slice maps of principal tectonic elements active at each time plotted on 36 Ma (post-Laramide) palinspastic base of McQuarrie and Wernicke (2005). Sediment thicknesses are from Roberts and Kirschbaum (1995) and are colored to have approximate uniformity of stratal accumulation rates across time slices. Orange dots (from NAVDAT; North American volcanic and intrusive rock database, www.navdat.org) are made more transparent as ages are more uncertain. High-quality measurements most likely to reflect emplacement and/or eruption ages such as U-Pb zircon ages are shown in larger red circles and include some measurements not in NAVDAT (Barth et al., 2004). Gray areas in lower left are regions where Pelona-type schists of oceanic affinity were being emplaced (Grove et al., 2003); black parts show outcrops of these schists. Heavy barbed line is the eastern edge of thin-skinned (Sevier) fold-and-thrust deformation in U.S.; lighter lines to east indicate active thick-skinned structures (DeCelles, 2004); finer barbed lines in eastern California–western Arizona show Maria fold-and-thrust belt (MFTB) and Mule Mountains thrust (Barth et al., 2004; Tosdal, 1990; Tosdal and Stone, 1994). Thrusts in southern New Mexico are from Seager (2004). Foreland faults active at each time are from Bird's (1998) data tables. Colorado Plateau fold ages are assigned from other literature. Goldstrand (1994) defined uplift of Circle Cliffs and Kaibab uplifts from Late Cretaceous–Paleocene stratigraphy as starting in latest Campanian, essentially coeval with Lawton's (1983) similar inference for the San Rafael Swell (SRS) to the northeast (see also Guiseppe and Heller, 1998). Deformation in Mexico is not usually shown. Plate motions at the trench at lower left are from Doubrovine and Tarduno (2008); four vectors reflect four possible reconstructions as noted in Figure 1. (A) 85 Ma. End of major intrusive episode in Sierran batholith and simple foredeep sedimentation in foreland. Isopachs of Coniacian age (83.5–88.5 Ma) are from Roberts and Kirschbaum (1995). (B) 80 Ma. Initial expansion of sedimentation away from the foredeep in northern Utah. Isopachs of Campanian I (83.5–79 Ma) are from Roberts and Kirschbaum (1995). (C) 75 Ma. Inception of Laramide deformation in foreland, expansion of schist emplacement, development of magmatic gap from Mojave Desert to Idaho. Isopachs of Campanian II (72–79 Ma) are from Robert and Kirschbaum (1995). Box outlines swath used for Figure 7, with lines every 500 km from 0 at lower left. Plateau monoclines Hogback monocline (HM) and San Rafael Swell (SRS) are labeled. (D) 70 Ma. Final regionally connected sedimentary basin of Maastrichtian age with profound subsidence. Isopachs of Campanian III–Maastrichtian (65.5–72 Ma) are from Roberts and Kirschbaum (1995). Cheyenne Belt (CB) demarks the southern edge of Archean crust. (E) 65 Ma. Local Laramide basins, Colorado Mineral Belt are certainly established. Basin thicknesses from the Paleocene is from Carroll et al. (2006), except for Denver Basin (from Raynolds, 2002) (D1 above Cretaceous-Tertiary boundary and D2 sequence), San Juan Basin (from Cather, 2004), and Raton Basin (from Cather, 2004; Pillmore and Flores, 1990). Note that these isopachs are preserved section and not interpolated to estimated original thicknesses as in other panels, largely because Paleocene basins were distinct. Blue hachured areas to north mark basins lacking detailed isopach information. Precambrian basement exposures in Sevier foreland (gray hachured area) are from Grose (1972). To view the interactive version of Figure 2, please visit http://dx.doi.org/10.1130/GES00575.S1. This animation can be viewed using Adobe Flash Player. Select layers can be viewed using the checkboxes in the lower left and the time window can be viewed by clicking on the bar at the top of the figure.



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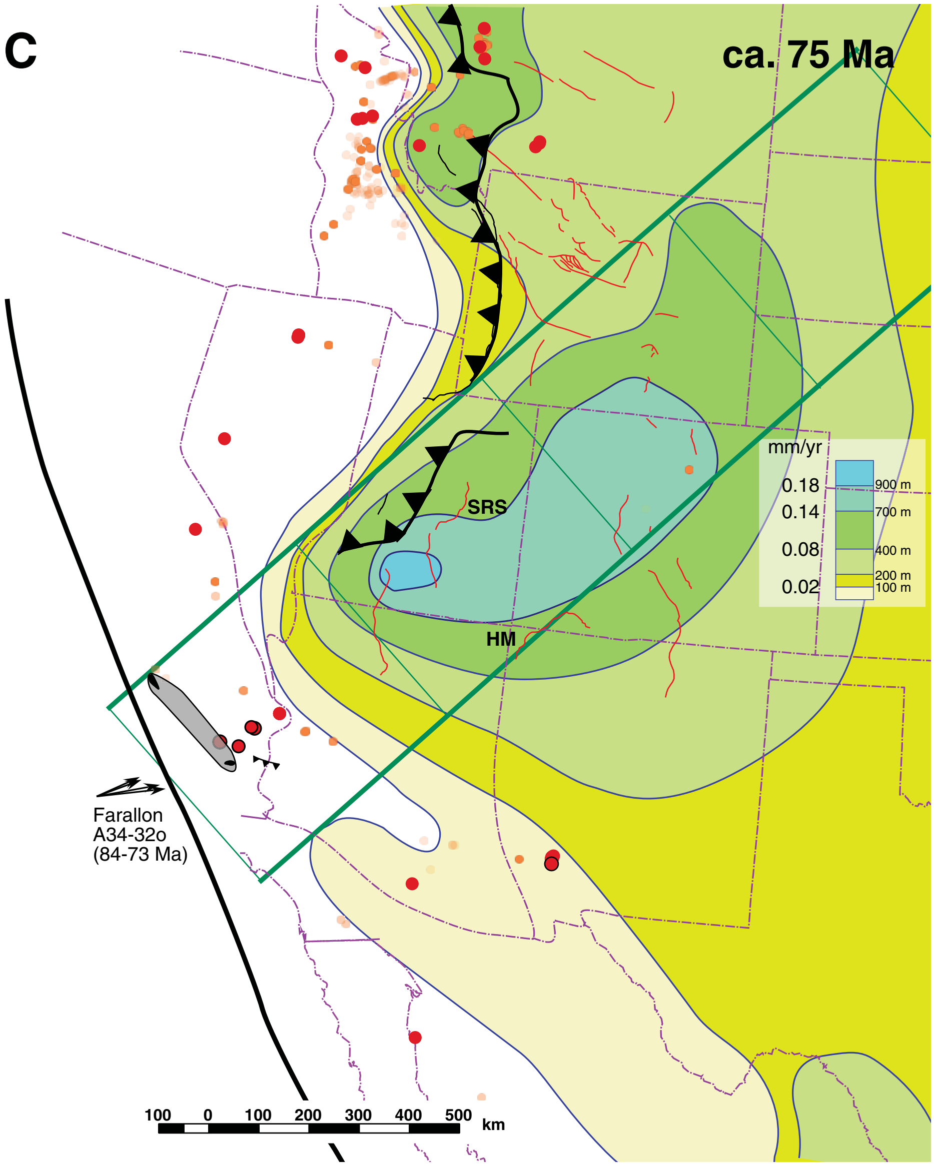
somewhat more limited shallowing of the slab; arc volcanism is disrupted to differing degrees by the foundering of mantle lithosphere thrust back under the arc and the change in slab geometry. It is thus less clear why this process was limited to the western U.S. and not northern Mexico and southernmost Canada.

Hildebrand (2009) posited that western North American arcs were allochthonous and sutured to North America just before the Laramide orogeny; in this view, the Sevier orogeny was the culmination of the collision and the Laramide orogeny occurred as east-dipping subduction developed under North America. As with the other ideas outlined here, the Colorado Plateau is presumed to be strong. The shutdown of the Sevier belt in southern Utah and Nevada is not explained, but is probably tied to changes in the foundering of the west-dipping slab extending off of North America. Similarly, the absence of arc volcanism in the bulk of the western U.S. is ascribed to some unspecified difficulty in penetrating the lithosphere of this region. Many questions remain on the testable predictions of this model.

For these reasons, the last hypothesis, that deformation arose as subducting oceanic lithosphere shallowed under the United States, has emerged as the preferred alternative (English et al., 2003; Humphreys et al., 2003; Spencer, 1996; Schmid et al., 2002; Humphreys, 2009). The initial interpretation of a gently dipping slab associated with the Laramide orogeny grew out of inferred relations between the K_2O content of volcanic rocks and slab depth and the chemistry of Laramide igneous rocks in the Southern Rocky Mountains (Lipman et al., 1971). Although the chemical basis for this inference has been abandoned (Meijer and Reagan, 1983; Mutschler et al., 1987), the general idea that the Laramide orogeny was related to an episode of shallow subduction continued to gain support due to favorable comparison with the basement-cored uplifts of the Sierra Pampeanas in Argentina, which are inboard of an inactive segment of the Andean arc and above a shallowly dipping segment of the subducting plate (e.g., Dickinson and Snyder, 1978; Humphreys et al., 2003; Jordan and Allmendinger, 1986; Barazangi and Isacks, 1976). The physical underpinnings of the flat-slab hypothesis arise from the balance of basal shear tractions by compressional stresses increasing with distance from the trench; such compressional stresses can drive crustal contraction and thickening (Bird, 1984, 1988; Dickinson and Snyder, 1978). A second geodynamic implication supporting shallowing subduction is the inference that such a change in subduction geometry will produce subsidence in the continental interior, consistent with the creation of the Western Interior Seaway (Burgess et al., 1997; Mitrovica et al., 1989). Although some alternatives have been advanced, the main discussion over the past 20 years has focused on the precise geometry for shallow or flat-slab subduction (e.g., Saleeby, 2003), the magnitude of shear stress applied to North America, and the means by which the slab was removed (e.g., Humphreys, 1995). Most workers have presumed (frequently implicitly) that nearly the entire western U.S. had lain over a flat slab in the early Tertiary, much as shown by Bird (1984, 1988) and Jordan and Allmendinger (1986). The presence and removal of this slab have been implicated as causing much of the tectonism of the western U.S. in the Cenozoic (e.g., Humphreys et al., 2003; Humphreys, 1995).

Although the cessation of magmatism along the Pacific margin was widespread, evidence that the slab shallowed is far more limited. Mesozoic garnet peridotites from paleodepths of 100 km or more as measured by garnet geobarometry were preserved into the Miocene under the Sierra Nevada arc (Ducea and Saleeby, 1996, 1998); to the south, in contrast, oceanic schists were juxtaposed against the crust of the Mesozoic arc in the latest Cretaceous and early Tertiary, as constrained by protolith and cooling ages (Grove et al., 2003; Saleeby, 2003; Malin et al., 1995; Burchfiel and Davis, 1981; Jacobson et al., 1988). If representative of deeper levels in the earth (as suggested



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by Luffi et al., 2009), this suggests that the along-trench extent of extremely shallow subduction was much more limited than previously inferred (Saleeby, 2003).

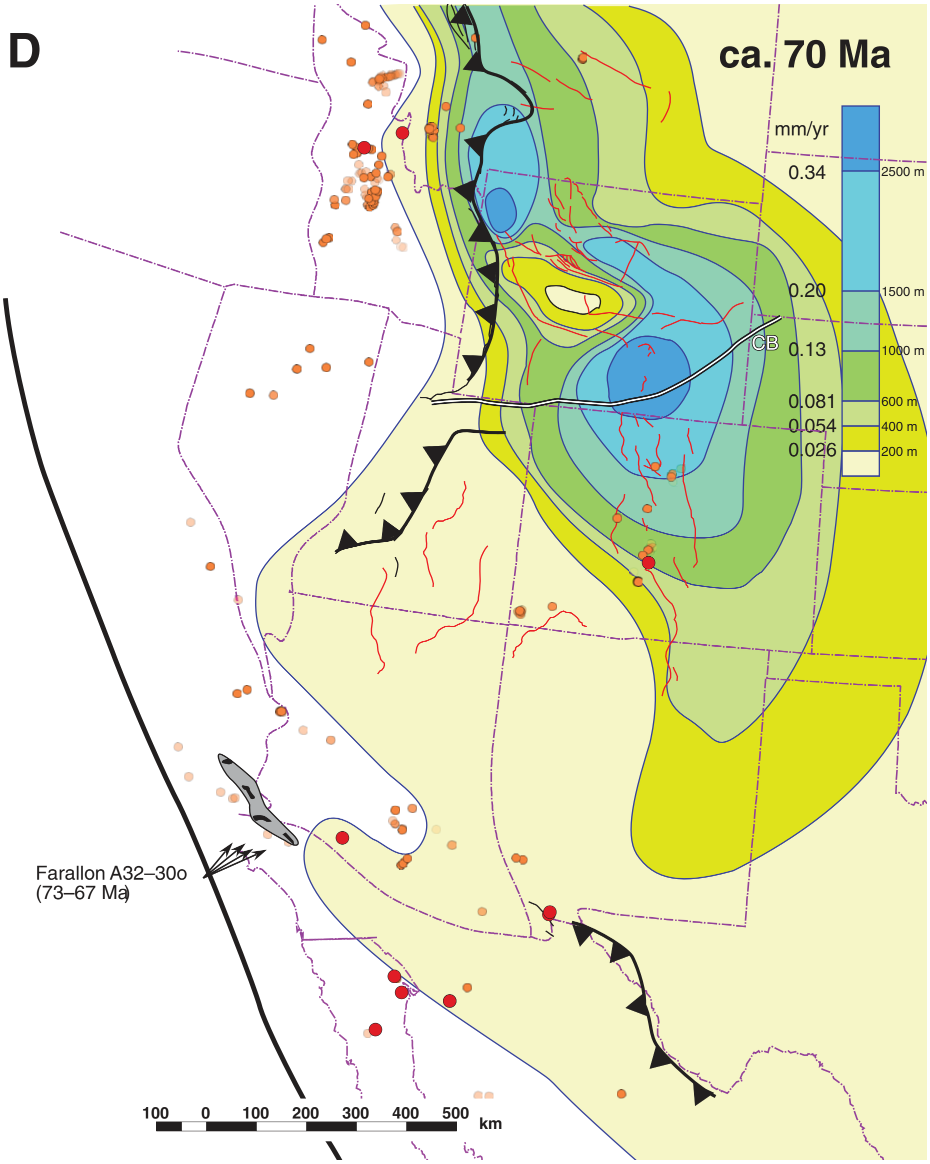
Only Bird's (1988) specific geodynamic version of the flat slab has provided quantitative predictions at a lithospheric scale from trench to foreland; it is based on a review of the physical relations of several aspects of the hypothesis (Bird, 1984). In developing his model, Bird sought to not only produce deformation far to the east of earlier shortening, but also tried to produce the thick crust found today in Colorado by entraining it in the shear between plates. We briefly deconstruct the four main elements of the flat-slab hypothesis as envisioned by Bird and their physical basis: production of large horizontal normal stresses well into the continent, creation of unusually thick crust well into the continent, subsidence of the Rocky Mountain foreland, and the cessation of arc volcanism.

The most elegant aspect of the original flat-slab hypothesis is that stresses are readily conveyed past the weak regions near the plate boundary and focused in the plate interior (Bird, 1988; Dickinson and Snyder, 1978). The subducting slab is in contact with the overriding plate; the resulting shear stresses are posited to have existed along the entire distance from near the trench to the Southern Rockies. The stresses transmitted would parallel the relative plate motion, which could explain the difference between the east-directed Sevier belt and the northeast-southwest shortening in the foreland (Bird, 1998; Erslev, 1993). The equation of equilibrium reveals that the horizontal normal stresses will be maximized where the basal shear stops, which is where the large uplifts are found (Fig. 3A). However, for this process to deform foreland lithosphere, there must be a significant shear stress on the base of the North American plate.

The effects of this basal shear on the internal structure of the North American plate depend on the rheology of the lithosphere. By positing a weaker lower crust than upper crust or upper mantle, Bird (1988) was able to effect the movement of large volumes of lower crust from west to east, movement accompanied by wholesale removal of mantle lithosphere through most of the western U.S. This movement of crust created thicker crust in the Southern Rockies and High Plains. A secondary cause of this flow of lower crust could have been basal suction forces associated with emplacement of an antibuoyant slab, although Bird (1984) argued that this is reversible and too local to explain the difference between modern crustal thicknesses and a roughly uniformly 35-km-thick crust inferred to exist prior to the Laramide.

The emplacement of an antibuoyant slab has been inferred to be the cause of subsidence of the continent above the flat slab (Bird, 1984; Cross, 1986; Cross and Pilger, 1978b). This requires that the shallowing of the slab occurs because of an instability in the dynamic pressures generated by flow in the asthenospheric wedge (Tovish et al., 1978). A broad correlation exists between the inferred extent of the flat slab and Late Cretaceous isopachs (Bird, 1984). Others have inferred that subduction of buoyant oceanic crust (e.g., Henderson et al., 1984; Livaccari et al., 1981; English et al., 2003) caused subduction to shallow, although this is apt to cause uplift of the overriding plate instead of subsidence (van Hunen et al., 2004), and such basalt-rich crust will convert to eclogite (Kelleher and McCann, 1976), negating any special ability to cause flat subduction (Cahill and Isacks, 1992). Liu et al. (2010) suggested that this discrepancy is solved if the oceanic plateau converts to eclogite as it travels under the continent.

The cessation of continental margin magmatism that accompanied the Laramide orogeny is also consistent with a period of shallow subduction. Arc magmatism is generally considered to be the result of melting in the mantle wedge initiated by the influx of volatiles produced during subduction of oceanic lithosphere (Davies and Stevenson, 1992; Gaetani and Grove, 2003; Gill, 1981). Although the dewatering reactions



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probably occur over a significant depth range (Schmidt and Poli, 1998), modern volcanic arcs are over Benioff zones from 65 to 130 km deep, the main variation apparently caused by changes in convergence speed (England et al., 2004). Thus as a slab shallows, arc magmatism should migrate inboard. Beneath some segments of the modern Andes, oceanic lithosphere is subducting at such shallow angles that subduction-related continental margin magmatism has been completely extinguished (Gutscher et al., 2000; Barazangi and Isacks, 1976).

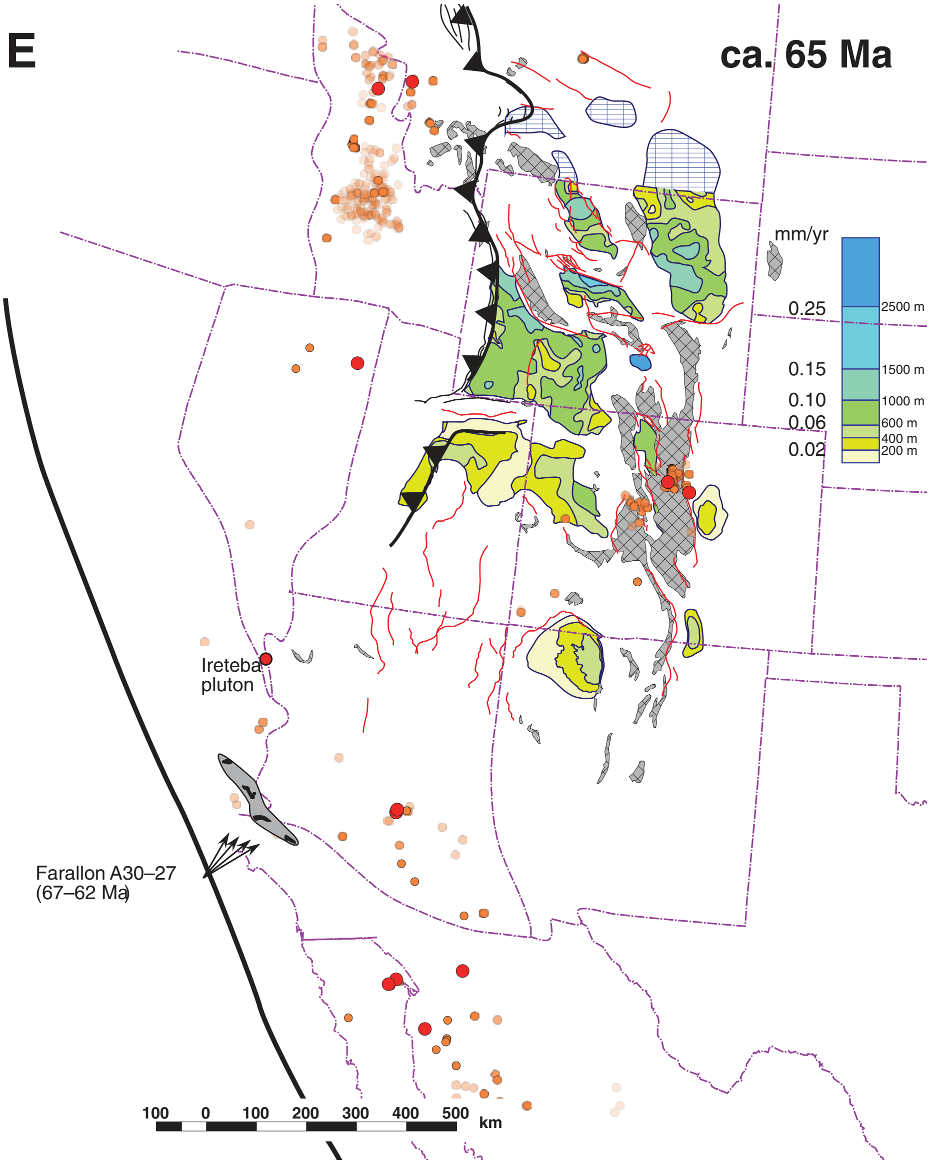
Thus the four main effects of shallow subduction, i.e., foreland deformation, foreland crustal thickening, foreland subsidence, and migration of the volcanic arc, are in fact mostly the products of four somewhat separable components of the system: magnitude of basal shear stress, weaknesses within the lithospheric rheology, antibuoyancy of the slab, and geometry at and above the top of the subducting slab. A product of shallow (but not necessarily flat) subduction not originally appreciated is the possible creation of dynamic topography (i.e., topography out of isostatic equilibrium owing to stresses induced by fluid flow) (Mitrovica et al., 1989). Such dynamic topography was proposed to explain the expansion of the Western Interior Seaway from its foredeep position earlier in the Cretaceous to extend well into the continent (Burgess et al., 1997; Mitrovica et al., 1989). The magnitude of dynamic topography depends on the flow field in the asthenosphere, which in turn depends on the rheology of the asthenosphere and the geometry and rate of subduction (Burgess et al., 1997; Mitrovica et al., 1989; McKenzie, 1969).

Although a flat slab is widely presumed, the cause of any shallow subduction remains unresolved. A slab might shallow if buoyant material is subducted, if the overriding plate accelerates, or through hydrodynamic forces in the asthenospheric wedge (slab suction) (van Hunen et al., 2004). Three specific events have been proposed for the Laramide: subduction of a buoyant plateau or young lithosphere (Henderson et al., 1984; Barth and Schneiderman, 1996; Livaccari et al., 1981; Saleeby, 2003), acceleration of North America (Cross and Pilger, 1978a), and changes in the velocity and/or age of the subducting slab (Engebretson et al., 1984). For our purposes, the chief difference between these is the extent and timing of the effects of flat-slab subduction. For example, the subduction of a buoyant plateau predicts that changes in the interior of the North American plate due to basal shear will lag effects at the margin by several million years (e.g., Espurt et al., 2008), while changes in the motion of North America will be more instantaneous but should affect the entire margin.

ALTERNATIVE HYPOTHESIS

Any alternative explanation of the Laramide should explain patterns of igneous activity, sedimentation, and tectonism, addressing both issues well covered by the existing flat-slab scenario and elements poorly understood in the existing framework, such as the timing of subsidence in the foreland and the evolution of the COMB. We outline such a hypothesis before discussing the components in detail (Fig. 5).

We posit that subduction did shallow along the entire western margin of North America, but that an Archean keel under the Wyoming craton narrowed asthenospheric counterflow, leading to an unusual amount of shallowing of the slab under part of the western U.S., more or less as delineated by Saleeby (2003), but not necessarily to the base of the lithosphere. We suggest that the flow field creating the stresses pulling up the slab also created a basal normal force on North America that created the peculiar Maastrichtian basin in Wyoming and Colorado. We accept the logic of Jones et al. (1998) in suggesting that the forces generated by this subsidence localized subsequent deformation far in the foreland. We suggest that this pattern of flow in the asthenosphere led to the cessation of arc volcanism in the latest Cretaceous and early Tertiary by disrupting flow of fertile



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asthenosphere to the Sierra Nevada arc, as suggested by Saleeby (2003). Finally, we propose that shear-parallel convection generated within this subduction system produced the northeast-trending COMB.

Shallowing of Subduction

We concur with others (Cross and Pilger, 1978a; DeCelles, 2004) that North America accelerated westward relative to the Farallon plate in the Late Cretaceous; this motion led the entire subducting slab to dip more shallowly (Fig. 5A). Unfortunately plate circuit reconstructions of Farallon–North America motion barely include the latest Cretaceous (Doubrovine and Tarduno, 2008; Stock and Molnar, 1988), and hotspot-based reconstructions (e.g., Engebretson et al., 1984, 1985) include considerable errors that limit interpretation (e.g., Doubrovine and Tarduno, 2008; Stock and Molnar, 1988). Accelerated motion of North America is supported both by the eastward migration of all the arcs in the western U.S. and northern Mexico (e.g., Armstrong and Ward, 1991; Lipman, 1992; Dickinson, 2006; Clark et al., 1982) (Fig. 1) and by estimates of opening across the North Atlantic Ocean (Fig. 4). An abrupt counterclockwise rotation of North America accompanied southward motion starting ca. 75 Ma (as shown by its apparent polar wander path; Torsvik et al., 2001); this and the smaller migration of the arc in southern Mexico (Henry et al., 2003) suggest that accelerated westward motion was higher to the north. The arc also migrated to the east in Canada (van der Heyden, 1992; Gehrels et al., 2009), but as the position of these rocks with respect to North America in the Late Cretaceous is disputed (e.g., Krijgsman and Tauxe, 2006; Cowan et al., 1997; Butler et al., 2001; Kim and Kodama, 2004), it is not entirely clear that this reflects accelerated motion of North America. Less directly, the marine transgression in the Cretaceous that led to the Western Interior Seaway connecting the Gulf of Mexico to the Arctic Ocean is likely to have been the product of subsidence due to changes in flow in the upper mantle induced by shallowing subduction (Burgess et al., 1997; Mitrovica et al., 1989).

Interaction with Archean Wyoming Craton

Most of the Farallon plate was subducting under Proterozoic or younger lithosphere (Fig. 1), but one segment would have impinged on the edge of the Archean Wyoming craton between ~1100 and 1400 km from the trench (Fig. 5B). If Wyoming had at this time Archean lithosphere comparable to that present today elsewhere in North America, the lithosphere could have extended to 200–300 km depth under this craton (Gung et al., 2003; Michaut et al., 2007). For this segment of slab, the space where asthenospheric counterflow occurs would be narrower than elsewhere, and so corner flow models predict that the flow gradients would be much higher and the slab suction forces increase (e.g., McKenzie, 1969; Tovish et al., 1978). The corner flow model therefore predicts that this segment of slab would be pulled up and the continent over it pulled down. On a mid-Cenozoic palinspastic base (McQuarrie and Wernicke, 2005) and well within the uncertainties of relative plate motions, the position where the sub-Wyoming slab would subduct corresponds to the reconstructed positions of the Orocopia, Pelona, and Rand Schists (Fig. 2). Based on the corner flow model, we thus suggest that the sub-Wyoming segment of the slab was pulled upward by dynamic forces and that this might have propagated upslip to the trench, generating conditions conducive to basal erosion of the continental margin and emplacement of the eugeoclinal schists.

The northern part of the Wyoming craton was probably also only a short distance from the trench in latest Cretaceous time, but it is probable that this region was above the subducting Farallon-Kula or Farallon-Resurrection spreading ridge (Breitsprecher et al., 2003; Haeussler et al., 2003; Madsen et al., 2006).

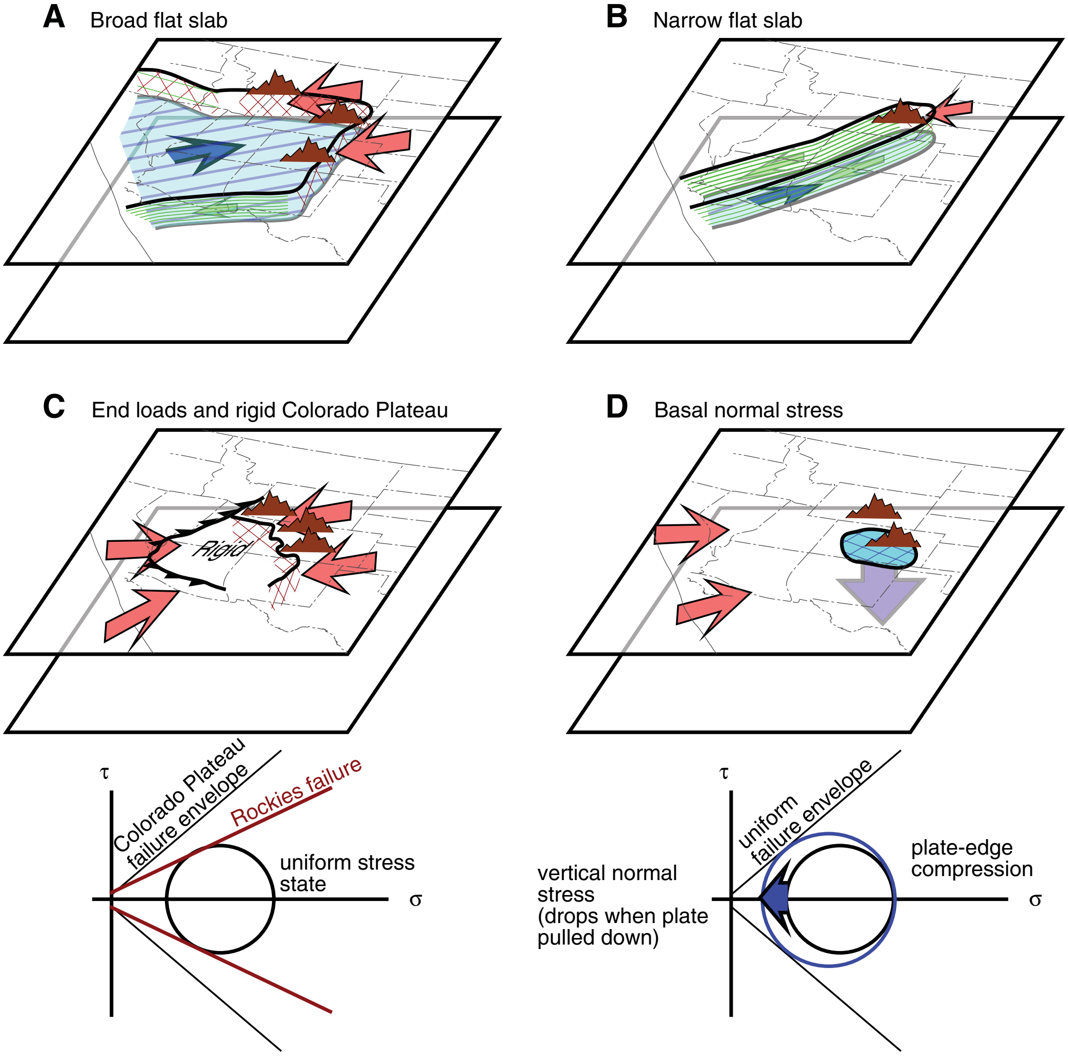

Figure 3. Illustration of the basic forces operating to make Laramide uplifts acting on the lithosphere. Red crosshatch indicates normal stresses acting on North American lithosphere within Laramide orogen, green lined areas indicate shear stresses within supra-flat slab lithosphere, blue filled and lined area indicates a basal shear traction. (A) Basal shear with a broad slab (e.g., Bird, 1984, 1988). Width of slab is such that basal shear is dominantly balanced by large normal stresses at edge of slab-North America contact. (B) Basal shear with a narrow ("tongue-depressor") slab (e.g., Saleeby, 2003). Basal shear is mostly balanced by shear applied from edges of flat-slab region. (C) End load with strong Colorado Plateau (e.g., Livaccari, 1991). Note that evidence for thrusting on south and southwest sides of plateau is minimal or nonexistent. (D) Basal normal stress and end load (e.g., Jones et al., 1998).

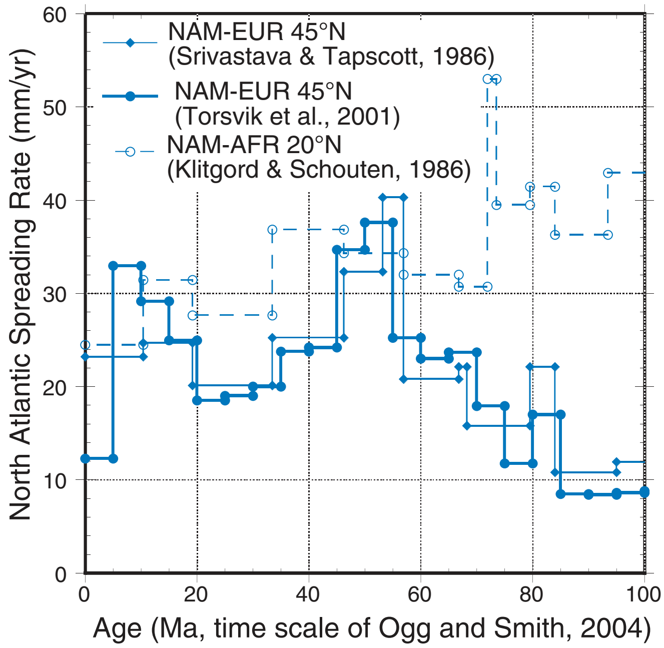

Figure 4. Opening rates across the North Atlantic near 50°N [rate of motion of European (EUR) point currently at 50°N, 15°W] calculated from both the plate reconstruction of Srivastava and Tapscott (1986) and a combined paleomagnetic and magnetic anomaly reconstruction of Torsvik et al. (2001) (solid lines). The opening rate between North America (NAM) and Africa (AFR) near 25°N (motion of an African point now at 20°N, 20°W) is from the plate reconstruction of Klitgord and Schouten (1986). Both plate reconstructions are corrected to the time scale of Ogg and Smith (2004). North Atlantic rates started increasing by 80 Ma (anomaly 33) with discrete increases near 70 Ma (which might be present in the Farallon–North America reconstruction of Doubrovine and Tarduno, 2008) and 55 Ma (which did not apparently change Farallon–North America motion). Marked reduction in North Atlantic rates at 45 Ma is possibly related to the end of the Laramide orogeny and a temporary slowing of Farallon–North America convergence (Doubrovine and Tarduno, 2008).

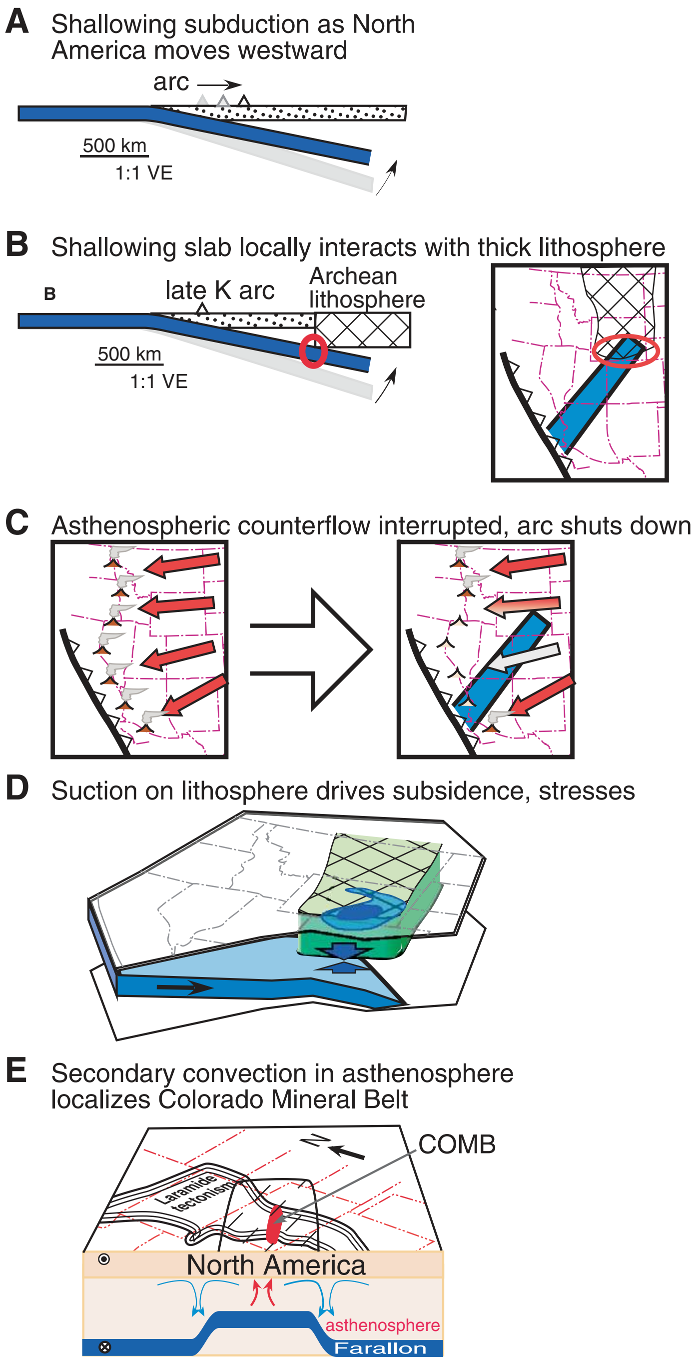

Figure 5. Schematic diagram of elements of an alternative hypothesis. (A) All of North America north of central Mexico accelerates westward; arcs migrate eastward as convergence increases. (B) Section of slab underthrusting the Wyoming craton rises even farther as dynamic normal stresses in the asthenosphere are generated by high-velocity gradients between the Archean keel and slab. (C) Shallow part of the slab interferes with asthenospheric counterflow that is dominantly trench-normal, starving arcs to the west of material sufficiently fertile to generate arc magmas if fluxed. (D) Dynamic stresses (from B) drive subsidence of the edge of the Archean craton, which in turn produces lower gravitational potential energies and induces shortening in this region. (E) Narrowed asthenospheric wedge above shallower slab segment induces small-scale convection parallel to net plate motion, localizing limited magmatism in upwelling limb and creating the Colorado Mineral Belt (COMB).

The distance from the northern craton to the trench is uncertain because the large allochthons of western Canada were to the west of the northern Wyoming craton and the position of the trench is essentially unknown. For these reasons we suspect that the interaction between any lithospheric keel under the northern Wyoming craton and any slab lacked the same behavior we propose occurred farther south.

Observational constraints on the lithospheric thickness of Wyoming and the Colorado Plateau in the Late Cretaceous are few. Regional seismological work has suggested little or no unusual thickness to the Wyoming craton at present (e.g., van der Lee and Frederiksen, 2005; van der Lee and Nolet, 1997), but similar Archean cratons have thicknesses of ~250 km (e.g., Gung et al., 2003; Michaut et al., 2007). Inferred early Tertiary hydration and alteration of the mantle under Wyoming as observed from xenoliths (Carlson et al., 2004; Eggler et al., 1987) suggest that the modern lithosphere is thinner and hotter than the pre-Laramide lithosphere (Carlson et al., 2004). Similarly, although the modern seismological estimate of a 120–150-km-thick lithosphere from surface waves (West et al., 2004) for the Colorado Plateau agrees with xenolith-based lithosphere thicknesses (Griffin et al., 2004), these could differ greatly from lithospheric thicknesses at 75 Ma: plateau xenoliths are all associated with post-Laramide magmatic activity. These xenoliths often record cooling through the Laramide (e.g., Helmstaedt and Schulze, 1991; Smith et al., 2004; Riter and Smith, 1996), so it is possible that modern lithosphere thicknesses are greater than those prior to the Laramide. Given these uncertainties, we posit that at 75 Ma Wyoming had an ~250-km-thick lithosphere that was cold and neutrally buoyant and that the lithosphere under the Colorado Plateau was thinner and probably not sufficiently chemically distinct to be neutrally buoyant, and so less likely than Wyoming lithosphere to interfere with asthenospheric counterflow.

Creation of the Wyoming-Colorado Basin

The development of the Western Interior Seaway has been associated by some with shallowing subduction at the western margin of North America (Burgess et al., 1997; Catuneanu et al., 1997; Gurnis, 1993; Mitrovica et al., 1989; Pang and Nummedal, 1995; Liu et al., 2008). While such models are appealing in explaining the continent-wide trough that extended from the Gulf of Mexico to the Arctic Ocean, they produce very long wavelength topography, generally in excess of 1000 km across strike and longer still along strike (e.g., Burgess et al., 1997). In contrast, the Wyoming-Colorado "backbulge" basin is roughly equant and ~500 km in diameter with sedimentary rocks about 4 times thicker than comparable distances from the trench to the north or south (Cross, 1986; Roberts and Kirschbaum, 1995)(Fig. 2C).

The same mechanism that would tend to pull up the slab subducting under the edge of a thick Archean craton would also act to pull down that craton at its edge (Fig. 5D). Such a connection, induced by the narrowing of the gap between slab and cratonal root, is plausibly a much narrower feature than exists in most published models of dynamic topography, and so potentially could reproduce the geometry of the Colorado-Wyoming basin. This basin straddles the southern edge of the Archean Wyoming craton (Fig. 2D), broadly consistent with these expectations.

To better understand the implications of this hypothesis, we have carried out some simplified two-dimensional (2-D) numerical experiments of topography in a subduction setting with a lithospheric keel (Fig. 6). Our 2-D dynamic models are similar to those of Gurnis (1993), in which the flow and dynamic topography are driven by the buoyancy force of subducted slabs, which can be estimated from the age of subducting lithosphere (Hager and O'Connell, 1981). Lithosphere (subducting and overriding) and the underlying mantle are modeled as fluids with high and low viscosities, respectively. A key feature is the continental keel structure, which is also modeled as having a high viscosity, similar to that in recent 3-D models (Becker, 2006; Conrad and Lithgow-Bertelloni, 2006; Zhong, 2001). The mantle viscosity structure is similar to that derived from the geoid studies (e.g., Hager and Richards, 1989) in which the upper mantle is 30–100 times weaker than the lower mantle. We use free slip boundary conditions for all the boundaries including the sidewalls. We use sufficiently large computational domain such that sidewall and bottom boundary conditions are not expected to affect the results.

Our calculations confirm that the presence of a stiff continental keel will influence dynamic topography for sufficiently shallow subduction, and the wavelengths of some features are similar to that of the Colorado-Wyoming basin (Fig. 6). The curve for a slab without any lithospheric keel reproduces the generally long wavelength subsidence previously used to match the Western Interior Seaway (Burgess et al., 1997). Introduction of the Archean keel provides a noticeable inboard edge to the subsidence signal, similar to that calculated by O'Driscoll et al. (2009). Introduction of an even weaker asthenospheric wedge produces a pronounced basin with a sharp edge at the edge of the Archean keel, and a broader but smaller basin extending well inboard over the craton. Such a weak asthenosphere is broadly consistent with stress-dependent rheologies and weakening of this mantle as it is hydrated by the slab (Hirth and Kohlstedt, 1996, 2003). Weak asthenosphere above the slab has also been suggested on observational grounds from modeling of topography in the western Pacific (Billen and Gurnis, 2001; Billen et al., 2003).

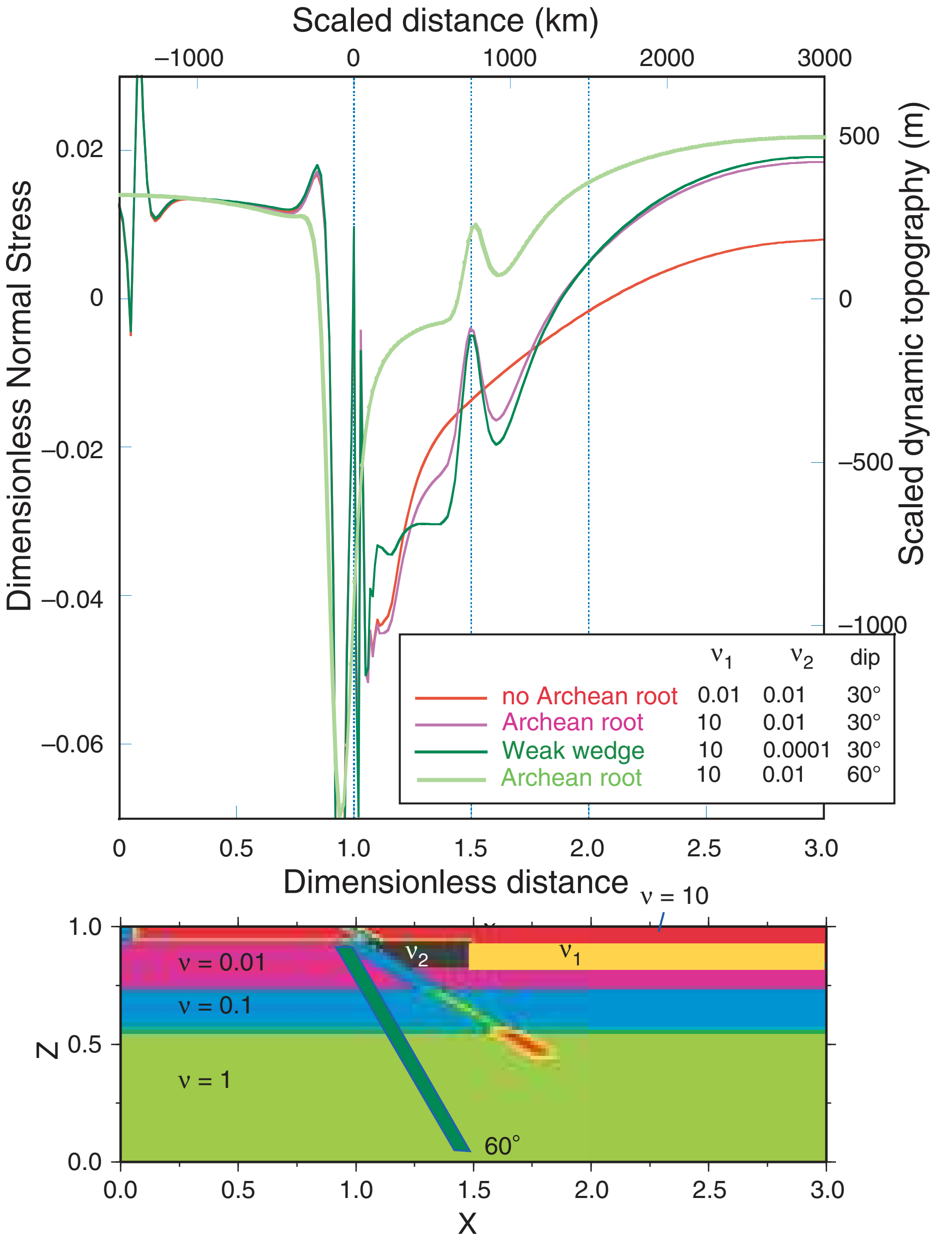

Figure 6. Dynamic topography generated by four two-dimensional models set to same value on oceanic plate; trench is at X = 1.0, left edge of thick Archean lithosphere is at X = 1.5 (750 km). The short-wavelength topography at X = 0 and at trench is caused by weak plate margins included in these models. Bottom panel shows the dimensionless viscosity structure. Dimensional topography assumes a mantle density of 3300 kg m^{-3}, and a slab density of 3350 kg m^{-3}.

Our results support the general idea that the presence of a stiff keel could change the dynamic topography from the very broad basins seen without a keel to the more limited and deeper basin produced here. A more direct comparison with the sedimentary record will require examination of effects such as oblique motion, three-dimensional geometry of the slab, temporal evolution of subsidence, and large-scale mantle flow.

Some numerical experiments by O'Driscoll et al. (2009) explored concepts relevant to this hypothesis; they found that the presence of a lithospheric root will lead to enhanced downward pressure (suction) on the base of the continent trenchward of the root and an increased upward force acting on the subducting slab. They did not investigate the role of slab dip, but noted that this effect increases with proximity to the slab, which probably reflects the narrowing distance between slab and root. Thus we infer that shallower slab dips should cause increased subsidence, but only on the trenchward side of the root. Some aspects of this model are inconsistent with Laramide observations: the numerical model predicts both subsidence and increased horizontal compression over the entire trench-root distance, which seems inconsistent with the cessation of Sevier-style shortening in southernmost Utah and Nevada, the appearance in much of the Sevier hinterland of extension, and the emergence of the Sevier foredeep in latest Cretaceous time (Fig. 2). We suggest that the O'Driscoll et al. (2009) geometry better fits North America during the Sevier orogeny. We suggest that once the Farallon slab shallowed enough to interfere with asthenospheric counterflow, the dynamic subsidence driven by high dynamic pressures (suction) in the Sevier asthenospheric wedge ceased. The resulting rise in the Sevier hinterland permitted the development of extensional deformation much as envisioned by Wells and Hoisch (2008), although the uplift is caused by a change in dynamic forces and not from foundering lithosphere.

Although sedimentation in the Cretaceous seaway in this region changes profoundly over time, some features remain surprisingly constant. Despite the slowing of the accumulation of sediments in large parts of the foredeep and the creation of a large basin in southern Wyoming, the overall rate of creation of sedimentary rock between 34.25°N and 47°N and west of 101.25°W remained nearly constant at ~0.11 km^3/yr from 82 to 65 Ma (as estimated by integrating contours in Fig. 2). This suggests that erosion and delivery of sediments to the seaway remained nearly constant through the end of the Cretaceous. Thus, the variation in sediment thicknesses in Figure 2 is due to the changes in accommodation space (i.e., tectonic subsidence) and not, to first order, to changes in sediment supply. The profound change in the Maastrichtian might be understated by the isopachs: Asquith (1970) noted clinoforms in Wyoming suggesting that the basin bottom had substantial topography and so the deepest parts of the Maastrichtian basin could be deeper than Figure 2D might suggest. In contrast, the Paleocene strata accumulated at a preserved rate of 0.01 km^3/yr; even allowing for sedimentary rock removed and not included in this calculation, the order of magnitude reduction in sediment accumulation as large amounts of sediment were being shed from Laramide uplifts indicates a second change in the regional surface elevation.

Forces Driving Foreland Uplifts

The downward displacement of the lithosphere due to the suction would decrease the vertical normal stress at any depth, which also reduces the vertical normal stress compared to adjacent areas. This increases the deviatoric horizontal stresses and is equivalent to reducing the gravitational potential energy, causing the foreland to fail in compression without any change in the boundary stresses (Jones et al., 1998). This is the mirror of the commonly cited tendency of thick crust to extend (Molnar and Lyon-Caen, 1988). This could be augmented by basal shear on the base of the Wyoming craton. A key effect of the application of the downward forces to the Colorado-Wyoming border region is to shift deformation past the Colorado Plateau without the Plateau being strong or any change in the stresses at the plate margin (Fig. 5D).

Arc Magmatism

The presence of Mesozoic crust and mantle to depths of 100 km or more under the Sierra Nevada (Ducea and Saleeby, 1996; 1998) suggests that slab shallowing did not occur under the Sierra Nevada, at least not in the manner in which it existed under the Mojave Desert (Saleeby, 2003). Cessation of arc magmatism is usually attributed to a slab being too shallow for dehydration reactions to generate fluids (Armstrong and Ward, 1991; English et al., 2003; Gutscher et al., 2000; Humphreys et al., 2003). If the Farallon plate was deep enough under the Sierra Nevada to generate such fluids, why did magmatism cease there? Saleeby (2003) argued that the asthenospheric wedge ceased to bring in undepleted material because shallow subduction to the east interfered with return flow of new asthenosphere.

If we accept that the tongue of shallowly subducting lithosphere entered the trench to the south of the Sierra Nevada, and that it extended northeastward to the Wyoming craton, then subduction of the Farallon plate had to be quite oblique, an inference supported both from imperfect plate reconstructions (Engebretson et al., 1985; Stock and Molnar, 1988) and right-lateral fault systems of Late Cretaceous age (cf. Saleeby, 2003). The existing literature does not provide an answer to whether a shallowly dipping slab will interfere with return flow in a highly oblique orogen, but we speculate that this is likely to occur. We suggest that asthenospheric counterflow in this oblique system was not parallel to relative plate motion, but instead that the counterflow far from the trench moved normal to the plate boundary, turning to be parallel with the downgoing slab only very near the slab. Such a supposition is based on the larger length scales of deformation at convergent margins than at strike-slip margins (England et al., 1985). In this case, the counterflow ceases to replace asthenosphere under the Sierra Nevada and Idaho batholiths, resulting in termination of volcanism in these arcs (Fig. 5C). Because the slab did not come into direct contact with North America, primary mantle melts from the remaining asthenosphere were still possible, perhaps generating a juvenile component to peraluminous granites such as the Ireteba pluton (Fig. 2E; Kapp et al., 2002).

Foreland Magmatism

The geometry of Laramide foreland magmatism is most unlike an arc. The dominant feature for most of Laramide time was the COMB, which trends nearly parallel to Farallon–North America motion (Fig. 2D). This parallelism suggests that some kind of shear-parallel mechanism for melt generation is more likely than a typical slab dewatering mechanism, which tends to produce arcs paralleling a trench. Such a mechanism is likely present if a small-scale sublithospheric convection system (SSC) emerges (Fig. 5E).

Shear-parallel small-scale convection was proposed to account for the divergence of depth and heat flow of old ocean floor from a half-space cooling model (Richter and Parsons, 1975; Parsons and McKenzie, 1978). Seismic observations have revealed upper mantle structure in the Pacific (Ritzwoller et al., 2004; van Hunen et al., 2005) and the western U.S. (Gilbert et al., 2003; Yang and Forsyth, 2006) consistent with SSC in the upper mantle. In numerical 3-D models with imposed surface plate motion, van Hunen and Zhong (2003, 2006) showed that small-scale convection may lead to linear thermal structures that align approximately with plate motion direction, reminiscent of Richter roll structures (Richter and Parsons, 1975), but with much richer features. The SSC can localize melt generation in its upwelling limbs both by replacement of infertile mantle with fertile mantle and the localization of a thermal anomaly in such limbs (Ballmer et al., 2009).

We suggest that as the sub-Wyoming slab was pulled upward, conditions became favorable for a secondary convection system to develop in the asthenosphere with axes parallel to plate shear. Such a system would produce localized upwellings parallel to the Farallon–North America plate motion much as work with a single plate moving over asthenosphere led to linear thermal structures parallel to plate motion (Richter and Parsons, 1975; van Hunen and Zhong, 2003, 2006). The motion could be sufficient to trigger decompression melting in the asthenosphere at upwellings, depending on the mantle potential temperature and/or lithospheric thickness (McKenzie and Bickle, 1988), as well as suppress volcanism elsewhere. Thus the COMB and perhaps the Great Falls tectonic zone to the north in Montana could represent such upwellings.

At present, too little is known about the evolution of such a shear-induced convective system and its magmatic consequences to conclude that such a system existed during the Laramide or contributed, for example, to COMB magmatism. The alignment of such SSCs parallel to shear tends to agree with the spatial distribution of Laramide volcanism in the COMB, but additional numerical work is needed to determine whether any time transgression in magma production along the trend of an SSC zone is to be expected, or if the volume of melt so produced is consistent with the relatively small volume of igneous rocks composing the COMB.

End of the Laramide

Although we have focused on the initiation of the Laramide, this hypothesis also differs from flat-slab models in the process that removed the anomalously shallow slab in the middle Tertiary. We suggest that as North Atlantic spreading slowed ca. 45 Ma (Fig. 4; Mosar et al., 2002), reducing North America–Farallon convergence (Doubrovine and Tarduno, 2008), subduction along the North American margin tended to return to a steeper dip, as recorded by a westward migration of the volcanic arc in Mexico (e.g., Gans, 1997; Ferrari et al., 1999, 2007; Nieto-Samaniego et al., 1999). The hydrodynamic forces that initially created the shallow slab collapsed, and the slab returned to a more normal dip, probably by the inward migration of the lateral ramps at the margins of the shallow slab. This migration had to be achieved through influx of asthenosphere from elsewhere, driving a component of upwelling over a broad region. This asthenosphere would encounter material that had been above the Farallon slab and so had been hydrated and cooled through the Laramide but had not produced any magma, much as Humphreys et al. (2003) envisioned. The replacement of the slab by asthenosphere would produce uplift, and heating of hydrated mantle would produce volcanism migrating toward the center of the shallow slab; such an uplift might have influenced the oxygen isotope record of sediments in the region (Davis et al., 2009). If small-scale convection had been active between the slab and the North American lithosphere, or if it developed as the lateral ramps migrated toward the core of the flat slab, it is possible that hydration was focused into northeast-trending bands, which might have influenced the late Cenozoic locations of the Jemez lineament and the Snake River Plain.

Uncertainty in the structure of North America at the close of the Laramide limits our ability to define differences between hypotheses for the Laramide, although such differences probably exist. Our hypothesis probably requires some changes in mean topography as the coupling between plates changes, but the internal changes to North America during the Laramide orogeny (which could include erosion of the keel to the Wyoming craton) as well as the likely evolution of this coupling during the Laramide prevent us from advancing specific predictions here. Similarly, we suggest that there should be some differences in the characteristics of the magmatic sweep from the north and south, as the southern sweep crossed a region that had been in a simple forearc position while the northern sweep crossed a region where we suggest the asthenosphere had become convectively isolated from the mantle, but we are uncertain at present exactly how this differs from the entire region transitioning from forearc to arc or backarc, as envisioned in most flat-slab scenarios.

COMPARISON OF HYPOTHESES

Understanding the Laramide orogeny will only improve once physically grounded hypotheses making testable predictions are available. Analogies to modern-day orogens are insufficient, both because there are elements of the Laramide orogen that are absent from modern analogues and because such analogies sidestep the physical processes acting to produce certain features. For example, while the Sierras Pampeanas has structural geology quite similar to the Southern Rockies, and they are behind an inactive part of the Andean arc, the Sierras Pampeanas lacks any significant preorogenic subsidence or any feature equivalent to the Colorado Plateau. In addition, other flat-slab segments in South America have failed to produce thick-skinned orogens (e.g., van Hunen et al., 2004). Thus it seems that flat subduction does not always produce thick-skinned orogens. It seems unlikely that the full spectrum of slab-continent interactions is present in the modern day, and those present have not yet provided clear insight into the physical basis for development of thick-skinned orogens, especially one landward of a relatively undeformed region of the scale of the Colorado Plateau.

We focus on five elements we think are essential to understanding the Laramide orogeny: thick-skinned tectonism, arc shutdown and migration, foreland subsidence, deformation landward of a relatively undeformed plateau, and syntectonic magmatic patterns. The first two are widely believed to be easily understood with a flat slab, by analogy with the Sierras Pampeanas if nothing else. The last three provide greater difficulties, as discussed here. We omit one element that was an important feature in Bird's (1984, 1988) original work, i.e., creation of a thick crust in the Southern Rockies and High Plains solely during the Laramide orogeny. We note that considerable variation in crustal thickness exists in central North America without topographic expression (cf. Pakiser and Mooney, 1989). Furthermore, the southern half of the Southern Rockies had been shortened in the late Paleozoic Ancestral Rockies orogeny; the northern boundary of that event appears to coincide with the southern edge of thin crust in Wyoming (e.g., Fig. 3 of Bird, 1984). Post-Laramide magmatism could also play a role in thickening the crust in the Southern Rockies. With all these other influences, modern crustal thickness variations place at best a weak constraint on the mechanisms of the Laramide.

Thick-Skinned Tectonism

The literature invoking a flat-slab appears to be split on the means by which compressive deviatoric stresses are generated in the foreland. Many follow Bird (1988) in invoking a basal shear stress, yet with the rheology used, this results in removal of continental mantle lithosphere from the western U.S.; however, such pre-Cenozoic continental mantle survived the Laramide orogeny over much of the region (Livaccari and Perry, 1993; Perry and Livaccari, 1994; Griffin et al., 2004), and the continued presence of mantle that remained at lithospheric temperatures in the Sierra Nevada (Ducea and Saleeby, 1996, 1998) and Colorado Plateau (Smith et al., 2004; Riter and Smith, 1996) indicates that this mantle remained as lithosphere and could not have been removed and returned, as suggested by Bird (1994). The presence of this lithosphere limits the degree to which crust could have been transported from west to east in the Laramide orogeny. A basal shear applied to a stiffer lithosphere might reconcile these issues.

If shallow subduction was limited to areas where the Rand, Pelona, and Orocopia Schists were emplaced (gray areas, Fig. 2; e.g., Saleeby, 2003), then the physical basis for transmitting stresses is more complex than the simple picture of a basal shear. With a narrow flat slab, the tractions on the base are balanced not only by the increasing normal stresses in the lithosphere farther downslip, but also by shear stresses within the continental lithosphere on either side of the tongue of flat slab (Fig. 3B). In addition, the expected hydration from slab dewatering would weaken the continental mantle (Hirth and Kohlstedt, 1996, 2003), thus requiring rapid displacements within the continental mantle lithosphere in order for stresses of any magnitude to be transmitted to the crust in the foreland.

An alternative to a basal shear is that the flat slab increased horizontal compressional stresses nearer the trench (e.g., Erslev, 1993). This produces difficulties in understanding the cessation of thrusting in southern Nevada and it requires a stronger Colorado Plateau than foreland, a requirement discussed in the following.

By combining unchanging end loads with locally derived vertical loads related to the observed pulse of subsidence and sedimentation, we provide a means of shortening the crust east of a Colorado Plateau that had already begun to deform (and thus should not have been unusually strong). Simple calculations demonstrate that the vertical loading necessary to produce the localized accumulation of 2–3 km of marine shales overcomes a significant fraction of the strength of continental lithosphere (Jones et al., 1998). The decreased vertical stresses result in higher deviatoric stresses in the basin than areas trenchward, causing the basin to fail as the other areas are little deformed (Fig. 3D).

Arc Shutdown

Most Laramide scenarios hold that cessation of arc magmatism indicates that a slab has come in contact with the overriding lithosphere; for scenarios with a broad flat slab (e.g., Bird, 1984, 1988) this is a direct prediction. If the slab is narrow, as suggested by Saleeby (2003), then the end of magmatism in areas not underlain by a flat slab is less direct. Our suggestion (following Saleeby, 2003) that magmatism ends as asthenospheric counterflow is disrupted requires that counterflow be essential to arc magmatism and that the upper limb of counterflow traversed the area occupied by the narrow slab, as discussed here (Fig. 5C). We differ from earlier models in having even the narrow slab dip somewhat, leaving some asthenosphere above the slab. As noted here, this would be consistent with the inference of a mafic source component to some Laramide-age peraluminous granites (Kapp et al., 2002).

Foreland Subsidence

Foreland subsidence has received a great deal of attention since Cross and Pilger (1978b; Cross, 1986) pointed out the relationship of subsidence to tectonism, yet nearly all of that work has focused on dynamic topography that yields very long wavelength basins (e.g., Burgess et al., 1997; Gurnis, 1993; Mitrovica et al., 1989) unlike the "backbulge basin" that developed in the Maastrichtian in Wyoming and Colorado (Fig. 2D). Sharply defined basins should result if an antibuoyant slab is in contact with North American lithosphere, but then the entire region overlying the slab should subside a fairly uniform amount (e.g., Bird, 1984). Observed subsidence trenchward from the Maastrichtian Colorado-Wyoming basin to the frontal Sevier thrusts is not evident despite continuous sedimentation in the Late Cretaceous (Fig. 2D). If flat subduction is caused by subduction of buoyant material (e.g., Henderson et al., 1984; Livaccari et al., 1981; English et al., 2003), then the flat-slab model no longer explains subsidence in the areas subsequently most shortened in the Laramide (Fig. 2; Cross, 1986; Cross and Pilger, 1978b; Roberts and Kirschbaum, 1995; Espurt et al., 2008). The inactive arcs related to subduction of plateaus in South America are not associated with profound subsidence of the foreland (e.g., Dávila et al., 2007, 2010; Pindell and Tabbutt, 1995).

We are at an early stage in understanding what might localize subsidence in this very three-dimensional orogen, but our simple numerical experiments to date (e.g., Fig. 6) combined with some basic physics suggest there is a causal relationship in the coincidence of the center of this basin with the edge of the Archean Wyoming craton. Our hypothesis predicts that there are viscosity structures and slab geometries that would reproduce the observed basin in both space and time that include a higher mantle viscosity under Wyoming than areas to the south.

Little Deformed Colorado Plateau

The small amount of shortening on the Colorado Plateau (under ~3%, Davis, 1999) is consistent with basal shear creating the normal stresses necessary to create Laramide uplifts to the north and east. However, if such shear is greatly reduced to avoid displacing mantle lithosphere (or avoid basal stresses at all, as with the collision and collapse models for the Laramide), the Colorado Plateau had to be strong in order to not deform as it experienced stresses as large as those of the deforming Southern Rockies. Such intrinsic strength precludes any early deformation of the Colorado Plateau unless, unlike most continental lithosphere, it is composed of a material that gains strength as it deforms. Otherwise early failure of the Plateau would continue while large deviatoric stresses were present until uplift might increase vertical normal stresses sufficient to reduce deviatoric stresses below failure (Fig. 3C).

We suggest that early deformation on the Colorado Plateau is inconsistent with the inference that it is intrinsically strong. Displacement histories on most Plateau monoclines are poorly dated, but the Hogback monocline in northwest New Mexico underwent most of its deformation as sediments accumulated on both sides of the fold (Cather, 2004; Brister and Chapin, 1994). Cather (2004) inferred from this that three-fourths of the displacement on the Hogback monocline occurred by 73 Ma, prior to slip on most Southern Rockies faults (Fig. 2C). An equally old age has been proposed for motion on the San Rafael Swell, ~300 km to the northwest of the Hogback monocline (Guiseppe and Heller, 1998), although the proportion of total slip at this time is unknown. Other folds are thought to have been active in the Campanian (Fig. 2C; e.g., Goldstrand, 1994), and many others lack any constraints on initial timing. This suggests that the Colorado Plateau was failing prior to the Southern Rockies (cf. Figs. 2C and 7); barring an increase in strength, if stresses were only applied at the margin, the Plateau should have deformed more than the areas to the east. This line of logic requires either that basal shear stresses continued through the Colorado Plateau to load the Southern Rockies, or that the changes in stresses in the Southern Rockies caused by subsidence (Fig. 2D) caused it to fail preferentially. The basal shear model predicts generally low strain rates in the Colorado Plateau through the Laramide, while our hypothesis predicts initially high rates prior to subsidence in the Colorado-Wyoming basin and lower rates until body forces in the Southern Rockies change so that deviatoric stresses there decline.

Colorado Mineral Belt

The COMB represents the bulk of syn-Laramide magmatism in the region where thick-skinned tectonism occurred, being nearly the only magmatism in the 1200 km gap between arcs to the north and south (Figs. 2D, 2E). The igneous activity within this belt is not easily explained by flat subduction (e.g., English et al., 2003), despite these being some of the very igneous rocks that originally spawned the flat-slab hypothesis. Some previous workers have suggested that these igneous rocks represent an inland continental arc above a shallowly dipping slab (Coney and Reynolds, 1977; Lipman et al., 1971; Snyder et al., 1976). The peculiar orientation of this presumed arc is explained as being controlled by the orientation of weaknesses in the Precambrian lithosphere of Colorado (e.g., Tweto and Sims, 1963; McCoy et al., 2005); arc magmas generated north and south of this area are presumed to have simply failed to penetrate the lithosphere. Although the emplacement of these intrusions was locally influenced by the orientation of weaknesses in the Precambrian crust (Tweto and Sims, 1963), these ancient shear zones have a consistently more eastern orientation (~N60°E) than that of the COMB as a whole (Wilson and Sims, 2003). These shear zones are no more substantial than shear zones that occur throughout Colorado and New Mexico, including the shear zones along which the late Cenozoic magmatism of the Jemez lineament was localized, as well as the Cheyenne belt, the profound discontinuity separating Proterozoic and Archean lithosphere in southern Wyoming (Fig. 1). On the whole, these rocks seem inconsistent with a flat slab at the base of continental lithosphere.

In contrast, we accept the exposures of the igneous rocks in the COMB as reflecting the area in the mantle that produced melts. From this, we speculate that these rocks were produced by the upwelling limb of shear-parallel small-scale convection in asthenosphere between the slab and Colorado lithosphere. We expect little or no time transgression to this igneous activity, while the expectations of the inland arc proposal are for a distinct transgression from west to east in the early part of the Laramide.

Timing

In addition to the individual elements of the Laramide, the temporal relationships between the evolution of these different phenomena are important. We note two primary mechanisms for producing a slab traveling at the base of the North American lithosphere: suction forces due to instability of the asthenospheric wedge at shallow subduction angles (Tovish et al., 1978), and subduction of buoyant slab (an oceanic plateau or young lithosphere). Both most likely progress from the trench toward the foreland. For a subducted buoyant feature, the leading edge of the flat slab presumably migrates at the convergence rate between plates. If asthenosphere is ejected by dynamic pressures, the slab might come in contact with the overriding plate over a period of ~5–20 m.y. (English et al., 2003), although shorter times seem feasible if material can be removed through motion parallel to the trench. We expect that the effects of a flat slab will migrate inland at a rate comparable to that of plate convergence, with arc magmatism ending first, subsidence migrating along the front of the flat slab, and shortening commencing only as the slab reaches a particular area. With an ~100 km/m.y. convergence rate between Farallon and North America, we expect that arc shutdown ca. 80 Ma would have been followed by subsidence in the foreland ~1000 km distant ca. 70 Ma (Fig. 7).

Many relationships in our hypothesis are less sharply defined. In our scenario, the trigger for all events is the beginning of interaction of the slab with the Archean continental keel. At this time we might expect the beginning of disruption of asthenospheric counterflow, the beginning of subsidence at the surface, and the beginning of unusual shallowing of the slab. Significant tectonism should occur once subsidence has passed some critical value, and the development of COMB magmatism should only emerge after thorough disruption of asthenospheric counterflow. As we expect there to be a positive feedback among these processes, things might start gradually and accelerate, but at present we lack information necessary to infer the time between initiation and completion of these feedbacks. We suggest that the initial signal of this process is found in unusual subsidence unrelated to deepening of the foredeep seen between 80 and 85 Ma in southern Wyoming (Figs. 2B and 7; Liu and Nummedal, 2004). For this case, we might expect events from trench to foreland to be more synchronous than in the flat-slab case.

These scenarios can be contrasted by plotting event ages with paleodistance from the trench parallel to Farallon–North America convergence (Fig. 7). We expect that if a flat slab caused the Laramide orogeny that Laramide events will be older when closer to the trench; if our flow-based hypothesis is correct, we expect events to be more synchronous. The greatest ambiguity may be the age at which the slab could have

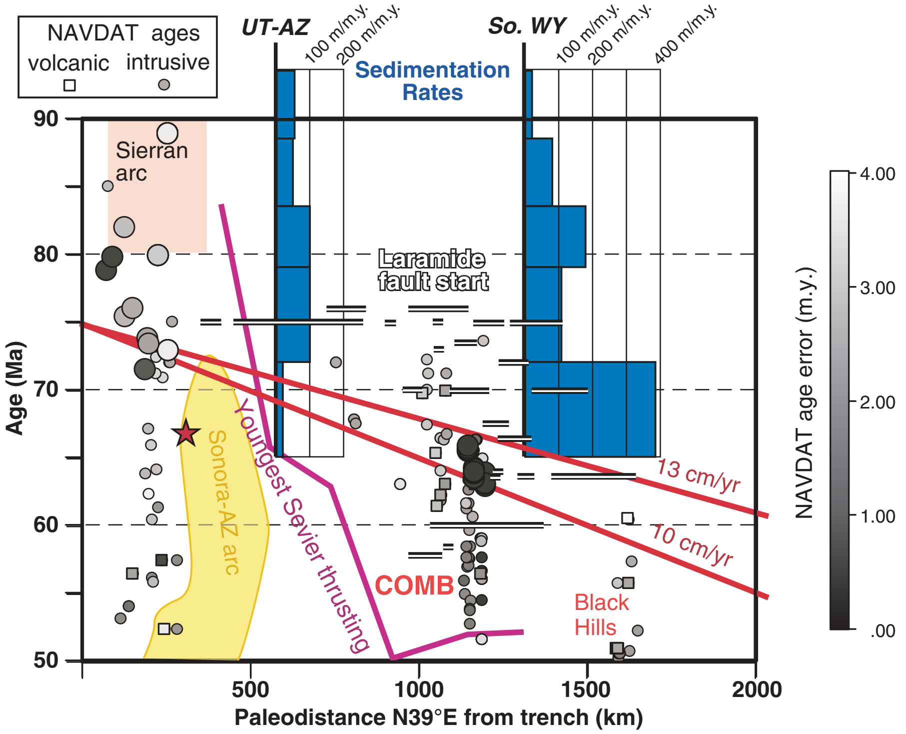

Figure 7. Timing of important events with paleodistance from the trench in a swath extending from the paleoposition of the oceanic schists of southern California. (Swath is shown in Fig. 2C.) Igneous ages are from NAVDAT (North American volcanic and intrusive rock database, www.navdat.org) with some additions from Barth et al. (2004). The age of the peraluminous Ireteba pluton (star) is from Kapp et al. (2002). Larger igneous date symbols are U-Pb and Ar-Ar ages thought to reflect emplacement ages. Note that most Laramide ages shown at left are cooling ages and are much younger than emplacement ages. The age of youngest Sevier thrusting just west of this swath is from DeCelles (2004). Sedimentation rates calculated at two locations well east of Sevier foredeep are from maps of Roberts and Kirschbaum (1995). The ages of initial motion of foreland structures (white lines outlined in black) are from Bird (1998). UT-AZ—Utah-Arizona; So. WY—southern Wyoming. Yellow region shows range of arc magmatism to the southeast of this profile.

started to be flat at the trench. Sierran magmatism ended by 80 Ma, but metaluminous granites to ca. 72 Ma are found in the Mojave Desert (Barth et al., 2004). If these granites are truly arc rocks, then a flat slab cannot have existed prior to ca. 72 Ma in this swath, well after Campanian shortening was occurring in the Colorado Plateau and nearly synchronous with the initiation of profound subsidence in southern Wyoming. If these are not arc rocks, it is possible for a flat slab to have progressed from trench to foreland just prior to igneous activity in the COMB and just as profound subsidence occurred in the Colorado-Wyoming area, although the absence of a similar subsidence event at the Utah-Arizona border is inconsistent with passage of an antibuoyant slab. In contrast, near synchronous development of Laramide faulting and folding near 75 Ma cannot have recorded passage of a flat slab.

CONCLUSIONS

The prevalent flat-slab hypothesis has a number of difficulties predicting specific observations. If the shallow deformation and emplacement of the Orocopia, Rand, and Pelona Schists are taken as representative for development of a shallow slab (e.g., Saleeby, 2003), then timing constraints indicate that the shallow slab developed after cessation of volcanism in the Sierra and initial Laramide volcanism and tectonism. If the slab is thought to shallow as buoyant material is subducted, then timing of subduction of this material at the trench conflicts with some events in the continental interior. None of the present flat-slab conceptualizations predicts the substantial but highly localized subsidence of the latest Cretaceous basin near the Colorado-Wyoming border, nor do they provide an obvious means of generating the igneous activity of the northeast trending COMB.

Our alternative hypothesis, although still invoking anomalous subduction, puts the causes of the Laramide more within the continent than the subducting plate. Extreme shallowing of subduction in a narrow region is driven by interaction of the less severe shallowing of the entire Farallon plate with the Archean root of Wyoming; this directly explains the localized subsidence on the southern edge of this craton. This subsidence, more than enhanced slab-continent shear stresses, combines with the regional stress field to drive contraction in the Southern Rocky Mountains. Magmatic changes are caused by disruption of asthenospheric flow fields and not outright displacement of the Mesozoic asthenosphere. Specific tests of the components of this hypothesis and others are needed to fully understand the nature of slab-continent interaction during the Laramide orogeny.

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REFERENCES CITED

Armstrong, R.L., and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, v. 96, no. B8, p. 13,201–13,224, doi: 10.1029/91JB00412.

Asquith, D.O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: American Association of Petroleum Geologists Bulletin, v. 54, p. 1184–1224.

Bailley, T., 2010, A reevaluation of the origin of Late Cretaceous and younger magmatism in the southern Rocky Mountain region using space-time-composition patterns in volcanic rocks and geochemical studies of xenoliths [Ph.D. thesis]: Boulder, University of Colorado, 153 p.

Ballmer, M.D., van Hunen, J., Ito, G., Bianco, T.A., and Tackley, P.J., 2009, Intraplate volcanism with complex age-distance patterns: A case for small-scale sublithospheric convection: Geochemistry Geophysics Geosystems, v. 10, Q06015, doi: 10.1029/2009GC002386.

Barazangi, M., and Isacks, B.L., 1976, Spatial distribution of earthquakes and subduction of Nazca plate beneath South America: Geology, v. 4, p. 686–692, doi: 10.1130/0091-7613(1976)4<686:SDOEAS>2.0.CO;2.

Barth, A.P., and Schneiderman, J.S., 1996, A comparison of structures in the Andean Orogen of northern Chile and exhumed midcrustal structures in Southern California, USA; an analogy in tectonic style?: International Geology Review, v. 38, p. 1075–1085, doi: 10.1080/00206819709465383.

Barth, A.P., Wooden, J.L., Jacobson, C.E., and Probst, K., 2004, U-Pb geochronology and geochemistry of the McCoy Mountains Formation, southeastern California: A Cretaceous retroarc foreland basin: Geological Society of America Bulletin, v. 116, p. 142–153, doi: 10.1130/B25288.1.

Becker, T.W., 2006, On the effect of temperature and strain-rate dependent viscosity on global mantle flow, net rotation, and plate-driving forces: Geophysical Journal International, v. 167, p. 943–957, doi: 10.1111/j.1365-246X.2006.03172.x.

Billen, M.I., and Gurnis, M., 2001, A low viscosity wedge in subduction zones: Earth and Planetary Science Letters, v. 193, p. 227–236, doi: 10.1016/S0012-821X(01)00482-4.

Billen, M.I., Gurnis, M., and Simons, M., 2003, Multiscale dynamic models of the Tonga-Kermadec subduction zone: Geophysical Journal International, v. 153, p. 359–388, doi: 10.1046/j.1365-246X.2003.01915.x.

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: Tectonics, v. 3, p. 741–758, doi: 10.1029/TC003i007p00741.

Bird, P., 1988, Formation of the Rocky Mountains, western United States; a continuum computer model: Science, v. 239, no. 4847, p. 1501–1507, doi: 10.1126/science.239.4847.1501.

Bird, P., 1994, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: Comment: Geology, v. 22, p. 670–671, doi: 10.1130/0091-7613(1994)022<0670:IEFPOC>2.3.CO;2.

Bird, P., 1998, Kinematic history of the Laramide orogeny in latitudes 35 degrees-49 degrees N, western United States: Tectonics, v. 17, p. 780–801, doi: 10.1029/98TC02698.

Boettcher, S.S., Mosher, S., and Tosdal, R.M., 2002, Structural and tectonic evolution of Mesozoic basement involved fold nappes and thrust faults in the Dome Rock Mountains, Arizona, *in* Barth, A., ed., Contributions to crustal evolution of the southwestern United States: Geological Society of America Special Paper 365, p. 73–97, doi: 10.1130/0-8137-2365-5.73.

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, doi: 10.1130/0091-7613(2003)031<0351:GCOTKF>2.0.CO;2.

Brister, B.S., and Chapin, C.E., 1994, Sedimentation and tectonics of the Laramide San Juan Sag, southwestern Colorado: The Mountain Geologist, v. 31, no. 1, p. 2–18.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis in the western United States: Extensions of an earlier synthesis: American Journal of Science, v. 275A, p. 363–396.

Burchfiel, B.C., and Davis, G.A., 1977, Geology of Sagamore Canyon Slaughterhouse Spring area, New York Mountains, California: Geological Society of America Bulletin, v. 88, p. 1623–1640, doi: 10.1130/0016-7606(1977)88<1623:GOTSCS>2.0.CO;2.

Burchfiel, B.C., and Davis, G.A., 1981, Mojave Desert and environs, *in* Ernst, W.G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 218–252.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, *in* Burchfiel, B.C., et al., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The geology of North America, v. G-3, p. 407–479.

Burgess, P.M., Gurnis, M., and Moresi, L., 1997, Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic, and stratigraphic processes: Geological Society of America Bulletin, v. 109, p. 1515–1535, doi: 10.1130/0016-7606(1997)109<1515:FOSITC>2.3.CO;2.

Butler, R.F., Gehrels, G.E., and Kodama, K.P., 2001, A moderate translation alternative to the Baja British Columbia hypothesis: GSA Today, v. 11, no. 6, p. 4–10, doi: 10.1130/1052-5173(2001)011<0004:AMTATT>2.0.CO;2.

Cahill, T., and Isacks, B.L., 1992, Seismicity and shape of the subducted Nazca Plate: Journal of Geophysical Research, v. 97, no. B12, p. 17,503–17,529, doi: 10.1029/92JB00493.

Carlson, R.W., Irving, A.J., Schulze, D.J., and Hearn, B.C., 2004, Timing of Precambrian melt depletion and Phanerozoic refertilization events in the lithospheric mantle of the Wyoming craton and adjacent Central Plains orogen: Lithos, v. 77, p. 453–472, doi: 10.1016/j.lithos.2004.03.030.

Carroll, A.R., Chetel, L.M., and Smith, M.E., 2006, Feast to famine: Sediment supply control on Laramide basin fill: Geology, v. 34, p. 197–200, doi: 10.1130/G22148.1.

Cather, S.M., 2004, Laramide Orogeny in central and northern New Mexico and southern Colorado, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: New Mexico Geological Society Special Publication 11, p. 203–248.

Catuneanu, O., Beaumont, C., and Waschbusch, P., 1997, Interplay of static loads and subduction dynamics in foreland basins: Reciprocal stratigraphies and the "missing" peripheral bulge: Geology, v. 25, p. 1087–1090, doi: 10.1130/0091-7613(1997)025<1087:IOSLAS>2.3.CO;2.

Chapin, C.E., and Cather, S.M., 1983, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountain area, *in* Lowell, J.D., and Gries, R., eds., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists Field Conference Proceedings, 1983, p. 33–56.

Chen, J.H., and Moore, J.G., 1982, Uranium-lead isotopic ages from the Sierra Nevada batholith, California:

Journal of Geophysical Research, v. 87, no. NB6, p. 4761–4784, doi: 10.1029/JB087iB06p04761.

Clark, K.F., Foster, C.T., and Damon, P.E., 1982, Cenozoic mineral deposits and subduction-related magmatic arcs in Mexico: Geological Society of America Bulletin, v. 93, p. 533–544, doi: 10.1130/0016-7606(1982)93<533:CMDASM>2.0.CO;2.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff Zones: Nature, v. 270, no. 5636, p. 403–406, doi: 10.1038/270403a0.

Conrad, C.P., and Lithgow-Bertelloni, C., 2006, Influence of continental roots and asthenosphere on plate-mantle coupling: Geophysical Research Letters, v. 33, L05312, 4 p., doi: 10.1029/2005GL025621, L05312.

Constenius, K.N., 1996, Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt: Geological Society of America Bulletin, v. 108, p. 20–39, doi: 10.1130/0016-7606(1996)108<0020:LPECOT>2.3.CO;2.

Cowan, D.S., Brandon, M.T., and Garver, J.I., 1997, Geologic tests of hypotheses for large coastwise displacements—A critique illustrated by the Baja British Columbia controversy: American Journal of Science, v. 297, p. 117–173, doi: 10.2475/ajs.297.2.117.

Cross, T.A., 1986, Tectonic controls of foreland basin subsidence and Laramide style deformation, western United States, *in* Allen, P.A., and Homewood, P., eds., Foreland basins: International Association of Sedimentologists Special Publication 8, p. 15–39.

Cross, T.A., and Pilger, R.H., 1978a, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in western United States: American Journal of Science, v. 278, p. 865–902, doi: 10.2475/ajs.278.7.865.

Cross, T.A., and Pilger, R.H., Jr., 1978b, Tectonic controls of Late Cretaceous sedimentation, Western Interior: Nature, v. 274, p. 653–657, doi: 10.1038/274653a0.

Cunningham, C.G., Naeser, C.W., Marvin, R.F., Luedke, R.G., and Wallace, A.R., 1994, Ages of selected intrusive rocks and associated ore deposits in the Colorado mineral belt, U.S. Geological Survey Bulletin 2109, 31 p.

Damon, P.E., Shafiqullah, M., and Clark, K.F., 1981, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 137–154.

Davies, J.H., and Stevenson, D.J., 1992, Physical model of source region of subduction zone volcanics: Journal of Geophysical Research, v. 97, no. B2, p. 2037–2070, doi: 10.1029/91JB02571.

Dávila, F.M., Astini, R.A., Jordan, T.E., Gehrels, G., and Ezpeleta, M., 2007, Miocene forebulge development previous to broken foreland partitioning in the southern Central Andes, west-central Argentina: Tectonics, v. 26, TC5016, 17 p., doi: 10.1029/2007TC002118.

Dávila, F.M., Lithgow-Bertelloni, C., and Giménez, M., 2010, Tectonic and dynamic controls on the topography and subsidence of the Argentine Pampas: The role of the flat slab: Earth and Planetary Science Letters, v. 295, p. 187–194, doi: 10.1016/j.epsl.2010.03.039.

Davis, G.H., 1999, Structural geology of the Colorado Plateau region of southern Utah, with special emphasis on deformation bands: Geological Society of America Special Paper 342, 157 p., doi: 10.1130/0-8137-2342-6.1.

Davis, S.J., Mulch, A., Carroll, A.R., Horton, T.W., and Chamberlain, C.P., 2009, Paleogene landscape evolution of the central North American Cordillera: Developing topography and hydrology in the Laramide foreland: Geological Society of America Bulletin, v. 121, p. 100–116, doi: 10.1130/B26308.1.

DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western USA: American Journal of Science, v. 304, p. 105–168, doi: 10.2475/ajs.304.2.105.

DeCelles, P.G., and Coogan, J.C., 2006, Regional structure and kinematic history of the Sevier fold-and-thrust belt, central Utah: Geological Society of America Bulletin, v. 118, p. 841–864, doi: 10.1130/B25759.1.

Dickinson, W.R., 2006, Geotectonic evolution of the Great Basin: Geosphere, v. 2, no. 7, p. 353–368, doi: 10.1130/GES00054.1.

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.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Janecke, S.U., Lundin, E.R., Mckittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2.

Doubrovine, P.V., and Tarduno, J.A., 2008, A revised kinematic model for the relative motion between Pacific oceanic plates and North America since the Late Cretaceous: Journal of Geophysical Research, v. 113, no. B12, doi: 10.1029/2008JB005584.

Druschke, P., Hanson, A.D., and Wells, M.L., 2009a, Structural, stratigraphic, and geochronologic evidence for extension predating Palaeogene volcanism in the Sevier hinterland, east-central Nevada: International Geology Review, v. 51, p. 743–775, doi: 10.1080/00206810902917941.

Druschke, P., Hanson, A.D., Wells, M.L., Rasbury, T., Stockli, D.F., and Gehrels, G., 2009b, Synconvergent surface-breaking normal faults of Late Cretaceous age within the Sevier hinterland, east-central Nevada: Geology, v. 37, p. 447–450, doi: 10.1130/G25546A.1.

Ducea, M.N., and Saleeby, J.B., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California: Evidence from xenolith thermobarometry: Journal of Geophysical Research, v. 101, no. B4, p. 8229–8244, doi: 10.1029/95JB03452.

Ducea, M.N., and Saleeby, J., 1998, A case for delamination of the deep batholithic crust beneath the Sierra Nevada, California: International Geology Review, v. 40, p. 78–93, doi: 10.1080/00206819809465199.

Eggler, D.H., McCallum, M.E., and Kirkley, M.B., 1987, Kimberlite-transported nodules from Colorado-Wyoming: A record of enrichment of shallow portions of an infertile lithosphere, *in* Morris, E.M., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Geological Society of America Special Paper 215, p. 77–90.

Engebretson, D.C., Cox, A., and Thompson, G.A., 1984, Correlation of plate motions with continental tectonics; Laramide to Basin-Range: Tectonics, v. 3, p. 115–119, doi: 10.1029/TC003i002p00115.

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 206, 59 p.

England, P., Houseman, G., and Sonder, L., 1985, Length scales for continental deformation in convergent, divergent, and strike-slip environments: Analytical and approximate solutions for a thin viscous sheet model: Journal of Geophysical Research, v. 90, p. 3551–3557, doi: 10.1029/JB090iB05p03551.

England, P., Engdahl, R., and Thatcher, W., 2004, Systematic variation in the depths of slabs beneath arc volcanoes: Geophysical Journal International, v. 156, p. 377–408, doi: 10.1111/j.1365-246X.2003.02132.x.

English, J.M., and Johnston, S.T., 2004, The Laramide orogeny: What were the driving forces?: International Geology Review, v. 46, p. 833–838, doi: 10.2747/0020-6814.46.9.833.

English, J.M., Johnston, S.T., and Wang, K.L., 2003, Thermal modelling of the Laramide orogeny: Testing the flat-slab subduction hypothesis: Earth and Planetary Science Letters, v. 214, , p. 619–632, doi: 10.1016/S0012-821X(03)00399-6.

Erslev, E.A., 1993, Thrusts, back-thrusts, and detachments of Rocky Mountain foreland arches, *in* Schmidt, C.J., et al., eds., Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 339–358.

Espurt, N., Funiciello, F., Martinod, J., Guillaume, B., Regard, V., Faccenna, C., and Brusset, S., 2008, Flat subduction dynamics and deformation of the South American plate: Insights from analog modeling: Tectonics, v. 27, TC3011, 19 p., doi: 10.1029/2007TC002175.

Ferrari, L., Lopez-Martinez, M., Aguirre-Diaz, G., and Carrasco-Nunez, G., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt: Geology, v. 27, p. 303–306, doi: 10.1130/0091-7613(1999)027<0303:STPOCA>2.3.CO;2.

Ferrari, L., Valencia-Moreno, M., and Bryan, S., 2007, Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America, *in* Alaniz-Álvarez, S.A., and Nieto-Samaniego, Á.F., eds., Geology of México: Celebrating the Centenary of the Geological Society of México: Geological Society of America Special Paper 422, p. 1–39, doi: 10.1130/2007.2422(01).

Gaetani, G.A., and Grove, T.L., 2003, Experimental constraints on melt generation in mantle wedge, *in* Eiler, J., ed., Inside the subduction factory: American Geophysical Union Geophysical Monograph 138, p. 107–134.

Gans, P.B., 1997, Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico: Tectonics, v. 16, p. 388–408, doi: 10.1029/97TC00496.

Gehrels, G., Rusmore, M., Woodsworth, G., Crawford, M., Andronicos, C., Hollister, L., Patchett, J., Ducea, M., Butler, R., Klepeis, K., Davidson, C., Friedman, R., Haggart, J., Mahoney, B., Crawford, W., Pearson, D., and Girardi, J., 2009, U-Th-Pb geochronology of the Coast Mountains batholith in north-coastal British Columbia: Constraints on age and tectonic evolution: Geological Society of America Bulletin, v. 121, p. 1341–1361, doi: 10.1130/B26404.1.

Gilbert, H.J., Sheehan, A.F., Dueker, K.G., and Molnar, P., 2003, Receiver functions in the western United States, with implications for upper mantle structure and dynamics: Journal of Geophysical Research, v. 108, no. B5, 2229, 19 p., doi: 10.1029/2001JB001194.

Gill, J.B., 1981, Orogenic andesites and plate tectonics: New York, Berlin, Springer-Verlag, 390 p.

Goldstrand, P.M., 1994, Tectonic development of Upper Cretaceous to Eocene strata of southwestern Utah: Geological Society of America Bulletin, v. 106, p. 145–154, doi: 10.1130/0016-7606(1994)106<0145:TDOUCT>2.3.CO;2.

Gries, R., 1983, North-south compression of Rocky Mountain foreland structures, *in* Lowell, J.D., and Gries, R., eds., Rocky Mountain foreland basins and uplifts: Rocky Mountain Association of Geologists Field Conference Proceedings, p. 9–32.

Griffin, W.L., O'Reilly, S.Y., Doyle, B.J., Pearson, N.J., Coopersmith, H., Kivi, K., Malkovets, V., and Pokhilenko, N., 2004, Lithosphere mapping beneath the North American plate: Lithos, v. 77, p. 873–922, doi: 10.1016/j.lithos.2004.03.034.

Grose, L.T., 1972, Tectonics, *in* Mallory, W.W., ed., Geologic atlas of the Rocky Mountain region: Denver, Colorado, Rocky Mountain Association of Geologists, p. 35–44.

Grove, M., Jacobson, C.E., Barth, A.P., and Vucic, A., 2003, Temporal and spatial trends of Late Cretaceous–early Tertiary underplating of Pelona and related schist beneath southern California and southwestern Arizona, *in* Johnson, S.E., et al., eds., Tectonic evolution of northwestern México and the southwestern USA: Geological Society of America Special Paper 374, p. 381–406, doi: 10.1130/0-8137-2374-4.381.

Guiseppe, A.C., and Heller, P.L., 1998, Long-term river response to regional doming in the Price River Formation, central Utah: Geology, v. 26, p. 239–242, doi: 10.1130/0091-7613(1998)026<0239:LTRRTR>2.3.CO;2.

Gung, Y.C., Panning, M., and Romanowicz, B., 2003, Global anisotropy and the thickness of continents: Nature, v. 422, no. 6933, p. 707–711, doi: 10.1038/nature01559.

Gurnis, M., 1993, Phanerozoic marine inundation of continents driven by dynamic topography above subducting slabs: Nature, v. 364, p. 589–593, doi: 10.1038/364589a0.

Gutscher, M.A., Spakman, W., Bijwaard, H., and Engdahl, E.R., 2000, Geodynamics of flat subduction: Seismicity and tomographic constraints from the Andean margin: Tectonics, v. 19, p. 814–833, doi: 10.1029/1999TC001152.

Haeussler, P.J., Bradley, D.C., Wells, R.E., and Miller, M.L., 2003, Life and death of the Resurrection plate: Evidence for its existence and subduction in the northeastern Pacific in Paleocene–Eocene time: Geological Society of America Bulletin, v. 115, p. 867–880, doi: 10.1130/0016-7606(2003)115<0867:LADOTR>2.0.CO;2.

Hager, B.H., and O'Connell, R.J., 1981, A simple global model of plate dynamics and mantle convection: Journal of Geophysical Research, v. 86, p. 4843–4878, doi: 10.1029/JB086iB06p04843.

Hager, B.H., and Richards, M.A., 1989, Long-wavelength variations in Earth's geoid: Physical models and dynamical implications: Royal Society of London Philosophical Transactions, ser. A, v. 328, p. 309–327, doi: 10.1098/rsta.1989.0038.

Helmstaedt, H.H., and Schulze, D.J., 1991, Early to mid-Tertiary inverted metamorphic gradient under the Colorado Plateau; evidence from eclogite xenoliths in ultramafic microbreccias, Navajo volcanic field: Journal of Geophysical Research, v. 96, no. B8, p. 13,225–13,235, doi: 10.1029/91JB00284.

Henderson, L.J., Gordon, R.G., and Engebretson, D.C., 1984, Mesozoic aseismic ridges on the Farallon Plate and southward migration of shallow subduction during the Laramide Orogeny: Tectonics, v. 3, p. 121–132, doi: 10.1029/TC003i002p00121.

Henry, C.D., McDowell, F.W., and Silver, L.T., 2003, Geology and geochronology of granitic batholithic complex, Sinaloa, México: Implications for Cordilleran magmatism and tectonics, *in* Johnson, S.E., et al., eds., Tectonic evolution of northwestern México and the southwestern USA: Geological Society of America Special Paper 374, p. 237–273, doi: 10.1130/0-8137-2374-4.237.

Hildebrand, R.S., 2009, Did westward subduction cause Cretaceous–Tertiary orogeny in the North American Cordillera?: Geological Society of America Special Paper 457, 71 p., doi: 10.1130/2009.2457

Hirth, G., and Kohlstedt, D.L., 1996, Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere: Earth and Planetary Science Letters, v. 144, p. 93–108, doi: 10.1016/0012-821X(96)00154-9.

Hirth, G., and Kohlstedt, D.L., 2003, Rheology of the upper mantle and the mantle wedge: A view from the experimentalists, *in* Eiler, J., ed., Inside the Subduction Factory: Washington, D.C., American Geophysical Union, Geophysical Monograph 138, p. 83–105.

Hodges, K.V., and Walker, J.D., 1992, Extension in the Cretaceous Sevier orogen, North American Cordillera: Geological Society of America Bulletin, v. 104, p. 560–569, doi: 10.1130/0016-7606(1992)104<0560:EITCSO>2.3.CO;2.

Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987–990, doi: 10.1130/0091-7613(1995)023<0987:PLROTF>2.3.CO;2.

Humphreys, E., 2009, Relation of flat subduction to magmatism and deformation in the western United States, *in* Kay, S.M., et al., eds., Backbone of the Americas: Shallow subduction, plateau uplift, and ridge and terrane collision: Geological Society of America Memoir 204, p. 85–98, doi: 10.1130/2009.1204(04).

Humphreys, E., Hessler, E., Dueker, K., Farmer, G.L., Erslev, E., and Atwater, T., 2003, How Laramide-age hydration of North American lithosphere by the Farallon slab controlled subsequent activity in the western United States: International Geology Review, v. 45, p. 575–595, doi: 10.2747/0020-6814.45.7.575.

Jacobson, C.E., Dawson, M.R., and Postlethwaite, C.E., 1988, Structure, metamorphism, and tectonic significance of the Pelona, Orocopia, and Rand Schists, southern California, *in* Ernst, G., ed., Metamorphism and crustal evolution in the western United States: Rubey Volume 7: Englewood Cliffs, New Jersey, Prentice-Hall, p. 976–997.

Johnson, P.L., and Anderson, D.W., 2009, Concurrent growth of uplifts with dissimilar orientations in the southern Green River Basin, Wyoming: Implications for Paleocene–Eocene patterns of foreland shortening: Rocky Mountain Geology, v. 44, no. 1, p. 1–16, doi: 10.2113/gsrocky.44.1.1.

Jones, C.H., Sonder, L.J., and Unruh, J.R., 1998, Lithospheric gravitational potential energy and past orogenesis: Implications for conditions of initial Basin and Range and Laramide deformation: Geology, v. 26, p. 639–642, doi: 10.1130/0091-7613(1998)026<0639:LGPEAP>2.3.CO;2.

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, doi: 10.2475/ajs.286.10.737.

Kapp, J.D., Miller, C.F., and Miller, J.S., 2002, Ireteba pluton, Eldorado Mountains, Nevada: Late, deep-source, peraluminous magmatism in the Cordilleran interior: Journal of Geology, v. 110, p. 649–669, doi: 10.1086/342864.

Karlstrom, K.E., Miller, C.F., Kingsbury, J.A., and Wooden, J.L., 1993, Pluton emplacement along an active ductile thrust zone, Piute Mountains, southeastern California–Interaction between deformational and solidification processes: Geological Society of America Bulletin, v. 105, p. 213–230, doi: 10.1130/0016-7606(1993)105<0213:PEAAAD>2.3.CO;2.

Kelleher, J., and McCann, W., 1976, Buoyant zones, great earthquakes, and unstable boundaries of subduction: Journal of Geophysical Research, v. 81, p. 4885–4896, doi: 10.1029/JB081i026p04885.

Kim, B.Y., and Kodama, K.P., 2004, A compaction correction for the paleomagnetism of the Nanaimo Group sedimentary rocks: Implications for the Baja British Columbia hypothesis: Journal of Geophysical Research, v. 109, B02102, 17 p., doi: 10.1029/2003JB002696.

Klitgord, K.D., and Schouten, H., 1986, Plate kinematics of the central Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, The geology of North America, v. M, p. 351–378.

Krantz, R.W., 1989, Laramide structures of Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 463–483.

Krijgsman, W., and Tauxe, L., 2006, E/I corrected paleolatitudes for the sedimentary rocks of the Baja British Columbia hypothesis: Earth and Planetary Science Letters, v. 242, p. 205–216, doi: 10.1016/j.epsl.2005.11.052.

Lawton, T.F., 1983, Late Cretaceous fluvial systems and the age of foreland uplifts in central Utah, *in* Lowell, J.D., and Gries, R., eds., Rocky Mountain foreland basins and uplifts: Denver, Colorado, Rocky Mountain Association of Geologists Field Conference Proceedings 1983, p. 181–199.

Lipman, P.W., 1992, Magmatism in the Cordilleran United States; progress and problems, *in* Burchfiel, B.C., et al., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The geology of North America, v. G-3, p. 481–514.

Lipman, P.W., Prostka, H.J., and Christiansen, R.L., 1971, Evolving subduction zones in western United States, as interpreted from igneous rocks: Science, v. 174, no. 4011, p. 821–825, doi: 10.1126/science.174.4011.821.

Liu, L.J., Spasojevic, S., and Gurnis, M., 2008, Reconstructing Farallon plate subduction beneath North America back to the Late Cretaceous: Science, v. 322, no. 5903, p. 934–938, doi: 10.1126/science.1162921.

Liu, L.J., Gurnis, M., Seton, M., Saleeby, J., Muller, R.D., and Jackson, J.M., 2010, The role of oceanic plateau subduction in the Laramide orogeny: Nature Geoscience, v. 3, p. 353–357, doi: 10.1038/ngeo829.

Liu, S.F., and Nummedal, D., 2004, Late Cretaceous subsidence in Wyoming: Quantifying the dynamic component: Geology, v. 32, p. 397–400, doi: 10.1130/G20318.1.

Livaccari, R.F., 1991, Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide orogeny, western United States: Geology, v. 19, p. 1104–1107, doi: 10.1130/0091-7613(1991)019<1104:ROCTAE>2.3.CO;2.

Livaccari, R.F., and Perry, F.V., 1993, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: Geology, v. 21, p. 719–722, doi: 10.1130/0091-7613(1993)021<0719:IEFPOC>2.3.CO;2.

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, no. 5795, p. 276–278, doi: 10.1038/289276a0.

Luffi, P., Saleeby, J.B., Lee, C.T.A., and Ducea, M.N., 2009, Lithospheric mantle duplex beneath the central Mojave Desert revealed by xenoliths from Dish Hill, California: Journal of Geophysical Research, v. 114, B03202, 36 p., doi: 10.1029/2008JB005906.

Madsen, J.K., Thorkelson, D.J., Friedman, R.M., and Marshall, D.D., 2006, Cenozoic to recent plate configurations in the Pacific Basin: Ridge subduction and slab window magmatism in western North America: Geosphere, v. 2, no. 1, p. 11–34, doi: 10.1130/GES00020.1.

Malin, P.E., Goodman, E.D., Henyey, T.L., Li, Y.G., Okaya, D.A., and Saleeby, J.B., 1995, Significance of seismic reflections beneath a tilted exposure of deep continental crust, Tehachapi Mountains, California: Journal of Geophysical Research, v. 100, no. B2, p. 2069–2087, doi: 10.1029/94JB02127.

Maxson, J., and Tikoff, B., 1996, Hit-and-run collision model for the Laramide orogeny, western United States: Geology, v. 24, p. 968–972, doi: 10.1130/0091-7613(1996)024<0968:HARCMF>2.3.CO;2.

McCoy, A.M., Karlstrom, K.E., and Shaw, C.E., 2005, The Proterozoic ancestry of the Colorado Mineral Belt: 1.4 Ga shear zone system in central Colorado, *in* Karlstrom, K.E., and Keller, G.R., eds., The Rocky Mountain region: An evolving lithosphere: American Geophysical Union Geophysical Monograph 154, p. 71–90.

McKenzie, D., 1969, Speculations on the consequences and causes of plate motions: Royal Astronomical Society Geophysical Journal, v. 18, p. 1–32.

McKenzie, D., and Bickle, M.J., 1988, The volume and composition of melt generated by extension of the lithosphere: Journal of Petrology, v. 29, p. 625–679 doi: 10.1093/petrology/29.3.625.

McQuarrie, N., and Wernicke, B.P., 2005, An animated tectonic reconstruction of southwestern North America since 36 Ma: Geosphere, v. 1, no. 3, p. 147–172, doi: 10.1130/GES00016.1.

Meijer, A., and Reagan, M., 1983, Origin of K_2O-SiO_2 trends in volcanoes of the Mariana arc: Geology, v. 11, p. 67–71, doi: 10.1130/0091-7613(1983)11<67:OOKTIV>2.0.CO;2.

Michaut, C., Jaupart, C., and Bell, D.R., 2007, Transient geotherms in Archean continental lithosphere: New constraints on thickness and heat production of the subcontinental lithospheric mantle: Journal of Geophysical Research, v. 112, B04408, 17 p., doi: 10.1029/2006JB004464.

Mitrovica, J.X., Beaumont, C., and Jarvis, G.T., 1989, Tilting of continental interiors by dynamical effects of subduction: Tectonics, v. 8, p. 1079–1094, doi: 10.1029/TC008i005p01079.

Molnar, P., and Lyon-Caen, H., 1988, Some simple physical aspects of the support, structure, and evolution of mountain belts, *in* Clark, S.P., Jr., et al., eds., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 179–207.

Moniz, R.E., Kimbrough, D.L., and Grove, M., 2007, Recognition of Laramide-age intrusives in the eastern Peninsular Ranges batholith of northern Baja California; implications for magmatism and tectonics at the onset of the Laramide orogeny: Geological Society of America Abstracts with Programs, v. 39, no. 4, p. 73.

Mosar, J., Lewis, G., and Torsvik, T.H., 2002, North Atlantic sea-floor spreading rates: Implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea: Geological Society of London Journal, v. 159, p. 503–515, doi: 10.1144/0016-764901-093.

Müller, R.D., Sdrolias, M., Gaina, C., and Roest, W.R., 2008, Age, spreading rates, and spreading asymmetry of the world's ocean crust: Geochemistry Geophysics Geosystems, v. 9, doi: 10.1029/2007GC001743.

Mutschler, F.E., Larson, E.E., and Bruce, R.M., 1987, Laramide and younger magmatism in Colorado—New petrologic and tectonic variations on old themes: Colorado School of Mines Quarterly, v. 82, no. 4, p. 1–47.

Nieto-Samaniego, A.F., Ferrari, L., Alaniz-Alvarez, S.A., Labarthe-Hernandez, G., and Rosas-Elguera, J., 1999, Variation of Cenozoic extension and volcanism across the southern Sierra Madre Occidental volcanic province, Mexico: Geological Society of America Bulletin, v. 111, p. 347–363, doi: 10.1130/0016-7606(1999)111<0347:VOCEAV>2.3.CO;2.

O'Driscoll, L.J., Humphreys, E.D., and Saucier, F., 2009, Subduction adjacent to deep continental roots: Enhanced negative pressure in the mantle wedge, mountain building and continental motion: Earth and Planetary Science Letters, v. 280, p. 61–70, doi: 10.1016/j.epsl.2009.01.020.

Ogg, J.G., and Smith, A.G., 2004, The geomagnetic polarity time scale, *in* Gradstein, F., Ogg, J., and Smith, A., eds., A geologic time scale 2004: Cambridge, U.K., Cambridge University Press, p. 63–86.

Pakiser, L.C., and Mooney, W.D., 1989, Geophysical framework of the continental United States: Geological Society of America Memoir 172, 826 p.

Pang, M., and Nummedal, D., 1995, Flexural subsidence and basement tectonics of the Cretaceous Western Interior basin, United States: Geology, v. 23, p. 173–176, doi: 10.1130/0091-7613(1995)023<0173:FSABTO>2.3.CO;2.

Parsons, B., and McKenzie, D., 1978, Mantle convection and thermal structure of the plates: Journal of Geophysical Research, v. 83, p. 4485–4496, doi: 10.1029/JB083iB09p04485.

Perry, F.V., and Livaccari, R.F., 1994, Isotopic evidence for preservation of Cordilleran lithospheric mantle during the Sevier-Laramide orogeny, western United States: Geology, v. 22, p. 671–672.

Pillmore, C.L., and Flores, R.M., 1990, Cretaceous and Paleocene rocks of the Raton Basin, New Mexico and Colorado; stratigraphic-environmental framework, *in* Bauer, P.W., et al., eds., Tectonic development of the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook, v. 41, p. 333–336.

Pindell, J.L., and Tabbutt, K.D., 1995, Mesozoic-Cenozoic Andean paleogeography and regional controls on hydrocarbon systems, *in* Tankard, A.J., et al., eds., Petroleum basins of South America: American Association of Petroleum Geologists Memoir 62, p. 101–128.

Raynolds, R.G., 2002, Upper Cretaceous and Tertiary stratigraphy of the Denver basin, Colorado: Rocky Mountain Geology, v. 37, p. 111–134, doi: 10.2113/gsrocky.37.2.111.

Richter, F.M., and Parsons, B., 1975, On the interaction of two scale convection in the mantle: Journal of Geophysical Research, v. 80, p. 2529–2541, doi: 10.1029/JB080i017p02529.

Riter, J.C.A., and Smith, D., 1996, Xenolith constraints on the thermal history of the mantle below the Colorado Plateau: Geology, v. 24, p. 267–270, doi: 10.1130/0091-7613(1996)024<0267:XCOTTH>2.3.CO;2.

Ritzwoller, M.H., Shapiro, N.M., and Zhong, S., 2004, Cooling history of the Pacific lithosphere: Earth and Planetary Science Letters, v. 226, p. 69–84, doi: 10.1016/j.epsl.2004.07.032.

Roberts, L.N.R., and Kirschbaum, M.A., 1995, Paleogeography of the Late Cretaceous of the Western Interior of middle North America—Coal distribution and sediment accumulation: U.S. Geological Survey Professional Paper 1561, 155 p.

Saleeby, J., 1992, Petrotectonics and paleogeographic settings of U.S. Cordilleran ophiolites, *in* Burchfiel, B.C., et al., eds., The Cordilleran orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The geology of North America, v. G-3, p. 653–682.

Saleeby, J., 2003, Segmentation of the Laramide slab—Evidence from the southern Sierra Nevada region: Geological Society of America Bulletin, v. 115, p. 655–668, doi: 10.1130/0016-7606(2003)115<0655:SOTLSF>2.0.CO;2.

Schmid, C., Goes, S., van der Lee, S., and Giardini, D., 2002, Fate of the Cenozoic Farallon slab from a comparison of kinematic thermal modeling with tomographic images: Earth and Planetary Science Letters, v. 204, p. 17–32, doi: 10.1016/S0012-821X(02)00985-8.

Schmidt, M.W., and Poli, S., 1998, Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation: Earth and Planetary Science Letters, v. 163, p. 361–379, doi: 10.1016/S0012-821X(98)00142-3.

Seager, W., 2004, Laramide (Late Cretaceous–Eocene) tectonics of southwestern New Mexico, *in* Mack, G.H., and Giles, K.A., eds., The geology of New Mexico: A geologic history: New Mexico Geological Society Special Publication 11, p. 183–202.

Silver, E.A., and Smith, R.B., 1983, Comparison of terrane accretion in modern Southeast Asia and the Mesozoic North American Cordillera: Geology, v. 11, p. 198–202, doi: 10.1130/0091-7613(1983)11<198:COTAIM>2.0.CO;2.

Simmons, E.C., and Hedge, C.E., 1978, Minor element and Sr-isotope geochemistry of Tertiary stocks, Colorado Mineral Belt: Contributions to Mineralogy and Petrology, v. 67, p. 379–396, doi: 10.1007/BF00383298.

Smith, D., Connelly, J.N., Manser, K., Moser, D.E., Housh, T.B., McDowell, F.W., and Mack, L.E., 2004, Evolution of Navajo eclogites and hydration of the mantle wedge below the Colorado Plateau, southwestern United States: Geochemistry Geophysics Geosystems, v. 5, no. 4, Q04005, doi: 10.1029/2003GC000675.

Snyder, W.S., Dickinson, W.R., and Silberman, M.L., 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in Western United States: Earth and Planetary Science Letters, v. 32, p. 91–106, doi: 10.1016/0012-821X(76)90189-8.

Spencer, J.E., 1996, Uplift of the Colorado Plateau due to lithosphere attenuation during Laramide low-angel subduction: Journal of Geophysical Research, v. 101, no. B6, p. 13,595–13,609, doi: 10.1029/96JB00818.

Srivastava, S.P., and Tapscott, C.R., 1986, Plate kinematics of the North Atlantic, *in* Vogt, P.R., and Tucholke, B.E., eds., The western North Atlantic region: Boulder, Colorado, Geological Society of America, The geology of North America, v. M, p. 379–404.

Stein, H.J., and Crock, J.G., 1990, Late Cretaceous–Tertiary magmatism in the Colorado Mineral Belt; rare earth element and samarium-neodymium isotopic studies, *in* Anderson, J.L., ed., The nature and origin of Cordilleran magmatism: Geological Society of America Memoir 174, p. 195–224.

Stock, J., and Molnar, P., 1988, Uncertainties and implications of the Late Cretaceous and Tertiary position of North America relative to the Farallon, Kula, and Pacific plates: Tectonics, v. 7, p. 1339–1384, doi: 10.1029/TC007i006p01339.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J., and Walderhaug, H.J., 2001, Reconstructions of the continents around the North Atlantic at about the 60th parallel: Earth and Planetary Science Letters, v. 187, p. 55–69, doi: 10.1016/S0012-821X(01)00284-9.

Tosdal, R.M., 1990, Constraints on the tectonics of the Mule Mountains thrust system, southeast California and southwest Arizona: Journal of Geophysical Research, v. 95, no. B12, p. 20,025–20,048, doi: 10.1029/JB095iB12p20025.

Tosdal, R.M., and Stone, P., 1994, Stratigraphic relations and U-Pb geochronology for the Upper Cretaceous Upper McCoy Mountains Formation, southwestern Arizona: Geological Society of America Bulletin, v. 106, p. 476–491, doi: 10.1130/0016-7606(1994)106<0476:SRAUPG>2.3.CO;2.

Tovish, A., Schubert, G., and Luyendyk, B.P., 1978, Mantle flow pressure and the angle of subduction—Non-Newtonian corner flows: Journal of Geophysical Research, v. 83, no. B12, p. 5892–5898.

Tweto, O., and Sims, P.K., 1963, Precambrian ancestry of the Colorado Mineral Belt: Geological Society of America Bulletin, v. 74, no. 8, p. 991–1014, doi: 10.1130/0016-7606(1963)74[991:PAOTCM]2.0.CO;2.

Unruh, J.R., Dumitru, T.A., and Sawyer, T.L., 2007, Coupling of early Tertiary extension in the Great Valley forearc basin with blueschist exhumation in the underlying Franciscan accretionary wedge at Mount Diablo, California: Geological Society of America Bulletin, v. 119, p. 1347–1367, doi: 10.1130/B26057.1.

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, doi: 10.1029/91TC02183.

van der Lee, S., and Frederiksen, A., 2005, Surface wave tomography applied to the North American upper mantle, *in* Levander, A.R., and Nolet, G., eds., Seismic Earth: Array analysis of broadband seismograms: American Geophysical Union Geophysical Monograph 157, p. 67–80.

van der Lee, S., and Nolet, G., 1997, Upper mantle S velocity structure of North America: Journal of Geophysical Research, v. 102, p. 22,815–22,838, doi: 10.1029/97JB01168.

van Hunen, J., and Zhong, S., 2003, New insight in the Hawaiian plume swell dynamics from scaling laws: Geophysical Research Letters, v. 30, p. 1785–1788, doi: 10.1029/2003GL017646.

van Hunen, J., and Zhong, S., 2006, The influence of rheology on realignment of mantle convective structure with plate motion after a plate re-organization: Geochemistry Geophysics Geosystems, v. 7, Q08008, doi: 10.1029/2005GC001209.

van Hunen, J., van den Berg, A.P., and Vlaar, N.J., 2004, Various mechanisms to induce present-day shallow flat subduction and implications for the younger Earth: A numerical parameter study: Physics of the Earth and Planetary Interiors, v. 146, p. 179–194, doi: 10.1016/j.pepi.2003.07.027.

van Hunen, J., Zhong, S., Ritzwoller, M.H., and Shapiro, N.M., 2005, New evidence for dislocation creep from 3-D geodynamic modeling the Pacific upper mantle structure: Earth and Planetary Science Letters, v. 238, p. 146–155, doi: 10.1016/j.epsl.2005.07.006.

Walker, J.D., Bowers, T.D., Black, R.A., Glazner, A.F., Farmer, G.L., and Carlson, R.W., 2006, A geochemical database of western North American volcanic and intrusive rocks (NAVDAT), *in* Sinha, A.K., ed., Geoinformatics: Data to knowledge: Geological Society of America Special Paper 397, p. 61–71, doi: 10.1130/2006.2397(05).

Wells, M.L., and Hoisch, T.D., 2008, The role of mantle delamination in widespread Late Cretaceous extension and magmatism in the Cordilleran orogen, western United States: Geological Society of America Bulletin, v. 120, p. 515–530, doi: 10.1130/B26006.1.

Wells, M.L., Dallmeyer, R.D., and Allmendinger, R.W., 1990, Late Cretaceous extension in the hinterland of the Sevier thrust belt, northwestern Utah and southern Idaho: Geology, v. 18, p. 929–933, doi: 10.1130/0091-7613(1990)018<0929:LCEITH>2.3.CO;2.

West, M., Ni, J., Baldridge, W.S., Wilson, D., Aster, R., Gao, W., and Grand, S., 2004, Crust and upper mantle shear wave structure of the southwest United States: Implications for rifting and support for high elevation: Journal of Geophysical Research, v. 109, no. B3, B03309, doi: 10.1029/2003JB002575.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, no. 4, doi: 10.1130/Ges00055.1, p. 220–259.

Wilson, A.B., and Sims, P.K., 2003, Colorado Mineral Belt revisited—An analysis of new data: U.S. Geological Survey Open-File Report 03–046, 7 p.

Yang, Y., and Forsyth, D. W., 2006, Rayleigh wave phase velocities, small-scale convection, and azimuthal anisotropy beneath southern California: Journal of Geophysical Research, v. 111, B07306, 20 p., doi: 10.1029/2005JB004180.

Zhong, S., 2001, Role of ocean-continent contrast and continental keels on plate motion, net rotation of lithosphere and the geoid: Journal of Geophysical Research, v. 106, p. 703–712, doi: 10.1029/2000JB900364.

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