Relation of Flat Subduction to Magmatism and Deformation in the Western USA

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ABSTRACT

Flat subduction of the Farallon plate beneath western USA during the Laramide orogeny was caused by the combined effects of oceanic plateau subduction and unusually great suction in the mantle wedge, the latter being a result of rapid slab sinking during the Sevier-Laramide orogeny. Once in contact with basal North America, the slab cooled and hydrated the lithosphere. Upon removal, asthenospheric contact with lithosphere resulted magmatic production that was especially intense where the basal lithosphere was fertile (in what now is the Basin and Range), and the heated lithosphre was weakened. This made the base of western USA lithosphere convectively unstable and small-scale convection has affected many areas. With slab sinking and the unloading of the continent, the North America elevated into a broad plateau, and the weak portion gravitationally collapsed. With development of a transform plate boundary the western part of the weak zone is partly entrained with the Pacific plate and deformation is dominated by shear.

INTRODUCTION

Tectonic and magmatic activity within the western USA has been unusually vigorous during the last 150 m.y., at times extending into the continent 1000-2000 km from the plate margin (Fig. 1a-b). Such non-plate like behavior, although not common at any time and place, is important through time in making geologic and continental structure and continent itself. The generally held accounting for western USA activity is one of progressively intense subduction coupling at the western plate margin and slab flattening during the Sevier-Laramide orogeny (Livacarri and Perry, 1993), followed by an intense magmatic flareup over much of the tectonically modified area during post-orogenic collapse (e.g., Burchfiel et al., 1992), the last stages of which we observe today. The occurrence of Laramide-age “flat slab” subduction of the Farallon slab beneath the western USA is accepted by most (including myself) as being related to the cause of the deeply penetrating tectonics. This to say, the last 150 m.y. of western USA tectonic and magmatic evolution is attributed to plate tectonic processes. With Farallon slab flattening and contact with North America and subsequent slab removal in mind, my goal is to account for the general aspects of western USA tectonism and magmatism during the last 150 m.y., i.e., during the Sevier-Laramide orogeny and the following episode of post-orogenic collapse. My desire is to understand what caused the western USA to behave as it did. In particular, how did plate tectonics create the western USA and what non-plate tectonic processes contributed to the tectonic and magmatic activity. In some regards, interpretations for this activity are generally agreed upon, and in other regards, the relationship between Farallon subduction and the geologic record is quite ambiguous. I present my own view, both on those aspects that represent a consensus and those that are untested speculations. The following discussion is divided into the time intervals pre-Laramide, Laramide, post-Laramide, and current physical state.

PRE-LARAMIDE SEVIER

Evidence for shallowing Farallon slab dip during the course of the Sevier orogeny is provided by an eastward migration of arc magmatism into Nevada (e.g., DeCelles**,** 2004), an inferred increase of subduction zone coupling evidenced by fold and thrust contraction across a wide belt extending east from the magmatic front to the Colorado Plateau and western Wyoming (e.g., DeCelles, 2004; Burchfiel et al., 1992) and the intense trans-pressional truncation of the Pacific Northwest continental margin (Giorges et al., 2005), and the dynamic subsidence of the continental interior creating the Cretaceous interior seaway (Mitrovica et al., 1989). I presume that the widespread interior subsidence and intensifying tectonism resulted from an "avalanching" through the 660 km discontinuity of Farallon slab that previously was laid out in the transition zone.

This inference is based on the fact that continuing arc magmatism near the California-Nevada border implies the subducting slab dipped into and exposed itself to asthenosphere near eastern California, avoiding direct slab contact with North America east of California, and yet the dynamic effects of the slab influenced continental subsidence as far east as the Great Lakes, suggesting the Farallon slab was near enough to the surface beneath this area to pull the surface down dynamically. A shallow dip with a vertically thin asthenospheric wedge extending across half a continent seems dynamically unreasonable. More likely is that the slab subducted to and was supported by the endothermic phase transition at the 660 km discontinuity (e.g., in a manner similar to that imaged beneath SE Asia, Bijwaard et al., 1998), and that it then avalanched into the lower mantle (e.g., Tackley et al., 1993) during the Sevier orogeny. With this history, only minor dynamic subsidence would occur prior to avalanching, followed by a strong suction in the upper mantle beneath the western and central USA that would pull the continent down (Pysklywec and Mitrovica, 1997) during the Sevier-Laramide orogeny. The presence of a large and thick North America craton, by restricting asthenospheric flow into the evacuated volume, would act to enhance the magnitude of the suction and its effects. Increased suction beneath the western USA would pull subducted slab near the western plate margin in an eastward direction and pull the craton westward toward the subduction zone. The west-directed force acting on the craton would increase North America absolute velocity and pull North America over the subduction zone, greatly intensifying compression of the western USA in the process (O'Driscoll et al., 2006).

LARAMIDE

The Laramide phase of the Sevier-Laramide orogeny is limited to the time duration ~75 to ~45 Ma, and is confined to the area of the western USA. It is characterized by a low rate of magmatic production and the strong tectonic activity reaching far into the continent. The quiescence of arc magmatism presumably was a result of subducted slab flattening against North America. These observations suggest that slab contact with the North American interior did not occur prior to the Laramide orogeny, and the extent of

Laramide slab flattening involved only a portion of the subducted slab. In particular, during the Laramide orogeny, normal arc magmatism continued in Canada and extended SE from the north Cascades across eastern Washington and Oregon, most of Idaho, western Montana and NE Wyoming as the Challis-Clarno-Absaraka volcanic trend (Fig. 2). I view this portion of the "arc" to be transitional between the region of normal subduction beneath Canada and flat subduction beneath the Laramide uplifts that extend from SW Montana to westernmost Texas.

Subduction of Oceanic Plateau

I suspect that slab Laramide flattening resulted from the combined effects of plateau subduction beneath southern California **(**Livacarri et al., 1981; Saleeby, 2003), the more regional subduction dynamics associated with the enhanced mantle-wedge suction, and the younging of subducted Farallon plate. The region affected by plateau subduction was narrow (Saleeby, 2003) compared to the width of slab that eventually flattened from northern USA to perhaps central Mexico, as evidenced by an eastward sweep of the magmatic front, quiescence of normal arc magmatism, and subsequent magmatic flareup over the broad area (i.e., as introduced by Coney and Reynolds, 1977). (Ferrari (2006) suggests that a continuation of magmatism near the old magmatic arc argues against slab flattening beneath Mexico.) While slab flattening may have occurred beneath most of Mexico, the Laramide style of basement-cored uplifts was limited to the area backed by thick continental lithosphere, which does not include Mexico (Fig. 1c).

Laramide Deformation

With slab flattening during the Laramide orogeny, Colorado Plateau compression against North America (e.g., Hamilton, 1989**;** Saleeby, 2003) drove NE- to ENE-directed shortening (Fig. 4, Varga, 1993, Erslev, 2005) across a relatively narrow north-trending belt in central New Mexico and Colorado and across a wide area in Wyoming and adjoining states. This direction of shortening is similar to the relative motion of the subducting Farallon slab (Fig. 4), suggesting that the tractions applied by this slab to the base of the Colorado Plateau supplied the most important force driving the Laramide contraction. The alternative – that the crustal welt created by earlier Sevier contraction of Great Basin crust – would have pushed the Colorado Plateau in a more easterly direction (Fig. 4a).

As illustrated in Fig. 3, Wyoming and Colorado lithosphere is about 200 km thick (Dueker et al., 2001; Humphreys et al., 2003), tapering to the SW (~140 beneath four-corners (Smith, 2000) and ~0 at the Pelona-type schist outcrops of southern California (Fig. 3). Tomographic imaging indicates that mantle beneath the area of crustal contraction in Colorado and New Mexico is slow to ~200 km depth (Humphreys et al., 2003), probably because it is partially molten, and suggesting that it was modified relatively recently. Considering that the Colorado Plateau has acted as a strong block (Figs. 1b and 4), has low heat flow and seismically high-velocity lithosphere (Fig. 1d-e), it seems reasonable that Laramide shortening in the Proterozoic lithosphere of Colorado and New Mexico (Fig. 4) occurred directly beneath the zone of crustal shortening, in the area now imaged as seismically slow (Figs. 1d and 3). In contrast, beneath Wyoming the mantle appears strong everywhere, based of flexural modeling (Lowry and Smith, 1995), low heat flow and seismic imaging (Fig. 1d-e). For these reasons I assume that the Wyoming lithosphere did not deform greatly during the Laramide orogeny, implying that the upper crustal shortening distributed broadly over this Achaean lithosphere (Fig. 4) was accommodated by a lower crustal detachment that rooted somewhere west of Wyoming.

POST-LARAMIDE

End of Laramide and Start of Ignimbrite Flareup

Laramide termination and initiation of the ignimbrite flareup that followed was caused by removal of the flat slab and exposure of the thinned and hydrated lithosphere to the infilling asthenosphere (Humphreys, 1995). The Laramide orogeny ended earlier in the northern part of the western USA, and coincides in time with the accretion of a large fragment of oceanic lithosphere (Siletzia and adjoining lithosphere, Fig. 2) to the Pacific Northwest at ~48 Ma (Madsen et al., 2006). Accretion of this lithosphere filled the Columbia Embayment and caused subduction to jump west of the accreted lithosphere, initiating the Cascade subduction zone. Rapidly, the Challis-Absaraka arc ceased volcanic activity and the Cascade arc became active across Oregon and Washington (Christensen and Yeats, 1992; Priest, 1990), signaling the establishment of a subduction zone of more typical slab dip.

Subducting Farallon plate must have torn at the southern margin of the accreted lithosphere (in central Oregon), separating a Cascadia slab of rather normal dip from the Laramide-related flat slab to the south. This opened a northern “window” in the slab. The white-on-black line in Fig. 2 shows the southern edge of the window created in 3 m.y. Once created, the southern edge of the window propagated from north to south across the Great Basin, progressively exposing the hydrated lithosphere to asthenosphere and causing the ignimbrite flareup (Fig. 2a). Figure G shows my preferred means of slab removal, although a north-to-south rollback of the slab edge (Dickinson, 2002) also is possible. My preference for a buckling style is based on seismic imaging (which shows a high-velocity feature where expected for this style of slab removal, Fig. 1f) and my sense for the mechanical difficulty of peeling slab off of the continent (especially when the slab is moving). Subduction of ocean lithosphere continued south of the Siletzia terrain. The northern portion of this slab steepened in dip, as evidenced by the southward propagation of the Cascade arc as far as Lake Tahoe. I am unaware of any post-Laramide arc activity in the USA south of the Lake Tahoe region (Henry et al., 2005), suggesting that a normal subduction zone never was reestablished beneath SW USA after the Laramide orogeny beneath the Rocky Mountains, Colorado Plateau and perhaps Great Plains. Slab removal would have brought asthenosphere in contact with an area that was not involved in the ignimbrite flareup. I attribute the remarkable volume of magma production from the Basin and Range province (and not the areas interior to this) to it being thinner (with greater volumes of melt created at the lower pressures) and more fertile (see Figs. 3a and 5a).

Great Basin lithosphere, being thermally weakened and increasing in elevation (as a result of slab removal and heating), gravitationally collapsed by expanding over the subducting Farallon plate. Within the deforming western USA, Siletzia and the Sierra Nevada-Great Valley blocks (the two terrains composed largely of oceanic lithosphere) retained sufficient strength to avoid deformation. As a result, Great Basin extension involved a westward drift of the Sierra Nevada-Great Valley block and a clockwise rotation of the Siletzia terrain, as illustrated in Fig. 2.

Transition to Shear-dominated Deformation

North America encountered the Pacific plate near the later part of the ignimbrite flareup, which initiated the transform margin and a second (the famous) slab window (Dickinson and Snyder, 1979). Sierra Nevada-Great Valley motion away from North America became regulated by the rate at which the Pacific plate moved away from North America, and Basin and Range extension occurred at this rate.

A change in Pacific-North America plate motion from NNW to WNW at 7-8 Ma (Atwater and Stock, 1998) caused the Pacific plate to move approximately parallel to the North America plate margin. This inhibited North America extension and caused North America deformation to reorganize. Southern Basin and Range extension became nearly inactive and Gulf of California opening began, which incorporated extension by stepping into the continent and placing the transform margin (the San Andreas fault) into

California. The Sierra Nevada-Great Valley block changed its motion from WNW to NNW (Wernickie et al., 1988), nearly parallel to Pacific-North America relative motion (shown by the kink in the arrows in Fig. 2). This block motion developed an interior shear zone, the eastern California-Walker Lane shear zone, which has accommodated ~cm/yr of right-lateral shear strain during the last ~7 m.y. The oceanic Siletzia terrain remained too strong to deform significantly, and accommodated right-lateral shear through continued clockwise block rotation. To accommodate the width of this block, the interior shear zone broadens across NW Nevada and SE Oregon. This broadening results in faults of a releasing orientation, and the shear zone becomes integrated with Basin and Range extension. North of the Siletzia terrain the shear zone narrows to the north by stepping westward toward the plate margin. The resulting restraining geometry results in north-south contraction in the Yakima fold and thrust belt, along the northern margin of the Siletzia terrain and extending to the Seattle area (Wells et al., 1998).

Extension in the northern Basin and Range and motion of the transform-entrained Sierra Nevada-Great Valley block both require space, and the Pacific plate does not permit continental growth to the west. The accommodation occurs by south Cascadia rollback. Northern Basin and Range faulting has reoriented so that extension is toward southern Cascadia, and the Sierra Nevada-Great Valley block moves to NNW over the subduction zone. Overall, shear strain dominates the marginal ~300 km of the continent, and dilatational strain dominates areas to the east where deviatoric stress is still controlled by high gravitational potential energy (Flesch et al., 2000; Humphreys and Coblentz, 2007); where strength is low deformation occurs at geologically significant rates (Fig. 1b).

CURRENT PHYSICAL STATE

Uplift and Buoyancy

Most of the lithosphere above which the flat slab is thought to have contacted North America lithosphere is, on average, seismically slow (Fig. 1c-d), and the surface has been elevated from near sea level to ~2 km (Fig. 1a). The western portion of the uplifted area has been and continues to be deformed (Fig. 1b) and magmatically modified. These indicate a rather widespread and profound increase in lithospheric buoyancy and temperature and a decrease in strength. The areas that have been uplifted involve a diverse set of distinctive geomorphic and tectonic provinces including the mildly contracted Colorado Plateau, more strongly contracted Rocky Mountains, the highly extended Great Basin, and the tilted Great Plains. The broad nature of uplift over this diversity of tectonic provinces suggests a broad-scale and deep underlying cause. Potential causes for the increased buoyancy include Laramide and post-Laramide contributions, and because the timing is poorly understood, the sources of buoyancy are poorly understood.

The amount of Laramide crustal shortening (Erslev, 1993; Hamilton, 1989) accounts well for the amount of Rocky Mountain elevation above its surrounding area. I assume this to be the cause of 0.5-1 km of Rocky Mountain elevation, and this local component of the uplift would have occurred during the Laramide orogeny. Most other potential buoyancy contributions are more regional. Pre-Laramide dynamic subsidence owing to the negative buoyancy of the Farallon slab would be replaced by an isostatic subsidence during the flat-slab subduction Laramide-age subduction (the difference being largely semantic). As the mass of old Farallon slab sank through the lower mantle and the age of the flat slab became younger, the influence of slab negative buoyancy diminished and uplift resulted. Simultaneously, hydration (Humphreys et al., 2003) and mechanical erosion (Spencer, 1996) of basal North America lithosphere by the flat slab would contribute buoyancy, as would post-Laramide heating associated with magmatic invasion of the lithosphere.

Within the uplifted western USA, areas of little magmatism occur where the lithosphere is thick. Lithospheric erosion, therefore, probably is not the primary cause of uplift in these areas. I infer that hydration-related buoyancy was widely important to holding the western USA region high, and that in areas of high-volume magmatism this buoyancy was replaced by thermal and compositional (basalt depletion) buoyancy. Thus I view lithospheric hydration under the cool conditions of flat slab contact as fundamental to post-Laramide western USA tectonic and magmatic activity (Humphreys et al., 2003). Most directly, it created buoyancy through the production of low-density minerals. Fig. 5b illustrates that under the hydrous and low temperature conditions created by flat-slab subduction, free-phase water is stable and hence available to migrate upward, where hornblende and chlorite would form above ~100 km depth. With lithospheric cooling, serpentine (antigorite) becomes stable at all depths (assuming sufficient cooling, Fig. 5b). Upon slab removal, hydrated and fertile lithosphere produced large volumes of magma (especially of the Basin and Range province). This mantle is expected to be dehydrated.

The corresponding loss of hydration-related buoyancy probably is compensated by the addition of thermal and depletion buoyancy (Humphreys and Dueker, 1994).

Below the Lithosphere

Subducting Gorda-Juan de Fuca plate retains a gap at the location of the inherited tear in central Oregon. The slab south of this gap involves only the Gorda plate. This subduction has been a continuation of previous Farallon subduction, and the width of the subduction zone has diminished as the Mendocino triple junction migrated north. This slab is imaged in the mantle extending beneath northern California to northern Nevada and beyond (Fig. 1f). The north-propagating southern edge of the Gorda slab is imaged where predicted by plate reconstruction models, extending from the Mendocino triple junction to central Nevada. North of central Oregon the subducting Juan de Fuca slab is imaged extending beneath Washington and northern Idaho. This represents slab that has been subducted at the Cascadia subduction zone since Siletzia accretion. The gap between the northern and southern slab segments is imaged starting at a depth of ~150 km beneath central Oregon (Rasmussen and Humphreys, 1988; Bostock et al., 1995) and extending NE across Oregon, central Idaho and Montana (Fig. 1f).

The weight of the sinking Gorda-Juan de Fuca slab drives a toroidal flow of asthenosphere from beneath the slab around its southern edge to above the slab (Zandt and Humphreys, 2007). The tectonic effects of this flow, if any, are not clear. Flow beneath the Great Basin will apply north-directed tractions that may be important in driving Great Basin lithosphere northward. It also supplies a means of sweeping away the base of the cooling lithosphere, thereby keeping the Great Basin hot, elevated and magmatically active (in contrast to the southern Basin and Range of Arizona and western Sonora). The WNW-directed flow across northern California and southern Oregon appears to have a more obvious effect on the magmatic propagation of Newberry and Medicine Lake volcanic activity, which is toward the WNW (Draper, 1991).

Seismic tomography of the upper mantle beneath Yellowstone images a plume-like structure dipping ~75° WNW to a depth of ~450 km (Yuan and Dueker 2005), and receiver function imaging finds a 410 km discontinuity deflected downward (consistent with anomalously high temperatures) at the location of the plume-like structure (Fee and Dueker 2004). Considering that Yellowstone has anomalously high ^{3}He/^{4}He (Hearn et al., 1990), which suggests a lower mantle source, and that excessively hot mantle probably has an origin in a lower thermal boundary layer, it seems reasonable to suggest that Yellowstone is sourced from the lower mantle. However, neither the plume-like structure nor the 660 km discontinuity indicate anomalous structure near or below this depth. It appears that Yellowstone involves anomalously hot mantle that ascends from the transition zone, but that its connection to the lower mantle (if any) is not a simple plume-like structure. I am intrigued that the gap between Gorda and Juan de Fuca slab extends to the location of the Yellowstone plume at ~400 km depth (Fig. 1f), and suggest that sinking Gorda–Juan de Fuca slab drives a return flow of lower mantle through this gap that is anomalously hot and elevated in ^{3}He/^{4}He. This would make Yellowstone fundamentally an interaction between subducted slab and a hot volume of upper mantle.

Small-scale Convection Everywhere

Following post-Laramide slab removal, activity in the upper mantle appears to have been dominated by small-scale convection of various form (Fig. 1c), including systems driven by positively buoyant asthenosphere and others driven by negatively buoyant lithosphere. Upwellings include: Yellowstone and low-velocity mantle left in its track (Yuan and Dueker, 2005); the central Colorado low-velocity zone associated with the large San Juan volcanic field (Dueker et al., 2001); the central Utah Springerville beneath the Colorado Plateau (Dueker and Humphreys, 1990), and Plateau-fringing areas of low-velocity; and the Salton Trough (Humphreys et al., 1984). Except for the Salton Trough, these low-velocity volumes appear to be active (i.e., ascend under the influence of their positive buoyancy). Downwellings include: the Transverse Ranges "drip" (Bird and Rosenstock, 1984) (lying beneath Laramide-age subduction complex, this probably is a sinking fragment of the abandoned Farallon slab); southern Sierra Nevada delamination, which owes its negative buoyancy as much to its composition as its temperature (Ducea and Saleeby, 1996): the apparent delamination to the east of the Rio Grande Rift (Gao et al., 2004); Wallowa delamination beneath NE Oregon (Hales et al., 2005), a past event associated with the Columbia River flood basalt eruptions; and subduction of the Gorda and Juan de Fuca slabs. All these cases are active, and except for sinking ocean slab, all involve destabilized North America mantle lithosphere; most appear to be related to the initiation of focused strain zones.

Individually these constitute a set of small-scale processes that are only partially understood, but important to the local tectonics and magmatic activity. Collectively they represent a poorly understood “meso-scale” event that clearly is important to the mass and heat flux through the lithosphere, and to the construction and modification of continental lithosphere. A major goal in the next decade is to understand how the set of active small-scale convective processes relate to one another, to prior and current mantle conditions, and act as an integrated whole beneath the western USA to create continental lithosphere.

SUMMARY

In the western USA, a host of processes related more-or-less directly to subduction have destabilized what was stable plate through processes involving strength and density reduction, which in turn have activated plate disintegration on scales ranging from small-scale convection to lithosphere-scale extension. Forces responsible for deformation have resulted from the plate tectonic boundary conditions and from the elevated land and gravitational potential energy of the western USA; over the western half of the uplifted area, a regional loss of lithospheric strength has enabled deformation. Magmatism has been both a result of and an agent for modification through effects on in temperature, strength, buoyancy and composition.

Although most western USA tectonic and magmatic activity over the last 150 Ma is related to plate tectonic processes in general and especially to subduction in particular, much of this activity is related to processes not typically thought of as plate tectonic in nature. Non-plate tectonic activities include: basal tractions acting on North America (e.g., dynamic downwarping and strong contraction caused by slab sinking, perhaps including slab avalanching); regional increases in lithospheric buoyancy (e.g., resulting from mantle lithosphere hydration and basaltic depletion) and the uplift and gravitational collapse it drives; loss of lithospheric strength (e.g., caused directly by hydration or by hydration-related magmatic heating); small-scale convection and the resulting loss of strength and density; thermal-mechanical effects of the asthenosphere flow around the edge of sinking Gorda-Juan de Fuca slab; and mantle flow driven by processes related to Yellowstone.

This view has plate tectonics playing a dominant role in shaping the western USA, but incorporates more mechanical coupling with the interior of the Earth and a more important role for vertical tectonics and far-from-boundary effects of plate interaction than most geologist usually consider. Once this region cools, the continent will stabilize (through the increase in strength and reduction in gravitational potential energy) as a largely reconstructed volume of continental lithosphere. Lithosphere that remains strongly hydrated or depleted will retain a component of long-term buoyancy and elevation.

FIGURE CAPTIONS

Figure 1. Geophysical observations of the western USA region. **(a)** Surface relief (Simpson and Anders, 1992). Along the length of the Cordillera, the region of uplift is unusually wide within the western USA. **(b)** Surface velocity field, modeled using GPS data. Projection is oblique Mercator about Pacific-North America pole. In Mexico and Canada accommodation of plate motion is confined nearly to the major plate-bounding faults (white-on-black lines), whereas it is distributed broadly over the western portion of the uplifted western USA. **(c)** Seismic S-wave velocity perturbations (Grand, 1994) averaged in the 100-175 km depth range (velocity range shown is 5%). The contrast between the fast North America craton and the slow western USA-East Pacific Rise volume is as great as any on Earth. **(d)** Seismic P-wave and rescaled S-wave velocity perturbations (Humphreys et al., 2003) at 100 km depth. The contrasts seen within the western USA are as great as those seen between the craton and the western USA. High-velocity mantle probably is continental or subducted ocean lithosphere and low-velocity mantle probably is partially molten. **(e)** Surface heat flow (Humphreys et al., 2003). Most areas of heat flow greater than 70 mW/m have experienced young magmatism (water-flow effects, apparent in Nebraska-South Dakota and in south-central Nevada, also affect this map). **(f)** Seismic P-wave velocity perturbations (Bijwaard et al., 2003) at indicated depths. Blue is fast and range of imaged variations is indicated in each frame. High velocities below 200 km represent slab subducted beneath western North America.

Figure 2. Simplified western USA evolution from 55-20 Ma. **(a)** Major volcanic activity. Green area shows the oceanic Siletzia terrain (with dark green seamounts indicated), which accreted at ~48 Ma (Madsen et al., 2006). Following accretion, the subduction zone (blue lines) and arc-related volcanism (yellow areas) jumped west to the Cascadia subduction zone and the Cascade arc, and the ignimbrite flareup initiated and propagated to the south across the northern Basin and Range and NW across the southern Basin and Range (age of initial magmatism indicated). **(b)** Map showing post-Laramide deformation of the western USA (modified from Dickinson, 2002). Red areas indicate the extent of Mesozoic accreted and plutonic terrains of the Sierra Nevada, Klamath and Blue Mountains, which are used as indicators of deformation in the continental interior. The green Siletzia terrain plays a similar role as a kinematic indicator (shown as broken at the Cascade arc; offshore portion not indicated). Current positions of these terrains are shown in the background (in dark gray). Yellow shows the Challis-Absaraka-Clarno arc, and darkest gray shows the locations of the major metamorphic core complexes in the region. Black and white line represents the southern edge of the slab window created by Siletzia accretion (~45 Ma, 3 m.y. after accretion).

Figure 3. Major inherited features of western North America lithosphere. **(a)** Creation of fertile lithosphere beneath the Basin and Range province (from Humphreys et al., 2003). Post-rift lithospheric cooling and subsidence west of the hingeline during the lower Paleozoic involved accretion of fertile asthenosphere to the base of the lithosphere (in contrast to the infertile Precambrian lithosphere to the east). This contrast between young (fertile) and old (infertile) North America occurs at the lavender dot; the rift margin

usually discussed (blue dot) is farther west. **(b)** Western USA lithospheric elements. The lavender and blue lines correspond to the colored dots in (a). Blue areas represent Achaean lithosphere (dark cratons and light mobile zones) and green areas represent Proterozoic lithosphere (accreted arcs that young to the SE). Gray area is Phanerozoic accreted continent, with the current plate boundary faults shown (white-on-black line). Red areas represent Pelona-type schist that underplated North America during the Laramide orogeny. Short dotted line refers to cross-section shown in (c), and yellow square outlines area shown in (d). Numbers refer to (e). **(c)** Tomographic image of Rocky Mountain lithosphere (Humphreys et al., 2003). Rectangular area shows Colorado and New Mexico. Yellow lines indicate major areas of Cenozoic volcanic activity, which correlate approximately with the low velocity (and presumably partly molten) upper mantle lithosphere. Seismic velocity contrast extends to ~200 km depth, suggesting that inherited North America lithosphere extends to this depth. The Southern Rocky Mountains are outlined with a solid black line, and the Rio Grande Rift is shown with a dashed line. **(d)** Receiver function image of Rocky Mountain lithosphere (Dueker et al., 2001). Layer structure beneath the region of Proterozoic-Proterozoic suture extends to ~200 km depth. Dashed line shows inferred suture at depth. **(e)** Representation of wedge-shaped lithosphere of SW USA, from southern California to central USA. This is the corridor under which the subducted oceanic plateau is thought to have passed during the Laramide orogeny (Livacarri et al., 1981; Saleeby, 2003). Each numbered location on this figure corresponds with a numbered location in (b) where a lithospheric thickness estimate exists.

Figure 4. Laramide contraction in relation to other structures. Relation of Laramide uplifts (thin blue outlines) to the Colorado Plateau (lavender outline) and the thickened crust of the Sevier crustal welt (light green). The crustal welt would push the Colorado Plateau toward the east (lavender arrows), whereas subduction is toward the NE (white arrows, with ages in m.y.), in the direction that the Colorado Plateau moved during the Laramide (large blue arrow). Achaean and Proterozoic lithosphere is separated by the blue-green line; note the difference in tectonic character of Laramide uplifts in each region. Subduction zone is shown with thick blue line and Pelona-type schist outcrops are shown in red. Enlargement to right shows shortening directions (short arrows) in the southern Rocky Mountains and Colorado Plateau (dark blue, Erslev, 2005; light blue, Bump and Davis, 2003; green, strike-slip faults from Karlstrom and Daniel, 1994, and Cather et al., 2006).

Figure 5. Laramide lithospheric hydration and post-Laramide mantle melting. (**a**) Relation of mantle processes to surface geologic activity. Top frame represents the Laramide orogeny, and shows the western margin of North America with subducted slab in contact with (and hydrating, green arrows) North America. The mantle types are from Fig. 3a. The bottom frame represents the ignimbrite flareup, and shows the magmatism of variable intensity (red for more intense, pink for less intense). (**b**) Hydrous mantle phases under the water-saturated and cool conditions expected during Laramide orogeny (phase diagram after Bromiley and Pawley, Elkins-Tanon, 2007, and Kawamoto and Holloway, 1997). Lithosphere 150 km thick can hold 0.1 km of water in olivine. Pink dotted line is the wet solidus. Green lines represent hypothetical geotherms. Prior to and during initial

slab contact (geotherm 1), the infusion of water would cause melting of basal lithosphere and some magmatism as the Farallon slab flattened. After cooling caused by slab contact (geotherm 2), free-phase water (at greater depth) and hydrous phases (at shallower depths) would be stable. Geotherm 3 shows temperature profile at conductive equilibrium for basal temperature of 750ºC (for reference). To the right is an illustration of lithosphere showing possible hydrous phases for the three geotherms shown.

Figure 6. Buckling option for post-Laramide removal of the Farallon slab. Accretion of Siletzia (stippled pattern) caused tear in the Farallon slab, which subducts steeply beneath northern USA. This tear has enabled the flat-slab portion to buckle, with its northern edge propagating to the south and exposing the hydrated lithosphere to asthenosphere. I find the situation more ambiguous on the south side of the downwelling. In the figure, a tear developed near the strength contrast at the Mendocino fracture zone (MFZ). By using the propagation of magmatism during the ignimbrite flareup (Fig. 2a), downwelling occurred along an axis extending WNE from southern Nevada. Plate motion in the 20 m.y. since the ignimbrite flareup ended leaves this buckled slab where high velocity mantle is imaged (Fig. 1f, lower frame; arrow shows 20 m.y. of North America absolute motion).

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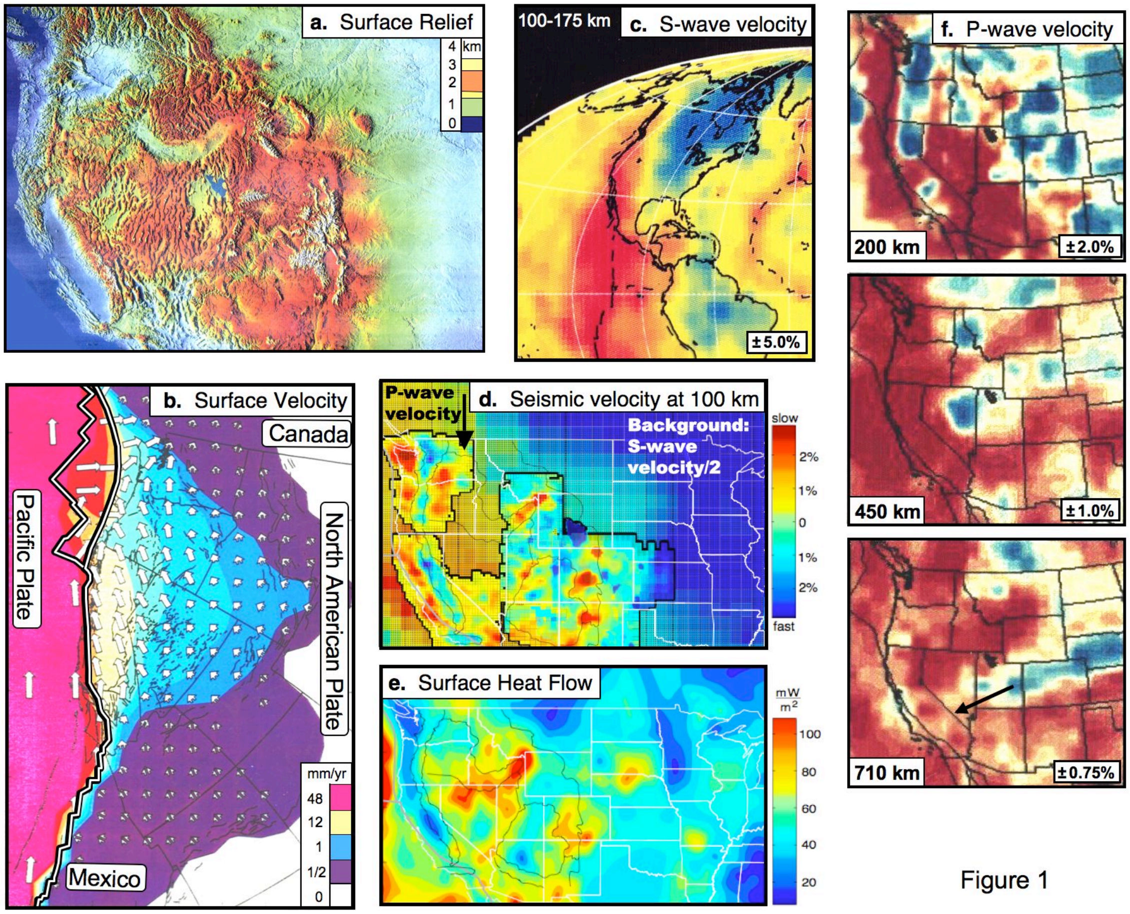


Figure 1

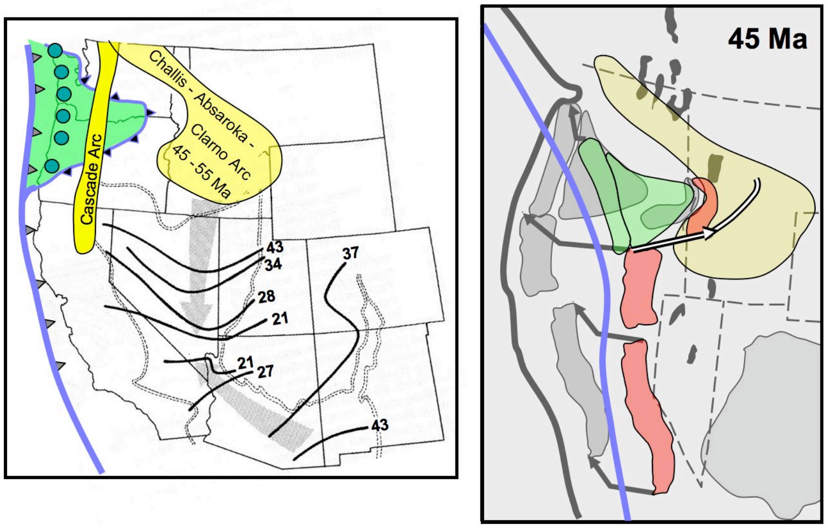
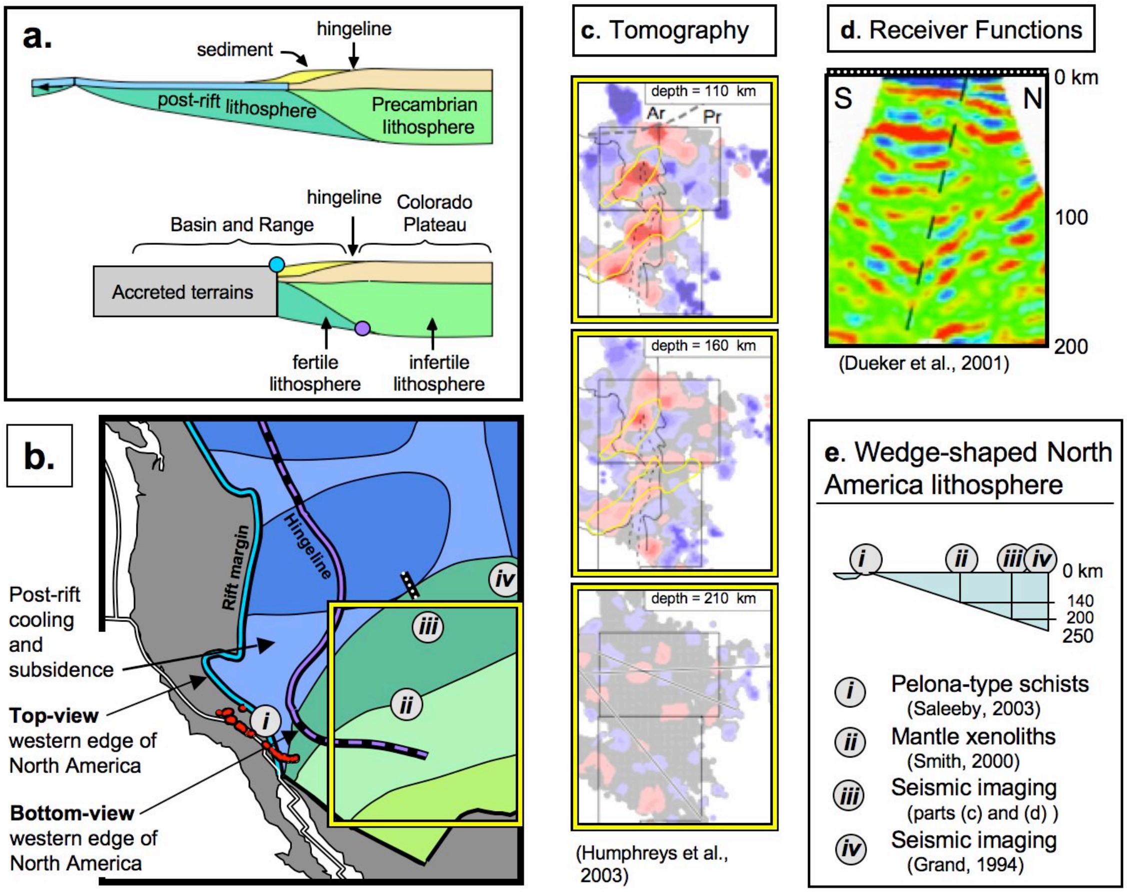


Figure 2



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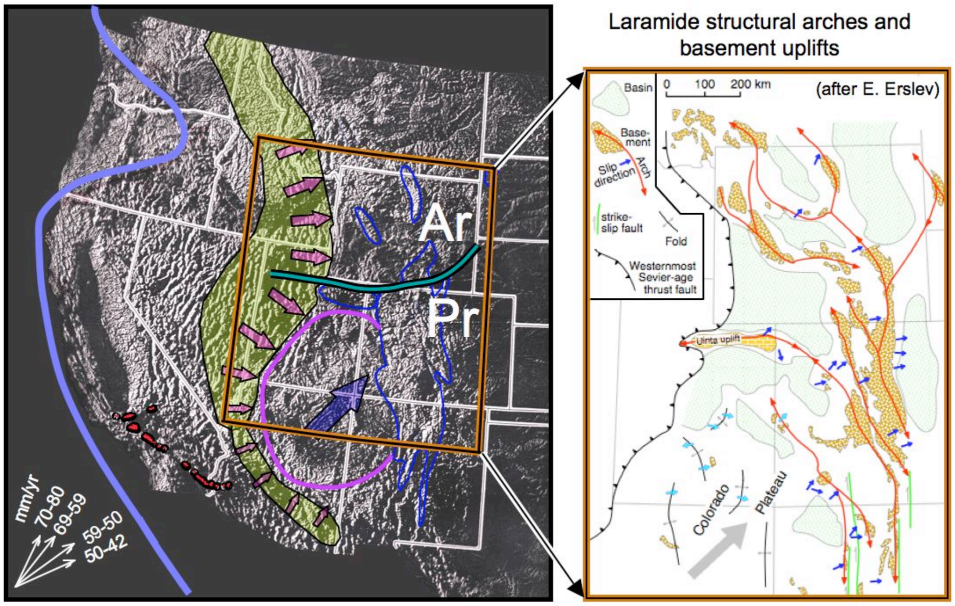

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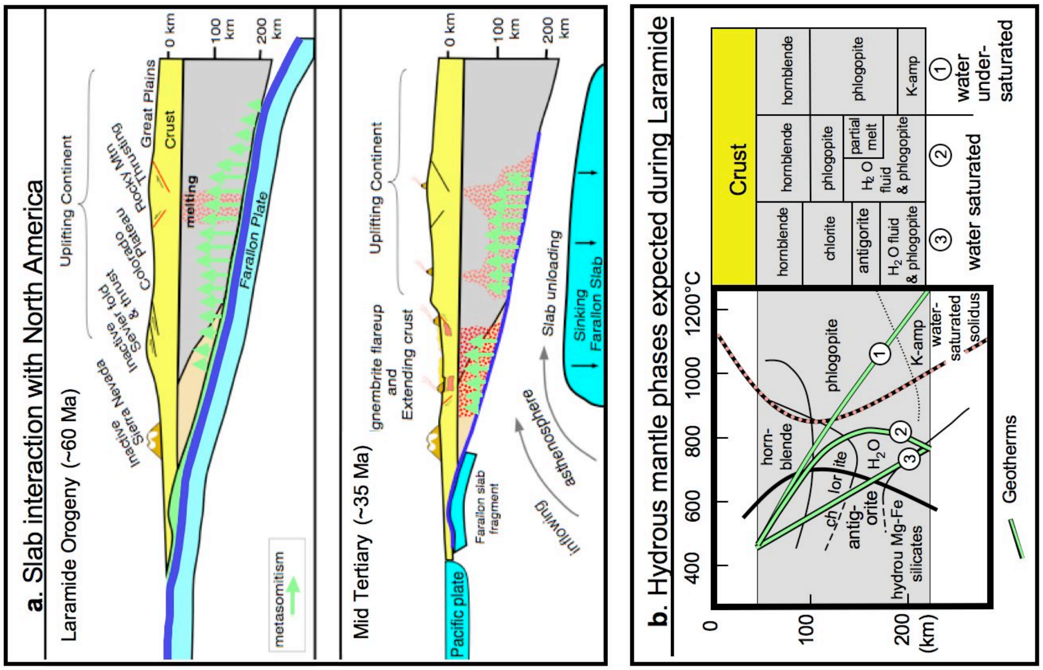

Figure 5

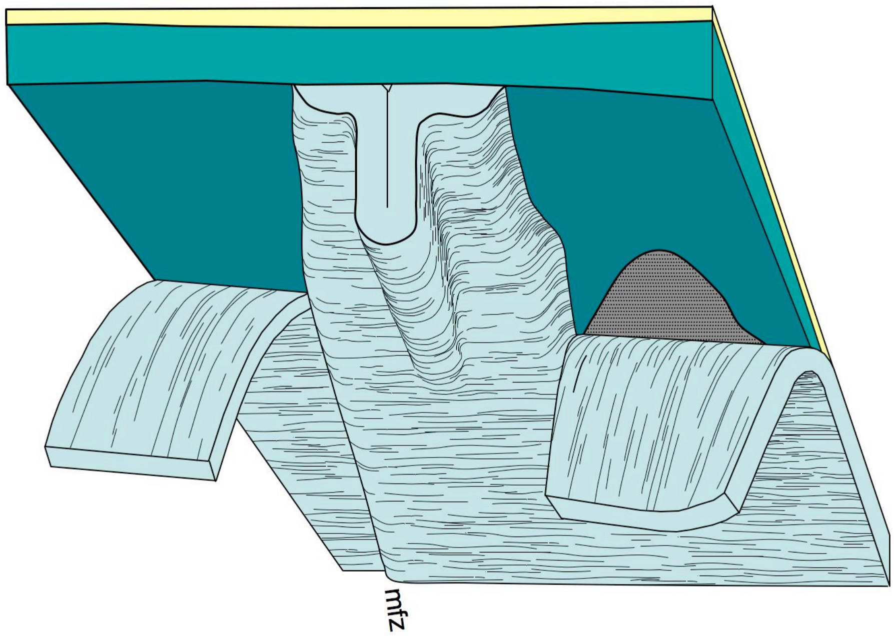

Figure 6