Post-Laramide removal of the Farallon slab, western United States

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ABSTRACT

I propose that post-Laramide removal of the subhorizontally subducting Farallon slab occurred by buckling downward along an approximately east-northeast–trending axis. This process was accomplished by a tearing or necking separation of the subducted slab near the northern and southern boundaries of the United States and propagation of the separated edges toward the central axis of downwelling, accompanied by aesthenosphic upwelling behind the trailing edges. Initial buckling probably began near 50 Ma, and slab removal was complete by 20 Ma. This model is based primarily on the space-time evolution of the "ignimbrite flare-up" (a major mid-Tertiary igneous event of mantle origin), which involved two propagating fronts of initiation of volcanism that followed the proposed motions of the separated slab edges as they converged on central Nevada from the north and southeast. Post-Laramide uplift, extension, establishment of the Cascadia subduction zone, and active magmatism may be consequences of lithosphere-scale modifications caused by the Laramide removal of the slab and the resulting asthenospheric upwelling.

INTRODUCTION

The occurrence of Laramide tectonism deep within the interior of the continent and the simultaneous existence of a "gap" in western U.S. arc magmatism have led many researchers to infer that subduction occurring at this time along the western margin of North America involved a subhorizontal slab (most reasonably the Farallon slab) beneath the western United States. Subhorizontal slab geometry has been attributed to the dynamics of rapid subduction of a relatively young plate (Engebretson et al., 1985; Jarrard, 1986) or perhaps to slab buoyancy associated with hypothesized thick oceanic crust (Livaccari et al., 1981; Cross and Pilger, 1982). Voluminous post-Laramide magmatism and general uplift of the Laramide-affected region provide strong evidence for the subsequent removal of the subhorizontal slab. More specific evidence is provided by seismic imaging of the western U.S. upper mantle. Large volumes of very low velocity (probably partially molten) upper mantle (Grand, 1994; Humphreys and Dueker, 1994a) extend up to near the base of the crust (Hearn et al., 1991), suggesting that significant volumes of abandoned slab currently do not exist beneath the continental interior.

The manner in which the slab was removed from beneath the continental interior, however, has not been well explained. A prevalent idea has been that slab dip increased rapidly after the Laramide. This idea is argued on the basis of an east-to-west time-transgressive excitation of post-Laramide magmatic activity across the southwestern United States (Coney and Reynolds, 1977) and northern Mexico (Clark et al., 1982). This sweep, shown in Figure 1, began at ~40 Ma in western Texas and Sonora and propagated west-northwest at ~30 km/m.y. across the southern Basin and Range (e.g., Christiansen and Yeats, 1992). However, initiation of mid-Tertiary magmatism north of Arizona propagated to the south at a rate of ~15 km/m.y., starting in northern Washington and central Idaho at 50–55 Ma, passing through northern Nevada and Utah at ~40 Ma, and nearly meeting the southwestern U.S. magmatic front in southernmost Nevada at ~20 Ma (Armstrong and Ward, 1991; Christensen and Yeats, 1992).

These propagating magmatic events are associated with the large-volume eruptions of the "ignimbrite flare-up" (Coney, 1978), which are attributed to large quantities of both heat and basaltic melt ascending across the Moho (Johnson, 1991). In contrast, preceding magmatism was of low volume and often derived entirely from a relatively cool, tectonically thickened crust (e.g., Patino-Douce et al., 1990). If one assumes that the slab was subhorizontal beneath the western United States prior to mid-Tertiary ignimbritic activity, then the arrival of large volumes of mantle-derived melt appears to require slab withdrawal from beneath North America, allowing asthenosphere to ascend and expel the required basaltic melt at the base of North America lithosphere. However, a simple rollback mechanism of the Farallon slab does not account for the two magmatic fronts of differing propagation direction, nor does a breaking of the Farallon slab near the subduction zone and its forward (eastward) withdrawal, which should have left a record of west-to-east propagating magmatism.

SLAB REMOVAL

Figures 2 and 3 present several models for slab removal that progressively expose North America lithosphere to asthenosphere

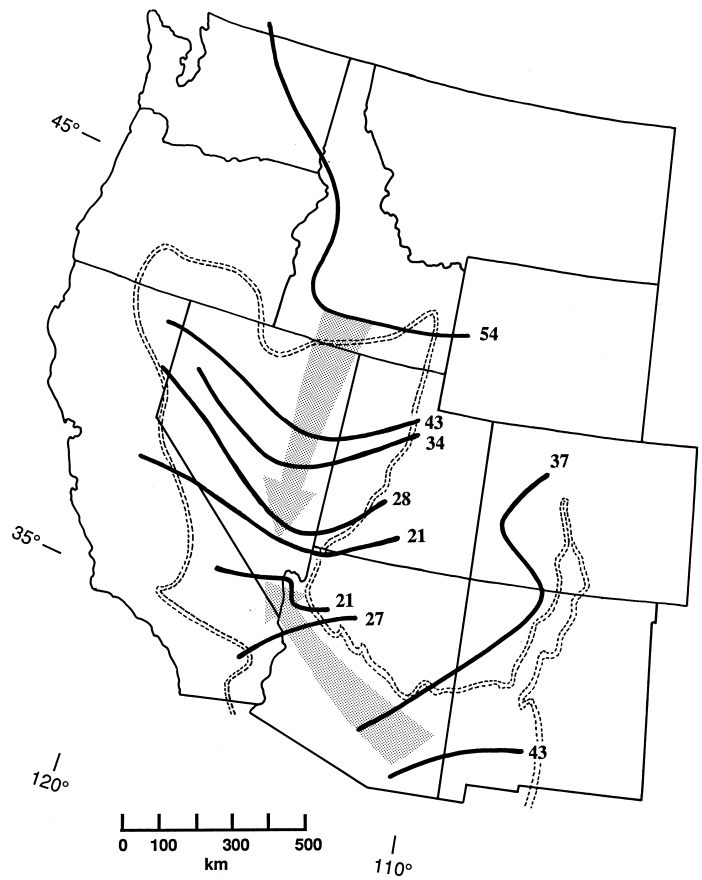

Figure 1. Propagating post-Laramide magmatic fronts. Heavy lines show limits of magmatic advance toward southern Nevada at indicated times (Ma, taken primarily from Christensen and Yeats, 1992). Double line represents current boundary of Basin and Range.

so as to follow the propagating fronts of magmatic initiation. Figure 2, my preferred model, shows a subhorizontal slab buckled downward along an approximately east-northeast–trending axis and descending beneath the western United States. It is proposed that this process was accomplished by a necking or tearing separation of the subducted slab near the northern and southern boundaries of the United States and a propagation of the separated edges toward the central axis. Magmatism is attributed to pressure-release melting of the aesthenosphere ascending behind the trailing edges. Buckling is thought to have begun within the weak slab of very young age that would have underlain northernmost Mexico and the southernmost western United States at ~50 Ma (Severinghaus and Atwater, 1990). Because southern and northern Basin and Range magmatism converged on southern Nevada, the axis of downwelling is inferred to have propagated northward (related to the northern component of Farallon–North America relative motion).

As shown in Figure 3A, either a double-sided rollback or a double-sided "peeling away" delamination from the north and the southeast also produces the observed pattern of magmatism. (These two cases differ from one another in that double-sided rollback would occur if the slab shown in Figure 3A were connected to the Farallon plate and was still involved in subduction, whereas double-sided delamination would occur if the slab had separated from the Farallon plate, with subduction reinitiated near the continental margin as is shown in the model in Figure 2.) Figure 3B shows another alternative, in which the Farallon slab beneath the western United States separates from the Canadian section of slab (as in Fig. 2), but descends beneath the southernmost western U.S. in a one-sided fashion. In this model, southern Basin and Range magmatism is attributed either to magmatic penetration of the thin and weak Farallon slab south of the Mendocino fracture zone (Severinghaus and Atwater, 1990) or the removal of this slab through its "dripping" away (i.e., small-scale convection) or entrainment in the flow established by the sinking of the more slablike northern Farallon lithosphere.

DISCUSSION

All of the above models remove the slab beneath the northern and southern Basin and Range, causing an ascent of the asthenosphere from which large volumes of basaltic melt can be created and segregated. The buckling model is distinguished by its "slippery" contact between the subhorizontal slab and North America, so that shear coupling is relatively small, and by a minimal amount of induced asthenospheric flow. A slippery contact is not viewed as a critical problem because it appears to occur beneath South America where there currently is subhorizontal subduction (Schneider and Sacks, 1987; Smalley and Isacks, 1987). Also, low-friction North American–Farallon slab contact during shallow subduction is supported by isotopic evidence indicating preservation of at least some North American mantle lithosphere (Livaccari and Perry, 1993), whereas dynamic modeling indicates that a nonslippery contact would remove North American mantle lithosphere through decoupling in the weaker lower crust (Bird, 1988).

It is on the basis of minimal induced mantle flow that I favor the slab-buckling model over the double-sided delamination or double-sided rollback models (such as shown in Fig. 3A). Although slab rollback is a common occurrence, rollback velocity is limited by the rates at which the sinking slab can push asthenosphere from beneath the slab and suck it into the region above the slab. Any slab motion due to subduction enhances the dynamic lift (e.g., Tao and O'Connell, 1992). For these reasons, rollback occurs at rates that are slow compared to ridge migration (Kincaid and Olsen, 1987). The additional problem that asthenosphere must flow into the narrow zone above the slab makes the rollback and delamination processes for removal of the subhorizontal slab more unlikely. Furthermore, in either case, the asthenosphere caught beneath the slab "parachute" is relatively confined, which would impede its escape. Hence, I conclude that buckling (Fig. 2) is the most likely mechanism for slab removal (at rates commensurate with the propagating magmatic fronts), that double-sided delamination may be possible, and that double-sided rollback is unlikely.

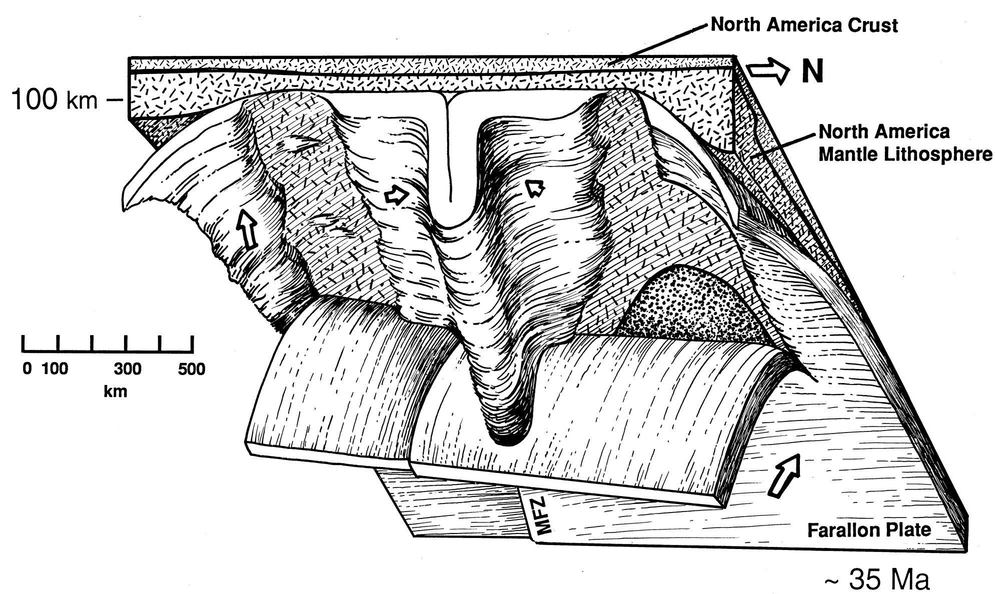

Figure 2. Preferred model of buckled Farallon slab descending beneath western United States, at ~35 Ma. View is looking *up* from beneath eastern Canada, and front of figure is near current longitude 105°W (i.e., near Denver, Colorado). Tears in Farallon slab are shown at edges of flat sections; actual separation may have occurred through necking of slab. Motion of decoupled flat and buckled Farallon slab is toward central downwelling, but with an overall north to northeast component of velocity (arrows represent velocities relative to North America). Subduction reestablished with more standard dip along most of western margin of North America (full length of normal-dip slab is not shown). Slab south of Mendocino fracture zone (MFZ) is younger and thinner. Stippled area in Pacific Northwest represents piece of Farallon plate abandoned when subduction jumped west to Cascadia subduction zone. Flat subduction of Farallon slab during Laramide has thickened crust and thinned mantle lithosphere beneath western United States.

A tear in the Farallon slab near the northern extent of Laramide-style tectonic activity is a feature common to Figures 2 and 3. Alternatively, the Farallon slab may have remained continuous by stretching greatly in the region between the flat section and the section subducting with a more standard dip beneath western Canada. This subduction style would have been similar to that of the subducted slab beneath analogous parts of South America (Schneider and Sacks, 1987; Smalley and Isacks, 1987). In either case, during Laramide tectonism, the Canadian and the western U.S. Farallon slab sections would have been mechanically decoupled.

Some Implications

Vancouver-Farallon Separation. The removal of the flat part of the subducted slab would have physically weakened the connection between the northern and central parts of the unsubducted Farallon plate. Consistent with this, the Vancouver (northern Farallon) plate was created at ~45 Ma, as evidenced by structures preserved in the Pacific plate which indicate left-lateral transpressive motion between the Vancouver and Farallon plates (Stock and Molnar, 1988; Severinghaus and Atwater, 1990).

Initiation of Cascadia Subduction. Removal of the flat part of the slab as proposed implies that it moved independently from the unsubducted Vancouver plate, requiring separation of the flat slab during the end of the Laramide orogeny. Consistent with this, the Cascadia subduction zone began to form at 45–50 Ma several hundred kilometres seaward of the previous convergent margin (immediately seaward of a young seamount chain currently found along most of the length of the Oregon and Washington Coast Ranges; Duncan, 1982), and the Cascade arc became active shortly thereafter (Christiansen and Yeats, 1992; Taylor, 1990). South of the Cascades, the convergent margin remained offshore of California near its Laramide location, but subduction presumably was reestablished with a more typical dip (see Fig. 2).

Uplift. Laramide removal of the Farallon slab and its replacement with asthenosphere, by replacing a negatively buoyant load with one that is positively buoyant, would cause uplift. Segregation of basalt from the upper mantle would add to net buoyancy, enhancing uplift (Humphreys and Dueker, 1994b). These contributions to uplift would have occurred during slab removal (i.e., after the Laramide orogeny).

Asthenosphere Transfer. The flattening Farallon slab and its subsequent removal transferred oceanic asthenosphere beneath western North America rather abruptly and generally earlier and in a different space-time pattern than predicted by an opening of a "slab-free window" (Dickinson and Snyder, 1979). Furthermore, if asthenosphere in the vicinity of the East Pacific Rise is unusually hot, as inferred by its anomalously low velocity (e.g., Grand, 1994), then the asthenosphere transferred to western North America probably was unusually hot, thereby enhancing basalt production and mantle buoyancy.

Transverse Ranges. Our preferred model (Fig. 2) is patterned after the proposed active lithospheric downwelling beneath the Transverse Ranges of southern California (Bird and Rosenstock, 1984; Humphreys and Hager, 1990), where numerical modeling demonstrates the physical possibility of this mechanism for lithosphere removal. Extending this comparison, the lithosphere that is downwelling beneath the Transverse Ranges also may be part of the Farallon slab. This is thought to be so because if the Pelona-type schists represent the Laramide-age base of North American lithosphere in this area, then the inferred ~50 km thickness of underlying mantle lithosphere (Humphreys and Clayton, 1990) appears to be greater than could have been created through mantle cooling following a slab withdrawal. If North American lithosphere extended no deeper than the Pelona schist, then the emplacement and abandonment of the Farallon slab appear to be the only alternative explanation for southern California lithosphere. Hence, the Transverse Ranges might represent a Laramide-like structure created by a recent destabilization of a Farallon slab remnant within what is now a transform accommodation zone. It also suggests that the buckling model for removal of a flat slab is not a unique event.

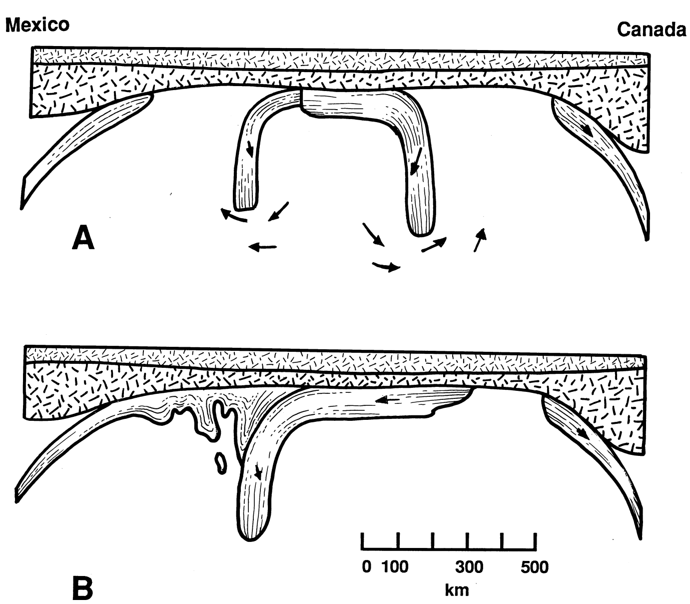

Figure 3. Cross sections of alternative models for removal of Farallon slab at ~35 Ma. View is from east, as in Figure 2. Thickness difference between southern and northern slabs results from age difference north and south of Mendocino fracture zone. A: Parachutelike model for slab removal, involving double-sided rollback or double-sided delamination. B: Single-sided, subductionlike downwelling of older, northern part of flat Farallon slab. Some "drips" of young southern Farallon slab are being entrained in flow excited by downwelling northern part of slab.

Post-Laramide Extension

Accompanying propagating ignimbritic activity was roughly contemporaneous and similarly propagating extensional activity that, in the crust, is represented by the core complexes (Gans et al., 1989; Armstrong and Ward, 1991; Wernicke, 1992). This extension, following Sevier-Laramide contraction, represents a major change in the state of stress in the western United States. Reduction of subduction rate often is cited as a cause for the termination of compression (e.g., Engebretson et al., 1985), and gravitational potential energy stored in the "crustal welt" of Sevier-Laramide origin provided forces driving post-Laramide extension (Coney and Harmes, 1984; Sonder et al., 1987). The proposed slab removal and reconfiguration of subduction also would contribute to extension by changing the forces acting on the continent. The newly subducted slab that was reestablished with a more normal dip angle offshore of California and the Pacific Northwest (see Fig. 2), being neither "anchored" nor supported by the deeper mantle, would tend to roll back (Jarrard, 1986) from North America, extending the continental interior by pulling the continental margin to the west. Additional changes in the horizontal forces would occur as the tractions basal to western North America caused by motion of the flat slab (Bird, 1988) would cease being oriented east-west and would acquire a north-south orientation. Furthermore, vertical forces related to removal of the slab load, discussed in the "uplift" section above, would add to the potential energy of the continental interior, contributing to the forces driving continental extension.

The relation between initial magmatism and extension is ambiguous (Wernicke, 1992), making unclear the distinction between "active" (magma buoyancy–driven) and "passive" (extension-driven) magma ascent. However, striving to resolve the active-passive issue may be misleading; vigorous magmatism and extension are both processes that I propose were subservient to slab removal. Because intrusion into the crust of great volumes of mantle-derived basalt seems impossible if the Farallon slab were in place against the base of the western United States, the appearance of such magmatism is taken as an indicator of slab removal and aesthenospheric upwelling. However, the isotopic evidence that the lithosphere was >70 km thick (Livaccari and Perry, 1993) suggests that the eruption of great volumes of magma also required accompanying lithospheric extension to enable asthenospheric ascent to depths more typically associated with high melt production.

CONCLUSIONS

Even a cursory examination of the western United States reveals that the area now standing as one of the world's great plateaus is the area affected by the Laramide orogeny. Apparently, the Laramide orogeny fundamentally altered the western United States. However, what forces created the Laramide uplifts, what modifications occurred to the North American lithosphere, and what forces currently hold up the western United States remain controversial issues (e.g., Livaccari and Perry, 1993; Bird, 1994). I propose that the mid-Tertiary ignimbrite flare-up, which occurred roughly throughout the Basin and Range part of the region affected by Sevier-Laramide tectonism, resulted from, and indicates the form of, Farallon slab removal. Many aspects of western U.S. post-Laramide magmatic and tectonic activity may be consequences of lithosphere-scale reconfigurations of temperature, composition, buoyancy, strength, and boundary forces that were brought on by the removal of the subhorizontal section of the Farallon slab and the resulting asthenospheric upwelling.

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