1/9/08

Toroidal Mantle Flow Through the Western U.S. Slab Window

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Abstract. The circular pattern of anisotropic fast-axis orientations of split SKS arrivals observed in the western U.S. can not be attributed reasonably to either preexisting lithospheric fabric or to asthenospheric strain related to global-scale plate motion. A plume origin for this pattern accounts more successfully for the anisotropy field, but little evidence exists for an active plume beneath central Nevada. We suggest that mantle flow around the edge of the sinking Gorda-Juan de Fuca slab is responsible for creating the observed anisotropy. Seismic images and kinematic reconstructions of Gorda-Juan de Fuca plate subduction have the southern edge of this plate extending from the Mendocino triple junction to beneath central Nevada, and flow models of narrow subducted slabs produce a strong toroidal flow field around the edge of the slab, consistent with the observed pattern of anisotropy. This flow may enhance uplift, extension and magmatism of the northern Basin and Range while inhibiting extension of the southern Basin and Range.

Western U.S. Mantle Anisotropy

The nature of split SKS arrivals (and other core-transiting S phases) provides our best data on the lateral variations in uppermost mantle fabric. A dense set of SKS observations from the western U.S. maps these variations with enough detail to recognize the regional patterns in this field (Fig. 1). An intriguing circular pattern in the orientations of SKS first arrivals (termed the fast split orientations) has become increasingly clear since it was first discussed by Savage and Sheehan (2000).

The dominant cause of split SKS arrivals is thought to be mineral alignment resulting from strain in the upper ~300 km of the mantle, where dislocation creep mechanisms are responsible for deformation (Zhang and Karato, 1995). In particular, it is the most recent strain event that should be indicated by split SKS arrivals, and where more than one process is active in straining the mantle it is the most active mechanism that should dominate the strain field. In regions of thick continental lithosphere, anisotropy often is attributed to fossil strain associated with tectonic assembly of the lithosphere, as evidenced by the common alignment of the observed SKS fast-axis direction with the geologic and tectonic fabric (Silver, 1996, Vinnik et al., 1992). In the area of the Rocky Mountains and Great Plains, where lithosphere is imaged to depths of ~200 km (Dueker et al., 2001, Humphreys et al., 2003), observed anisotropy can be interpreted this way (Fox and Sheehan, 2005).

In contrast, the Basin and Range and outboard accreted terrains of the western U.S. occupy an area where lithospheric strength is low (Lowry and Smith, 1995) and anisotropy of lithospheric origin is considered unimportant to SKS splitting (Silver and Holt, 2002). Consistent with this interpretation is the observed misalignment between fast split orientations and the tectonic grain for structures associated with the Phanerozoic assembly in the western U.S.

This has led to an expectation that young and ongoing asthenospheric simple-shear strain associated with plate motion is the primary cause of the observed anisotropy, with little interference by other causes. Much of the observed SKS fast split orientation field lends a general support for this idea, where outside the radius of the circular pattern, observed fast split directions are commonly oriented close to the direction of absolute plate motion (e.g., across the Snake River Plain (Schutt et al., 1998), portions of the Colorado Plateau (Gok et al., 2003) and near the Pacific plate in California (Silver and Holt, 2002)), with fast-axis directions tending to align NE-SW except near the Pacific plate, where orientations turn NW-SE toward the direction of Pacific plate motion (Fig. 1). Observations of the general direction of absolute plate motion have been modeled as simple shear in the asthenosphere (Silver and Holt, 2002; Becker et al., 2006; Gung et al., 2003).

However, in and around the Great Basin the fast split orientations are poorly predicted by plate motion models, and more generally by models that also incorporate the component of flow excited by deep subducted slabs (e.g., the Farallon slab in the lower mantle (Becker et al., 2006)). If the pattern of SKS fast split orientations indicate upper mantle strain, then clearly the more local processes that created this strain field are dominating over those caused by global-scale plate motion and flow.

The failure of the above-mentioned models to account for the SKS observations in the Great Basin led Savage and Sheehan (2000) and Walker et al. (2005) to propose that asthenosphere flow caused by mantle upwelling beneath central Nevada is the cause of the circular SKS pattern. Although geodynamic models suggest that focused mantle upwelling could create a strain field that explains the SKS observations (Ribe and Christensen, 1994; Steinberger, 2000), there is no other evidence for an active plume beneath central Nevada. Particular problems with the plume model are a paucity of young volcanism and an absence of a geoid high coinciding with the location of the proposed upwelling, and the absence of a similar circular pattern of SKS fast orientations around the Yellowstone hotspot (Waite et al., 2005), where a prominent geoid high and active magmatism occur and tomographic imaging resolves a low-velocity plume-like structure beneath the hotspot (Yuan and Dueker, 2005).

Toroidal Flow Caused by Slab Rollback

The circular pattern of SKS fast split orientations is strikingly similar to that predicted by simple rollback of a narrow slab (Figs. 1 and 2). Both numerical and laboratory experiments have investigated the nature of toroidal flow of mantle around the edges of narrow subducting slabs (Dvorkin et al., 1993, Schellart, 2004, Stegman et al., 2006, Royden and Husson, 2006), confirming Harper's (1975) prediction of such flow. Fig. 1b shows results from Piromallo et al.'s (2006) numeric simulations, which predict that mantle flows vigorously up and around the slab edges from the high-pressure bottom side of the slab to the low-pressure top side. This pattern of flow is seen in laboratory (e.g., Schellart, 2004) and numeric (e.g., Stegman et al., 2006) simulations of slab rollback, where a strong ascending toroidal flow is resolved at depths where slab is present. The induced toroidal flow dominates the mantle flow driven by rollback, and the associated loss of dynamic slab support allows the slab to steepen and retreat rapidly. The center of flow vorticity is located near the slab edge and, for narrow slabs, the rotational flow extends out 0.5-1 slab-widths in distance from the center. Because flow speed diminishes away from the center, shear strain (hence the expected orientation of the anisotropic fast axis) is parallel to flow velocity. A similar pattern of anisotropy has been observed near southern Italy (Civello and Margheriti, 2004, Faccenna et al., 2006), which these authors attribute to mantle flow driven by slab rollback in a manner similar to our suggestion for the western U.S.

Geometry and Motion of the subducted Gorda-Juan de Fuca slab

The G-JdF plate (and its subducted southern edge) first developed as an independent plate ~25Ma as the Pacific-Farallon ridge intercepted the coastline of North America at the latitude of southern California and spawned two oppositely migrating triple junctions (Atwater, 1970; Severinghaus and Atwater, 1990). The northerly migrating Mendocino triple junction occurs where the southern edge of the G-JdF plate (defined by the Mendocino transform fault) is overridden by North America. The southern edge of the subducted G-JdF slab defines the northern edge of an enlarging triangular "slab window" (Dickinson and Snyder, 1979) or "slab-free gap" (Severinghaus and Atwater, 1990) beneath the western U.S.

The G-JdF plate is nearly stationary in an absolute (i.e., hotspot) reference frame (Gripp and Gordon, 2002), and subduction is accommodated almost entirely by slab rollback. This is expected to lead to steep subduction (Piromallo et al., 2006), which is observed seismically

(Bijwaard et al., 1998) and represented in Fig. 2. Based on recent slab-mantle flow modeling discussed above, we hypothesize that the combination of westward slab rollback of the G-JdF slab and northward opening of the slab window promotes a strong toroidal mantle flow from beneath the slab to above by a circular (and slightly upward) path around the southern edge of the G-JdF slab, basically through the opening slab window.

Based on both plate reconstruction models and seismic imaging, the southern edge of the Gorda-Juan de Fuca (G-JdF) slab currently extends from the Mendocino triple junction to central Nevada and on to greater depths. The global tomography models of Bijwaard et al. (1998) (Fig. 1) provide the best seismic resolution currently available at these depths. Because high-velocity bodies below the base of the lithosphere are reasonably attributed to subducted slabs, these images provide a view of subduction history beneath the Pacific Northwest. In these images we can follow the high-velocity Gorda-Juan de Fuca slab continuously into the mantle along a trajectory that takes its southern edge from Cape Mendocino at shallow depths to central Nevada at depths of 350-600 km. Also shown on Fig. 1 is the location of the southern edge of the G-JdF slab inferred by plate motions over the past 30 m.y. (Dickinson and Snyder, 1979; Severinghaus and Atwater, 1990). The two estimates are similar.

Farther north, Fig. 1 suggests that the subducted Juan de Fuca slab develops a gap or becomes disrupted at the latitude of Oregon and at depths below ~200 km. This behavior also was observed in tomographic images based on regional arrays (Rasmussen and Humphreys, 1988, Bostock and Vandecar, 1995, Harris and et al., 1991). Nonetheless, for our concerns, it seems safe to assume that subducted G-JdF slab exists beneath the Pacific Northwest more or less as expected, and that the southern edge in particular is well located near the center of the circular pattern of fast split orientations beneath central Nevada at a depth of 350-450 km.

Discussion

In the western U.S. away from the region of the circular pattern of fast split orientations, upper mantle strain development by North American and Pacific plate motion accounts well for the fast split directions (e.g., Silver and Holt, 2002, Becker et al., 2006). The circular pattern of anisotropy, then, suggests that their causative strains are greater than those associated with the larger scale plate motion. A model in which the circular pattern of fast split orientations is attributed to toroidal flow driven by slab rollback explains the observed circular pattern of fast split orientations well. It is centered as we expect for toroidal flow associated with the southern edge of the subducted G-JdF slab and it has the expected radius (as best as it can be estimated from rollback models) and area of null observations centered on central Nevada. If the circular flow pattern is related to G-JdF rollback, it may be a regionally transient, but nonetheless geodynamically important, "eddy" within the larger scale mantle flow. On yet smaller scales, other processes also may be affecting split orientations. These may include the influences of the Sierra Nevada microplate motion, the Yellowstone hotspot (Waite et al., 2005), ongoing delamination beneath the Sierra Nevada (Zandt et al., 2004), the influence of San Andreas transform shear, and the direct influence of the slab edge (Peyton et al., 2001). Anisotropy caused by these small-scale processes may require a greater density of observation to resolve, especially if they produce orientations similar to the larger scale anisotropy field. If we are correct, then, the circular pattern of western U.S. split orientations indicate recent mantle flow, and the time integrated effect of the northwestward migration of the eddy with other causes of upper mantle strain (especially plate motion) would account for mantle features left in the wake of the eddy.

The circular pattern is exceptionally well developed beneath the Great Basin province. A simple explanation may be that the presence of asthenosphere to relatively shallow depths beneath the Great Basin allows for a thicker layer of more strongly developed anisotropy within the asthenosphere. Also possible are mechanical or thermal interactions between the inferred asthenosphere flow and patterns of uplift, tectonics and magmatism. Magmatic and extensional activity responsible for creating the Great Basin appears to be related to earlier slab removal ~45-20 Ma (Dickinson, 2002; Humphreys, 1995). However, the subsequent evolution of the Basin and Range differs between the high-standing and deforming northern Basin and Range and the low-lying and nearly inactive southern Basin and Range.

Mechanically, flow-related basal tractions work to inhibit southern Basin and Range extension while contributing to extensional strain that increases in rate and becomes more northwesterly in orientation to the north. Because lithospheric stresses related to plate interactions also create a similar effect (Humphreys and Coblentz, 2007), it may be difficult to determine the relative importance of edge and basal loading without careful modeling that includes both processes simultaneously. But it is possible that basal tractions derived from regional-scale asthenospheric flow are important to the western U.S. strain pattern and that aspects of the regional tectonics have been incorrectly attributed to lithospheric processes.

Thermally, the vertical component of asthenosphere flow around the slab edge (from below to above the slab) emplaces hot, low-density asthenosphere beneath the Great Basin region, and the toroidal flow also would help sweep away the lowermost portion of the lithospheric thermal boundary layer. Such warming would enhance magmatic production and help maintain high Great Basin elevations. Thus, accounting for the fast split orientations with toroidal flow circumvents the problems with the plume model while still providing an alternate explanation for regional asthenospheric upwelling and support of the high elevations in Nevada and western Utah (Parsons et al., 1994; Lowry et al., 2000).

Xue and Allen (2006) argue that attributing the WNW propagation of the Newberry hotspot across Oregon to subduction-related corner flow (e.g., by Draper, 1991) is inconsistent with their observed SKS split orientations across this region (Fig. 1). However, these split arrivals are a part of the circular pattern that we attribute to toroidal flow, and this subduction-related flow may account for both Newberry propagation and mantle anisotropy.

Finally, although the tectonic manifestations of the Mendocino slab window are most clearly observed in the coastal regions (Zandt and Furlong, 1982; Dickinson, 2002; Furlong and Govers, 1999), the toroidal flow provides direct evidence for the development of a slab window that extends far inboard as originally hypothesized by Dickinson and Snyder (1979), and this flow may be important to continued Great Basin tectonic and magmatic activity generally as envisioned by Dickinson and Snyder.

Acknowledgments

We thank Ian Bastow for providing SKS splitting analyses results for the Sierra Nevada prior to publication, and Alan Levander and Martha Savage for their constructive reviews. Martha Savage pointed out the early work on subduction zone vortices by Harper. GZ acknowledges the support of NSF EarthScope Program Award No. EAR-0454554. EH acknowledges the support of NSF Geophysics Program Award No. EAR-0409965.

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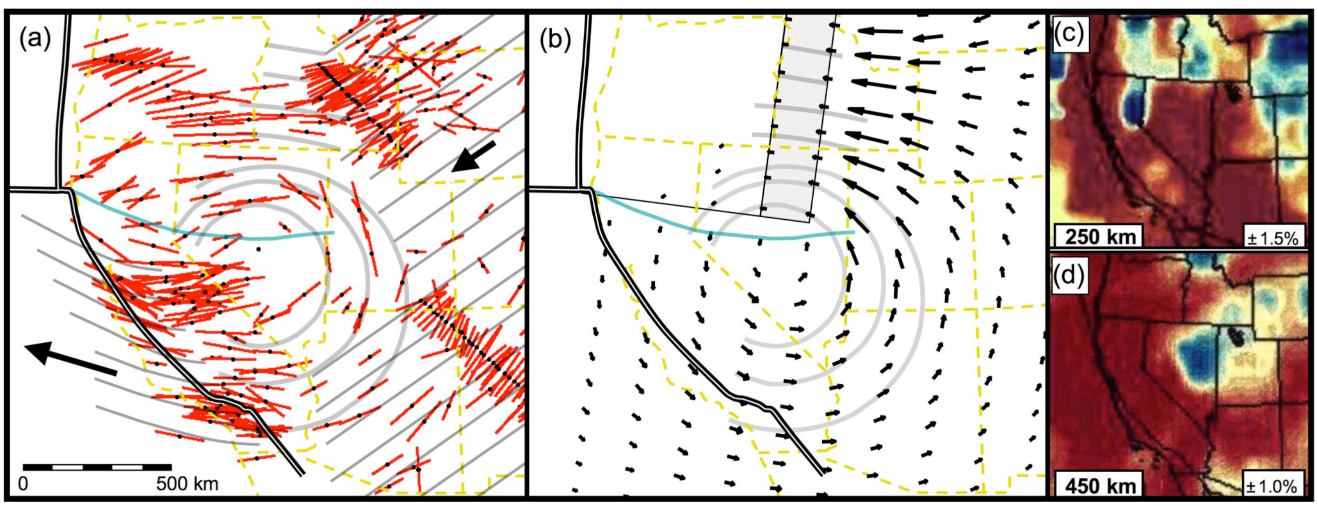

Figure 1. Western U.S. upper mantle anisotropy. (a) SKS fast-axis split orientations and split-time magnitudes (red line segments, with length proportional to split time). The SKS split times average about 1 s. Also shown are plate velocities (black arrows) and reference lines (gray) that indicate expected orientations of SKS splits caused by absolute plate motion and toroidal flow. Observed SKS split orientations tend to align with absolute plate motion except in the circular area of radius ~500 km centered on Nevada. Also shown is the southern limit of the G-JdF slab (blue line) estimated from plate reconstructions (Severinghaus and Atwater, 1990, and Dickinson and Snyder, 1979) and major plate boundaries (double lines). SKS data are from Polet and Kanamori (2002), M. Fouch (2007, web), Schutt and Humphreys, 2001, Xue and Allan (2006), Savage and Sheehan (2000) and references therein. (b) Mantle flow at ~150 km depth (black arrows) from numeric simulation of flow driven by rollback of a narrow slab (Piromallo et al., 2006) at the location indicated with the fine-line rectangle (shaded portion is steeply dipping portion of slab). Both the vertical and horizontal derivatives of this velocity field parallel the velocities shown, which would create a mantle anisotropy generating SKS fast splits oriented parallel to the velocities. (c) Tomographic image of P-wave velocity (Bijwaard et al., 1998) at 250 km depth. High-velocity (blue) mantle beneath the Pacific Northwest is thought to be subducted Gorda-Juan de Fuca (G-JdF) slab. Seismic velocity varies by ±1.5% (as indicated). (d) Same as (c) except at a depth of 450 km. The G-JdF slab is imaged dipping steeply to the east, as represented in Figure 2.

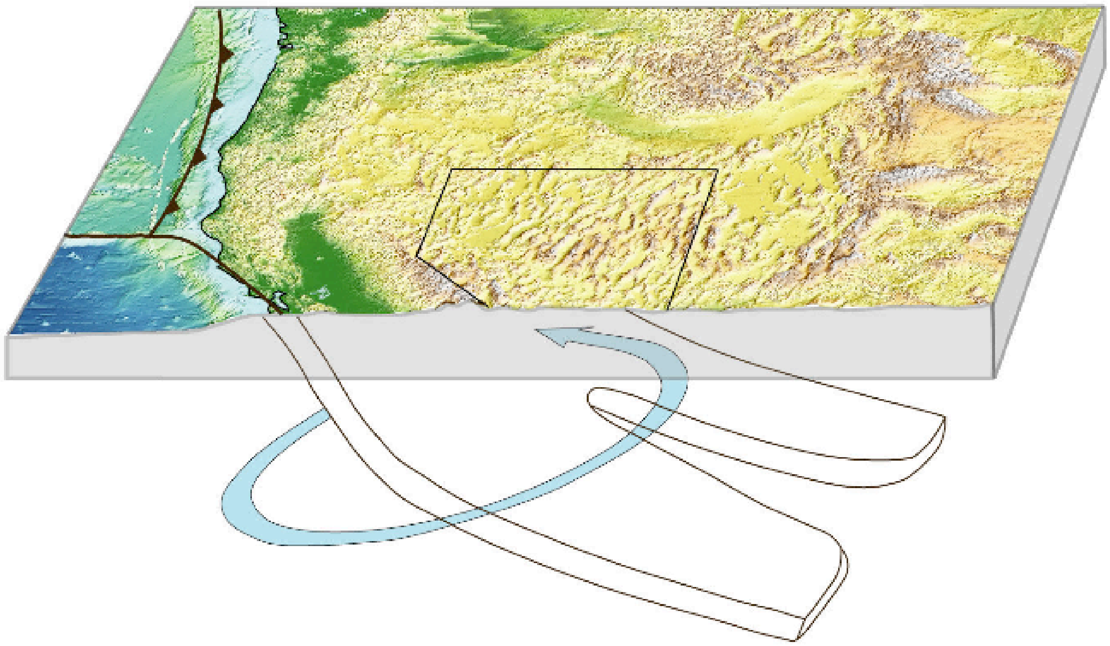

Figure 2. Schematic diagram showing an ascending toroidal flow beneath the western North American plate around the edge of the Gorda-Juan de Fuca slab. This flow results in a loss of dynamic slab support, causing rapid slab roll back and steepening in the mid-upper mantle. Slab geometry represents seismically imaged slab (Bijwaard et al., 1998, Bostock and Vandecar, 1995). The toroidal flow creates an anisotropy field that results in a circular pattern of fast split directions, as observed in Fig. 1. Outline of Nevada is shown for comparative location with Figure 1. Abbreviations: CP = Colorado Plateau, JdF = Juan deFuca, NA = North America, Pac = Pacific, SAF = San Andreas Fault, SN = Sierra Nevada, SP = Snake River Plain, NHT = Newberry Hotspot Track, Y = Yellowstone.