Evidence for a deep asthenosphere beneath North America from western United States SKS splits

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ABSTRACT

The uniform southwesterly trend of fast-traveling split SKS waves that traverse the upper mantle beneath the Yellowstone swell provides good evidence for both southwesterly motion of North America over a relatively stable deep Earth interior, and young strain accommodation within the Yellowstone swell mantle via dislocation creep of olivine. These results contrast with the many SKS splits recorded across the western United States, the splitting behavior of which often is very complex at individual sites, and the orientations of which, as a set, cannot be attributed simply to plate motion or to small-scale convection beneath North America lithosphere. These data suggest that, away from Yellowstone, (1) mantle fabric is complex, and (2) North America motion is accommodated by strain at depths greater than those typically associated with asthenosphere.

Keywords: asthenosphere, anisotropy, plate motion, western United States.

INTRODUCTION

The upper mantle is made seismically anisotropic where olivine deforms by dislocation creep, and at strains greater than ~1, the *a*-axis of olivine tends to align with the finite-strain extension direction (Ribe, 1992; Zhang and Karato, 1995). This alignment affects the propagation of SKS waves, which are nearly vertically incident and, in the absence of anisotropy, would be radially polarized (i.e., vibrating in the plane that contains the SKS ray). Anisotropy causes the wave to split into two orthogonally polarized waves traveling at different velocities. The polarization orientation of the fast-traveling wave is aligned with the horizontal component of the average *a*-axis orientation. Thus, split SKS waves are useful for inferring upper mantle strain. Silver and Chan (1991) developed a method to estimate two split parameters (split time and fast-axis orientation) by finding the inverse split operator that minimizes transverse (nonradial horizontal) motion. Many SKS splitting observations were made on continents in the past decade, and the orientations of fast axes have been attributed to either simple shear within the asthenosphere (the fast axis being oriented in the direction of plate motion) or to tectonic strain within the lithosphere (see review by Silver, 1996).

WESTERN UNITED STATES SKS SPLITS

SKS waves recorded by the PASSCAL-supported Yellowstone swell array during a six-month deployment of three-component broadband seismometers (Fig. 1) show an especially simple and uniform pattern of splitting (Schutt et al., 1998; PASSCAL is the Program for the Array Seismic Studies of the Continental Lithosphere). Null SKS splits (i.e., unsplit SKS arrivals) occur when waves are naturally polarized with the fast-axis orientation. The top row of Figure 2 shows a near-null example from the Yellowstone swell array. This event has a back azimuth (and hence polarization) that is nearly aligned with the fast-axis orientation estimates for the other two events shown, and very little transverse motion occurs (left side of figure). The combination of (1) well-resolved split parameters for some events at this site and (2) little transverse energy for events polarized with the resolved fast-axis orientation indicates that anisotropy orientation below this site does not vary with depth.

The presence of thin lithosphere beneath the Yellowstone swell (Lowry and Smith, 1995) and absence of crustal anisotropy (Peng and Humphreys, 1998) imply that observed SKS splits occur dominantly beneath the lithosphere. There are two plausible explanations for the development of a uniformly oriented sublithospheric fabric with a southwest-trending olivine *a*-axis: (1) a southwestward motion of North America over a more stable interior of Earth (Vinnik et al., 1992), such as the hotspot reference of Gripp and Gordon (1990), and (2) a flow of flattening Yellowstone plume drifting away from the current plume location confined primarily within previously emplaced (and thermally weak) plume mantle. In either case, we conclude that a shallow asthenosphere exists beneath this part of western United States and that deformation within this asthenosphere creates a coherent and uniform anisotropy with the expected strain field. Furthermore, both cases suggest that Earth's deep interior is relatively stable and that North American plate motion is accommodated in the upper mantle. Such statements are completely consistent with the traditional view of Earth, in which asthenosphere is within Earth's upper few hundred kilometers and is associated with the seismic low-velocity zone (e.g., Hess, 1964; Nishimura and Forsyth, 1989), that when deformed creates seismic anisotropy (Gaherty and Jordan, 1995; Karato, 1992).

The thorough consistency of Yellowstone-related anisotropy with the common notions of upper mantle strain and seismic anisotropy is made remarkable by an absence of the expected anisotropy throughout the rest of western United States. Figure 1 shows that away from Yellowstone, SKS fast-axis orientations are extremely variable, and where null splits have been reported, their orientations often are inconsistent with the observed splits (data from Silver and Chan, 1991; Ruppert, 1992; Vinnik et al., 1992; Sandvol et al., 1992; Savage and Silver, 1993; Silver and Kaneshima, 1993; Sandvol and Ni, 1994; Bostock and Cassidy, 1995; Fabritius, 1995; Liu et al., 1995; Ozalaybey and Savage, 1995; Savage et al., 1996; Barruol et al., 1997; Schutt et al., 1998; Savage and Sheehan, 2000; this study). A high density of SKS splitting data from the area immediately east of the Yellowstone swell, obtained recently from the PASSCAL-supported Deep Probe and Lodore broadband arrays (Fig. 1B), shows the rapid transition in SKS splitting behavior as one moves away from the Yellowstone swell. Figure 2 shows a typical example for a site in the Lodore array. The estimates for splitting parameters result in null-split determinations, meaning that assuming an anisotropy orientation different from the back azimuth would cause an increase in transverse energy (see center column of Fig. 2). However, significant transverse energy is observed. There is no accounting for this with a single layer of anisotropic mantle. Furthermore, the null directions determined for different events differ from one another; this result also is inconsistent with the assumption of a single anisotropy orientation. Figure 3 illustrates that this complex splitting behavior is typical for sites away from the Yellowstone swell: unlike SKS arrivals to the Yellowstone swell, those arriving to a site east of the swell tend to be inconsistent with one another (Fig.

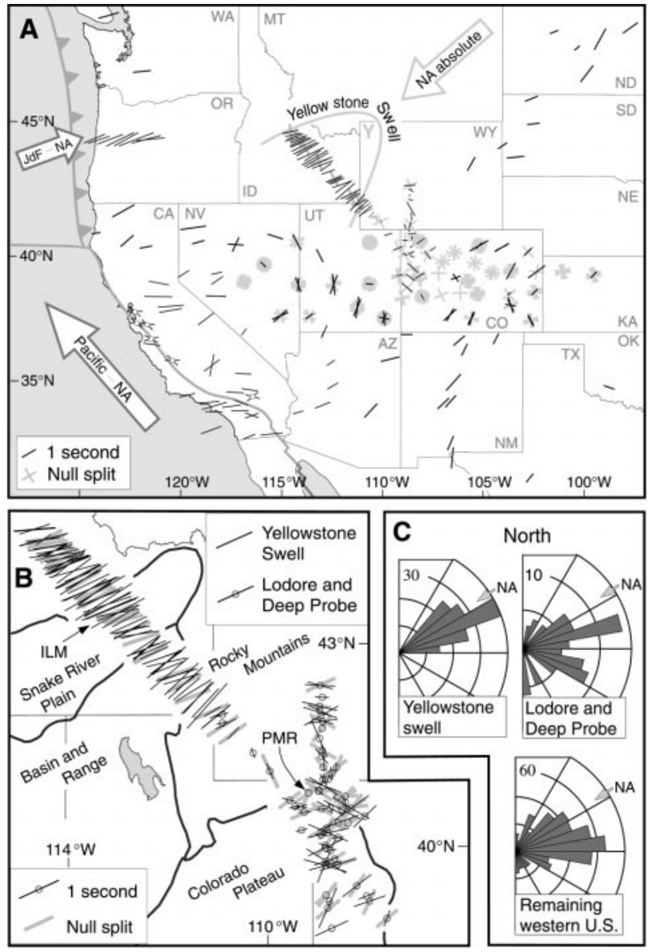

Figure 1. Western United States SKS splits. A: Map of SKS splits. Line length is proportional to split time, oriented with fast-axis direction. Null splits are shown with gray crosses, indicating both possible fast-axis orientations. Dots indicate sites where two layers of anisotropic mantle are interpreted (Savage and Silver, 1993). For clarity, some split data are not shown in densely sampled areas, and splits near Yellowstone swell are station averages. Arrows show directions of plate motion, either North America (NA) absolute (Gripp and Gordon, 1990) or, for Pacific and Juan de Fuca (JdF) plates, with respect to North America (DeMets et al., 1990). Bold lines show plate boundaries (strike slip and, for toothed line, subduction) and margin of Yellowstone swell. Y indicates current location of Yellowstone hotspot. B: Detailed map of SKS splits measured by three arrays highlighted in our study. Choices of null split orientations are those most consistent with split orientations at site. Stations ILM and PMR (see Fig. 2) are identified. C: Orientation distribution of SKS splits and null splits, emphasizing uniform orientation of Yellowstone swell splits nearly in direction of North America absolute motion (shown with arrows). Scale showing count is given for each rose diagram.

3A), and application of the best splitting parameters reduces transverse energy by relatively small amounts (Fig. 3B). This behavior probably represents a more complex anisotropy structure (e.g., multiple layers [Saltzer et al., 2000] or three-dimensionally heterogeneous anisotropic mantle) or a less developed anisotropy than exists beneath the Yellowstone swell.

WESTERN UNITED STATES UPPER MANTLE DEFORMATION

The implications of the SKS results on interpretation of upper mantle anisotropy structure are perplexing. A shallow asthenosphere is expected beneath the western United States, on the basis of seismic (Iyer and Hitchcock, 1989; Grand, 1994), thermal (Lachenbruch and Morgan, 1990), and flexural (Forsyth, 1985; Lowry and Smith, 1995; May et al., 1991) arguments. However, the simple-shear strain expected within the asthenosphere (which would align the fast axis in the direction of plate motion) is not obvious in the pattern of SKS splits. Clearly, most splitting observations seen in Figure 1 are not consistent simply with North American absolute plate motion to the southwest (Gripp and Gordon, 1990). For example, the many null measurements in Colorado and Utah are inconsistent with well-developed anisotropy, and fast-axis arrivals display a wide range of orientations.

Most splitting orientations are consistent with the expected finite extension direction associated with the last large-strain tectonic event to affect each region: ongoing Juan de Fuca subduction, east-northeast–directed Eocene subduction at the base of California, Nevada, and Arizona (Coney and Reynolds, 1977), east-directed Sevier contraction in Utah, west- to southwest-directed pre-Basin and Range extension in parts of the Basin and Range province (Gans et al., 1989), a fragment of Farallon oceanic slab left beneath southern California (Humphreys, 1995), and Precambrian tectonics in the northeast corner of the area shown in Figure 1A (Silver and Chan, 1991). Such a tectonic interpretation, however, ignores the widely held view that the lithosphere is too thin to contribute significantly to SKS splitting throughout most of western United States and does not address the absence of expected strain in the asthenosphere.

One can imagine a variety of passive and active asthenospheric-flow models that give rise to the observed SKS splitting patterns. Savage and Sheehan (2000) suggested one active and two passive asthenospheric-flow models to account for this field, paying special attention to the semicircular arch-like pattern in the Basin and Range province of northern Nevada and western Utah (Fig. 1A). In the passive models, flow associated with North American absolute motion is deflected by protrusions at the base of the lithosphere beneath the Colorado Plateau, Sierra Nevada, and possibly part of the Basin and Range province. However, if North American motion occurs over a relatively stable interior, passive flow should integrate over depth to the absolute plate motion. Such behavior is not reflected in the SKS observations. Even where simple splitting behavior (presumably indicating uniform anisotropy orientation with depth) is reported (e.g., northern Nevada), the fast-axis orientations are not aligned with plate motion. Active asthenospheric-flow models involve some form of small-scale convection (e.g., ascending plumes or delamination). The active-flow model of Savage and Sheehan (2000) has a large plume-like body ascending beneath the northern Basin and Range, which they suggest may be counterflow associated with a delamination event. For this (or any other) active

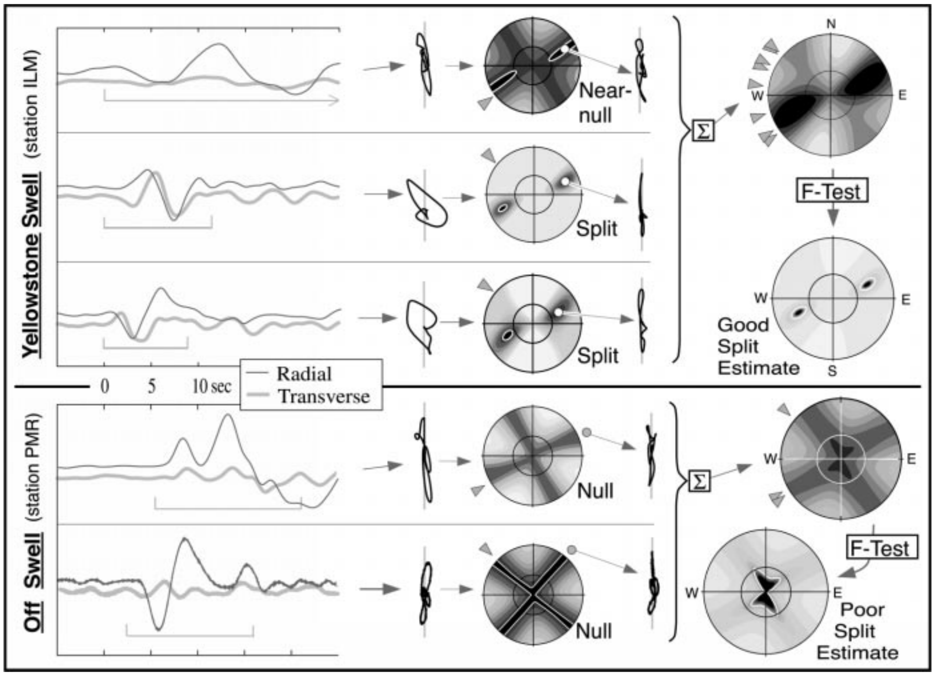

Figure 2. Differences in SKS splitting behavior between sites on and off Yellowstone swell. Examples are taken from stations ILM and PMR (see Fig. 1). Radial and transverse seismograms are shown at left (analyzed over duration shown with bracket). Corresponding particle motion plots are shown immediately to right (vertical lines show radial direction). Next column of plots shows magnitude of transverse energy remaining after correction by splitting parameters: orientation and split time (reference circles at 1 s and 2.5 s). Darker shades indicate less transverse energy; perfect correction would yield no energy. White line indicates 1 σ uncertainty area, and white or gray circle indicates best estimate (gray for split times greater than 2.5 s). Earthquake back azimuths are indicated with triangles. Application of best splitting parameters results in particle motion shown at right. Far right column shows sum of transverse-energy magnitude plots, and resulting probability density function, estimated with F-test on summed plots (Schutt et al., 1998). Darker colors are more probable. Contour at 65% confidence level is white. For Yellowstone swell data, splitting measurements are typically of high quality and, for given station, yield splitting parameters that are consistent from event to event. For station PMR, as is typical of stations located away from Yellowstone swell, well-defined splitting measurements are uncommon, and inconsistent splitting parameters result from different earthquakes. Estimated anisotropy orientations for two earthquakes shown differ by ~30°. Also note that estimates for split time are poorly constrained and unrealistically large for individual events (~4 s in this example), whereas combined-event estimate for split time is small.

flow model to dominate the strain field beneath a plate, convective strain must occur at rates exceeding that of the simple shear related to plate motion. Although such a convective event is possible, it is considered unlikely at any given place and time. Calculations of small-scale convection (e.g., Fleitout et al., 1985; Liu and Zandt, 1996) yield strain rates or vertical-flow rates that seldom exceed, respectively, the North American plate rate of 25 mm/yr (Gripp and Gordon, 1990) or asthenospheric strain rates of ~7 × 10^{-15}/s (a simple-shear rate of ~7 × 10^{-15}/s would occur across a 100-km-thick asthenosphere accommodating a plate rate of 25 mm/yr). Circumstances that would have the last increment of strain caused by local, small-scale flow would not be important because generally they would not cause the strains of about >0.5 required to create significant anisotropy (Ribe, 1992; Zhang and Karato, 1995).

CONCLUSIONS

Various explanations have been suggested for the complex western United States SKS orientations that rely on ongoing local asthenospheric processes. However, if one assumes that asthenospheric simple shear accommodates plate transport, as is standard in plate tectonic theory, it appears to us that the simple shear expected across the asthenosphere would dominate deformation to produce a more or less uniform southwesterly trend to fast-axis split waves. Hence, we take the lack of a coherent anisotropic pattern (Fig. 1A) and presence of complex splitting behavior in the western United States south of ~lat 41°N (Figs. 2 and 3) as evidence for plate-like coherency through most of the depth interval where dislocation creep of olivine is the dominant deformation mechanism. Gaherty and Jordan (1995) suggested that the ~250-km-deep Lehmann seismic discontinuity separates anisotropic mantle above from isotropic mantle below, and Karato (1992), using rheologic parameters controlling olivine deformation physics, calculated that dislocation creep dominates deformation above the Lehmann discontinuity. It appears that much of the western United States mantle in the depth interval typically associated with asthenosphere moves as a coherent unit, in spite of the fact that this mantle has a low strength (e.g., Lowry and Smith, 1995).

One possibility is that only the deepest mantle within the dislocation-creep deformation domain accommodates plate transport; then, any coherent SKS splitting would be destroyed as SKS waves propagated up through more complex mantle (Saltzer et al., 2000). If so, this zone of mechanical decoupling between the plate and Earth's interior (i.e., asthenosphere in its traditional sense) is deeper than usually assumed. Furthermore, it seems likely that a large fraction of strain accommodation must occur even deeper, outside of this narrow zone.

Another possibility is that most strain accommodation occurs largely below the upper mantle, such as within the potentially weak transition zone between 410 and 670 km (Forte and Mitrovica, 1993; Peltier and Jiang, 1996; King and Masters, 1992) or by superplasticity across the 410 km discontinuity (Panasyuk and Hager, 1998). Strain in the shallow mantle beneath the Yellowstone swell presumably occurs nearer to the surface because of unusual conditions in this mantle (e.g., anomalously high temperatures that make it weaker or plume-related pressure gradients that drive local flow). The plausibility of such deep strain accommodation is made attractive by the fact that North America's ~300-km-deep cratonic root (Grand, 1994) moves with the continent. It is our suggestion that this thick-continent behavior extends down into the region where traditional asthenosphere is expected. Thus, if one thinks of the asthenosphere as the depth interval accommodating plate motion, then perhaps the asthenosphere beneath continents is deeper than normally thought.

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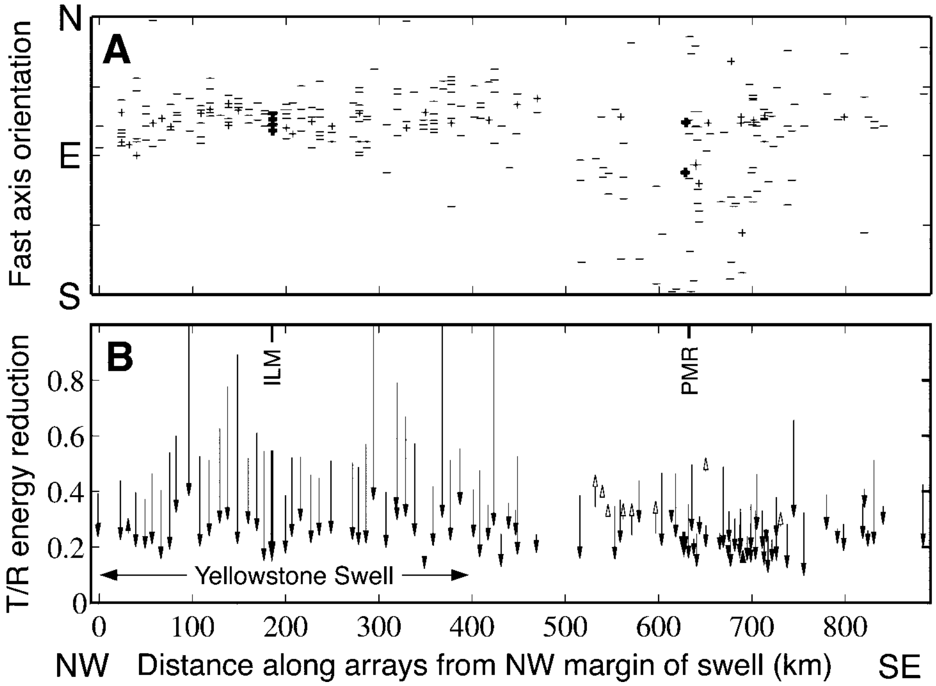

Figure 3. Summary of splitting behavior across Yellowstone swell and beyond, showing that differences in behavior illustrated in Figure 2 are typical for stations in their respective areas. A: Orientation of fast SKS arrival as function of location. Dash symbols indicate splitting estimates, and plus symbols represent null splits (where orientation closest to average split is shown). Dashed gray line shows North America absolute motion (e.g., hotspot reference frame of Gripp and Gordon, 1990). Bold symbols show results illustrated in Figure 2. In contrast to splitting orientations southeast of Yellowstone swell, splitting orientations from swell are generally consistent at each station and among stations, and they align nearly with orientation of North America absolute velocity. B: Reduction in transverse root mean square (RMS) energy (normalized by radial RMS value) that occurs through application of best splitting parameters. Tail shows initial ratio and head shows corrected ratio. Open arrows indicate cases in which ratio of transverse to radial energy increased. Dashed lines indicate average initial (upper lines) and corrected (lower lines) values for Yellowstone swell data and off-swell data. Transverse energy and transverse-energy reductions are smaller for sites east of Yellowstone swell.

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