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Mantle Flow at a Slab Edge: Seismic Anisotropy in the Kamchatka Region

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Abstract. The junction of the Aleutian Island and the Kamchatka peninsula defines a sharp turn in the boundary of the Pacific and North American plates, terminating the subduction zones of the northwest Pacific. The regional pattern of shear-wave birefringence near the junction indicates that trench-parallel strain follows the seismogenic Benioff zone, but rotates to trench-normal beyond the slab edge. Asthenospheric mantle is inferred to flow around and beneath the disrupted slab edge, and may influence the shallowing dip of the Benioff zone at the Aleutian junction.

Introduction

When oceanic lithosphere subducts into the mantle, it may undergo trench-axis rollback [*Dewey*, 1980; *Otsuki*, 1989], in which the asthenosphere under the slab is forced out of the way, either downward or along the trench towards the "free" end of the subduction zone. Trench-parallel mantle flow has been proposed for a variety of convergent settings [*Alvarez*, 1982; *Giardini and Woodhouse*, 1986; *Russo and Silver*, 1994; *Yu and Park*, 1994], and simulated in physical analog experiments [*Buttles and Olson*, 1998].

In Kamchatka, land-based observations can probe the upper mantle at and beyond the side edge of a mature subducting slab. A subduction zone underlies southern Kamchatka, terminating at the junction with the Aleutian Arc (Figure 1), where the Pacific plate boundary rotates into a transcurrent shear zone [*Cormier*, 1975]. Kamchatka and eastern Siberia constitute the western extremity of the North American Plate [*Fujita et al.*, 1990; *DeMets*, 1992; *Kogan et al.*, 2000], though some have argued for an Okhotsk subplate in the region [e.g., *Riegel et al.* 1993]. Rapid convergence (60-80 mm/yr) of the Pacific plate relative to North America is accommodated by subduction zones that flank the Aleutian, Kamchatka, and Kurile volcanic arcs. Near the Kamchatka-Aleutian junction, the subduction zone lacks deep earthquakes, and Benioff-zone dip decreases from 55° to 35° [*Gorbatov et al.*, 1997]. Magmatism shifts inland, following the shallowing slab. Present-day activity terminates in the vigorous Klyuchevskoy and Sheveluch volcanic centers.

Lattice-preferred orientation (LPO) of olivine and orthopyroxene crystals is thought to form by ductile flow in upper mantle peridotite [*Ribe*, 1992; *Zhang and Karato*, 1995]. Olivine is highly anisotropic, and constitutes 40–60% of the mantle above 420 km depth. Mantle flow, both ongoing and fossil, is the likely cause of shear-wave birefringence in teleseismic body waves [*Vinnik et al.*, 1984; *Russo and Silver*, 1994] and Love-to-Rayleigh scattering in long-period surface waves [*Yu and Park*, 1994; *Levin and Park*, 1998].

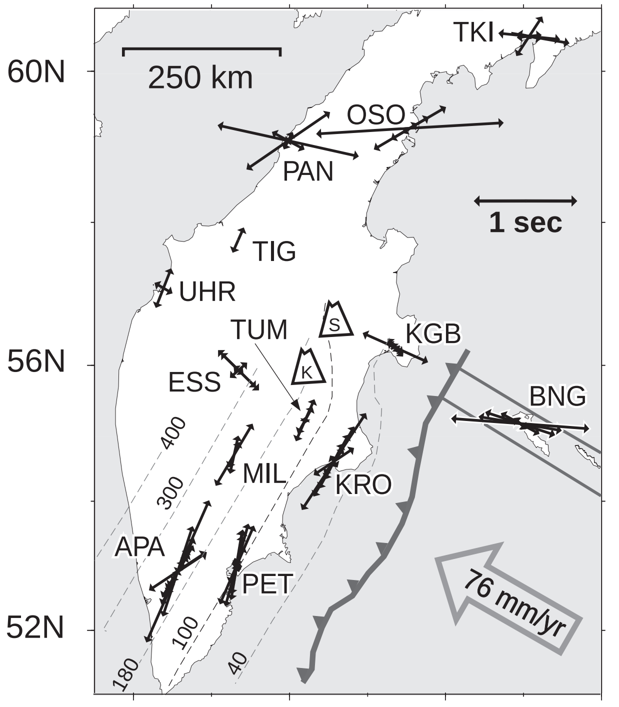

Figure 1. Shear-wave splitting observations at permanent seismological station PET and a portable broadband seismic network in the Kamchatka region. Arrows represent single-record birefringence observations. The contours of the Benioff zone under Kamchatka are adapted from *Gorbatov et al.* [1997]. The thick gray arrow shows Pacific plate motion that leads to subduction along the Kamchatka trench and transcurrent motion along Bering Fault. The transcurrent boundary, distributed across the overriding North American plate [*Geist and Scholl*, 1994], is indicated by two thin grey lines. Two volcanoes are marked on the map: *K* - Klyuchevskoy; *S* - Sheveluch.

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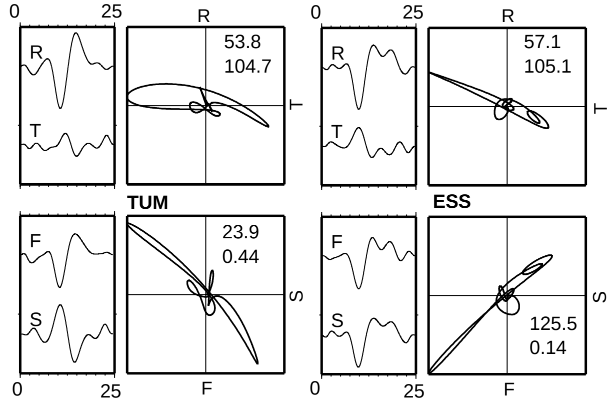

Figure 2. Shear wave splitting examples for stations TUM (left four panels) and ESS (right four panels). For each station, the upper left panel graphs the horizontal waveforms of the observed shear phase, rotated into the radial-transverse coordinate frame. Birefringence in the waveform is manifested by ellipticity of the particle motion (upper right panels). The numbers in the particle-motion box are back-azimuth and epicentral distance, in degrees. For each station, the lower left panel graphs the waveforms rotated into the fast and slow polarizations, with the slow component advanced by the estimated splitting delay. The lower right panel graphs corrected near-rectilinear particle motion. The numbers in the particle-motion box are fast-polarization azimuth in degrees and time delay (in seconds) between fast and slow components.

These effects are absent if the anisotropy has a vertical axis of symmetry, and so are indicators of lateral mantle flow.

SKS Splitting in Kamchatka

We analyzed data from station PET of the Global Seismographic Network and 12 broad-band seismic observatories deployed in Kamchatka from mid-1998 to mid-1999. Figure 1 plots shear wave splitting observations for core-refracted shear phases discernible above the noise, typically after lowpassing at periods $T > 5$ s. At some stations (KRO, OSO) only waveforms lowpassed at $T > 10$ s were useful, due to surf noise. Many SKS observations involved phases arriving from the northeast (sources in Central and South America). Splitting observations at other backazimuths originated in the southern Pacific, central Atlantic and Indian Oceans. An electronic supplement file lists all observations of shear wave splitting for each station, with directions of approach and uncertainty estimates, performed using the cross-correlation technique described in *Levin et al.* [1999]. The small number of observations prevent us from interpreting backazimuth and incident-angle variations in splitting values, behavior that could resolve depth variation in anisotropic parameters [*Levin et al.*, 1999]. However, fast-polarization direction is consistent within groups of adjacent stations, and the inferred orientation differences can be confirmed in simultaneous SKS waveforms from single events (Figure 2).

Shear-wave birefringence (splitting) parameters for SKS phases fall into two groups. Stations located above the Benioff zone (APA, PET, KRO, MIL, TUM) show a trench-parallel fast-polarization direction. Stations away from the slab show other fast-polarization orientations. Trench-normal directions at sites near the Kamchatka-Aleutian junction (ESS, KGB, BNG) rule out a continuous trench-parallel mantle fabric beyond the plate boundary corner, as might be expected for strong trench-parallel flow. Trench-normal splitting at ESS, in particular, argues that the slab does not extend downdip beyond its seismogenic zone. This interpretation agrees with seismic tomography studies [*Gorbatov et al.*, 2000] which report low seismic velocity beneath central Kamchatka. Few SKS phases exhibit splitting delay times $\delta t > 1$ s, and these are mostly recorded at the northern stations. Typically, splitting delays of $0.4 < \delta t < 0.8$ s, with formal uncertainties of 0.1–0.3 s, define the fast-polarization trends in Figure 1. Figure 2 shows a clear SKS phase simultaneously observed at stations TUM and ESS, yielding different birefringence parameters: trench-parallel fast-polarization and a delay of 0.44 sec at TUM; and trench-normal fast-polarization and a very small delay at ESS.

The product of anisotropy and layer thickness produces the splitting delay δt. If we assume 3% anisotropy with mean $V_s = 4.5$ km/s, a shear wave that traversed 90 km would accumulate $\delta t = 0.6$ s, consistent with a typical δt estimate from our data set. For the same δt, a thicker strained layer would imply weaker anisotropy. Previous "source-side" estimates of mantle anisotropy near Kamchatka [*Kaneshima and Silver*, 1992; *Fischer and Yang*, 1994] were based on the differential splitting of teleseismic shear-phase pairs (e.g., S and sS) recorded at stations in North America. Our splitting delays δt are significantly smaller than the source-side estimates, which range between 1 and 2.35 s. Therefore the level and/or extent of anisotropic mantle beneath Kamchatka is less than indicated by earlier studies.

Discussion

Two lines of evidence support the notion that the trench-parallel SKS splitting at APA, PET, KRO, MIL, and TUM originates below the Benioff zone: weak local-S splitting and the deformation of mantle xenoliths. S waves from earthquakes within the Kamchatka Benioff zone traverse the supra-slab mantle wedge and crust and do not sample anisotropy within and beneath the slab. For PET and APA, the observed local-S fast-polarization axes vary greatly, with splitting delays $\delta t = 0.1 - 0.3$ s that are much smaller than

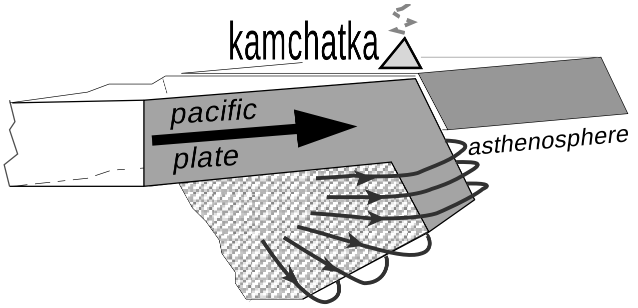

Figure 3. Schematic diagram for slab-edge mantle flow suggested by shear-wave splitting observations from a portable seismic network in Kamchatka. Mantle extension is trench-parallel beneath the slab itself, driven by asthenospheric flow as the slab descends and retreats from the Eurasian landmass. At stations above the slab, shear-wave splitting is trench-parallel. Near the tattered slab edge, asthenosphere flows from beneath the Pacific Plate to beneath the overriding plate. Here the olivine LPO aligns its fast axis with the flow to become trench-normal.

teleseismic splitting values. Similar weak splitting and irregular polarization in local S-waves for Kamchatka earthquakes was found by *Guseva et. al.* [1991]. Mantle xenoliths found at Avachinsky Volcano near PET [*Graybill et al.*, 1999] lack the kind of rock fabric that develops in a simple-shear flow. The xenoliths do not provide evidence for either a subduction-induced corner flow or a trench-parallel shear flow in the mantle wedge. Weak mantle-wedge fabric is consistent with other subduction-zone observations where back-arc spreading is weak [*Fischer et al.*, 1998; *Wiemer et al.*, 1999],and with the tank experiments of *Buttles and Olson* [1998].

We interpret the anisotropy implied by *SKS* splitting in terms of trench-parallel asthenospheric extension and/or flow beneath the Pacific plate. It is unlikely that the strain resides entirely in the slab itself, whether due to along-trench extension or fossil fabric. Present-day slab extension would not occur without strain in the adjoining asthenosphere. As for fossil slab fabric, an extrapolation of magnetic anomalies beyond the Cretaceous “quiet” magnetic zone predicts that the paleospreading direction within the slab under Kamchatka should be near-normal to the trench.

The anisotropic fast-polarization directions for stations that border the shallow seismogenic zone are trench-normal, suggesting strain and/or mantle flow across the plate boundary. Splitting at BNG is likely influenced by the transcurrent deformation along the western Aleutians [*Cormier*, 1975; *Geist and Scholl*, 1994]. Splitting at KGB and ESS argues for flow around and beneath the tattered slab edge. North of the Aleutian junction along an extinct subduction zone bordering the Bering Sea [*Seliverstov*, 1997], splitting at PAN, OSO and TKI is larger and scattered, but inconsistent with any trench-parallel flow. Though 1.3 Ma volcanic rocks have been reported in the region [*Honthaas et al.* 1995], *Hochstaedler et al.* [1994] argue from geochemical evidence that subduction in northern Kamchatka had weakened or halted during the eruption of the Valovayam volcanic field near OSO at 6–8 Ma.

Trench-normal fast-polarization near the Kamchatka-Aleutian corner could indicate the shearing of asthenosphere as the slab falls through it. Trench regression would also induce asthenospheric flow from the Pacific to the North American side of the plate boundary (Figure 3). If trench regression occurs, it is likely smaller than near the Lau Basin and the Phillipine Sea, where back-arc spreading is vigorous. However, the Sea of Okhotsk is thought to be underlain by extended continental lithosphere [*Gnibidenko and Khvedchuk*, 1982; *Melankholina*, 1998], and a central graben divides southern Kamchatka into east and west mountain ranges. Weaker slab regression is plausible, given the small *SKS* splitting delays in Kamchatka.

In tank experiments to simulate the regression of a dipping slab through the mantle, *Buttles and Olson* [1998] observed significant displacement of asthenosphere beneath the slab as well as around it laterally. Beneath Kamchatka, where *Davaille and Lees* [2000] argue that the slab edge may have been lost through small-scale convective instability, such “pass-through” flow is likely. The change in Benioff-zone dip near the Aleutian corner could be facilitated by the loss of the downdip load and a lofting of the plate edge by mantle flow beneath it. A consequent shallowing of the plate edge and the supra-slab mantle would induce pressure-release volcanism, and could be partly responsible for the voluminous Klyuchevshoy volcanism, the inferred contribution of “adakite” slab-derived melts to Sheveluch volcanism [*Kepezhinskas et al* 1997; *Yogodzinski et al* 2000], and the widening of the central Kamchatka graben opposite the plate corner.

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