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Crustal anisotropy in northeastern Tibetan Plateau inferred from receiver functions: Rock textures caused by metamorphic fluids and lower crust flow?

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ABSTRACT

The crust of Tibetan Plateau may have formed via shortening/thickening or large-scale underthrusting, and subsequently modified via lower crust channel flows and volatile-mediated regional metamorphism. The amplitude and distribution of crustal anisotropy record the history of continental deformation, offering clues to its formation and later modification. In this study, we first investigate the back-azimuth dependence of Ps converted phases using multitaper receiver functions (RFs). We analyze teleseismic data for 35 temporary broadband stations in the ASCENT experiment located in northeastern Tibet. We stack receiver functions after a moving-window moveout correction. Major features of RFs include: 1) Ps arrivals at 8–10 s on the radial components, suggesting a 70–90-km crustal thickness in the study area; 2) two-lobed back-azimuth variation for intra-crustal Ps phases in the upper crust (<20 km), consistent with tilted symmetry axis anisotropy or dipping interfaces; 3) significant Ps arrivals with four-lobed back-azimuth variation distributed in distinct layers in the middle and lower crust (up to 60 km), corresponding to (sub)horizontal-axis anisotropy; and 4) weak or no evidence of azimuthal anisotropy in the lowermost crust. To study the anisotropy, we compare the observed RF stacks with one-dimensional reflectivity synthetic seismograms in anisotropic media, and fit major features by "trial and error" forward modeling. Crustal anisotropy offers few clues on plateau formation, but strong evidence of ongoing deformation and metamorphism. We infer strong horizontal-axis anisotropy concentrated in the middle and lower crust, which could be explained by vertically aligned sheet silicates, open cracks filled with magma or other fluid, vertical vein structures or by 1–10-km-scale chimney structures that have focused metamorphic fluids. Simple dynamic models encounter difficulty in generating vertically aligned sheet silicates. Instead, we interpret our data to support the hypothesis of vertical metamorphic-fluid domains whose alignment is determined by shear motion within the boundary layers of crustal channel flow.

1. Introduction

The Tibetan Plateau has the largest area of elevated topography on Earth and is widely considered to be the result of India-Eurasia collision starting ~50 Ma (e.g. Allegre et al., 1984; Yin and Harrison, 2000). The plateau is bounded by the Kunlun Fault in the north and the Indus-Zangbo Suture in the south, and consists of microplates, namely the Lhasa, Qiangtang and Songpan-Ganzi terranes, separated by the Bangong-Nujiang and Jinsha sutures. Due to its complex deformation history, the formation and evolution of the plateau remain in debate. Various formation models have been proposed, such as underthrusting of the Indian Plate (e.g. Jackson et al., 2008; Zhao and Morgan, 1987), underthrusting of the Asian Plate (e.g. Gray and Pysklywec, 2012; Kind et al., 2002; Willett and Beaumont, 1994), and crustal shortening and thickening (e.g. Dewey et al., 1988; England and Houseman, 1989). After formation, crustal flow (e.g. Clark and Royden, 2000; Klemperer, 2006; Royden et al., 1997) mediates plateau spreading and collapse. In addition to kinematic flow effects, regional-scale metamorphism can generate foliation, veining and juxtaposed metasomatized lithologies that generate an effective anisotropy (Connolly and Podladchikov, 2013; Shea and Kronenberg, 1993; Volland and Kruhl, 2004).

Geophysical observations have provided useful constraints on the geodynamic evolution of the plateau. Seismic-velocity structures beneath Tibet using seismic tomography and receiver functions (RFs) have been inferred by Kind et al. (1996), Xu et al. (2007), Yao et al. (2008), Li et al. (2009), Guo et al. (2009), Acton et al. (2010), Yang et al. (2010; 2012), and Jiang et al. (2011). Consistently, the crustal models indicate mid-crustal low-velocity zones (LVZs) across most of Tibet. In addition, magnetotelluric studies have imaged highly conductive zones in the mid-to-lower crust in northern and eastern Tibet (Bai et al., 2010; Unsworth et al., 2004). Both seismic velocity and electrical resistivity can be reduced by increased temperature or the presence of fluids. The observations imply that the deep Tibetan crust has weakened

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(Kirby, 1984), and ductile shear zones or channel flows could occur (Klemperer, 2006; Yang et al., 2012). Thus, finding evidence of crustal deformation is key to improving our understanding of the plateau history.

One of the most powerful approaches to trace deformation processes is by detecting seismic anisotropy (e.g. Long, 2013; Park and Levin, 2002). Anisotropy in seismic-wave propagation can be caused by various conditions, such as aligned cracks, periodic layering, parallel fractures, preferred orientation of mineral grains and metamorphic foliation. The anisotropy of each rock texture can be approximated, to first order, by hexagonal symmetry (transverse isotropy). In Tibet, shear-wave splitting shows various fast-polarization patterns in different areas (Huang et al., 2000; Lev et al., 2006; McNamara et al., 1994). The birefringence of S waves has typically been interpreted with the lattice-preferred orientation (LPO) of upper-mantle minerals, such as olivine. In terms of Tibetan crust, strong radial anisotropy has been detected in the mid-to-lower crust (Duret et al., 2010; Huang et al., 2010; Shapiro et al., 2004; Xie et al., 2013). Radial anisotropy assumes a transverse-isotropic symmetry with a vertical symmetry axis, where horizontally and vertically polarized shear waves travel at different speeds. In contrast, azimuthal anisotropy requires a horizontal or tilted symmetry axis such that seismic velocities vary as a function of incoming wave direction. Observations of azimuthal anisotropy, therefore, are needed to infer the lateral shear predicted by geodynamic models for the plateau.

Azimuthal anisotropy has been investigated in different locales using receiver functions (e.g. Frederiksen and Bostock, 2000; Levin and Park, 1997a, 2000; Park et al., 2004; Peng and Humphreys, 1997; Savage, 1998; Savage et al., 2007; Wirth and Long, 2012, 2014). RF analysis detects interfaces with sharp velocity contrasts beneath the seismic station. Assuming that source and path effects are embedded within the vertical component of the P-wave coda, the deconvolution of horizontal components from the vertical component produces radial RFs and transverse RFs. Radial RFs are sensitive to isotropic seismic structure. Transverse RFs are sensitive to anisotropic layering and/or a dipping interface. Analysis involving both radial and transverse component will provide a good estimate of seismic structure.

In central and eastern Tibet, crustal anisotropic or dipping structures have been detected by RF waveform modeling (Ozacar and Zandt, 2004; Sherrington et al., 2004). Alternatively, an average azimuthal anisotropy of the crust can also be estimated by harmonic analysis of the Moho Ps arrival time (Liu and Niu, 2012) to determine its birefringence. Sun et al. (2012) observed significant anisotropy with 0.5 s–0.9 s birefringence time in the southeastern Tibetan crust. In their study, this birefringence was associated with 6% anisotropy distributed evenly in the lower crust. However, seismic anisotropy may exist in single or multiple crustal layers rather than throughout the lower crust. Levin and Park (1998) demonstrated that Ps converted waves from the top and bottom of a thin shear zone would mimic the effect of Ps birefringence in a uniformly strained crust. It is important to determine how seismic anisotropy is distributed through the crust. A crust composed of thin shear zones would be preferred over evenly distributed anisotropy if Ps converted phases with harmonic back-azimuth variations are generated at many levels within the crust. Shiomi and Park (2008) extracted the back-azimuth harmonics of both radial and transverse RFs as a function of the incoming P-wave direction, suggesting thin anisotropic layers along dipping interfaces beneath the Kii peninsula above the Nankai subduction zone.

In this study, we apply the harmonic-decomposition technique (Bianchi et al., 2010; Shiomi and Park, 2008) to 35 stations of the ASCENT temporary network (Yang et al., 2012) in northeastern Tibet. Harmonic stacks of RFs from these stations offer strong evidence for layered seismic anisotropy through much of the thick Tibetan crust, consistent with complex deformation. Because the RF stacks of most stations share common features in the arrival times of anisotropic signals, we run trial-and-error forward modeling on five selected stations with the most clear and robust RF signals that can be interpreted most readily with simple layered models. In the current paper, combining individual RFs from neighboring stations is not performed due to the weak clustering of the mid-crust piercing points. In this dataset, neighboring stations are typically separated by ~40–55 km. For two stations separated by 40 km to share a common conversion point at mid-crustal depth (~30 km), a phase velocity of ~6.3 km/s is needed (assuming Vs = 3.5 km/s), which is too low for teleseismic waves.

In the following sections, we will show the results from the analysis after a description of the data and harmonic-stacking methods. The Discussion ponders the geophysical implications of our receiver function stacks. Many crustal processes can generate anisotropy, and we argue that the geometry of anisotropy can be used to select between options. In particular, we interpret the RFs to reveal two shear zones that bound a lower crust that flows away from the north-converging Indian plate. We argue that the anisotropy that we infer for these shear layers has geometry that does not comport with plausible lattice-preferred orientation (LPO) of sheet-silicate minerals, whose slow axes of symmetry ought to dominate the LPO (Okaya and Christensen, 2002; Shea and Kronenberg, 1993). We argue instead for anisotropic rock textures caused by veining, cracking, channelized metasomatism or other macroscopic processes. These processes associated with regional metamorphism have been invoked to explain lower crust exposures of older continental collisions (Ague, 1995, 2003; Bohlen et al, 1985; Connolly and Podladchikov, 2004; Dörr and Zulauf, 2010; McLelland, 1984; Valley et al., 1990), and are plausibly active within the deep crust of Tibet. Finally, we observe that the lowermost layer of the crust has mafic V_P (~7 km/s) and lacks strong anisotropy. We suggest that this mafic layer has not underthrusted laterally along the Moho, but has formed in place as a mafic granulite, either via ponded melts from the mantle (Fountain, 1989) or via intense metamorphism of Tethyan dolomitic and pelitic sediments (Ague, 2003; Orville, 1969).

2. Data and method

2.1. Data

We compute RFs using three-component seismic data from ASCENT network (and station CBNAQ) in northeastern Tibet (Fig. 1). Ground motion was sampled at 25 Hz. We chose 35 stations with available data from 2007 (or 2008) to 2009, which provides good back-azimuth coverage. We selected teleseismic events (epicentral distance $30° < D < 100°$) with $M > 5.5$ to ensure a high signal-to-noise ratio (Fig. 2).

2.2. Methods

2.2.1. Receiver functions processing

Receiver functions are estimated in the frequency domain from multiple-taper spectrum estimates (Park and Levin, 2000). Multitaper spectrum estimates balance resistance to spectral leakage against spectral information in a fixed bandwidth (Park et al., 1987; Thomson, 1982). To derive RFs, the E and N horizontal components of seismic records are rotated to the radial–transverse (R–T) system. We high-pass the seismic records at $f = 0.03$ Hz to eliminate long-period drift and to select data with high signal-to-noise ratio. We use a time-bandwidth product of $p = 2.5$ and apply the first three eigentapers to the first 80 s of the original data series to compute three “eigenspectra” that are statistically uncorrelated. We deconvolve the R and T time series from the Z (vertical component) time series via a least-squares correlation between their eigenspectra. Multitaper correlation is more stable than spectral division in the frequency domain (Park and Levin, 2000), and does not require water-level damping with real data. Uncertainties are estimated from the coherence between horizontal and vertical components (Park and Levin, 2000). Finally, we compute time-domain RFs by applying the inverse fast Fourier transform (FFT) to the frequency-domain RFs. To achieve a layer resolution of 3–4 km, we choose a cutoff frequency of $f_C = 1$ Hz, tapering the spectrum band-edge to suppress Gibbs-effect oscillation in the inverse FFT.