Tectonophysics 462 (2008) 99–108

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Seismic anisotropy indicators in Western Tibet: Shear wave splitting and receiver function analysis

Vadim Levin [a,*], Steven Roecker [b], Peter Graham [a], Afsaneh Hosseini [b]

[a] Department of Earth and Planetary Sciences, Rutgers University, United Sates
[b] Department of Earth and Environmental Sciences, RPI, United Sates

ARTICLE INFO

Article history:
Received 1 February 2007
Received in revised form 25 February 2008
Accepted 5 March 2008
Available online 22 August 2008

Keywords
Crust
Upper mantle
Tibet
Seismic structure
Anisotropy

ABSTRACT

Using recently collected data from western Tibet we find significant variation in the strength, vertical distribution and attributes of seismic wave speed anisotropy, constrained through a joint application of teleseismic shear wave splitting techniques and a study of P-S mode-converted waves (receiver functions). We find that the crust of Tibet is characterized by anisotropy on the order of 5%–15% concentrated in layers 10–20 km in thickness, and with relatively steep (30°–45° from the vertical) slow symmetry axes of anisotropy. These layers contribute no more than 0.3 s to the birefringence in teleseismic shear waves, significantly smaller than splitting in many of the observations, and much smaller than birefringence predicted by models developed through group inversions of shear-wave recordings. Consequently, we interpret models constrained with shear-wave observations in terms of structures in the upper mantle.

Near the Altyn–Tagh fault our data favor a two-layer model, with the upper layer fast polarization approximately aligned with the strike of the fault. Near the Karakorum fault our data are well fit with a single layer of relatively modest (~0.5 s delay) anisotropy. Fast polarization in this layer is ~60°NE, similar to that of the lower layer in the model for the Altyn Tagh fault site. Assuming that layers of similar anisotropic properties at these two sites reflect a common cause, our finding favors a scenario where Indian lithosphere under-thrusts a significant fraction of the plateau.

Data from a site at the southern edge of the Tarim basin appear to be inconsistent with a common model of seismic anisotropy distribution. We suspect that thick sediments underlying the site significantly distort observed waveforms.

Our ability to resolve features of anisotropic structure in the crust and the upper mantle of western Tibet is limited by the small amount of data collected in a 6 month observing period. We stress the importance of future teleseismic data collection in Tibet over extended periods, to insure better directional distribution of observed seismic sources.

1. Introduction

If only because of its size and level of activity, Tibet is the laboratory of choice for studying ongoing large-scale geodynamic processes. Knowledge of this region has grown rapidly over the past 20 years, but for the most part detailed studies have focused on the more accessible eastern part of the plateau. We know for example that, although the Indian lithosphere appears to underthrust the southern part of the plateau, north central Tibet, where recent and active volcanism is most pronounced, appears to be underlain by relatively warm upper mantle material. Both high attenuation of seismic shear waves (Ni and Barazangi, 1983) and low Pn speeds (e.g., Zhao and Xie, 1993; Namara et al., 1997) characterize the uppermost mantle of northern Tibet. The lack of any conspicuous change in surface features from east to west might be construed as evidence that this pattern of high wavespeeds in the south and low wavespeeds in the north, applies throughout the plateau. However, evidence accumulated over the years suggests otherwise. For example, S-waves passing through the uppermost mantle beneath the western end of the plateau and the Karakorum are advanced a few seconds. Brandon and Romanowicz (1986) suggested very high speeds in this area from Rayleigh wave dispersion; advances of S-wave travel times from earthquakes in Tibet (e.g., Molnar, 1990) and of SS phases that bounce off Earth's surface in this area (Woodward and Molnar, 1995; Dricker and Roecker, 2002) corroborate their inference. In a global study of SS-S travel-time differences, Woodward and Masters (1991) found the sharpest contrast between advanced and delayed SS phases to be between those bouncing beneath western Tibet and beneath adjacent regions. An analysis of SS-S by Dricker and Roecker (2002) suggests that the region of high wavespeed mantle extends as far east as 88°E. Vertical resolution of structure by SS techniques is poor, but

* Corresponding author.
E-mail address: vlevin@rci.rutgers.edu (V. Levin).

0040-1951/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.tecto.2008.03.019

even if a low-Q, low-speed zone exists in western Tibet, surface wave dispersion requires that zone to be very thin (Shapiro and Ritzwoller, 2002). Moreover, intermediate depth earthquakes occur more commonly beneath western Tibet and the Karakorum than nearly everywhere on Earth where subduction of oceanic lithosphere does not occur (Chen and Molnar, 1983). Recent tomographic inversions of surface wave dispersion call for unusually high-speed material in the uppermost mantle beneath this region (Huang et al., 2002; Shapiro and Ritzwoller, 2002; Friederich, 2003; Priestley et al., 2006).

These studies call attention to the unusual nature of the mantle beneath western Tibet. Unlike the more intensely studied eastern part of the plateau where warm upper mantle is envisaged (Ni and Barazangi, 1983; Zhao and Xie, 1993; McNamara et al., 1997), the combination of high seismic wave speeds and intermediate depth seismicity implies relatively low temperature beneath much if not all of western Tibet. It is likely therefore that either western Tibet is at a different stage of development from eastern Tibet, or current geodynamical models for the eastern plateau do not apply to the west.

Our understanding of the tectonics of western Tibet, and hence of Tibet as a whole, is hampered by a lack of detailed observation in this remote area. One such data collection effort was made during a six-month deployment of broadband seismometers in this part of the plateau in 2001. The purpose of the study discussed here is to glean information from this deployment relevant to the distribution of anisotropy in seismic wave speed within the crust and upper mantle beneath western Tibet. Our interest in anisotropy is motivated by the link it provides to the past and present deformation of rocks at depth (e.g., Park and Levin, 2002).

In areas of intense tectonic deformation one may expect systematic fabrics to develop through systematic alignment of mineral crystals in both the crust and the underlying mantle, in olivine of the mantle peridotite (Ribe, 1992) or in mica of crustal rocks (Babuska and Cara, 1991), and also through systematic formation of cracks in near-surface layers (e.g. Babuska and Proz, 1984), and through coherent deformation of rocks in shear zones. A consequence of coherent rock fabric is often a directional dependence (anisotropy) of seismic wave speed. If we can detect anisotropy, and infer the sense of fabric that causes it, we get an insight into the deformation state (or history) of the rocks at depth.

Indicators of seismic anisotropy along the path of a seismic wave are many, including directional variation in arrival times, perturbations to pulse shapes, and the presence of special seismic phases that arise only when anisotropy is present. Although the detection of anisotropy is relatively straight-forward, the characterization and quantification of specific attributes of anisotropic wave speed, such as the exact location of anisotropic material at depth, the sense of anisotropy (fast or slow axis), and the orientation of the axis, are less so.

Although some tectonic environments allow inferences of the causative processes that induce seismic anisotropy (e.g. olivine alignment in case of oceanic lithosphere formation at a mid-ocean ridge, (Hess, 1964; Anderson, 1981), several processes could lead to anisotropy beneath Tibet, and both the extremely thick crust and the continental lithosphere beneath it (if and where it is present) are likely to be anisotropic.

We report observations of anisotropy measured using two techniques, shear-wave splitting and receiver function analysis that complement each other in their sensitivity. The main difficulty with shear-wave splitting observations is the lack of depth resolution, and the primary weakness of the receiver functions (a converted-wave technique) is that it resolves well only the interfaces between regions with homogeneous or smoothly varying anisotropic properties.

We present observations of birefringence from both SKS and PKS phases. Also, at a number of sites with sufficient data coverage, we perform simultaneous inversions of multiple shear-wave observations for anisotropic structure, and test the relative merits of models with one or two layers of horizontal-axis seismic anisotropy, as well as models with arbitrarily oriented anisotropic symmetry axis.

1.1. Data

The data used in this study were collected by a temporary array of broadband seismographs deployed in western Tibet for ~6 months during 2001 by a Sino-French group (Fig. 1; Wittlinger et al., 2004). At some sites data from STS-2 sensors (100 s response) were recorded

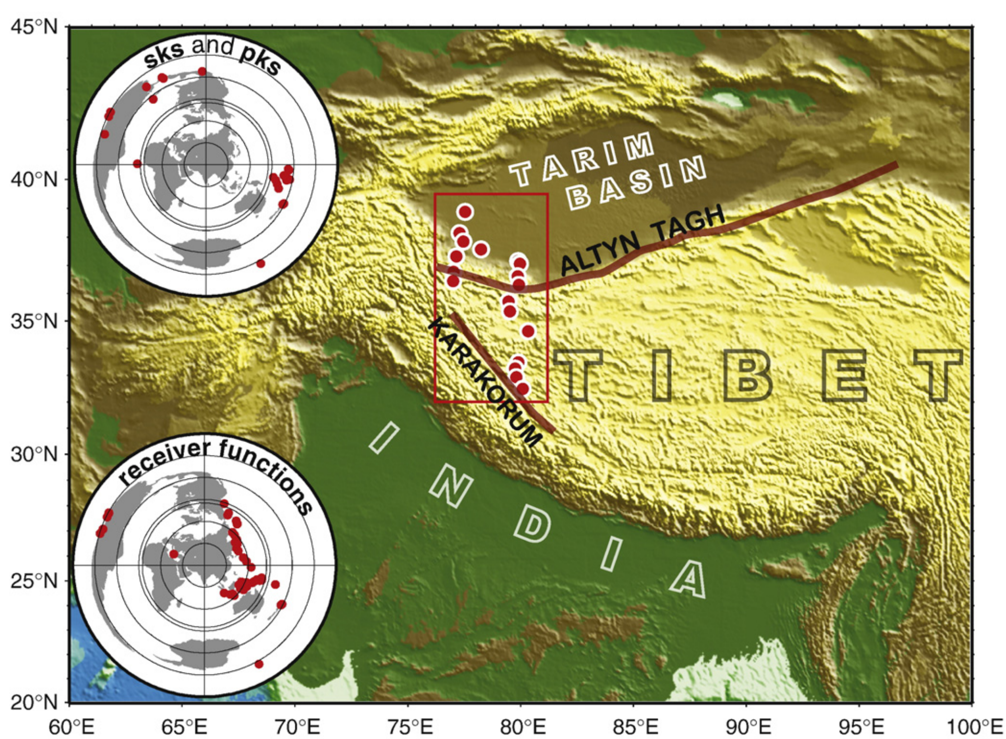

Fig. 1. A map showing regional geography, and the location of the observing array. Red box shows the area presented in Figs. 2 and 5. Insets show earthquakes used in the analysis of shear-wave birefringence (SKS and PKS), and P-S mode-converted waves (receiver functions). Dates and coordinates of these earthquakes are given in Tables A2 and A4.