Evidence for upper crustal anisotropy in the Songpan-Ganze (northeastern Tibet) terrane

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When analyzing teleseismic data, the crust could be locally high and has to be taken into account 25 km of the crust. This study shows that anisotropy in the presence of highly deformed flyschs and schists in the first 20 km of the crust could be locally high and has to be taken into account when analyzing teleseismic data. INDEX TERMS: 7203 Seismology: Body wave propagation; 7205 Seismology: Continental crust (1242); 7260 Seismology: Theory and modeling; 8015 Structural Geology: Local crustal structure.


1. Introduction

The radial and transverse receiver functions obtained at several stations located on the Songpan-Ganze terrane (Tibetan plateau) are characterized by strong P to S conversions in the first 4 s after the direct P wave. We show that the amplitude variations of these phases with back-azimuth can be well explained by a simple model with one or two anisotropic layers. The anisotropy we obtained is quite strong (about 15%) and might be related to the presence of highly deformed flyschs and schists in the first 25 km of the crust. This study shows that anisotropy in the crust could be locally high and has to be taken into account when analyzing teleseismic data.

2. Observations

During the 90’s, Sino-American and Sino-French teams deployed three temporary seismic arrays in northeastern Tibet. Here we mainly focus on the RFs obtained at two of these stations, BUDO and 121E. BUDO is a broad-band station of the Sino-American 91/92 PASSCAL experiment and 121E is an intermediate period (5 sec) station of the Sino-French 98 LITHOSCOPE experiment (Figure 1). At each station, we selected events with epicentral distance between 20° and 80° and with a good signal to noise ratio. Each seismogram is band-passed filtered between 0.05Hz to 0.8Hz. The radial and transverse RFs are computed using a time domain iterative deconvolution and stacked according to the back-azimuth in windows of 20° span with 10° overlapping. At stations BUDO and 121E, separated by ~400 km, the TRFs show two converted phases with similar amplitudes (Figures 2a and 2b). These phases, labeled hereafter PS1 and PS2, have reverse polarities and for some events their amplitudes are larger than on the corresponding RRFs. Both PS1 and PS2 phases amplitudes are approximately sinusoidal versus back azimuth with a period of ~360° and with a phase lag of ~180° between each other. Phase PS2 is clearly identified on the RRFs with a strong negative amplitude for back azimuth between 110° and 270° (i.e. over a span of ~180°) and a positive amplitude, seen well at station 121E, for the azimuths 0° to 110°. Since phase PS1 overlaps the direct P-arrival, it is more difficult to describe clearly. However, the broadening of the P-phase peak between 110° and 270° is an evidence for the existence of this PS1 phase on RRFs and of its ~360° periodicity.
Moreover, for both phases, a 90° phase lag exists between the radial and the transverse components.

3. Source of TRF Energy

Similar observations concerning PS1 and PS2 have been made at other stations in this region (TUNL, 116E, 118E and 123E; Figure 1) although these phases are generally of smaller amplitude. Since these phases are observed at stations not systematically located nearby major tectonic singularities and since these stations are separated by hundreds of kilometers, this rules out diffraction on heterogeneities as a possible cause of these observations. Repetitive observations of phases with significant energy in the first 4 s after the direct P-arrival on the transverse component is therefore an evidence that the upper 25 km of the crust cannot be simply modeled by flat and isotropic layers. The existence of a steeply dipping interface in the upper crust of the same Songpan-Ganze region has already been proposed [Zhu et al., 1995]. However the observed small azimuthal dependence of the relative time-delay of the PS phase favor a model with horizontal anisotropic layers rather than inclined interfaces. Moreover, the azimuthal periodicity and phase lags between radial and transverse components observed for PS1 and PS2 phases, is in agreement with the existence of anisotropic layers in the upper crust. Under the single assumption of transverse anisotropy with a horizontal axis of symmetry, the two PS phases generated at the base and the top of an anisotropic layer (respectively PS2 and PS1), are 180° periodic on both the TRF and RRF [Vinik and Montagner, 1996]. However, these amplitudes will increase and the periodicity can reach 360° if the axis of symmetry is tilted [Savage, 1998]. The behavior of PS1 and PS2 phases can thus become very similar to the observed one. Moreover, if the anisotropic layer producing PS1 and PS2 phases does not reach the surface, i.e. if we suppose the uppermost layer isotropic, then no energy is observed on TRFs at the time corresponding to the direct P-wave arrival. The lack of energy, at time t = 0 s at station 121E (Figure 2b), cannot be explained solely considering a dipping interface and isotropic layers.

4. Processing

The inversion of RFs to recover layer thickness and wave velocities is non-unique even in flat-layered isotropic media [Ammon et al., 1990]. Adding anisotropy parameters would even worsen this non-unicity. For this reason, we use only forward modeling and show that synthetic RFs computed for very simple models, including 2 layers, fairly match the observations at BUDO and 121E.

Synthetic seismograms in a stack of flat anisotropic layers are generated with a method based on Thomson-Haskell propagator matrices. We consider only transverse anisotropy with the angle ϕ referring to the orientation of the symmetry axis (counter clockwise from the north), and the angle δ to its tilt (from the horizontal, positive down). In such medium, the phase velocity surfaces can be represented by quasi-ellipsoids for which the amount of P and S anisotropy, dVp and dVs, controls the ellipticity, and the parameter η controls the distortion from the pure ellipsoid [Girardin and Farra, 1998]. For highly anisotropic crustal rocks such as schists dVp/Vp and dVs/Vs are negative (which corresponds to slow axis of symmetry) and may

Figure 1. Topography of northeastern Tibetan plateau and location of the two profiles. Stars and squares stand for stations that exhibit a clear anisotropic signature on RFs. White bolt arrows with length proportional to anisotropy percentage indicate the mean direction of the (slow) axis of symmetry in anisotropic layers (see text for details).

Figure 2. (a) Stack over 20° back-azimuth intervals of radial (RRF) and transverse (TRF) receiver functions at station BUDO, ordered with back-azimuth. The number of stacked RF and the mean ray parameter (in brackets) are written between the RRF and TRF traces. Arrows mark phases P, PS1 and PS2 discussed in text. (b) Same as (a) but for station 121E.
reach values as high as −20%, while \( \eta \) ranges between 0.4 and 0.9 [Godfrey et al., 2000].

[10] As phases PS1 and PS2 are generated respectively at the top and at the base of the anisotropic layer, our models are simple. Layer L1 is the upper layer, considered isotropic or anisotropic. Layer L2 is anisotropic and the underlying half space isotropic. We use the back-azimuths and ray parameters of the observations to compute the synthetic RRFs and TRFs. If the top and the base of anisotropic layers are assumed horizontal, then \( \varphi \) can be well defined and corresponds to the back-azimuth for which the energy of corresponding PS converted waves vanishes on TRFs. For both stations 121E and BUDO, this occurs for a back azimuth of \( \approx 30^\circ \pm 180^\circ \). Since the periodicity of PS1 and PS2 phases is close to 360°, the anisotropy symmetry axis could no longer be considered as horizontal. Depending on the value we consider for \( \eta \), a \( \sim 360^\circ \) periodicity is obtained for a tilt \( \delta \) between 30° to 70°. The thickness and velocities of each layer are linked together by a strong trade-off and thus are the less accurately determined parameters in this forward modeling. We reduce this trade-off by fixing \( V_p \) at 6.1 km/s and \( V_s \) at 3.6 km/s in the underlying half space according to results derived from a seismic refraction survey [Galvé, 2002] and \( V_p/V_s \) estimations [Vergne et al., 2002]. Thicknesses and velocities of layers L1 and L2 are estimated from the arrival times and amplitudes of phases PS1 and PS2 on RRFs. The parameters \( dV_p/V_p \), \( dV_s/V_s \) and \( \eta \) are deduced from the amplitudes and variations with back-azimuth of phases PS1 and PS2 on TRFs. The retained models for stations BUDO and 121E are given in Table 1. Similar models, but with lower values of \( dV_p/V_p \) and \( dV_s/V_s \) values sometimes reaching −20% [Christensen, 1965; Godfrey et al., 2000]. Thus, combined anisotropy from layering and intrinsic rock properties may account for the average 15% of anisotropy that we have to introduce in layer L2. The \( \sim 45^\circ \) tilt of the symmetry axis in layer L2 might be related to dVp/Vp and dVs/Vs generally up to only 5%.

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Vp (km/s)</th>
<th>Vs (km/s)</th>
<th>dVp/Vp</th>
<th>dVs/Vs</th>
<th>( \eta )</th>
<th>Az</th>
<th>( \delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 13</td>
<td>6.1</td>
<td>3.9</td>
<td>−15%</td>
<td>−15%</td>
<td>0.8</td>
<td>22°</td>
<td>0°</td>
</tr>
<tr>
<td>L2 26</td>
<td>6.2</td>
<td>3.6</td>
<td>−15%</td>
<td>−15%</td>
<td>0.5</td>
<td>30°</td>
<td>48°</td>
</tr>
<tr>
<td>( \infty )</td>
<td>6.1</td>
<td>3.6</td>
<td>−0%</td>
<td>−0%</td>
<td>1</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

Table 1. Anisotropic Models Retained for Stations BUDO and 121E

5. Possible Origin of Anisotropy

[12] Azimuthal anisotropy caused by lattice-preferred orientation of anisotropic minerals is much weaker in the crust, and particularly in its upper brittle part, than in the mantle. Thus, major causes invoked for crustal anisotropy are generally fine layering [Backus, 1962] or pore and cracks alignments [Babuška and Pros, 1984], both leading to dVp/Vp and dVs/Vs generally up to only 5%.

At stations BUDO and 121E, the high value of dVp/Vp and dVs/Vs we found is an evidence for a more specific source of anisotropy. These stations are located on the Songpan-Ganze terrane, which constitute the only region of the Tibetan plateau that does not originate from a continent-like block. It has been formed by the closure of a Triassic oceanic basin, filled by as much as 15 km thick flysch deposits [Mattauer et al., 1992] coming from the Kunlun block and the Qiangtang block [Bruguière et al., 1997]. During the shortening of this region, this sediment layer should have been thickened and its lower part might have been methamorphized to schist-like rocks due to temperature and pressure conditions. The presence of such kind of schists is observed, below a 16 km thick sedimentary column, in the gulf of Bengal [Curray, 1991], a region where the rapid infill and the huge amount of deposits might be very similar to what occurred in the past for the Songpan-Ganze region [Nie et al., 1994]. Schists are known to be highly anisotropic with dVp/Vp and dVs/Vs values sometimes reaching −20% [Christensen, 1965; Godfrey et al., 2000]. Thus, combined anisotropy from layering and intrinsic rock properties may account for the average 15% of anisotropy that we have to introduce in layer L2. The \( \sim 45^\circ \) tilt of the symmetry axis in layer L2 might be related to the lack of energy at time t = 0 s on TRF.

![Figure 3. Synthetic receiver functions computed with model given in Table 1 and stacked in the same manner as the observations, (a) for station BUDO and (b) for 121E.](image-url)
to the main orientation of schistosity resulting from Mesozoic and Cenozoic deformation of this layer. The average orientation of the symmetry axis (30°), which is perpendicular to the Jinsha and the Kunlun suture, correlates with the main direction of compression of the sediment and metamorphic complex. We note also that underplating of the Songpan-Ganze crust toward the south and/or toward the north [Kapp et al., 2000] during the Triassic might explain why the anisotropic layer L2 has also been detected at stations ERDO and TUNL (Figure 1) which both stay out of the actual limits of the Songpan-Ganze terrane.

6. Discussion and Conclusion

[14] The strong and coherent seismic energy observed on TRFs at several stations located in the Songpan-Ganze terrane could be explained by significant anisotropy, with a tilted axis of symmetry, localized in an upper-crustal layer between ~10 and ~25 km depth. This is an alternative explanation to the one invoking a 20° south-dipping interface at ~25 km depth [Zhu et al., 1995]. To match the observed amplitude and polarity of PS2 phase on the RRFs, this dipping interface has to be associated with a 22% decrease of Vp. Such a strong velocity inversion has already been advocated and attributed to a thick low velocity zone caused by partial melt in the northeastern Tibetan crust [Owens and Zandt, 1997].

[15] We favor the anisotropy hypothesis rather than the dipping interfaces one, for two main reasons. Firstly, we showed that one anisotropic layer is sufficient to explain both PS1 and PS2 phases, whereas a dipping interface will only produce the phase PS2. Secondly, a 20° dipping interface would project energy of the direct P wave on TRFs with a 360° periodicity and with amplitudes similar to PS2. At station 121E, no such signal is visible on TRFs at t = 0 s and at station BUDO, the P wave is of small amplitude as compared to PS2 and shows a clear 180° periodicity. Moreover, the anisotropic model does not require a strong VP inversion at ~25 km depth, and thus, there is no need for a partially melted zone in the middle crust. In turn, this is consistent with the mean crustal Vp/Vs ratio estimated by RF analysis [Vergne et al., 2002] that remains close to the average value of continental crusts. Anisotropy with slow symmetry axis may exist in the upper crust owing to the nature and composition of its rocks and the model proposed here to explain this anisotropy is geologically consistent.

[16] This study shows that anisotropy in the upper crust could be locally very high. Discarding this anisotropy may be misleading in studies where an isotropic crust is assumed. For instance, the anisotropic upper crust under station BUDO produces P-wave arrival time variations versus back-azimuth that reach 0.3 s. Such delays may contribute significantly to the teleseismic travel time residuals that are commonly used to recover the Vp variations in the lithosphere. Furthermore, a strongly anisotropic crust influences SKS splitting for which crustal contributions are generally ignored. In our model at station BUDO, for quasi-vertical incidence, there is a ~0.5 s time delay between the two quasi-shear-waves generated at the base of L2. This might indicate that at BUDO, at least 20% of the amount of shear wave splitting measured on SKS phases (2.4 s at BUDO [McNamara et al., 1994]) would originate from the upper crust.

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