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Crustal origin of trench-parallel shear-wave fast polarizations in the Central Andes

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ABSTRACT

In this study, SKS and local S phases are analyzed to investigate variations of shear-wave splitting parameters along two dense seismic profiles across the central Andean Altiplano and Puna plateaus. In contrast to previous observations, the vast majority of the measurements reveal fast polarizations sub-parallel to the subduction direction of the Nazca plate with delay times between 0.3 and 1.2 s. Local phases show larger variations of fast polarizations and exhibit delay times ranging between 0.1 and 1.1 s. Two 70 km and 100 km wide sections along the Altiplano profile exhibit larger delay times and are characterized by fast polarizations oriented sub-parallel to major fault zones. Based on finite-difference wavefield calculations for anisotropic subduction zone models we demonstrate that the observations are best explained by fossil slab anisotropy with fast symmetry axes oriented sub-parallel to the slab movement in combination with a significant component of crustal anisotropy of nearly trench-parallel fast-axis orientation. From the modeling we exclude a sub-lithospheric origin of the observed strong anomalies due to the short-scale variations of the fast polarizations. Instead, our results indicate that anisotropy in the Central Andes generally reflects the direction of plate motion while the observed trench-parallel fast polarizations likely originate in the continental crust above the subducting slab.

1. Introduction

Seismic anisotropy provides a unique link between the splitting of shear-waves into orthogonally polarized fast and slow components and deformation processes within the earth. It is often interpreted in terms of strain-induced crystallographic preferred orientation (CPO – sometimes also referred to as lattice preferred orientation, LPO) of mineral fabric due to flow fields (Long and Silver, 2009a; Savage, 1999; Buttles and Olson, 1998; Rabbel et al., 2013) or in terms of shape preferred orientation (SPO) due to sub-parallel structures such as stress-induced cracks or fine alternating layers (Park and Levin, 2002; Leidig and Zandt, 2003; Hammond et al., 2010; Buontempo and Wuestefeld, 2012). One of the major constituents of the Earth's mantle, olivine, tends to align under most conditions of deformation with the fast axis sub-parallel to the shear direction, i.e. sub-parallel to the plate motion (Long and Silver, 2009a; Savage, 1999). However, previous studies worldwide have shown that fast polarizations above subduction zones are often oriented perpendicular to the direction of slab movement (Russo and Silver, 1994; Long and Silver, 2008, 2009b; Hanna and Long, 2012; Lynner and Long, 2013). Other studies have reported variations from trench-parallel directions in the fore arc to trench-normal orientations in the back-arc region (Tono et al., 2009; Fischer et al., 2000; Liu et al., 2008). These observations have been explained by models of trench-parallel mantle flow beneath the subducting slabs induced by trench rollback (Long and Silver, 2008, 2009b) or slab geometry (Russo and Silver, 1994; Kneller and van Keken, 2007; Di Leo et al., 2012).

Alternative explanations emanate from mineralogical constraints. Olivine can develop different CPOs depending on water content, pressure, and shear stress conditions (Jung and Karato, 2001; Jung et al., 2009; Katayama and Karato, 2006; Ohuchi et al., 2011). The prevalent A-type fabric (with the (010)[100] slip system as described above) forms in dry olivine under low stress conditions. In water-rich mantle, however, the B-type fabric (with the (010)[001] slip system) can develop when the shear stress is high or when the temperature is rather low. Such conditions are expected in subduction zones. This slip transition is expressed in a rotation of the fast-axis orientation perpendicular to the plate motion. Ohuchi et al. (2012) have further demonstrated that the existence of B-type olivine is most likely restricted to the fore-arc region of the mantle wedge, where water is released from the subducting slab. Serpentine is another highly anisotropic mineral that is likely to occur in subduction zones. Faccenda et al. (2008) suggest that the slab significantly

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contributes to SKS splitting due to a combination of CPO and SPO originating from aligned sub-vertical fluid-filled cracks and serpentinized rocks. Serpentine is also present in the hydrated mantle wedge above the slab, where it also likely develops CPO as a consequence of mantle flow. The resulting serpentine fabric would also contribute with a fast-axis component perpendicular to the flow direction, i.e. sub-parallel to the trench (Katayama et al., 2009; Jung, 2011).

The Nazca–South American margin was one of the first subduction zones where seismic anisotropy has been investigated in greater detail. Russo and Silver (1994) have reported dominant fast axes of trench-parallel orientations with the exception of three confined zones where trench-normal alignments prevail. One of which was interpreted as a stagnation point in the center of the sub-slab mantle flow towards the north and the south while the other two zones coincide with changes of the slab dip influencing the flow field. This interpretation was derived, to a large degree, from investigations of source-side S-wave splitting based on a rather sparse set of intra-slab earthquakes. The corresponding ray paths were, thus, restricted to the sub-slab mantle. The analysis of SKS and local S phases (Polet et al., 2000) recorded at three different temporary networks indicated the existence of a zone, between 18°S and 20°S, where fast axes are predominantly oriented EW, while trench-parallel directions were reported north and south of this area. In the study presented here, we analyze data recorded as part of the ReFuCA project (Heit et al., 2008; Wölbern et al., 2009) along two EW oriented profiles in the Central Andes. From SKS and local S phases splitting parameters are determined to investigate short-scale lateral variations of anisotropy patterns from the Pacific coast near the trench towards the interior of the South American continent. The results are used to test a series of 2D anisotropic subduction zone models to evaluate the effects of different anisotropic zones on the shear-wave propagation and to discriminate between contributions from the mantle and the crust.

2. Shear-wave splitting analysis

2.1. Data and method

Within the ReFuCA project seismic stations were operated along two EW aligned profiles from March 2002 until January 2004. The northern profile at 21°S ranges from the Pacific coast to the Bolivian Interandean Zone while the southern profile transects the Puna plateau at 25.5°S (Fig. 1). The profiles extend over distances of ∼600 km and ∼200 km, respectively, with an average station spacing of ∼10 km (Heit et al., 2008; Wölbern et al., 2009). We investigate SKS phases of events at distances ⩾85° with magnitudes ⩾6.5 and further analyze local S phases from events within the Nazca slab with magnitudes ⩾4.5 and focal depths between 150 and 350 km unless the incidence angle exceeds 30° at the recording station. Based on these criteria we have extracted SKS phases from seven events and also S phases from seven local events of sufficient quality from the ReFuCA data. Source parameters of the selected events are listed in the Supplementary Table S1.

We use a transverse-component minimization method (Silver and Chan, 1991; Rümpker and Silver, 1998; Long and Silver, 2009a) to investigate the shear-wave splitting. At first, seismograms are rotated into the RT coordinate system. A grid-search approach is utilized to find the pair of splitting parameters Φ and δt that best minimizes the energy on the transverse component. This is equivalent to the linearization of the particle motion. Uncertainties are estimated from the extent of the 95% confidence region of the splitting parameters determined from the transverse-component energy (Silver and Chan, 1991). For this purpose we have adopted the corresponding routines of the SplitSlab software

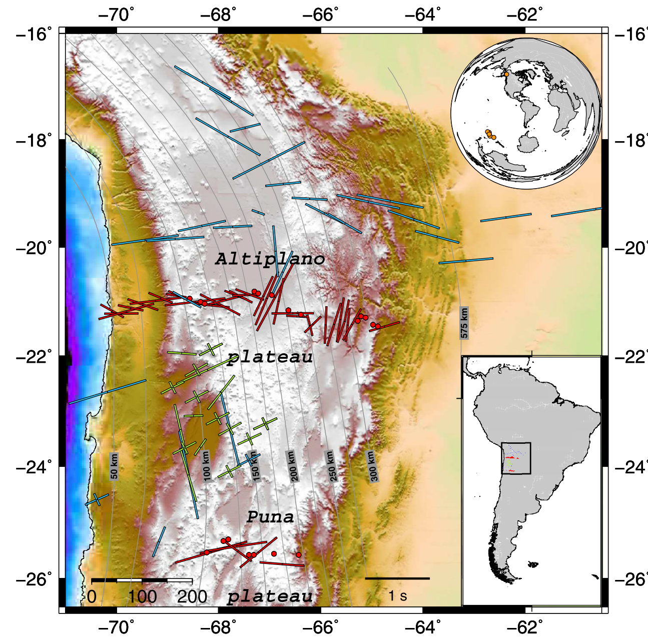

Fig. 1. Splitting parameters obtained from SKS phases. Bars denote orientations of apparent shear-wave fast polarization Φ with the length referring to the delay time δt (see scale at the bottom). Red bars display the new results of our study obtained from a joint-splitting analysis of the ReFuCA data. Dots denote null measurements obtained from joint-splitting. Green bars refer to reprocessed data from the PISCO experiment (Bock et al., 1998) also derived from joint-splitting analysis where applicable. Blue bars illustrate results and errors directly taken from a previous study (Polet et al., 2000). Green and blue crosses mark null measurements with the long bars indicating the orientation of initial polarization. Grey contour lines give the depths to the subducting Nazca slab as derived from local seismicity (Cahill and Isack, 1992). The inset in the upper right corner displays the locations of teleseismic events used in the SKS analysis.

package (Wüstefeld et al., 2008). For the SKS phases we use a bandpass in a frequency range from 0.02 Hz to 0.25 Hz and for the local S phases a frequency range from 0.02 Hz to 1 Hz. In principle, SKS phases are affected by anisotropy of the entire mantle beneath the receiver, whereas local slab events will be mainly affected by anisotropy within the mantle wedge and the overriding plate.

So-called "null" measurements either indicate the absence of anisotropy along the ray path or the alignment of the fast or slow axis of the anisotropic medium with the initial polarization of the observed phase (Long and Silver, 2009a; Hanna and Long, 2012). Alternatively, null measurements can be obtained in the case of two horizontal layers, e.g. if the fast axes orientations differ by 90°, such as a transition from A-type to B-type olivine in the same flow field. The initial polarization of the SKS phase is readily known from the backazimuth of the event location, but we also derive the initial polarization independently from the long-period fraction ($T > 15$ s) of the waveform in order to account for possible misalignments of horizontal components at the stations. The initial polarization of local S phases is determined directly from the long-period particle motion with $T > 5$ s (Rümpker and Silver, 1998).

Event-station pairs with incidence angles ⩾30° have been discarded from the study, because shear phases may be affected by nonlinear particle motion if the incidence angle exceeds ∼35° at the surface (Long and Silver, 2009a; Savage, 1999). It is a frequent problem that Φ and δt determined with this method are sensitive to the selected shear-wave window (Teanby et al., 2004), most likely due to interfering phases or noise. Splitting parameters are, therefore, repeatedly analyzed for a number of randomly selected time windows enclosing the SKS or S wavelet in order to test for