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# Large-scale trench-normal mantle flow beneath central South America

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ABSTRACT

We investigate the anisotropic properties of the fore-arc region of the central Andean margin between 17–25°S by analyzing shear-wave splitting from teleseismic and local earthquakes from the Nazca slab. With partly over ten years of recording time, the data set is uniquely suited to address the long-standing debate about the mantle flow field at the South American margin and in particular whether the flow field beneath the slab is parallel or perpendicular to the trench. Our measurements suggest two anisotropic layers located within the crust and mantle beneath the stations, respectively. The teleseismic measurements show a moderate change of fast polarizations from North to South along the trench ranging from parallel to subparallel to the absolute plate motion and, are oriented mostly perpendicular to the trench. Shear-wave splitting measurements from local earthquakes show fast polarizations roughly aligned trench-parallel but exhibit short-scale variations which are indicative of a relatively shallow origin. Comparisons between fast polarization directions from local earthquakes and the strike of the local fault systems yield a good agreement. To infer the parameters of the lower anisotropic layer we employ an inversion of the teleseismic waveforms based on two-layer models, where the anisotropy of the upper (crustal) layer is constrained by the results from the local splitting. The waveform inversion yields a mantle layer that is best characterized by a fast axis parallel to the absolute plate motion which is more-or-less perpendicular to the trench. This orientation is likely caused by a combination of the fossil crystallographic preferred orientation of olivine within the slab and entrained mantle flow beneath the slab. The anisotropy within the crust of the overriding continental plate is explained by the shape-preferred orientation of micro-cracks in relation to local fault zones which are oriented parallel to the overall strike of the Andean range. Our results do not provide any evidence for a significant contribution of trench-parallel mantle flow beneath the subducting slab.



## 1. Introduction

The subduction of an oceanic plate beneath a stable continent is one of the major geodynamic processes. However, the deformation of the mantle beneath the plates and the resulting flow fields have been subject to a long-standing debate, where two contradicting hypotheses have been put forward: on one hand it is thought that mantle material above and below the subducting plate is entrained by the down-going slab such that the surrounding flow is aligned parallel to the down-dip direction of subduction; alternatively, the slab and the underlying mantle may be decoupled such that the flow beneath the slab aligns parallel to the trench in response to large-scale compressional forces acting along the plate boundary. This can be investigated by the observation of shear-wave splitting, i.e. the splitting of a shear-wave into orthogonally polarized fast and slow components due to seismic anisotropy. This, in turn, provides direct constraints on the dynamic processes of earth's interior as seismic anisotropy is thought to be caused by the response of crustal and mantle materials to strain. In the mantle, anisotropy is usually due to the crystallographic preferred orientation (CPO) of olivine (Savage, 1999; Long and Silver, 2009b), the main constituent of the upper mantle. Using an experimental set-up with simple shear, which is most likely the dominant mode of deformation in the upper mantle, Zhang and Karato (1995) showed that the a-axis of olivine aligns in the direction of flow for large strains assuming relatively dry conditions. In the crust, alternating sedimentary layers or oriented cracks cause shape-preferred orientation (SPO) of anisotropy (Crampin, 1994; Park and Levin, 2002). The orientation and strength of an anisotropic fabric can be inferred from the polarization of the fast-wave component ($\phi$) and the delay time ($\delta t$) between fast and slow components, respectively.

In this context, subduction zones yield a complex signal of shear-wave splitting as the mantle flow beneath the slab, the slab itself, the mantle wedge and the overriding plate may all

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contribute different anisotropic signatures (Long and Silver, 2008, 2009a; Long et al., 2016). During plate formation at the mid-ocean ridges, the mantle flow produces CPO parallel to the spreading direction which is then 'frozen-in' as the plate cools (Hess, 1964; Becker et al., 2014). Additionally, the rigid movement between the plate and upper mantle can cause significant CPO parallel to plate motion (Savage, 1999). During the subduction process, the mantle flow field and thus the anisotropic pattern may be affected by the retrograde motion of the subducting slab, trench migration and geometry of the slab itself (Russo and Silver, 1994; Long and Silver, 2008; MacDougall et al., 2012).

In the fore-arc region, additional mineralogical and geodynamical constraints must also be considered. Faccenda et al. (2008) suggests that a combination of CPO and SPO develops in the slab from hydrated faults and serpentinized minerals. Furthermore, the relationship between flow and alignment of the olivine a-axes may not be as simple as previously suggested. While the A-type olivine may form in low stress and dry conditions, Jung and Karato (2001) demonstrated that temperature, pressure, and water content have a significant impact on the development of the slip system. For subduction systems, B-type olivine, which has a fast axis perpendicular to the flow direction, may be prevalent in the fore-arc region in a water-rich mantle (e.g. Ohuchi et al., 2012). Both mechanisms lead to trench-parallel fast polarizations, while the flow remains aligned with the down-dip direction. Above the slab, a possible two-dimensional corner flow within the mantle wedge is conceivable, which is induced by the downward motion of the slab (Long and Silver, 2009a) and causes olivine crystals to align parallel to the plate motion.

The South American margin was one of the first regions where trench-parallel flow due to retrograde motion of the slab combined with a flow barrier at depth was proposed (Russo and Silver, 1994). Shear-wave splitting results yielded fast polarization directions which were mostly interpreted to be trench-parallel with the exception of three confined areas, of which one was explained by a stagnation point of the mantle flow field. In a later study, a 150-km wide stagnation zone, centered at ∼18°S, was proposed (Polet et al., 2000). Since then, many more studies along the Nazca subduction were carried out (Bock et al., 1998; Anderson et al., 2004; MacDougall et al., 2012; Hicks et al., 2012; Eakin and Long, 2013; Wölbern et al., 2014; Eakin et al., 2015, 2016; Long et al., 2016). While the concept of trench-parallel mantle flow beneath subducting slabs became accepted and many studies reported trench-parallel polarizations, the growing number of observations often yielded more complex splitting patterns which could not be reconciled with simple mantle flow models or one layer of anisotropy.

Wölbern et al. (2014) reported mostly trench-perpendicular fast polarizations of SKS phases along a seismic profile in the Central Andes at ∼21°S which were interpreted due to fossil anisotropy in the slab. Others have argued for an overprinting of the fossilized slab fabric by extension further by analyzing deep local S phases (Eakin et al., 2016). Most recently, trench-parallel mantle flow beneath subducting slabs has been questioned by a study of world-wide source-side splitting measurements, which utilize the ray paths of slab events traversing the subslab mantle and are uncontaminated from anisotropic structures above the slab. The study finds that the measurements are best characterized by tilted transverse isotropy with a slow symmetry axis orthogonal to the slab dip and that trench-parallel fast polarization directions are associated with relatively shallow events (Walpole et al., 2017).

In our study, we analyze data from 21 stations of the IPOC network (GFZ, 2006) which are located between 17°–25°S and directly situated in the fore-arc (Fig. 1). This data set is uniquely suited for the analysis of shear-wave splitting in this region as it covers a range of 780 km along the central South American margin, extending about 160 km east–west and most of the seismic stations have been in operation for more than 10 yrs. We use teleseismic and local S phases to investigate the anisotropic properties and sample different parts of the subduction zone (Fig. 1, lower inset). We constrain two anisotropic layers which yield important findings for the mantle flow pattern. Furthermore, we test the influences of anisotropy within the crust upon the teleseismic measurements by using a two-layer inversion of all waveform data at one given station.

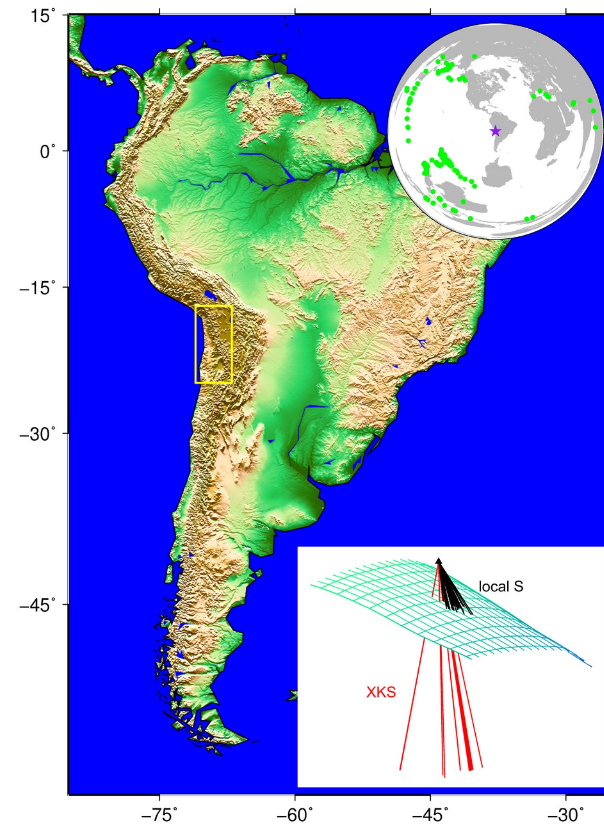


**Fig. 1.** Map of South America with the study area highlighted in yellow. The upper inset shows the distribution of the teleseismic events used in the study. The lower inset shows a sketch of the ray paths through the subduction system. Teleseismic 'XKS' phases traverse the entire subduction zone nearly vertically, while local S phases originate in the slab and have shallower incidence angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 2. Methods

The Integrated Plate boundary Observatory Chile (IPOC, GFZ, 2006) consists of 21 stations in northern Chile between 17°–25°S. This is a permanent station deployment with ongoing data acquisition. About half of the stations started recording in 2006 and now have 10 yrs of data available while the remainders were successively installed in the years after.

We use the SplitRacer software package (Reiss and Rümpker, 2017) to measure teleseismic shear-wave splitting by minimizing the transverse energy (see Silver and Chan, 1991). We analyze data from teleseismic earthquakes between 85°–180° distance to include all core phases such as SKS, SKKS and PKS (called XKS in the following). A minimum event magnitude of 6 of the USGS earthquake archive was used to find suitable events. We conduct the entire processing flow for two filter ranges: As most teleseismic core phases have a period of ∼8–12 s, we first use a traditional bandpass filter of 4–50 s for the analysis. As evidence for depth-dependent anisotropy can be also observed by using different frequency bands (Rümpker et al., 2003), we repeat our analysis using a bandpass filter of 1–4 s, which is comparable to the fre-