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Subduction-controlled mantle flow and seismic anisotropy in South America

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ABSTRACT

Seismic anisotropy records both the past and present deformation inside the solid Earth. In the mantle, seismic anisotropy is mainly attributed to the lattice preferred orientation (LPO) of mineral fabrics, caused by the shear deformation due to mantle flow. However, contributions from different tectonic processes remain debated, and a single geodynamic model that simultaneously explains the observed mantle structures and various seismic anisotropy measurements is still lacking. Here, we present a model for the Cenozoic subduction history in South America using a geodynamic simulation constrained by both past plate reconstructions and present mantle seismic structures. With a recently developed software package DRexS, we further predict azimuthal seismic anisotropy at different depths and generate synthetic shear wave splitting (SWS) measurements using the resulting mantle flow. Our results provide a good match to both depth-dependent surface wave anisotropy and various land-based SWS records. We find that the dominant control on seismic anisotropy in South America comes from subduction-induced mantle flow, where anisotropy below the subducting Nazca Plate aligns with plate-motion-induced Couette flow and that below the overriding South American Plate follows slab-induced Poiseuille flow. This large-scale mantle flow can be diverted by secondary slabs, such as that below the Antilles subduction zone. In contrast, the contribution to SWS from fossil continental anisotropy and from the effects due to mantle flow modulation by lithosphere thickness variation are minor. Upper-mantle fast seismic anomalies beneath the southern Atlantic margin should have close-to-neutral buoyancy in order to satisfy the observed seismic anisotropy.

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1. Introduction

Seismic anisotropy is defined as the dependence of wave speed on the direction of seismic polarization and wave propagation. It has been generally attributed to lattice preferred orientation (LPO) of anisotropic minerals (Nicolas and Christensen, 1987; Zhang and Karato, 1995; Kaminski and Ribe, 2001) or shape preferred orientation (SPO) of locally concentrated isotropic materials with distinct elastic properties (Mainprice and Nicolas, 1989; Kendall and Silver, 1996). Since the first observation of seismic anisotropy made by Hess (1964), an enormous amount of research has been done both globally and regionally. However, the origin of seismic anisotropy remains debated and the proposed causes of anisotropy vary from place to place (Long and Silver, 2009; Long and Becker, 2010).

By analyzing shear wave splitting (SWS), Silver and Chan (1991) and Silver (1996) argued that the fast-polarization direction in stable continents correlated well with tectonic structures in the crust, implying that "frozen anisotropy" (e.g. Ismaıl and Mainprice, 1998) imprinted by past crustal deformation was the dominant source. This idea was adopted in some regional studies, such as in SE Brazil (James and Assumpção, 1996) and Fennoscandia (Vecsey et al., 2007; Eken et al., 2010). In contrast, Vinnik et al. (1992) and Fouch et al. (2000) analyzed SKS splitting in North America and argued that most of the anisotropy is parallel to the plate motion. Recent studies further invoked the role of lithosphere thickness variation in the formation of SWS (Fouch et al., 2000; Assumpção et al., 2006; Wang et al., 2008; Assumpção et al., 2011; Miller and Becker, 2012; Foster et al., 2014). For example, Fouch et al. (2000) and Wang et al. (2008) related the SWS to mantle flow perturbed by the North American Craton and Colorado Plateau. Similarly, Assumpção et al. (2006, 2011) and Miller and Becker (2012) proposed the thick continental roots in South America modulate the anisotropy pattern by diverting mantle flow below southeastern Brazil and northern South America, respectively. However, SWS measurements have little depth resolution

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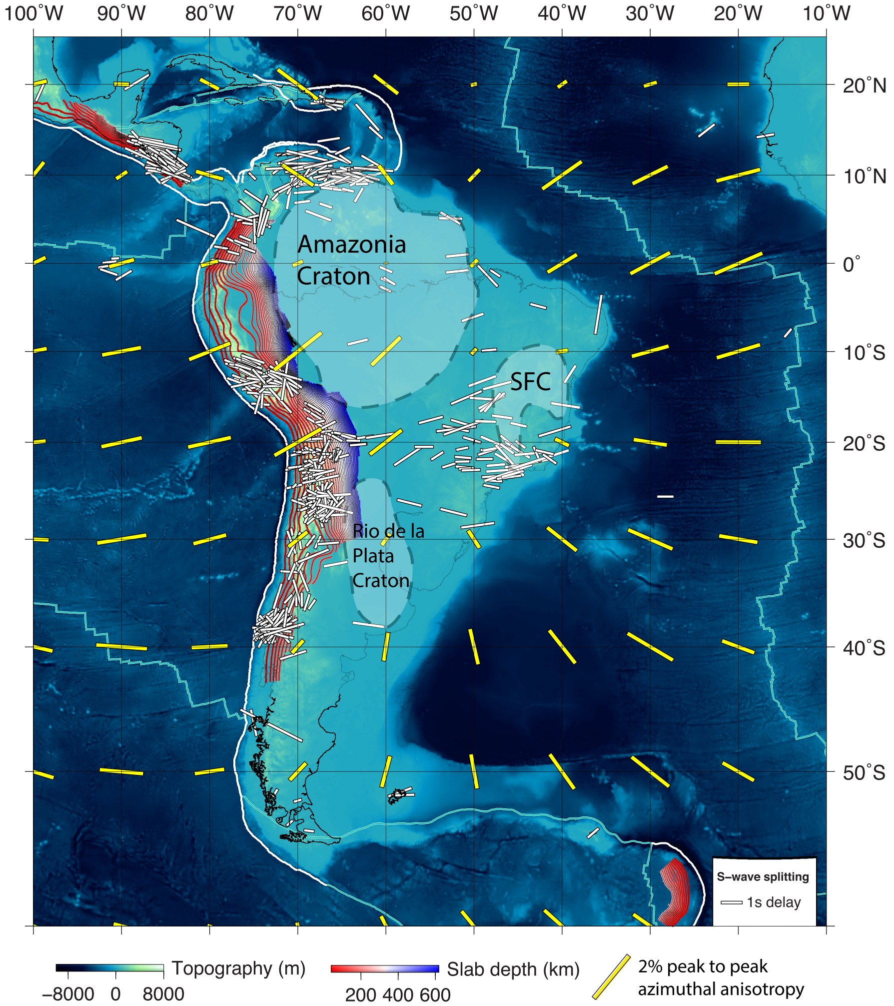

Fig. 1. Geological settings of South America. The topography and bathymetry are shown with background colors. The yellow bars represent the azimuthal anisotropy of Rayleigh waves at 200 km depth from Yuan and Beghein (2013), while the white bars are station-averaged shear wave splitting from Becker et al. (2012). Purple lines show slab depth contours represented by Benioff zones (Hayes et al., 2012). Dashed lines outline the shape of major cratons (modified from Loewy et al., 2004) in South America. SFC: Sao Francisco Craton. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Favier and Chevrot, 2003), which renders the associated tectonic interpretation non-unique.

Relative to SWS, surface wave and normal mode studies could better resolve the depth distribution of seismic anisotropy (Gung et al., 2003; Debayle et al., 2005; Marone and Romanowicz, 2007; Yuan and Beghein, 2013). For example, Gung et al. (2003) measured radial anisotropy at depths from 250–400 km that reconciles the discrepancy of different isotropic tomography models. Debayle et al. (2005) observed significant azimuthal anisotropy beneath Australia at 175–300 km depths that correlates well with the present plate motion. By simultaneously matching waveforms and shear wave splitting data, Marone and Romanowicz (2007) proposed a layered anisotropy structure in the cratonic part of North America, implying contributions from both the lithosphere and the underlying asthenosphere. Although with a likely different origin, a layered anisotropy structure was also observed in the Pacific (Smith et al., 2004; Beghein et al., 2014), where the Pacific upper lithosphere records the paleospreading direction, while anisotropy at greater depth reflects present-day plate motion. However, this interpretation was challenged by a more recent study by Lin et al. (2016), who showed that the anisotropy at asthenosphere depth has a different fast direction from that due to present plate motion, and they attributed this to pressure-driven channel flow beneath the ocean basin (e.g., Höink et al., 2012).

The diverse observations of seismic anisotropy have propelled many geodynamic modeling efforts (Conrad et al., 2007; Conrad and Behn, 2010; Faccenda et al., 2008; Faccenda and Capitanio, 2013; Becker et al., 2003, 2006a, 2006b, 2014). Conrad et al. (2007) and Becker et al. (2003, 2014) built global mantle convection models based on seismic tomography. They demonstrated that LPO due to density-driven mantle flow matches the observation of asthenospheric anisotropy beneath ocean basins, a better prediction than that only due to plate motions. By matching the SWS data at the South American–Caribbean plate margin, Miller and Becker (2012) showed that mantle flow in the region can be deflected by cratonic keels and nearby subduction zones, suggesting a significant effect of cratons on SWS. However, these studies only utilized instantaneous mantle flow models when calculating LPO. In theory, a time-dependent flow is needed to accurately predict seismic anisotropy, due to the response of anisotropic minerals to the cumulative strain (Ribe, 1992). Recently, such efforts have been made to account for both the deformation history and the full 3D strain field (Faccenda and Capitanio, 2012, 2013).

In this paper, we simultaneously investigate the origin of surface wave anisotropy and SWS data in South America (Fig. 1). We present a data-oriented convection model that simulates South American subduction since the Mid-Cretaceous. Then we use the resulting Cenozoic mantle flow to generate synthetic seismic anisotropy that is subsequently compared with SWS measure-