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Origin of azimuthal seismic anisotropy in oceanic plates and mantle

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ABSTRACT

Seismic anisotropy is ubiquitous in the Earth's mantle but strongest in its thermo-mechanical boundary layers. Azimuthal anisotropy in the oceanic lithosphere and asthenosphere can be imaged by surface waves and should be particularly straightforward to relate to well-understood plate kinematics and large-scale mantle flow. However, previous studies have come to mixed conclusions as to the depth extent of the applicability of paleo-spreading and mantle flow models of anisotropy, and no simple, globally valid, relationships exist. Here, we show that lattice preferred orientation (LPO) inferred from mantle flow computations produces a plausible global background model for asthenospheric anisotropy underneath oceanic lithosphere. The same is not true for absolute plate motion (APM) models. A ~200 km thick layer where the flow model LPO matches observations from tomography lies just below the ~1200 °C isotherm of a half-space cooling model, indicating strong temperature-dependence of the processes that control the development of azimuthal anisotropy. We infer that the depth extent of shear, and hence the thickness of a relatively strong oceanic lithosphere, can be mapped this way. These findings for the background model, and ocean-basin specific deviations from the half-space cooling pattern, are found in all of the three recent and independent tomographic models considered. Further exploration of deviations from the background model may be useful for general studies of oceanic plate formation and dynamics as well as regional-scale tectonic analyses.

1. Introduction

Observations of seismic anisotropy in the upper mantle provide important constraints on the nature of the lithosphere as well as the morphology and time-integrated dynamics of mantle flow over millions of years. Oceanic plates and the relatively weaker asthenosphere beneath them are particularly promising study subjects. Their tectonic history of deformation is one order of magnitude shorter than that of the continental plates, and readily accessible to plate tectonic reconstructions. Moreover, we expect that oceanic plates are less affected by differentiation and chemical heterogeneity than continental plates, and in this sense can be more simply and quantitatively linked to mantle convection models. We can therefore anticipate that inferences from large-scale geodynamic models, be they of quantitative or conceptual type, should match the imaged patterns of seismic anisotropy in oceanic plate systems quite well. Yet, the origin of azimuthal anisotropy remains debated, even for the oceanic mantle realm.

The full elastic tensor anisotropy that describes seismic wave propagation is usually imaged by means of the tensor entries that are expected if a medium with hexagonal anisotropy is aligned such that the symmetry axis is in the horizontal or vertical orientation (Montagner and Nataf, 1986). The corresponding azimuthal and radial types of anisotropy, respectively, capture much of the signal, even though we know that mantle minerals such as olivine have non-hexagonal crystal symmetry contributions (Montagner and Anderson, 1989; Becker et al., 2006; Mainprice, 2007; Song and Kawakatsu, 2013). Given their sensitivity to different depth intervals within the lithosphere–asthenosphere depth range at different periods, surface waves are most suited for the exploration of the vertical variations of anisotropy in the upper mantle. Azimuthal anisotropy constrained using surface waves is our focus here.

Traditionally, two related causes for observed patterns of azimuthal anisotropy in oceanic plates have been considered (Hess, 1964; Forsyth, 1975; Nishimura and Forsyth, 1989; Montagner and Tanimoto, 1991; Smith et al., 2004; Maggi et al., 2006; Debayle and Ricard, 2013). One is the alignment of the fast propagation orientations of azimuthal anisotropy ("fast axes") within intrinsically anisotropic olivine in a way that reflects relative plate motion at

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the time of oceanic lithosphere creation, i.e. paleo-spreading orientations. Paleo-spreading orientations and rates can be inferred by computing the gradient of seafloor ages from magnetic anomalies in a relatively straightforward way (e.g. Conrad and Lithgow-Bertelloni, 2007). The resulting anisotropic fabric may then become "frozen in" once the lithosphere cools sufficiently, away from the spreading center (here used interchangeably with "ridge"). As a consequence, this component is perhaps most important for the shallowest layers above ∼100 km. The anisotropic record of this process may then potentially provide clues about the partitioning between rigid motion with brittle deformation and ductile flow within the lithosphere. This is, for example, suggested by variations in the strength of inferred fossil anisotropy in the relatively slowly spreading Atlantic and the fast spreading Pacific (Gaherty et al., 2004). Compositional variations and possible anisotropic layering are also expected to play a role (Gaherty and Jordan, 1995; Beghein et al., 2014).

The other mechanism that is typically invoked for the generation of azimuthal anisotropy is the alignment of fast propagation orientations with current, or geologically recent, mantle flow (Tanimoto and Anderson, 1984; Nishimura and Forsyth, 1989; Montagner and Tanimoto, 1991; Smith et al., 2004; Maggi et al., 2006). The depth dependence of the match between observed azimuthal anisotropy and mantle flow may then allow us to infer the radial extent of a relatively low viscosity, high strain-rate, asthenosphere, or the thickness of the mechanically defined lithosphere on top of it (Nishimura and Forsyth, 1989; Smith et al., 2004; Debayle and Ricard, 2013; Beghein et al., 2014). However, inferring mantle flow with depth is fraught with complexity because of uncertainties in temperature, density, and viscosity variations, which is why absolute plate motion (APM) models are typically considered as a first step. APM models apply plate models of NUVEL (DeMets et al., 1994) type, which provide information about relative plate motions on geological timescales, in some absolute reference frame. The latter can be characterized by different degrees of net rotation of the whole lithosphere with respect to the lower mantle, ranging from zero (no net rotation, NNR) to relatively large values, as in some hotspot reference frames, for example. One can then compare fast axes from imaged azimuthal anisotropy with orientations of plate motions, under the assumption that the mantle at some larger depth is relatively stationary, such that surface velocities are directly related to asthenospheric shear.

While there are pleasingly few geodynamic assumptions involved in APM models, we know that even plate-associated flow alone leads to regional deviations in mantle circulation from the simple shearing that may be expected if the "plate is leading the mantle" (Hager and O'Connell, 1981). Seemingly non-intuitive scenarios where "the mantle is leading the plate", and flowing in directions quite different from plate motions, may, in fact, be widespread (e.g. Long and Becker, 2010; Natarov and Conrad, 2012). Those differences between surface motions and mantle shear are expected to be even more pronounced for additional contributions due to density-driven flow (Hager and Clayton, 1989; Ricard and Vigny, 1989).

Both explanations of imaged anisotropy in terms of paleo-spreading and present-day asthenospheric mantle flow are related to the assumption that it is mainly the lattice preferred orientation (LPO) of intrinsically anisotropic minerals such as olivine in mantle flow that is causing the anisotropy (Nicolas and Christensen, 1987; Zhang and Karato, 1995; Mainprice, 2007). If this is the case, we can model the details of the anisotropic signal that is created by plate tectonics and mantle flow (McKenzie, 1979; Ribe, 1989). This promising link between seismology and geodynamics has motivated a number of first order models of oceanic plate anisotropy derived from mantle flow (e.g. Gaboret et al., 2003; Becker et al., 2003, 2006, 2008; Behn et al., 2004; Conrad et al., 2007; Conrad and Behn, 2010). If the LPO mechanism is dominant beneath oceanic plates, then any differences in anisotropy strength with depth for different age oceanic lithosphere can fuel further inference, for example on the partitioning between diffusion and dislocation creep (Podolefsky et al., 2004; Becker et al., 2008; Behn et al., 2009). Moreover, the general match of these large-scale models provides credence to the application of mineral physics methods derived from laboratory experiments to nature, such as regional explorations of mantle dynamics and tectonics constrained by seismic anisotropy (e.g. Silver, 1996; Savage, 1999).

If we assume perfect seismological models, complications from the relatively straightforward association between mantle flow, LPO, and seismic anisotropy may still arise in a number of ways, including due to the effects of water (Jung and Karato, 2001) or melt (Holtzman et al., 2003; Kawakatsu et al., 2009). While some mechanisms other than dry, solid LPO, such as high melt-fraction realignment of olivine fabrics, may be limited to certain regions like spreading centers or continental rift zones, volatile content variations in the mantle may be more wide-spread (e.g. Becker et al., 2008; Meier et al., 2009). Further, it is intriguing that recent, global-scale seismological studies have found discrepancies between the imaged azimuthal anisotropy and models of mantle flow, including a pronounced lack of alignment of asthenospheric anisotropy with APM models across broad oceanic regions (Debayle and Ricard, 2013; Burgos et al., 2014; Beghein et al., 2014). Moreover, Song and Kawakatsu (2013) suggested that the entrainment of an orthorhombic asthenospheric layer can explain some of the complexities of subduction zone anisotropy. Whatever the nature of such a layer, it may then also be expected to behave differently than LPO anisotropy formed in mantle flow, further motivating a reexamination of the origin of oceanic mantle azimuthal anisotropy.

Here, we ask the question if these discrepancies between models for and observations of azimuthal anisotropy indicate large-scale differences between oceanic basin dynamics (such as due to their hydration and temperature state), the influence of regional variations in mantle flow operating beneath the plates, or if a general reassessment of the LPO model for anisotropy may be required. This reassessment of azimuthal anisotropy is motivated not only by the inferred incongruities among the LPO-mantle flow models for the origin of anisotropy, but also by dramatic advances in anisotropic imaging in recent years (e.g. Ekström, 2011; Debayle and Ricard, 2013; Schaeffer and Lebedev, 2013b; Yuan and Beghein, 2013; Burgos et al., 2014). For example, recent Rayleigh surface wave models of upper mantle anisotropy have significantly improved in resolution compared to earlier generation v_{SV} models, e.g. those by Debayle et al. (2005) or Lebedev and van der Hilst (2008) (anisotropic signal discussed in Becker et al., 2012) as used in earlier geodynamic studies (Conrad and Behn, 2010; Long and Becker, 2010).

We find that LPO-based anisotropy estimates from mantle flow, rather than APM, do indeed furnish a plausible, global background model of azimuthal anisotropy for oceanic plates and their underlying asthenosphere. How closely this geodynamic background model approximates observed azimuthal anisotropy varies from one oceanic basin to another, and these variations are consistent among different recent anisotropy models. From these comparisons, we infer that anisotropic fabrics below the oceanic thermal boundary layer, as defined by half-space cooling, are well-explained by LPO-induced anisotropy due to mantle shear.