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Discussion

Comment on the article “Probability of radial anisotropy in the deep mantle” by Visser et al. (2008) EPSL 270:241–250

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Based on the inversion of a large surface waves dataset, including both fundamental and higher modes, Visser et al. (2008) constructed new maps of the probability of surface wave polarization (or radial) anisotropy. These maps bring new constraints on the variation of radial anisotropy with depth as a function of the geodynamic environment. However, the interpretation of the seismic anisotropy distribution in terms of mantle deformation is oversimplified, since it is essentially based on data of the evolution of olivine crystal preferred orientations and seismic anisotropy at high temperature, but low pressure conditions, neglecting recent findings on the deformation of mantle minerals under high-pressure *in-situ* mantle conditions.

Three points, in particular, deserve a throughout discussion, since they highlight the limitations of using basic concepts that have been established from the analysis of shallow mantle rocks and low pressure deformation experiments, as for instance: (i) lack of anisotropy implies deformation by diffusion creep or (ii) fast polarization (or propagation for P or SV waves) directions mark systematically the flow direction, to interpret seismic anisotropy data below depths of 200–250 km in the mantle.

1. Absence of anisotropy does not necessarily imply diffusion creep

Estimation of seismic anisotropy using polycrystal plasticity models based on recent experimental data on the deformation of olivine, wadsleyite, and perovskite highlights that development of a crystal preferred orientation does not necessarily result in significant seismic anisotropy, even if the single crystal has strongly anisotropic elastic constants (Tommasi et al., 2004; Mainprice et al., 2005, 2008). Strong anisotropy at the rock scale is produced when the crystal preferred orientations have strong single maxima concentrations of the crystallographic directions corresponding to the highest and lowest propagation velocities or S-wave splitting of the single crystal. This is the case, for instance, for olivine under shallow mantle conditions, where dislocation creep with dominant activation of the (010)[100] slip system leads to a strong orientation of the [100] axis, which is the fastest P-wave propagation and the lowest S-wave splitting direction, and of the [010] axis, which is the slowest P-wave propagation direction (Tommasi et al., 2000). In contrast, dominant activation of {*hk*0}[001] systems in the deep upper mantle results in a point concentration of the [001] axis that has intermediate values for both P-wave propagation velocities and S-wave splitting and in girdle distributions of the [100] and [010] axes in a plane normal to the flow direction and hence in averaging between high and low values (Mainprice et al., 2005). Similarly, for wadsleyite, seismic velocity and anisotropy distributions of a polycrystalline aggregate do not correlate in a simple manner with the single-crystal properties (Tommasi et al., 2004). In the single crystal, P-wave propagation is fastest parallel to the [010] axis and slowest parallel to [001]. The maximum S-wave polarization anisotropy is observed for propagation parallel to <110>, the fast S-wave being polarized parallel to the [010] axis. In wadsleyite-rich polycrystals, the slowest P-wave propagation is still parallel to the [001] maximum, but the fastest propagation direction and the polarization of the fast S-wave are not parallel to the [010] maximum, but at low angle to the [100] maximum, i.e., at low angle to the shear direction. The dispersion of [010] axes in the polycrystal results in a weak seismic anisotropy for wadsleyite-rich rocks (>2%), even if the single-crystal is clearly anisotropic (~13%, Mainprice et al., 2000) and the rock has a well-developed wadsleyite CPO. Finally, in the lower mantle, coupling of *ab initio* and polycrystal plasticity models suggests that even if deformation by dislocation creep produces clear perovskite CPO, the resulting seismic anisotropy is weak (Mainprice et al., 2008). The maximum polarization anisotropy is >2% at the low temperatures and pressures that prevail just below

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the transition zone and it decreases with increasing temperature and pressure.

2. Variations in sign of radial anisotropy (from $V_{SH}>V_{SV}$ to $V_{SV}>V_{SH}$) with increasing depth cannot be univocally interpreted as a change in flow direction

This interpretation is based on the premise, derived from experiments at high temperature and moderate pressure and extensive data on naturally deformed shallow upper mantle rocks, that olivine deforms by dominant slip on $\{0kl\}[100]$ slip systems. Under these conditions, the deformation-induced CPO results in the fastest S-waves being polarized parallel to the flow direction. It also leads to faster propagation of P and Rayleigh waves parallel to the flow direction. However, if the relation between finite strain axes and olivine CPO changes, this relation is no longer valid. Recent experimental data show that at the high pressures that prevail in the deep upper mantle (Couvy et al., 2004; Raterron et al., 2007) or at high water contents (Jung and Karato, 2001) olivine deforms by dominant glide on $\{hk0\}[001]$ systems. There is still debate on the relative importance of these two parameters, but they are not independent, since water solubility in olivine increases with pressure (Bolfan-Casanova et al., 2000). Moreover, both pressure and water have the same effect, resulting in the same olivine CPO evolution and hence in fast polarization directions normal to the flow direction. Polycrystal plasticity models based on these data show indeed that the change in intensity and sign ($V_{SH}<V_{SV}$) of anisotropy with increasing depth in the upper mantle observed in previous studies (Montagner and Kennett, 1996; Panning and Romanowicz, 2006; Zhou et al., 2006) and confirmed by Visser et al. (2008) is perfectly explained as resulting from the change in olivine deformation with depth from dominant [100] slip to dominant [001] slip (Mainprice et al., 2005).

3. Anisotropy in the transition zone cannot be interpreted based on olivine deformation data

It is essential to consider the phases that are actually present at this depth range: wadsleyite or ringwoodite and pyrope-rich garnet. New high pressure, high temperature experimental data show that garnet (Li et al., 2006), wadsleyite (Thurel and Cordier, 2003; Thurel et al., 2003a; Wenk et al., 2004), and ringwoodite (Wenk et al., 2004) deform by dislocation creep under high-pressure conditions. TEM analysis of experimentally deformed samples (Karato et al., 1998; Thurel et al., 2003b) and *ab initio* modelling of dislocation plasticity (Carrez et al., 2006) allow constraining the active slip systems and their relative strength. Based on these data, one may use polycrystal plasticity models to simulate the evolution of crystal preferred orientations in garnet (Mainprice et al., 2004), wadsleyite (Tommasi et al., 2004), and ringwoodite polycrystals (Carrez et al., 2006) during plastic flow and estimate the resulting anisotropy. For the upper part of the transition zone, which is essentially composed of wadsleyite and garnet, these models predict a weak seismic anisotropy for a polycrystal of pyrolitic composition (60% wadsleyite, 40% garnet) at transition zone conditions: ~2% for P and ~1% for S-waves for a shear strain of 1 with fastest propagation of P-waves at low angle to the shear direction and the maximum shear wave splitting in the shear plane, perpendicular to the shear direction (Tommasi et al., 2004). S-wave anisotropy is characterized by faster propagation of waves polarized at low angle to the shear direction. Horizontal shearing results therefore in higher velocities for horizontally-propagating P-waves (PH) and horizontally-polarized S-waves (SH), as well as in weak azimuthal variation of SV and SH velocities. On the other hand, vertical flow leads to higher velocities for vertically-propagating P-waves (PV) and vertically-polarized S-waves (SV) and to a weak azimuthal variation of SV velocity, but to a roughly constant SH velocity. In the light of these models, the higher probability of $V_{SV}>V_{SH}$ in the transition zone below convergent or divergent plate boundaries observed by Visser et al. (2008), Beghein and Trampert (2004), and Panning and Romanowicz (2006) may imply dominant vertical flow beneath plate boundaries, whereas the global azimuthal anisotropy patterns inferred from Love-wave overtone data by Trampert and van Heijst (2002) are better explained by horizontal shearing, which may predominate in most of the transition zone, away from plate boundaries. Similar models using lower transition zone, ringwoodite-rich compositions show that anisotropy below 520 km depth cannot be explained by strain-induced CPO of ringwoodite (Carrez et al., 2006). Thus, if, as suggested by Visser et al. (2008) probability maps, seismic anisotropy is higher in the lower transition zone, another mechanism, such as alternating layers with highly contrasting seismic properties has be invoked explain the observations. Such a layering may, for instance, be associated with stagnant hydrated slabs in the transition zone as proposed by Ritsema et al. (2004) and Mainprice et al. (2007).

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