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Deformation and mantle flow beneath the Sangihe subduction zone from seismic anisotropy

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ABSTRACT

Subduction of oceanic lithosphere is the most direct feedback between the Earth's surface and deep interior. However, the detail of its interaction with the broader convecting mantle is still unclear. Mantle flow around subduction zones can be constrained using seismic anisotropy, but despite many such studies, a simple global picture is lacking. The Sangihe subduction zone (where the Molucca Sea microplate is subducting westward beneath the Eurasian plate) is part of the tectonically complex Sulawesi–Philippine region, and an ideal natural laboratory to study complex subduction processes. We investigate the anisotropic structure of the Sangihe subduction zone with shear wave splitting measurements of local *S* and *SKS* phases at two stations (MNI in Sulawesi, DAV in the Philippines), as well as downgoing *S* phases at five stations at teleseismic distances. Combining different phases allows a better vertical resolution of anisotropic fabrics than is possible with a single phase. The broad depth distribution of local events ($\sim$60–630 km) allows us to observe a change in splitting behaviour at $\sim$380 km depth: above, fast directions (ϕ) are trench-parallel and delay times (δt) are $\sim$0.34–0.53 s with no increase with depth. We suggest this anisotropy is caused by aligned cracks, possibly melt-filled beneath the volcanic arc, and fossil anisotropy in the overriding plate. Below $\sim$380 km, ϕ is predominantly trench-normal and δt are slightly higher ($\sim$0.53–0.65 s). As no correlation is observed with inferred distance travelled inside the slab, we attribute this anisotropy to shear layers atop the slab, which are coherent from $\sim$200 to 400 km depth and perhaps extend into the transition zone. *SKS* and source-side measurements show larger δt ($\sim$1.53 and 1.33 s, respectively) and trench-parallel ϕ. Since these phases predominantly sample sub-slab mantle, we consider along-strike lateral flow associated with the double-sided subduction of the Molucca Sea microplate to be the most likely explanation. We thus infer three dominant regions of anisotropy at the Sangihe subduction zone: one within the overriding lithosphere, one along the slab–wedge interface, and one below the subducting Molucca Sea slab. The mantle wedge above 200 km depth and the slab itself do not seem to contribute notably to the measured anisotropy. This study demonstrates the insight seismic anisotropy can provide into mantle dynamics even in tectonically complex subduction systems.

1. Introduction

Spanning a total length of more than 51,000 km (Bird, 2003), subduction zones are a key feature of plate tectonics. Fluxes of heat and material between the Earth's interior and the surface are perpetual at these convergent plate boundaries, and it is here that nearly 90% of all earthquakes are generated (e.g., Giardini et al., 2003). However, subduction zone dynamics, e.g., the mantle flow-field and state of stress around subducting slabs, are not yet fully understood. Seismic anisotropy, the variation of seismic wave speed with direction, is a direct result of deformational processes. Hence, it allows one to make inferences about the nature of mantle flow as well as large-scale lithospheric deformation, both past and present.

Seismic anisotropy can be intrinsic, due to crystal alignment (lattice preferred orientation, LPO), which, in the upper mantle, results primarily from LPO of anisotropic olivine crystals due to finite strain (e.g., Hess, 1964; Christensen, 1984; Nicolas and Christensen, 1987; Zhang and Karato, 1995; Jung and Karato, 2001; Jung et al., 2006).

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Under dry mantle conditions, the olivine *a*-axis aligns in the mantle flow direction and the *b*-axis perpendicular to the flow plane (A-type LPO) (e.g., Ribe, 1989; Babuška and Cara, 1991; Mainprice et al., 2000; Mainprice, 2007; Blackman and Kendall, 2002). A change in fluid content, pressure, and temperature, however, can alter the relationship between deformation and olivine LPO, as discussed further below.

Anisotropy can also be extrinsic, due to the alignment of larger-scale features such as fractures, intrusions or fine layers of two or more materials with different elastic properties (shape preferred orientation, SPO; e.g., Mainprice and Nicolas, 1989). Temperature and the presence of fluids can also have an effect. For example, fluid-filled cracks are deemed to be the primary cause of anisotropy in the shallow continental crust (e.g., Crampin and Booth, 1985; Savage et al., 1989; Kaneshima et al., 1988; Kaneshima and Ando, 1989; McNamara and Owens, 1993). Oriented melt veins and dykes have also been shown to be a cause of lithospheric anisotropy, e.g., at mid-ocean ridges (e.g., Kendall, 1994; Blackman and Kendall, 1997; Holtzman and Kendall, 2010) or in continental rift zones (e.g., Kendall et al., 2005; Bastow et al., 2010).

Seismic anisotropy is thus sensitive to deformation, state of stress, mantle flow, and mineralogy, as well as melt content in the lithosphere and upper mantle. These anisotropic fabrics can remain over long periods of time. Fossil anisotropy will reflect the last episode of significant deformation, provided it is not overprinted subsequently (e.g., Silver and Chan, 1991; Helffrich, 1995; Bastow et al., 2007; Bastow et al., 2011).

Shear wave splitting is one of the least ambiguous signatures of seismic anisotropy. When a shear wave impinges upon an anisotropic medium, it splits into two orthogonally polarised components travelling at different speeds. Orientation of the fast shear wave (ϕ) and delay time between the two components (δt) are measured. In the presence of strain-induced LPO in olivine, the leading shear wave will align parallel to the olivine *a*-axes and therefore parallel to the mantle flow. Splitting measurements can thus provide information about deformation and flow in the upper mantle. In the case of SPO, the fast orientation will be parallel to the alignment of the fractures or cracks, indicating the direction of the maximum horizontal stress.

One of the difficulties of shear wave splitting is that it is an aggregate measurement, i.e., a single measurement will not necessarily provide information as to where between the source and the receiver (in the case of upgoing *S* phases) or where between the core–mantle boundary and the receiver (for *SKS* phases) the anisotropic fabrics are located. Delay time is proportional to the thickness of the anisotropic layer and to the strength of anisotropy, but there is a trade-off between the two.

In order to constrain the depth distribution of anisotropy, we compare splitting measurements of local *S*, teleseismic *SKS*, as well as downgoing *S* phases recorded at teleseismic distances. For example, if *SKS* delay times are larger than δt of the deepest local event, this implies that anisotropic fabrics are present below the sub-receiver region being sampled by local earthquakes, provided the dominant frequency has no strong effect. Despite the advantages of combining these three types of splitting observations to improve vertical resolution of anisotropy, this study is one of the few (e.g., Russo and Silver, 1994; Sandvol and Ni, 1997) to date to do so.

1.1. Causes of seismic anisotropy in subduction zones

A topic of debate is the nature of the mantle flow-field at subduction zones. Although seismic anisotropy has been observed in most subduction zones (e.g., Fouch et al., 1996; Brisbourne et al., 1999; Currie et al., 2004; Long and van der Hilst, 2005; Morley et al., 2006; Pozgay et al., 2007; Hammond et al., 2010), no truly coherent global pattern has been recognised so far (e.g., Long and Becker, 2010).

The traditional model for subduction zone mantle flow constitutes two dimensional corner flow within the mantle wedge and entrained flow below the slab (Ribe, 1989; Hall et al., 2000). If a parallelism of LPO and fast shear wave polarisation is assumed, as discussed above, this model would result in trench-perpendicular fast directions. This has indeed been observed, e.g., beneath Cascadia (Currie et al., 2004). However, trench-parallel fast directions are also present in various subduction zones, in the mantle wedge, e.g., Tonga (Smith et al., 2001), Costa Rica, and Nicaragua (Hoernle et al., 2008), as well as underneath the subducting slab, as appears to be the case beneath the Nazca Plate (Russo and Silver, 1994) or the Carribean Plate (Piñero-Feliciangeli and Kendall, 2008). Furthermore, some regions feature both trench-parallel and -normal fast directions, e.g., Kamchatka (Levin et al., 2004), the Marianas (Pozgay et al., 2007), Ryukyu (Long and van der Hilst, 2006), New Zealand (Morley et al., 2006), and Japan (e.g., Sandvol and Ni, 1997; Nakajima and Hasegawa, 2004; Long and van der Hilst, 2005).

One model that would allow for trench-parallel fast directions in the wedge while maintaining two dimensional corner flow is that of a change from A-type to B-type LPO, which changes the relationship between strain, crystal alignment and the resulting anisotropy, i.e., the flow is perpendicular to the fast direction instead of parallel (e.g., Nakajima and Hasegawa, 2004; Kneller et al., 2005; Kneller and Kekenvan, 2007; Long et al., 2007; Tasaka et al., 2008). Experiments suggest that this change can occur due to the presence of water (Jung and Karato, 2001). Other authors argue that pressure is of greater importance for this transition (Mainprice et al., 2005; Jung et al., 2009).

Faccenda et al. (2008) propose another model that predicts trench-parallel fast directions. This postulates anisotropy in forearc regions being caused by LPO of hydrous, anisotropic minerals such as serpentine and talc in hydrated faults in the upper part of the slab, associated with its downward bending, rather than ascribing it exclusively to mantle flow. They essentially attribute anisotropy in the slab to a combination of SPO, LPO, and fluid-filled cracks. Healy et al. (2009) propose a similar model and support it with field observations of brittle hydrofractures in exhumed slab rocks. Both studies limit the occurence of hydrated, trench-parallel faults to the section of the slab between the trench and the volcanic arc.

Recent studies by Katayama et al. (2009) and Jung (2011) suggest that serpentine in the cold forearc tip of the mantle wedge could be the source of trench-parallel anisotropy. Both studies agree that this has the potential to explain the large delay times (1–2 s) measured in the Ryukyu arc (Long and van der Hilst, 2006).

Long and Silver (2008), Long and Silver (2009) propose a three dimensional flow-field, with two dimensional corner flow induced by the downdipping motion of the subducting slab, combined with flow beneath the slab due to trench migration, and a sideways return flow around the edge of the slab. This concept is supported by numerical models; e.g., Lowman et al. (2007) show how significant toroidal flow can be generated around the edges of slabs in addition to a more intricate flow pattern within the mantle wedge. Such a complex 3D flow field has also been observed in analogue experiments (e.g., Buttles and Olson, 1998).

Other authors invoke transpression caused by oblique subduction (e.g., Mehl et al., 2003) or flow due to crustal foundering (e.g., Behn et al., 2007) to explain their observations.

Each of these models appear to be reasonable for individual subduction systems, but none of them are globally applicable. However, to obtain a more global understanding of subduction zone dynamics, one cannot omit any active subduction zones that can readily be studied. This study is the first to investigate seismic anisotropy around the Sangihe subduction zone. As outlined in the