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Insights on slab-driven mantle flow from advances in three-dimensional modelling

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ABSTRACT

The wealth of seismic observations collected over the past 20 years has raised intriguing questions about the three-dimensional (3D) nature of the mantle flow field close to subduction zones and provided a valuable constraint for how the plate geometry may influence mantle flow proximal to the slab. In geodynamics, there has been a new direction of subduction zone modelling that has explored the 3D nature of slab-driven mantle flow, motivated in part by the observations from shear wave splitting, but also by the observed variations in slab geometries worldwide. Advances in high-performance computing are now allowing for an unprecedented level of detail to be incorporated into numerical models of subduction. This paper summarizes recent advances from 3D geodynamic models that reveal the complex nature of slab-driven mantle flow, including trench parallel flow, toroidal flow around slab edges, mantle upwelling at lateral slab edges, and small scale convection within the mantle wedge. This implies slab-driven mantle deformation zones occur in the asthenosphere proximal to the slab, wherein the mantle may commonly flow in a different direction and rate than the surface plates, implying laterally variable plate-mantle coupling. The 3D slab-driven mantle flow can explain, in part, the lateral transport of geochemical signatures in subduction zones. In addition, high-resolution geographically referenced models can inform the interpretation of slab structure, where seismic data are lacking. The incorporation of complex plate boundaries into high-resolution, 3D numerical models opens the door to a new avenue of research in model construction, data assimilation, and modelling workflows, and gives 3D immersive visualization a new role in scientific discovery.

1. Introduction

Geologic observations (Casey and Dewey, 1984; Bird, 2003; Eberhart-Phillips et al., 2003), geochemical constraints (Hoernle et al., 2008; Gazel et al., 2009; Heyworth et al., 2011; Durance et al., 2012), and geophysical data (Russo and Silver, 1994; Gudmundsson and Sambridge, 1998; Fischer et al., 2000; Smith et al., 2001; Syracuse and Abers, 2006; Long and Silver, 2008; Müller et al., 2008) from subduction zones indicate that the two-dimensional paradigm for plate tectonic boundaries is no longer adequate to explain the observations. For example, inspection of global tectonic features reveals lateral changes in trench geometry (Bird, 2003), lateral and radial changes in slab morphology (Jarrard, 1986; Gudmundsson and Sambridge, 1998; Gutscher et al., 2000; Grand, 2002; Lallemand et al., 2005; Syracuse and Abers, 2006; Li et al., 2008; Hayes et al., 2012), and lateral gradients in seafloor age, in both modern and ancient times (Sdrolias and Müller, 2006; Müller et al., 2008) (Fig. 1). Subduction zones can have (a) a high radius of curvature, such as in the Lesser Antilles and Scotia subduction zones, (b) vary significantly in slab dip along strike, such as in Japan, Alaska, and South America, (c) have tears or slab gaps, as in the Middle America-South America subduction zones, and (d) have complex interactions at triple junctions (Fig. 1) (Jarrard, 1986; Gudmundsson and Sambridge, 1998; Ratchkovski and Hansen, 2002; Lallemand et al., 2005; Syracuse and Abers, 2006; Nakajima and Hasegawa, 2007; Li et al., 2008; Hayes et al., 2012; Zhao et al., 2012; Dougherty and Clayton, 2014; Scire et al., 2016; Syracuse et al., 2016).

The wealth of seismic observations collected over the past 20 years has raised intriguing questions about the three-dimensional nature of the mantle flow field close to subduction zones (Russo and Silver, 1994; Hall et al., 2000; Peyton et al., 2001; Smith et al., 2001; Hoernle et al., 2008; Zandt and Humphreys, 2008; Long and Silver, 2008) and provided a valuable constraint for how the subducting plate geometry may influence mantle flow proximal to the slab (Buttles and Olson, 1998; Kneller and van Keken, 2007; Zandt and

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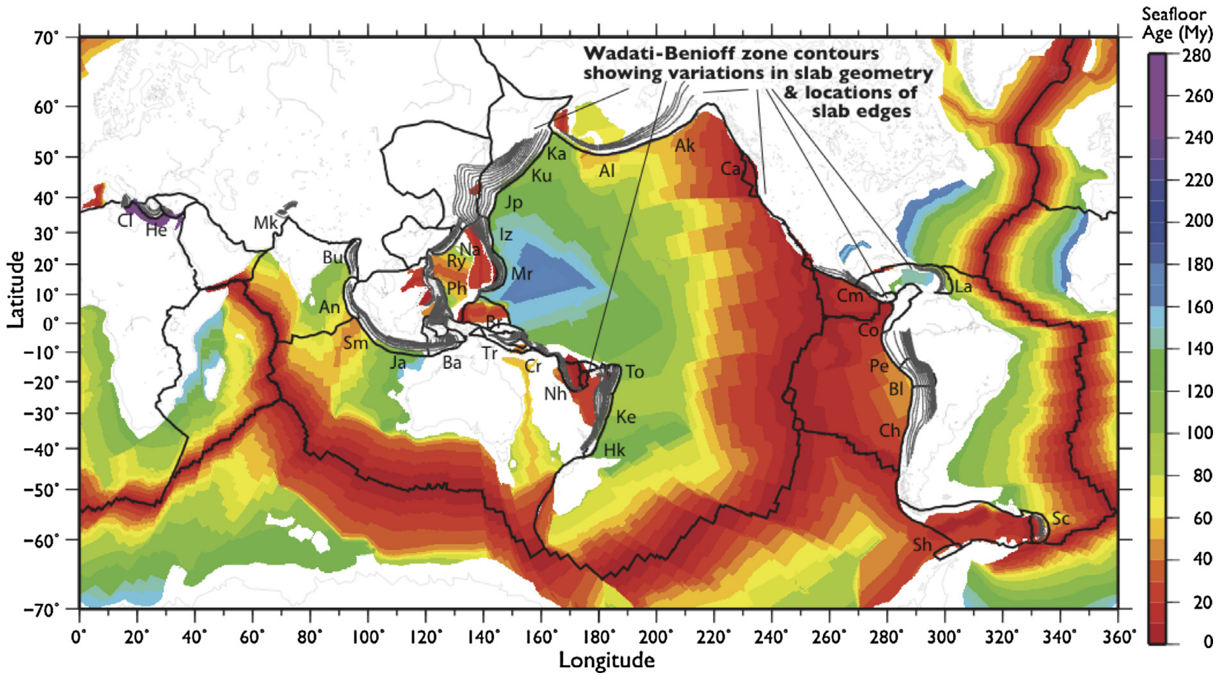

Fig. 1. Global tectonic map of plate boundaries (black lines – Bird (2003)), slab surface contours in 50 km intervals (gray lines – Gudmundsson and Sambridge (1998)), and ages of the oceanic plates (colour – Müller et al. (2008)). Subduction zones: Ak – Alaska, Al – Aleutian, An – Andaman, Ba – Banda, Bl – Bolivia, Br – New Britain, Bu – Burma, Ca – Cascadia, Ch – Chile, Cl – Calabria, Cm – Central America, Co – Columbia, He – Hellenic, Hi – Hikarangi, Iz – Izu, Ja – Java, Jp – Japan, Ka – Kamchatka, Ke – Kermadec, Ku – Kurile, La – Lesser Antilles, Mk – Makran, Mr – Marianas, Na – Nankai, Nh – New Hebrides, Pe – Peru, Ph – Philippine, Ry – Ryuku, Sc – Scotia, Sh – South Shetland, Sm – Sumatra, To – Tonga, Tr – Trobriand. For additional plate boundary labels see Schellart et al. (2008).

Humphreys, 2008; Jadamec and Billen, 2010; Song and Kawakatsu, 2013). In the warm upper mantle, where A-, C-, or E-type olivine fabric are expected to dominate, the deformation of olivine by dislocation creep can lead to lattice preferred orientation that results in splitting of seismic shear waves, wherein the azimuth of the seismic fast axis tracks the direction of shear within the mantle (Nicolas and Christensen, 1987; Savage, 1999; Tommasi et al., 1999; Kaminiski and Ribe, 2002; Karato et al., 2008; Long and Silver, 2009; Long and Becker, 2010). Away from plate margins, in the centre of the oceanic plates, the direction of plate motion and the azimuth of the fast seismic axes measured from shear wave splitting observations tend to be sub-parallel (Becker et al., 2003; Conrad et al., 2007; Kreemer, 2009; Conrad and Behn, 2010), implying simple shearing flow and alignment of the mantle flow field with surface plate motion.

However, near subduction zones, the azimuth of the fast axes of the polarized waves are commonly oriented non-parallel to the direction of local plate motion (Fig. 2) (Russo and Silver, 1994; Fischer et al., 1998; Peyton et al., 2001; Smith et al., 2001; Pozgay et al., 2007; Long and Silver, 2008; Abt et al., 2010; Long and Becker, 2010; Hanna and Long, 2012; Long and Wirth, 2013; Long, 2013). This implies that the warm upper mantle proximal to subduction zones locally flows in a different direction than the tectonic plates (Long, 2013) and possibly at a greater speed (Conder and Wiens, 2007; Hoernle et al., 2008; Jadamec and Billen, 2010; Stadler et al., 2010).

It is important to point out, that, because the splitting signal is cumulative along the ray-path, teleseismic observations recorded near a subduction zone can include effects from the subslab region, from within the slab, from the cold region of the inner wedge corner, and from the overlying plate, as well as from within the dynamic mantle wedge (Jung and Karato, 2001; Kneller et al., 2007; Faccenda et al., 2008; Hammond et al., 2010; Song and Kawakatsu, 2012). Studies that use local S waves, sourced from within the slab, are thus very valuable in resolving anisotropy of mantle wedge origin, as they do not sample subslab material, and many of these studies do show seismic fast axes oriented in a different direction that surface plate motions, implying the decoupling of motion (Fig. 2) (Yang et al., 1995; Fouch and Fischer, 1996; Smith et al., 2001; Audoine et al., 2004; Pozgay et al., 2007; Abt et al., 2010; MacDougall et al., 2012; Long and Wirth, 2013). The local studies will, however, still sample mantle and lithospheric material affected by water, melt, temperature, and discontinuities that can also contribute to the splitting pattern (Savage, 1999; Jung and Karato, 2001; Holtzman et al., 2003; Crampin and Peacock, 2005; Kneller et al., 2007; Karato et al., 2008; Long, 2013). Thus, the ability to quantitatively link the mantle flow field with a specific observed splitting pattern for a given location is still actively being studied.

In geodynamics, there has been a new direction of subduction zone modelling that has explored the three-dimensional nature of mantle flow in subduction zones, motivated in part by the observations from shear wave splitting, but also by the observed variations in slab geometries worldwide. The 3D models show that although the 2D models can provide important physical realism, 2D models cannot capture the truly 3D features of the mantle flow field that can occur at subduction zones, due to toroidal flow around slab edges (Stegman et al., 2006; Jadamec and Billen, 2010), lateral changes in slab geometry and buoyancy (Kneller and van Keken, 2007; Capitanio and Faccenda, 2012), small scale convection within the mantle wedge (Honda and Saito, 2003; Wirth and Korenaga, 2012), lateral gravitational instabilities above the mantle wedge (Behn et al., 2007), and lateral changes in thickness of the upper plate (Miller and Becker, 2012; Rodríguez-González et al., 2014). Three-dimensional slab-driven flow can be fundamental to understanding geophysical and geochemical processes in subduction systems (Kneller and van Keken, 2007; Hoernle et al., 2008; Durance et al., 2012). However, incorporating the detailed slab complexities has previously been out of reach of most computational infrastructure and software.

Therefore, one might ask, how feasible is it to model the geometric complexities of plate boundaries and the tectonic