Mapping Tertiary mid-ocean ridge subduction and slab window formation beneath Sundaland using seismic tomography

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SUMMARY

Based on tectonic reconstructions, Whittaker et al. (2007) proposed that a slab window formed beneath Sundaland between 70 and 43 Ma, due to subduction of the Wharton Basin spreading ridge between India and Australia. They suggest that extension in the Java Sea region at this time was exacerbated as a result of upwelling asthenosphere associated with the slab window.

Active ridge subduction and subsequent slab window formation can severely affect basin formation, heatflow and petroleum systems development on the overriding margin. A slab window forms between diverging plates when a mid-ocean ridge is subducted, leading to anomalous thermal effects like increased mantle wedge temperatures and thermal gradients in the overlying crust.

Whittaker et al.'s (2007) kinematic reconstructions rely on restoring now-subducted lithosphere based on preserved ocean crust, but the inherent uncertainties in this process call for an independent evaluation of this model. Mantle seismic tomography models provide qualitative boundary conditions for modelled tectonic histories.

We compare seismic tomography models with the model of Whittaker et al. (2007) at a range of mantle depths to confirm the existence of a slab window, and obtain bounds for its maximum regional extent. We identify a break in the high-velocity, down-going Indian-Australian slab at depths between 950-1350 km and longitudes between 85° and 110°, supporting the presence of a slab window. However, we find that the window is located approximately 5° further north and 10°-15° further west than previously proposed, implying that the Wharton Ridge was subducted farther west than previously suggested.

Key words: Slab window, seismic tomography, Sundaland, Southeast Asia, geodynamics

INTRODUCTION

Extension in back-arc settings is known to be related to retreating upper plates whereas compressional back-arcs result from advancing upper plates. In the Sundaland region however, the subduction of the Wharton Ridge (Figure 1) and the formation of a slab window have further complicated the regional tectonic and geological history (Whittaker et al., 2007).

Slab windows form at ridge-trench encounters, were sea-floor spreading ridges intersect with subduction zones. If oceanic plates continue diverging after they have been subducted a slab window opens between the trailing edges of the down-going slabs. The magma that may continue forming between the plates is too hot to solidify onto the plate edges and may even melt them partially. As a consequence a gap forms and continuously widens between the downgoing oceanic slabs. Thorkelson (1996) calls this process: " [an] unzipping of the divergent plate boundary" (Thorkelson, 1996, p. 49). Figure 2 shows this "unzipping" of oceanic lithosphere at a subduction zone.

Upper plate strain regimes like extension and basin formation are related to both kinematic and mantle parameters. A slab window causes changes in the thermal, physical and chemical character/condition of the mantle surrounding a slab window and lead to an alteration of the overriding plate's tectonic and magmatic evolution (Thorkelson, 1996).

Based on Heine et al.'s (2004) model, Whittaker et al. (2007) assume that Wharton Ridge subduction began 75-70 Ma beneath eastern Java (Whittaker et al., 2007, Heine et al., 2004). At the present day, the bathymetric ridge, which became extinct around 43 Ma, is subducted beneath northern-central Sumatra (Whittaker et al., 2004).

The geometry and position of a slab window beneath Sundaland suggested by Whittaker et al. (2007) is based on some simple assumptions made with respect to the geometry and orientation of the now subducted portion of the Wharton Ridge. Based on this model, the slab window would have opened around 70 Ma beneath eastern Java and shifted northwest to southern Sumatra where it stopped forming due to the extinction of the Wharton Ridge around 43 Ma.

Based on these suggestions Whittaker et al. (2007) hypothesise a correlation between the slab window and exacerbated extension in the Java Sea region between 70 and 40 Ma.

In this paper we use seismic tomography in order to "ground-truth" the presence and position of a slab window beneath Sundaland introduced by Whittaker et al. (2007), whose model relies on many uncertainties, to improve the understanding of the Wharton Ridge subduction and the distribution/pattern of back-arc extension.

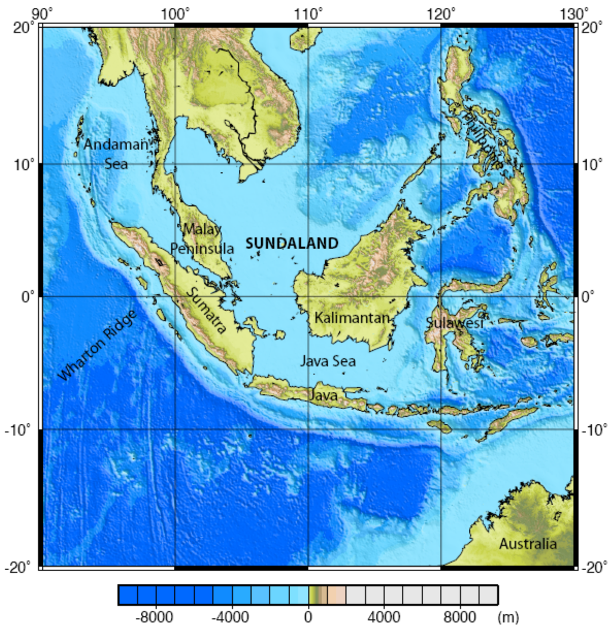

Figure 1: Sundaland and assumed Wharton Ridge location

METHOD AND RESULTS

Whittaker et al. (2007) proposed the presence of a slab window beneath Sundaland (Figure 1) between 70 and 43 Ma. If present, evidence supporting the existence of the slab window should be found in the deep mantle. In order to ground-truth the existence of the proposed slab window we looked at different present day P- and S-wave seismic tomography models. We chose the three models that are best for our purposes: *Montelli06_S* (Montelli et al., 2006) *sb4l18* (Masters et al., 1999) and *ngrand* (Grand et al., 2002), and zoomed into the region of interest, Sundaland.

Different studies (e.g. Richards et al., 2007; Replumaz et al., 2004) interpret negative seismic tomography anomalies in the mantle beneath Sundaland and link them to tectonic events in order to find a correlation between depth and age of the subducted Australian plate. Richards et al. (2007) interpret the geometry of the subducted Indo-Australian plate to a depth of 1340km and propose the base of their interpreted slab at 1340km to be ~70Myrs old. An alternative interpretation (Replumaz et al., 2004) is based on the assumption that subduction beneath Sundaland did not start until 50Ma. Based on the plate tectonic model of Müller et al. (2008), onset of Wharton Ridge subduction began at around 70Ma. Therefore, we use Richards et al.'s (2007) interpretation of Indo-Australian slab sinking rates for our age-depth calculation of the subducted oceanic slab.

The slab window is proposed to have formed in crust subducted between 70 Ma and 43 Ma, which based on Richards et al. (2007), should presently be located in the depth range between 1030 and 1340km. To identify the slab window we interpret gaps in the anomalous fast slab as representing the slab window in both vertical and horizontal seismic tomography slices. We compare our interpreted slab window locations with Whittaker et al.´s (2007) proposed slab window locations and reconstructed regional tectonic blocks (Müller et al., 2008) for different times (different depths) (Figure 3).

SEISMIC TOMOGRAPHY

Tectonic events that occurred millions of years ago are still persistent in the deeper mantle of the earth. Over recent years bodywave seismic tomography has become a successful tool for mapping cold lithosphere sinking into the mantle (Replumaz et al., 2004). A slab, especially below 660 km depth, is a feature which can be shown well in both P and S wave tomography models (Becker and Boschi, 2002) because the seismic-wave-velocities are contingent on the mantle´s temperature distribution which gets affected by plate subduction. Since horizontal motions at the surface are coupled through plate subduction to vertical displacement of material (Hafkenscheid et al., 2001), seismic tomography models offer the opportunity of reconstructing the surface by looking at the lower mantle.

In order to test and improve the kinematic models Whittaker et al.´s (2007) proposed slab window is based on, we use three global S- wave seismic tomography models, *Montelli06_S, ngrand* and *sb4l18* (Montelli et al., 2006, Masters et al., 1999, Grand et. al., 2002).

The age-depths conversion we use to find the assumed slab window has been made for the down-going slab only and does not apply necessarily for the surrounding mantle.

SLAB WINDOW

Slab windows form when there is an interaction between a mid-ocean ridge and a subduction zone. As a consequence of hot temperatures in the mantle, sea-floor spreading ceases and a gap forms between the two oceanic slabs (Figure 2) (Thorkelson, 1996).

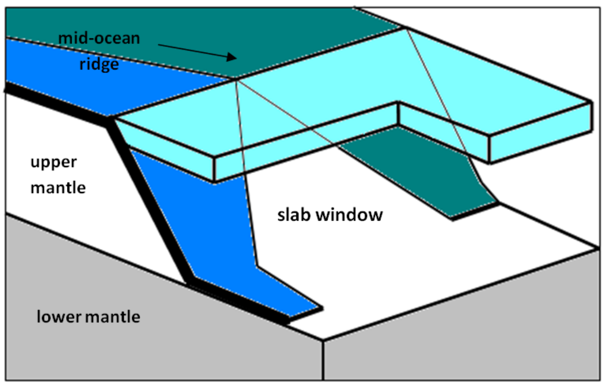

Figure 2: Slab window formation (after Thorkelson, 1996)

In a horizontal cross-section of a seismic tomography model, this gap can be found as a break in the cold and seismically fast down-going slab, represented by bluish to greenish colours in Figure 3.

We can find such a break in all three models at depths that represent the assumed time frame of 70 Ma to 43 Ma. Figure 3 shows a comparison of horizontal cross-sections through the mantle for the three different models *ngrand Montelli06_S* and *sb4l18* at three different depths (1340, 1185 and 1030 km) which represent three different times (69, 56 and 43 Ma). The subducted slab can be seen as a blue area that stretches in NW-SE direction. The red to yellow areas show the normal to anomalously hot surrounding mantle. In all figures a gap in the downgoing slab can be seen (highlighted by white ellipses). We assume that this gap is the slab window that, proposed by Whittaker et al. (2007), has opened between 70 Ma and 43 Ma due to the subduction of the Wharton Ridge. The black polygons show Whittaker et al.'s (2007) proposed position of the slab window.

Figure 3 shows clearly for all depths that the slab window has been located approximately 5° further north and 10°-15° further west than assumed by Whittaker et al. (2007).

The position of the slab window as imaged in three different seismic tomography models (Figure 3) implies that the reconstructed shape and/or strike of the Wharton Ridge in the plate tectonic model by Müller et al. (2008) is incorrect, as it results in the formation of a slab window too far to the east. The revised position of the slab window suggests that extension in the Java Sea may not be related to the presence of an underlying slab window. Instead, the slab window likely affected North Sumatra and the proto-Andaman Sea area.

A way to further ground-truth the location of the slab window could be an investigation of the volcanic signatures along the Sundaland island chain. Since slab windows can alter the magmatic evolution of the overriding plate (Thorkelson, 1996), a systematic change in the geochemistry of back-arc volcanoes would be expected.

The reconstructed position of the slab window also affects paleo-heathflow considerations for the East Java Sea and the revised location further north-west. The presence of a slab window is likely to lead to elevated heatflow and can therefore be important for the maturation history of petroleum systems. The type of basin that may be found above a slab window may also be different to normal extensional basin formation, as extension would be driven by dynamic asthenospheric uplift.

CONCLUSIONS

The slab window proposed by Whittaker et al. (2007) has been found in three different seismic tomography models to be located farther west and slightly farther north (Figure 3) than proposed based on kinematic reconstructions alone. That implies that the orientation and location of the Wharton Ridge must have been different than assumed by Müller et al. (2008).

Using seismic tomography we have been able to demonstrate that a slab window did exist in the Late Cretaceous/Early Tertiary, but the revised location implies that Java Sea region extension was probably not influenced by slab window effects. Instead extension further to the northwest in North Sumatra and the proto-Andaman Sea may have been at least partly a result of slab window tectonics.

Since seismic tomography models are only one way of ground-truthing tectonic models and rely on many uncertainties themselves, future geodynamic model construction should utilise an iterative approach incorporating plate kinematic models, mantle seismic tomography as well as mantle convection models which include plate kinematics and tomography as boundary conditions. Ultimately other geological observations can then be used to validate such models.

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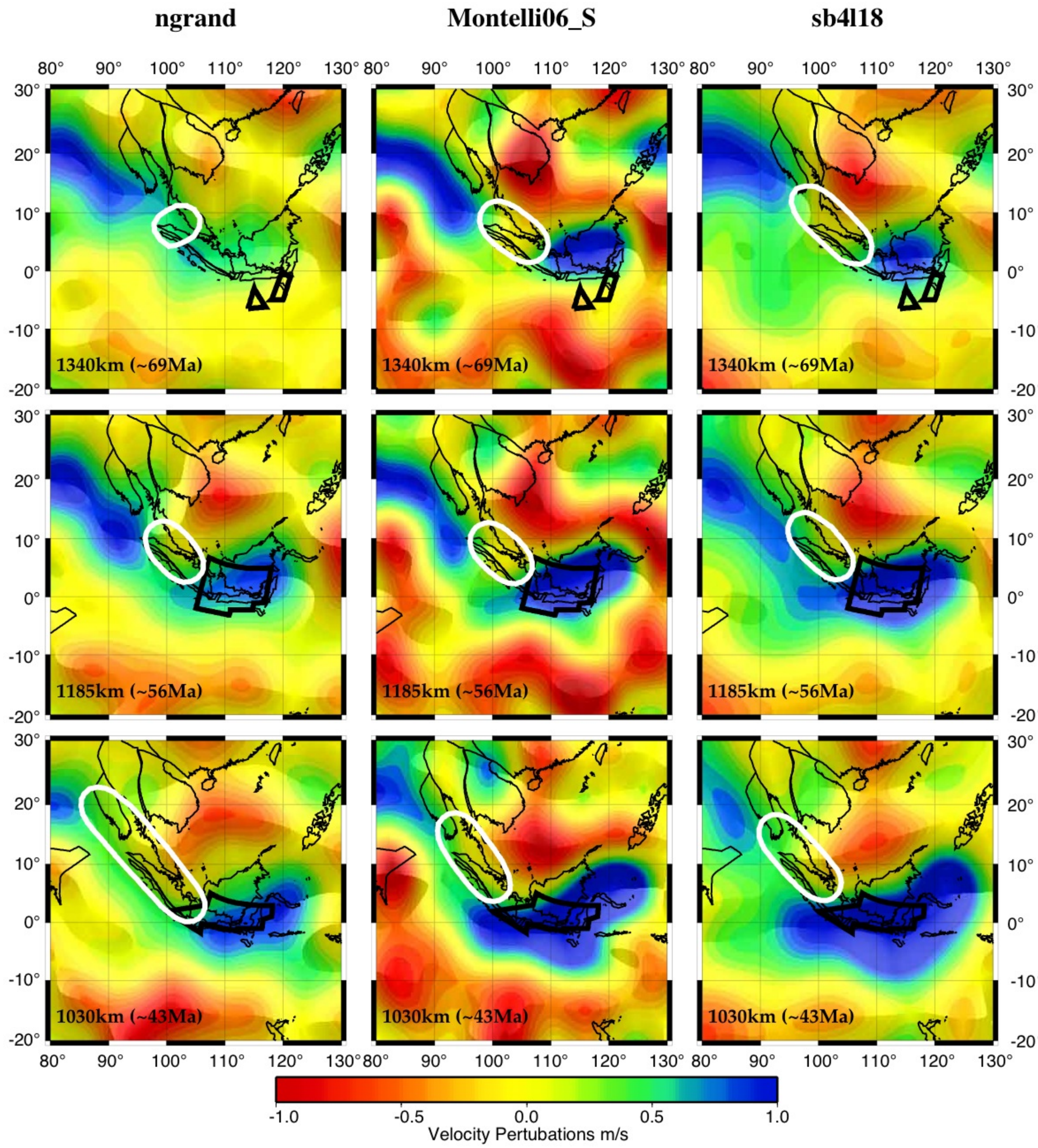

Figure 3: Horizontal cross-sections at three different depths for three s-wave seismic tomography models