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Crustal thickness beneath Central and East Java (Indonesia) inferred from P receiver functions

Ingo Wölbern *, Georg Rümpker

Institute of Geosciences, Goethe University Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany

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ABSTRACT

We compute receiver functions from teleseismic earthquake data recorded at the dense MERAMEX network in Central and East Java, Indonesia. In order to map the Moho depths H and the bulk crustal v_P/v_S-ratio κ we apply the H–κ stacking technique of Zhu and Kanamori (2000). Though the interpretation of the results is hampered by the high complexity of the recorded waveforms, in the context of a high noise level and of the heterogeneous assemblage of continental fragments and ophiolitic suture zones forming Southeast Asia, we were able to derive an average crustal thickness of about 34 km. Support for the assumption of ophiolitic basement in the center of the island related to the Meratus suture zone comes from shallowing of the Moho to about 30 km beneath the Kendeng zone. North and west of the Kendeng zone the Moho is imaged at anomalous depths down to 39 km. The observed anomalies line up along the hypothetical boundary between the continental SW Borneo fragment and the Meratus suture and are indicative of crustal thickening caused by overthrusting and compressional deformation in the context of a former collision zone. Resulting v_P/v_S-ratios cannot be inferred reliably due to the complexity of the waveforms. Our results do not corroborate the hypothesis of a major structural change along the southern coast at the division between Central and East Java. Likewise, we do not find clear evidence for the existence of the postulated Muria-Progo lineament.

1. Introduction

Southeast Asia comprises a complex assemblage of allochthonous continental terranes, volcanic arcs and suture zones (e.g. Hamilton, 1979; Audley-Charles, 1983; Metcalfe, 1994, 2011, 2013; Clements and Hall, 2011; Hall, 2012; Hall and Sevastjanova, 2012). The formation of SE Asia is assumed to have started in the Early Devonian with the opening of the Palaeo-Tethys ocean which was accompanied by the rifting of continental fragments from the NE margin of Gondwana. Two other episodes of rifting took place during the Early Permian (Metcalfe, 1994, 2011, 2013) and the Late Triassic to Jurassic (Metcalfe, 2013; Hall, 2012; Hall and Sevastjanova, 2012) and were connected with the opening of the Meso-Tethys and the Ceno-Tethys ocean, respectively. The continental fragments have subsequently moved northward and have been amalgamated to form the continental core of SE Asia. However, there is an ongoing debate about the origin, the history of movement, and the time of accretion of individual fragments (Hall and Sevastjanova, 2012), particularly because there is still a lack of detailed information such as ages of events, boundaries between individual blocks, or the thickness of the crust (Hall, 2012).

The emergence of the continental core, commonly termed Sundaland, was largely completed by the end of the Triassic (Sevastjanova et al., 2011; Hall, 2012; Metcalfe, 2013). Successive accretion of various fragments has taken place over millions of years. Today, Indonesia is situated at the southern continental margin of SE Asia with Sumatra and Java being part of the volcanic Sunda Arc. While Sumatra is assumed to have been accreted to Sundaland by Late Permian to Early Triassic, the development of Java is more complex. Presumably, the formation of Java started with the collision of the Southwest Borneo block (also termed the Banda block; SWB hereafter) in the Early Cretaceous and was completed with the accretion of East Java–West Sulawesi (also termed the Argo block; EJWS hereafter) during the Late Cretaceous. These fragments are divided by the Meratus suture complex representing the remnants of the subducted Meso-Tethys ocean. However, the width and location of this suture zone are not well constrained and differ in previous publications (Wakita, 2000; Smyth et al., 2007; Clements and Hall, 2011; Sevastjanova et al., 2011; Hall, 2012; Hall and Sevastjanova, 2012; Metcalfe, 2011, 2013).

* Corresponding author.
E-mail addresses: woelbern@geophysik.uni-frankfurt.de (I. Wölbern), rumpker@geophysik.uni-frankfurt.de (G. Rümpker).

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There is ample evidence for the Gondwana origin of several SE Asian terranes as derived from multi-disciplinary data such as palaeomagnetism, zircon ages, faunal and floral affinities, palaeoclimatic indicators, and many others. However, direct imaging of the crust–mantle boundary, i.e. the Moho discontinuity, is still sparse. Crustal-thickness measurements can also be used to distinguish between thin oceanic and much thicker continental crust. Continental crust has been inferred to exist beneath Sumatra from active seismic refraction studies revealing thicknesses of about 30 km beneath the forearc basin and onshore Sumatra (Kieckhefer et al., 1980). Rather thin crust with decreasing Moho depths towards Central Java has been suggested in an early study (Curray et al., 1977), while Hamilton (1979) has assumed a crustal thickness of about 20–25 km offshore below the Outer-Arc Ridge. More recent active seismic studies have investigated the oceanic crust offshore Java mainly focusing, however, on subduction processes south of the island (e.g. Kopp et al., 2006, 2009). Offshore East Java the oceanic Roo Rise plateau exhibits variable crustal thicknesses between 12 and 18 km as derived from seismic data and gravity modeling. The gravity data indicate a sharp increase of the thickness below Java supporting for a continental origin of the crust (Shulgin et al., 2011). Continental basement forming part of the Sunda Shelf has also been imaged beneath the East Java Sea (Granath et al., 2011).

In this study we aim to constrain the depths of the Moho discontinuity beneath onshore Central and East Java. We employ seismological data from a dense passive source network that was deployed approximately between 109.5°E and 111.5°E. Previous studies have analyzed the same data set by applying seismic travel-time tomography (Koulakov et al., 2007, 2009; Wagner et al., 2007; Haberland et al., 2014), ambient noise (Zulfakriza et al., 2014), and seismic attenuation (Bohm et al., 2013). However, these studies did not attempt to determine the crustal thickness. To map the Moho depths we apply the H–κ stacking method of Zhu and Kanamori (2000) to teleseismic receiver functions.

2. Geological setting and previous results

According to the history of accretion described above Java is composed of five major blocks (Fig. 1): The continental West Sumatra block the Woyla arc, the SWB, the EJWS, and the Meratus suture (Sevastjanova et al., 2011; Hall and Sevastjanova, 2012). Java can be divided into three structurally distinct sectors roughly corresponding to the regions of West, Central and East Java. The most fundamental division has been reported to exist between Central and East Java, as the volcanic Southern Mountains Arc in East Java was built on a Gondwana-derived continental fragment while the volcanoes directly to the west are underlain by ophiolitic basement. This is thought to have significantly affected the structural development (Clements et al., 2009). In the southern part of Java, the division is represented by the NNE–SSW trending Muria-Progo lineament (MPL) which links several major features onshore and offshore and has first been described by Smyth (2005). Additional evidence for a continental basement beneath East Java arises from inherited zircons of Precambrian ages found beneath the Southern Mountains Arc (Smyth et al., 2007).

Subduction of the Australian plate beneath Sundaland started after the emergence of present-day SE Asia in the Middle Eocene at about 42 Ma (Hall, 2012). This coincides with the onset of volcanism forming the Southern Mountains Arc (Fig. 1) situated along the southern coast of Java (e.g. Smyth et al., 2008; Clements et al., 2009). This volcanic arc remained active until Early Miocene (~18–20 Ma). After a period of quiescence volcanism resumed in the Late Miocene (~10–12 Ma), approximately 50 km further north at the position of the modern Sunda Arc (Smyth et al., 2008). Large scale thrusting was reported to have taken place in the Middle Miocene or later throughout Java and a total northward displacement of the Southern Mountains Arc in the order of 50 km to 100 km was deduced (Clements et al., 2009). In the same study, the cessation of the arc volcanism and the shift of arc activity towards the north is linked to this thrusting event. The volcanism of the Southern Mountains Arc has probably provoked the formation of the flexural Kendeng Basin (Fig. 1) beneath East Java, which started to develop at approximately the same time as the volcanic activity. The Kendeng zone is located directly north of the Southern Mountains Arc and oriented parallel to it with an EW extension of at least 400 km coinciding with a pronounced negative Bouguer anomaly (Smyth, 2005; Smyth et al., 2008). The basin was filled with volcaniclastic material and sediments that are reported to be 6–10 km thick. The material is assumed to have been eroded from the Southern Mountains Arc. The former sedimentary basin is nowadays under compression and partially overlain by the Modern Sunda Arc (Smyth et al., 2008). To the north, the Kendeng zone is bordered by the EW oriented Kendeng thrust which continues further west as the Barabis thrust. It is assumed that the Kendeng thrust constitutes the southern edge of the early Cenozoic Sunda shelf (Smyth et al., 2008; Clements et al., 2009) i.e. the boundary of the former SWB fragment. Today, a large part of the Sunda shelf of East Java is transected by the Meratus suture zone (Sevastjanova et al., 2011; Hall and Sevastjanova, 2012; Clements and Hall, 2011) as shown in Fig. 1.

Previous travel-time tomography studies for Java have revealed a significant reduction of seismic P- and S-wave velocities by as much as 30% in the upper 15 km of the crust (Koulakov et al., 2007, 2009; Wagner et al., 2007). This anomaly (referred to as the Merapi-Lawu Anomaly, MLA) is mainly observed between the Merapi and Lawu volcanoes in the western part of the Kendeng zone. High contents of gas and fluids in the sediments have been suggested to contribute to the anomaly. However, fluids are also suspected below the sediments because the MLA is linked to an inclined low-velocity zone in the upper mantle which has been interpreted as migration paths of fluids and partial melt from the slab (Koulakov et al., 2007, 2009; Wagner et al., 2007). This interpretation is supported by results from attenuation tomography which also reflects a strong effect of thick fluid-saturated sediments of the Kendeng zone in the upper 15 km, while another high attenuation zone directly above the slab indicates the location of melt generation (Bohm et al., 2013). Ambient noise tomography further supports the existence of the MLA, but the results indicate that the anomaly is concentrated in the upper 5 km of the crust (Zulfakriza et al., 2014). In contrast, a large zone of elevated seismic velocities along with low v_P/v_S ratios has been reported in the northern part of Java underneath the Muria volcano which is not connected to the MLA (Koulakov et al., 2007). The travel-time data have been reassessed in a recent tomographic inversion by Haberland et al. (2014) confirming the location and the strength of the MLA, but also revealing further structural details: A continental fragment is reported beneath the Southern Mountains Arc adjacent to an inclined high-velocity body, interpreted either as mantle material associated with this fragment or obducted oceanic lithosphere, thus, supporting previous observations by Smyth et al. (2007, 2008) and Clements et al. (2009) as described above. Alternatively, the high-velocity bodies could be explained by dense basic cumulates resulting from significant differentiation of arc magmas as discussed in Waltham et al. (2008). Moderate velocities are observed by Haberland et al. (2014) down to 40 km beneath the center of the island which are interpreted as indicative of the ophiolitic and arc rock assemblage of the Meratus suture.