Mechanism of slab thickening near 670 km under Indonesia

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Abstract. We examine a new data set of reliably relocated earthquakes deeper than 400 km under Indonesia, developed by [Schöffel and Das, 1999]. The accuracy of this data allows us to demonstrate that the slab thickens, shortens and weakens before penetrating below 670 km by shearing along conjugate fault planes on the upper and lower portions of the seismic zone. We also show that the earthquakes in the lower portion of the Wadati-Benioff zone width are generally fewer and smaller than those in the central portions, with only 8% of the total moment released in the period 1976-1996 being due to earthquakes on the lower side.

Introduction

A question of very wide interest in the study of plate tectonics is what happens to slabs as they descend into the mantle. The fate of the slab under Tonga, the most seismically active region of the world, was elucidated earlier [Giardini and Woodhouse, 1984], and it was shown that the seismicity forms cross-cutting bands, along which the nodal planes of the earthquakes were aligned, with strong resistance to penetration of the subducted material below the 670 km discontinuity. We investigate the behaviour of the deep portion of the Indonesian subduction zone by considering the earthquakes deeper than 400 km.

Accurate Earthquake Hypocenters and CMT Mechanisms

The study region and the deep relocated seismicity [Schöffel and Das, 1999] are shown in Figure 1. Generally depths of earthquakes are the least reliable part of its location. Schöffel and Das [1999] used the joint hypocenter determination method of relocating deep earthquakes and used thousands of handpicked P, S, pP, sP, PcP and ScP phases from digitally recorded seismograms of recent earthquakes, together with available phase data reported by the International Seismological Centre (ISC). The significant improvement of the locations obtained by using phases not traditionally used in hypocentral locations, such the core reflected phases, which are often large, impulsive and have a different take-off angle than commonly used phases, was demonstrated by Schöffel and Das [1999], see their Figures 2 and 3. The size of the error ellipses in those figures show that with these improved locations, it is possible to distinguish the earthquakes that occur in the different portions of the Wadati-Benioff zone (WBZ) width (lateral extent perpendicular to slab strike), namely, its upper, central and lower portions. Thus, use of these new hypocentral locations together with the centroid moment tensor (cmt) solutions permits us to understand how the slab behaves near the 670 km boundary.

Vertical profiles of the relocated seismicity and the relocation error ellipses, together with cmt solutions are shown in Figure 2. A narrowing of the seismic zone between 400-500 km is generally seen. Below this depth, the seismic zone widens, particularly well illustrated in profiles 33' and 44', which have sufficient activity spanning the entire depth range under consideration. The thinning of the seismic zone could be due to necking of the descending slab at such depths, and such necking has been interpreted in models of mantle phase changes as being due to the exothermic olivine-spinel phase change [Brunet et al., 1998]. Figure 2 shows that the number of earthquakes on the lower portion of the WBZ width are fewer than those in the central

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Figure 2. Vertical profiles showing the relocated seismicity (filled dots) together with 90% confidence error ellipses, cmt solutions and not relocated ISC seismicity (open squares). The latitude and longitude of the center position of each profile is marked at the center top. The “upper” portion of the slab is on the right side of each profile. The cmt mechanisms are rotated into the plane of projection and are identified by their dates (mm-dd-yy), the $M_w$ for each being given below it. The projection of the rupture area of the 1996 Flores Sea event (20 km along dip) [Tibi et al., 1999] is shown as a thick black line in 55°. The cmt mechanisms for earthquakes identified as being on the lower portion of the WBZ width are plotted to the left in each profile. Due to the distortion in the WBZ demonstrated by Schöffel and Das [1999], the decision on which earthquake falls on the lower side was made using the narrow arc-perpendicular profiles of that study, and the profiles were then combined into the six shown.
and the upper portion and generally have lower $M_w$. The largest known deep earthquake in this region, the $M_w = 7.9$ 1996 Flores Sea earthquake, initiated in the upper portion and ruptured towards the central portion of the WBZ width [Tinker et al., 1998; Tibi et al., 1999]. Only 8% of the total moment released in the 400-670 km depth range in the period 1976-1996 was due to earthquakes on the lower portion. The upper portion is the one that was initially colder, that is, when the slab was near the Earth’s surface. Models of thermal structure of descending slabs indicate that this portion remains colder than the lower portion as the slab heats up while descending into the mantle [Plate 3 of Kirby et al., 1996].

The cmt mechanisms in Figure 2 are remarkably consistent. Of the 74 mechanisms shown, only 12 do not satisfy the dominant pattern, and except for one, all these 12 earthquakes are small. The 1937 earthquake is the exception, but the reliability of the cmt mechanism of earthquakes from that period is unknown. The axes of compression for the earthquakes below about 500 km consistently align with the seismic zone, which together with the associated compression axes bend backwards in the 500-670 km depth range [Schöffel and Das, 1999]. Near the part of the back-bending zone where the curvature is maximum, some compression axes do not align with the zone. Three of the 12 earthquakes which do not have the dominant focal mechanism lie in this region, indicating that these earthquakes reflect the local bending stresses.

It is well known that deep earthquakes generally have few aftershocks, and therefore identifying the rupture plane of earthquakes by using aftershocks is not generally viable for deep earthquakes. The large 1996 Flores Sea earthquake was an exception and had several aftershocks. The rupture plane was identified using waveform studies [Tinker et al., 1998], as that nodal plane (strike 100°, dip 55°, the southeast striking plane in map view) for which the rotated cmt in the vertical profile (Figure 2) has a left-lateral sense. It was also shown that the plane of faulting coincided with the aftershock-delineated plane. For the other earthquakes in this region, the few reliably relocated aftershocks were too close to the main shock to be used to identify the fault plane, even for the earthquake 052490 ($M_w = 7.1$). Earthquake 080885 of profile 22° lies in the upper portion of the WBZ and has one aftershock, which lies on the left-lateral nodal plane.

We examine the seismicity viewed from the direction of the intermediate axis of the dominant earthquake focal mechanism in the 6 profiles, to try to identify faulting planes for other earthquakes. The focal mechanisms appear as pure strike-slip in this projection. The pattern of cross-cutting bands of seismicity, found in Tonga [Giardini and Woodhouse, 1984], is seen in profiles 33°, 44° and 66° (Figure 3), with the seismicity aligned along nodal planes. This pattern is less clear in the other 3 profiles (not plotted). The faulting plane for earthquakes on the central and upper portion of the WBZ, was shown above to be left-lateral. The seismicity band aligning with that nodal plane which would result in right-lateral faulting suggests that for the earthquakes in the

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**Figure 3.** Seismicity viewed from the direction of the intermediate axis of the dominant earthquake focal mechanism of three selected profiles. Only the portion of the profile containing seismicity is shown. The mechanism of the largest, but relatively recent, earthquake among those with consistent focal mechanism, was chosen as the dominant one in each profile, and is plotted, with the inferred plane of faulting indicated by the dashed line.

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**Figure 4.** Schematic representation of the seismic zone projected perpendicular to the slab strike (not drawn to scale), illustrating the mechanism of slab thickening, accumulation and shattering as it descends to the 670 km depth level. The thick arrow indicates the overall motion of the slab. Thin arrows show the position and the relative slip direction of the faults. The direction of compression is indicated by the dashed arrows.
lower portion, the rupturing is along this plane. Since earthquakes on the lower portion are generally smaller and fewer, they are more difficult to study, and this pattern can be reconfirmed when a larger amount of well located hypocenters in this region has been accumulated in future.

**Proposed Physical Mechanism**

The above observations lead to our suggested slab-shattering model of the physical mechanism by which the seismic zone (and the associated slab) shortens and thickens above 670 km, shown schematically in Figure 4. The slab, which is under vertical compression here, is shortening, thickening and weakening by shearing along conjugate planes on the two sides of the seismic zone. The planes of rupturing lie at an angle to the upper and lower surface of the seismic zone, and the lower part of the faults move in the direction out of the slab on both sides. This results in the dominant normal type focal mechanism, when looked at in map view. The shape of the seismic zone above the 670 km depth level indicates slab accumulation as the descending slab encounters the 670 km boundary. The seismic zone is the metastable region of the slab [Kirby et al., 1996], and our study shows that it is not wedge-shaped, but broadens near 670 km. Roth and Wiens [1999] suggest a widening of the metastable zone near 660 km under Tonga from analysis of ScS reverberations. Use of reliable hypocenters such as those used in this study can provide further insights into the behaviour of other subducting slabs.

**References**


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