Observations of the mid-mantle discontinuity beneath Indonesia from S to P converted waveforms

Elizabeth Vanacore,[1] Fenglin Niu,[1] and Hitoshi Kawakatsu[2]

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[1] S to P conversions were employed to derive a coherent discontinuity structure beneath Indonesia. Analysis of data recorded by three regional arrays from nine deep earthquakes not only confirmed the results of previous studies on the existence of the mid-mantle discontinuity beneath the Java arc but also revealed its presence north to Kalimantan Island. S to P waves converted at the discontinuity were observed on the stacked diagrams with a negative slowness relative to the P wave and a conversion depth ranging from ∼1080 km in the west to ∼930 km in the east. **Citation:** Vanacore, E., F. Niu, and H. Kawakatsu (2006), Observations of the mid-mantle discontinuity beneath Indonesia from S to P converted waveforms, *Geophys. Res. Lett.*, *33*, L04302, doi:10.1029/2005GL025106.

1. Introduction

[2] Mapping seismic heterogeneities in the upper part of the lower mantle (mid-mantle) is important to the understanding of mantle dynamics and the distribution and the nature of geochemical reservoirs [*Wen and Anderson*, 1997; *Kellogg et al.*, 1999; *van der Hilst and Karason*, 1999; *Tackley*, 2000; *Helffrich and Wood*, 2001]. Recent seismological studies indicate seismic discontinuities [*Kawakatsu and Niu*, 1994; *Niu and Kawakatsu*, 1997; *Vinnik et al.*, 1998, 2001] and strong seismic reflectors/scatterers at mid-mantle depths in the western Pacific subduction regions [*Kaneshima and Helffrich*, 1999; *Castle and Creager*, 1999; *Kruger et al.*, 2001; *Niu et al.*, 2003; *Kaneshima and Helffrich*, 2003; *Kaneshima*, 2003]. The mid-mantle discontinuities are absent in other regions such as beneath the South American subduction zone [*Castle and van der Hilst*, 2003]. Most of the seismic observations are based on the detection of S to P conversion at the discontinuities.

[3] This study's goal is to conduct a search for seismic structure using S to P conversions over an expanded area compared to our previous study [*Niu and Kawakatsu*, 1997, hereinafter referred to as NK97] including the entire Kalimantan Island (Figure 1) for future comparison with SS precursor data. We chose this region as our testing example for two reasons: first, NK97 suggests that the mid-mantle discontinuity has the largest S-wave velocity contrast in the region; the S to P conversion at the discontinuity (hereafter $S_{1000}P$) is visible in most of the individual recordings, so there is no issue of stacking artifacts; second, a SS precursor study by *Deuss and Woodhouse* [2002] found several negative/positive reflection peaks at same depth range. Our previous studies [*Kawakatsu and Niu*, 1994; NK97] employed short-period seismograms recorded by Jarray [*J-Array Group*, 1993] to identify $S_{1000}P$. The major concern of using Jarray data is whether the complicated mantle structure beneath the array could affect the slowness measurement and phase identification. We accordingly analyzed the Indonesia region earthquake data recorded by the Southern Africa Seismic Experiment broadband array (Kaapvaal array) [*Carlson et al.*, 1996].

2. Data and Method

[4] Nine regional events with depths greater than ∼500 km (Table 1) were studied in order to observe S to P conversions; the events consist of eight newly analyzed events and one data result from NK97 recorded by Jarray, Hinet, and the Kaapvaal array. Event data from the three networks available to us are before 1995 for Jarray, after 2001 for Hinet, and 1997–1999 for Kaapvaal array. The nine deep events are selected from the Harvard CMT catalog [*Dziewonski et al.*, 1981] with a moderate size ($5.5 < M_w < 6.5$) and a simple source-time function.

[5] Prior to stacking seismograms for the individual events, the raw data are preprocessed in three basic steps. First, the signal to noise ratio (SNR) of the individual seismograms is calculated with based on amplitudes of the P wave and the background noise; seismograms with a minimum ratio of ∼2 are retained for further analysis. For the individual events analyzed, the number of retained seismograms ranged from ∼50 to 600. In all but two events, the number of retained traces was greater than 100. Secondly, the remaining seismograms are low pass filtered with a corner frequency of 1 Hz. Thirdly, handpicked P-wave first arrivals of the individual seismograms are aligned to 0s, to allow for stacking with reference to the P wave arrival. In Figures 2a and 3a, we show two examples of the data after preprocessing. Here, the waveform data are recorded by the borehole short-period Hinet (Figure 2a) and the broadband Kaapvaal array (Figure 3a). In both examples the S to P converted phase is clearly visible before stacking in the time window of 35–45s after the direct P wave. No seismic waves are expected to arrive in this time window based on 1D global reference velocity models, such as iasp91 [*Kennett and Engdahl*, 1991].

[6] The preprocessed data are 4th-root stacked with respect to the P wave arrival to highlight coherent later arrivals [*Muirhead*, 1968; *Kanasewich*, 1973]. Details of the stacking procedure are given by *Kawakatsu and Niu* [1994]. In the stacked seismograms the S_DP phase is characterized by an arrival time between the direct P and pP phase arrivals and a negative slowness that separates these arrivals from P wave arrivals associated with aftershocks. Stacked results

[1]Department of Earth Science, Rice University, Houston, Texas, USA.
[2]Earthquake Research Institute, University of Tokyo, Tokyo, Japan.

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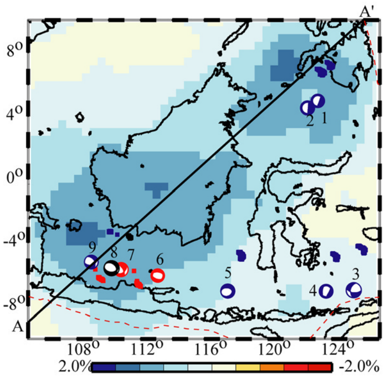

Figure 1. Map view of the nine events and respective $S_{1000}P$ conversion points. P-wave tomographic model of *Fukao et al.* [2001] for the layer of 900 to 1000 km is shown by the color contour. Line A-A′ is the cross section shown in Figure 4.

(Figures 2b and 3b) are employed to estimate the conversion depth of the observed S_DP phases. Arrival times relative to the P-wave arrival are compared to corresponding theoretical travel times estimated using the iasp91 model from which the conversion depths and the theoretical slowness are derived. The conversion points within the mantle are calculated for each earthquake-station pair for a discontinuity at 1000 km depth, the approximate average depth of the discontinuity in the study region, shown as point clusters in Figure 1.

3. Results

[7] 4th-root stacks of the nine events analyzed exhibit a discontinuity throughout the region with the exception of events three and four, located in the southeast corner of the study region. The lack of a $S_{1000}P$ arrival for these two events does not necessarily imply a limit on the extent of the discontinuity; NK97 contains data from two earthquakes in the same sub-region occurring at (−6.86°, 125.41°) in 1990 and (−7.26°, 122.57°) in 1991 with mid-mantle discontinuities observed at 940 km and 945 km respectively. Amplitudes of the $S_{1000}P$ of these two events are about half of the other events. The lack of a clear $S_{1000}P$ arrival after the stacking process may be due to unfavorable focal mechanisms associated with the two events from this study. Conversion depths calculated by matching arrival times of the $S_{1000}P$ arrivals based upon the IASP91 velocity model yield depths ranging from 1080 km to 930 km (Table 1). The predicted slowness listed in the table is the relative slowness calculated for an S wave converted from P at the observed depths for each event. We assumed a horizontal discontinuity in the calculation. In general, the observed slowness matches the expected one quite well. Data from two events, however, show a relatively large discrepancy, ∼0.1 s/deg. Many factors including anomalous structure near the source and beneath the arrays could affect the slowness measurement. Since the anomalous slowness of the two events is measured from two different arrays, it is easier to explain the discrepancy by a dipping structure, although the uncertainty in the slowness measurement is almost at the same level (Figures 2b and 3b). The major feature of the mid-mantle discontinuity shown here is that its depth is shallow in the east; depth observations of less than 1000 km are restricted to longitudes greater than 113°E.

[8] Conversion points of $S_{1000}P$ for events #1, 2, 6, 7, 8 and 9 are located within the intense mid-mantle high velocity anomaly (HVA) beneath the Indonesia region (Figure 1), which has been consistently imaged by most tomographic studies using different data sets as summarized by *Fukao et al.* [2001]. $S_{1000}P$ amplitudes of these events are very large, indicating some sort of correlation between the mid-mantle discontinuity and the HVA (Figure 4).

[9] We noticed a series of arrivals between ∼30–60 s after the direct P, similar to observations at the Mariana arc [*Niu et al.*, 2003; *Kaneshima and Helffrich*, 2003; *Kaneshima*, 2003]. Since we used a nonlinear stack scheme and assumed horizontal discontinuities, scattering energies from small-scale heterogeneities [*Kaneshima and Helffrich*, 2003] did not show up in the stacked traces. The coexistence of these small-scale heterogeneities might be very important to understanding the nature of the mid-mantle discontinuity. Further investigations with more sophisticated seismic methods, such as migration, are preferred to image the small scale heterogeneities.

4. Discussion

[10] Observations of mid-mantle discontinuities in the Indonesia region at depths ranging from ∼920–1080 km depths and dipping to the west are prevalent throughout the region as demonstrated in this study by S to P converted energy. The abruptness and geometry of this depth change is, however, not well constrained by our results. Given the consistency of the depth estimates from the events in the western portion of the region, numbered 6–9 (Figure 1 and

Table 1. Earthquakes Used in the Study and Observations of the $S_{1000}P$

Event #	Event Date	Tobs, s	Pobs, s/deg	Depth, km	Pcal, s/deg	Lat.	Long.	Event Depth, km	Mag., Mw
1	12/21/02	34.0	−0.24	930	−0.32	4.97	123.12	596	5.6
2	07/01/03	38.0	−0.30	970	−0.35	4.57	122.55	595	6.0
3	12/17/02	—	—	—	—	−6.97	125.38	493	5.7
4	02/03/03	—	—	—	—	−7.07	123.68	585	5.8
5	02/16/01	40.5	−0.23	960	−0.26	−7.05	117.50	533	6.0
6	04/27/98	41.2	−0.16	1080	−0.15	−6.08	113.10	571	5.7
7	07/11/97	43.3	−0.24	1080	−0.15	−5.70	110.80	574	6.0
8[a]	11/15/94	48.6	−0.30	1080	−0.32	−5.61	110.20	570	6.2
9	05/13/95	49.6	−0.30	1080	−0.28	−5.22	108.92	554	5.9

[a]Indicates event from previous study [*Niu and Kawakatsu*, 1997].

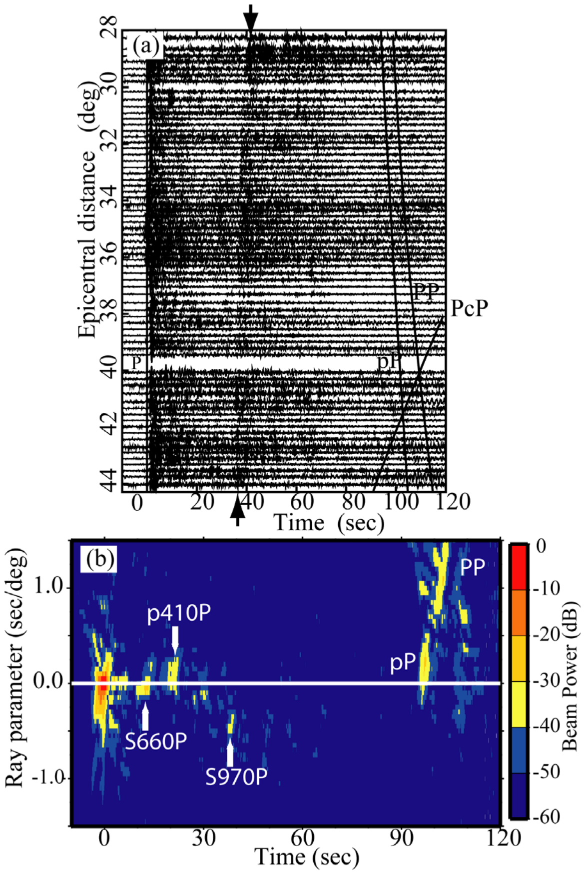

Figure 2. (a) A subset of Hinet seismograms plotted in the order of epicentral distance for a deep event that occurred at the Celebes Sea in July 1, 2003. Arrows indicate a later arrival shown in most of the seismograms. (b) Amplitudes of the 4th-root stacked traces are shown in color code as a function of slowness for the same events. Later arrivals are identified by the observed time and ray parameter. Both are shown with respect to the direct P wave.

Table 1) and the shallow discontinuity depths observed in the east, it is reasonable to hypothesize that the discontinuity has a large amount of topography, over 100 km in magnitude, between ∼113° and ∼120°.

[11] Although there are some suggestions that the observed mid-mantle reflectors/scatterers are associated with subducted oceanic crust [*Kaneshima and Helffrich*, 1999; *Niu et al.*, 2003], we still don't have a conclusive explanation for the mid-mantle discontinuities beyond the fact that it is not caused by global phase transitions. Furthermore, it has been recently proposed the mantle contains a chemical boundary layer at ∼1000 km depth where one line of evidence is the correlation between the surface location of subduction in the Jurassic to Eocene and the Permian to Triassic with the presence of a tomographic anomaly at 800 to 1000 km depth [*Wen and Anderson*, 1997; *Anderson*, 2002]. Our study area is within a correlated zone, suggesting that the seismic discontinuities observed are associated with slab material accumulated at mid-mantle depths. The correlation between ancient subduction zones and the presence of HVA's at depths of 500 to 1000 km has been previously examined in regions directly to the east and south of our study area [*Hall and Spakman*, 2002]. Extrapolating this correlation in combination with the correlation between the observed discontinuity and the regional HVA, we associate our observations with slab material stagnated at depth. A global search for the observed ∼1000 km discontinuity is necessary to determine if this phenomena is directly associated with slab stagnation at mid-mantle depths or is associated with a global discontinuity possibly due to a compositional boundary within the mantle. One study by *Shen et al.* [2003] observed a P to S conversion at ∼1000 km depth beneath the Hawaii and Iceland hotspots and suggested that the mid-mantle discontinuity might be associated with a compositional boundary [*Wen and*

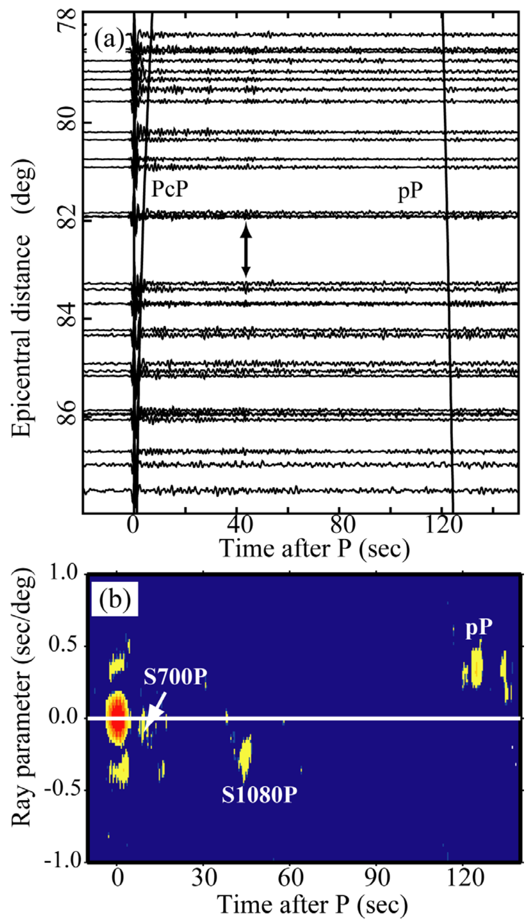

Figure 3. Another example. Seismograms are recorded by the Kaapvaal broadband seismic array, clear S to P conversion at ∼1080 km depth is also observed here.

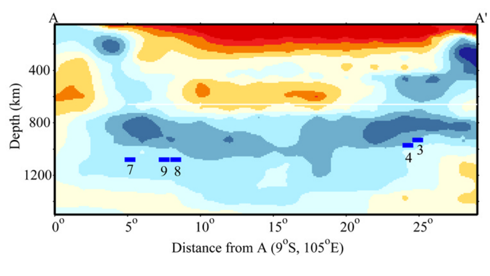

Figure 4. Cross section of A-A′ labeled in Figure 1 from 9°S, 105°E to 10°N, 126°E with labeled conversion points for 5 events with tomography of *Fukao et al.* [2001].

Anderson, 1997; *Kellogg et al.*, 1999; *van der Hilst and Karason*, 1999; *Tackley*, 2000]. This single phase observation occurring in a region without a recent history of subduction is not sufficient evidence to argue for a global discontinuity at ~1000 km depth due to a compositional change.

[12] If the structure observed here is related to subducted slabs, as indicated by the $S_{1000}P$ observations, then we can speculate on two physical mechanisms to explain the presence of this phase. One possible explanation is the breakdown of the dense hydrous magnesium silicates (DHMS) within the cold slabs [*Shieh et al.*, 1998; *Ohtani et al.*, 2001]. Such a breakdown may trigger chemical segregations within slabs that forms the seismic discontinuity as observed in this study. Another possible origin is the post garnet phase transition of MORB, which is observed to occur at mid-mantle depths [*Ono et al.*, 2001]. This interpretation has some difficulty in explaining the relatively flat geometry of the structure, as the subducted oceanic crust probably undergoes significant deformation once it enters into lower mantle. Even if a simple flat geometry is preserved then a low velocity layer instead of discontinuity is expected. A recent mineral physics study by *Kubo et al.* [2002] suggested that the post garnet phase transition might not occur since MORB garnet can survive in metastable state on the order of ten million years when temperature is a couple hundred degrees Kelvin lower. This may lead to an accumulation of a metastable garnet layer at the top of the lower mantle; the lower boundary of the layer is a possible cause for the regionally observed discontinuity [*Kubo et al.*, 2002]. Dynamically the metastable garnet model provides a mechanism explaining the stagnation of slab material in the region at depths of ~800 to 1000 km without invoking the presence of a stratified mantle with a chemical boundary layer at similar depths as suggested by *Wen and Anderson* [1997] and *Anderson* [2002]. If the DHMS or metastable garnet scenario is valid and the observed discontinuity is related to subducted slab material, then further research is needed to determine the consistency of this feature within other subduction regions as well as possible factors controlling the formation or lack thereof of this discontinuity.

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H. Kawakatsu, Earthquake Research Institute, University of Tokyo, Tokyo 113, Japan.
F. Niu and E. Vanacore, Department of Earth Science, MS-126, Rice University, 6100 Main St., Houston, TX 77005, USA. (evanacor@rice.edu)