Crustal thickness investigation on three broadband stations in Northern Sumatra

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Abstract. We present a preliminary result of crustal thickness in Northern Sumatra from receiver function analysis and grid search. Total of 111 teleseismic events from three broadband stations (TPTI, KCSI, and BSI) of IA-Network were used to calculate the receiver functions. We identified direct P and S arrival from the receiver function. Converted phases Ps were relatively clear for all three broadband stations. Ps-P time was estimated about 2 - 3 s, 2 s, and 5 - 6 s for station TPTI, KCSI, and BSI, respectively. We applied H-k stacking method to obtain crustal thickness and Vp/Vs ratio beneath the three broadband stations. At station TPTI, we obtained the crustal thickness is about 19.54 ± 3.84 km, Vp/Vs ratio is about 1.73 ± 0.14. At station KCSI, the crustal thickness was estimated to be 37.07 ± 4.47 km, Vp/Vs ratio is about 1.84 ± 0.10. At station BSI, which is located to the north of these two stations, the crustal thickness was estimated to be 40.56 ± 2.26 km, Vp/Vs ratio is about 1.81 ± 0.05. These results show relatively large variation of crustal thickness in the Northern Sumatra.

1. Introduction

Sumatra Island is located along the Eurasian and Subducting Indo-Australian plate boundary. Along the western coast of Sumatra, the Indo-Australian plate is subducting beneath the Eurasian plate. Sumatra is dominated by volcanic arc resulting from magma generation along the underlying Wadati-Benioff zone. The incoming Indo-Australian plate is approaching the trench in oblique angle. The motion caused slip partitioning to trench-normal thrust component along the plate interface and strike-slip component accommodated by fault zone [1, 2]. The subduction process causes high seismicity activity along this region. In the last decade, two devastating megathrust earthquakes occurred in the region of northern Sumatra, which were 2004 Mw 9.2 Sumatra-Andaman earthquake and 2005 Mw 8.7 Nias earthquake.

Sumatra has been estimated to be a volcanic arc since late Permian but the intensity went up during the Tertiary period [3, 4]. It was suggested that volcanic rocks were distributed along the west coast of Sumatra during the late Eocene and in Aceh area might have been resulted from back-arc volcanism [5, 6]. Cameron et al. [5] generally sequenced stratigraphy in northern Sumatra into four major volcano-sedimentary sequences. Three are pre-tertiary and the other covers Cenozoic. The oldest rocks belong to the Late Palaeozoic Tapanuli Group which is elastic and probably glaciomarine origin. In this study, we analyze receiver functions to obtain information on the crustal characteristics of its thickness and seismic properties beneath northern Sumatra.
2. Data and method

Investigation of crustal thickness has been extensively studied by using receiver function method [e.g. 7-9]. In this method, the teleseismic waveform is used to image the crustal characteristics beneath the selected seismic stations. It is based on the use of the converted S-wave from the teleseismic P-wave ($Ps$) at the crustal-mantle discontinuity. The $Ps$ phase arrives directly after the direct P-wave. The resulting $Ps$ conversion has stronger amplitude on the horizontal components. The receiver functions are obtained from the deconvolution of vertical and horizontal components. The deconvolution process will remove the effects of source structure and propagation path.

In this study, seismogram records between 2005 and 2012 from three broadband seismometers of IA-network were used to calculate the receiver functions. Three stations are located in the northern Sumatra Island (figure 1). We computed receiver functions at these three stations from teleseismic events between distances of 30° and 95° with magnitude greater than 5.5. Total of 111 events were used to compute the receiver functions. Most of the events were from the east of the stations, which are from Western Pacific, Indonesian and Kermadec - Tonga subduction zones.

We employed time domain interactive deconvolution to calculate the receiver functions [10]. The raw seismograms were windowed between -10 and 50 s around the P-wave arrival and rotated into vertical, radial and transverse components. The iterative deconvolution estimates radial receiver functions using Gaussian pulses and convolves the estimation with the recorded vertical component. We filtered the receiver function with Gaussian width factor of 2.5, which corresponds to frequency band > 1.25 Hz. We selected of high quality of the receiver functions by using misfit criterion. The misfit criterion measures the similarity of receiver function to an ideal problem by calculating the difference between radial component of seismogram and the convolution of the vertical component.
with the obtained radial receiver function. We used receiver functions with at least 90% fit for further analysis.

We applied $H$ - $k$ stacking method of Zhu and Kanamori [11] to investigate the crustal properties. $H$ refers to the crustal thickness and $k$ is $V_p/V_s$. The method uses the delay time of $P_s$, $PpPs$ and $PpSs+PsPs$ to transform the time domain receiver function into $H$-$k$ space for stacking. The best estimation of crustal thickness of $V_p/V_s$ is obtained when the three phases stack is the most coherent. We applied the procedure to the three broadband seismometers using all possible receiver functions. The effect of lateral variation is reduced by stacking the computed receiver functions with many different ray parameters and back azimuths [12]. For the calculation of $H$-$k$ stacking, we used averaged crustal velocity of 6.3 km/s and weighting parameters of 0.7 for $P_s$ phase, 0.2 for $PpPs$ and 0.1 for $PpSs+PsPs$ multiples.

Figure 2. Radial component of receiver functions from three broadband seismometers. The theoretical arrival times of the converted $P_s$, and the $PpPs$ and $PpSs+PsPs$ multiple phases are also indicated by dashed lines.

3. Results and Discussion
The computed radial receiver functions organized by slowness or ray parameter are shown in figure 2. The observation at stations BSI and KCSI show relatively clear $P_s$ arrival around 5.0 s, with $PpPs$ and
$PpSs+PsPs$ multiple phases are not clear enough. The mantle-crustal discontinuity or Moho layer can be indicated by the clear appearance of $Ps$ phase. At station TPTI, the arrival $Ps$ phase seems closer to the direct $P$-wave compared to that of stations BSI and KCSI. $PsPs$ and $PpSs+PsPs$ multiple phases are not clear enough to be determined manually. Station TPTI shows relatively complicated waveform of receiver functions compared to the other stations. Theoretical arrival times of converted $Ps$ phase and the multiple phases are also indicated in the figure 2. It was calculated from the estimated crustal thickness obtained from the $H$-$k$ stacking method.

The estimated crustal thickness or Moho depth and $Vp/Vs$ ratio beneath three stations from $H$-$k$ stacking analysis are shown in figure 3. The crustal thickness beneath station BSI was estimated to be $40.56 \pm 2.26$ km, beneath station KCSI is $37.07 \pm 4.47$ km and beneath station TPTI is $19.54 \pm 3.84$ km. $Vp/Vs$ ratio beneath KCSI station is estimated to be $1.81 \pm 0.05$, beneath KCSI is $1.84 \pm 0.10$, and beneath TPTI is $1.73 \pm 0.14$. The results of $H$-$k$ stacking method are summarized in table 1.

| Station | Crustal Thickness (km) | $Vp/Vs$ ratio | Poisson's ratio | Number of receiver functions |
|---------|------------------------|---------------|----------------|----------------------------|
| BSI     | $40.56 \pm 2.26$       | $1.81 \pm 0.05$ | $0.281 \pm 0.017$ | 32                        |
| KCSI    | $37.07 \pm 4.47$       | $1.84 \pm 0.10$ | $0.291 \pm 0.029$ | 63                        |
| TPTI    | $19.54 \pm 3.84$       | $1.73 \pm 0.14$ | $0.250 \pm 0.049$ | 25                        |

The obtained crustal thicknesses from $H$-$k$ stacking analysis show large variation in such small area. At stations BSI and KCSI the crustal thickness is about 38 km. Station TPTI shows the crustal thickness differs significantly of about 20 km. Station TPTI is located at the forearc basin, while both KCSI and BSI are located close to the volcanic arc [12]. Such difference in tectonic regime may cause difference in the crustal thickness. Studies by Li et al. [13] also suggested that the presence of sediment beneath a station may affect the phases between direct $P$ and $Ps$ phases. It was also suggested that the addition of sedimentary layer obscures the phases up to the Moho multiples, which shape the earlier part of receiver function [13, 14]. Station TPTI also has relatively few numbers of receiver functions and complicated waveforms that may affect the result of $H$-$k$ stacking analysis.

Several previous studies showed crustal thickness in Sumatra subduction region range from about 16 km at the forearc to about 30 km at back arc basin [9, 15, 16]. Condie [17] suggested that there are three crustal divisions, mainly oceanic (typically about 3-15 km thick), transitional (about 15-30 km thick), continental (about 30-70 km thick). Based on the crustal thickness and the location of the station, we suggest that Sumatra Island might be located at the transitional crust.

$Vp/Vs$ ratio, as well as Poisson's ratio, gives an indication of crustal composition [18]. Based on $Vp/Vs$ ratio, Christensen [19] divided rock characteristics into three, which are felsic ($\sim 1.7$), intermediate ($\sim 1.76$) and mafic rocks ($\sim 1.84$). The $Vp/Vs$ ratio increases with density as rock composition changes from felsic to mafic as well as to temperature. The changes might be correlated to the variation of the quartz and feldspar content [17]. It estimated that the global average of $Vp/Vs$ ratio is about 1.77 by assuming average $Vp$ and $Vs$ of 6.45 km/s and 3.65 km/s respectively [20].

The obtained $Vp/Vs$ ratio ranges between 1.73 and 1.84. Station TPTI, located in Tapaktuan, has $Vp/Vs$ ratio of 1.73, which is less than global average of $Vp/Vs$ continental crust. Based on the $Vp/Vs$ ratio, we suggest the composition beneath this station is mainly felsic. Stations BSI and KCSI show relatively high $Vp/Vs$ ratio of 1.81 and 1.84, respectively. Both stations are located or close to the Sumatra fault zone. As mentioned above that the seismic velocity may change due to rock composition, temperature and also pressure. In the fault zone, the rock changes are mostly physical or mechanical properties. The rock velocity changes might occur due to the porosity, fluid/gas content, pressure or heat. These effects generally stronger to the propagation of $P$-waves than to the $S$-waves due to the physical characteristics of the wave propagation. If the fault zone is filled by fluid than the $Vp/Vs$ ratio is suggested to be high. However, if the fault zones are empty or filled by gas, the $Vp/Vs$
ratio will be low [21]. Isaac et al. [22] through borehole studies at Mozumi fault, Japan estimated that the Poisson's ratio for the fault zone is about 0.263 - 0.393, which is similar to our results from $H$-$k$ stacking analysis (table 1).

![Figure 3. $H$-$k$ stacking results for three broadband stations to estimate the crustal thickness and $V_p/V_s$ ratio. Crossbar represent the maximum stacking amplitude with its uncertainty.](image)

4. Conclusions
We have estimated the crustal characteristics beneath three broadband seismometers BSI, TPTI, and KCSI in Northern Sumatra by analysis of receiver functions. We obtained that the crustal thickness range between 20 km in the forearc basin to more than 30 km in the backarc basin. $V_p/V_s$ ratio ranges between 1.73 and 1.84. We observed that $V_p/V_s$ ratio changes significantly over a relatively short distance at station TPTI and KCSI. We suggest that the difference in tectonic regime may cause such differences.

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References
[1] Curray J R 2005 *J. Asian Earth Sci.* **25** 187-232
[2] McCaffrey R 2009 *Annual Rev. Earth Planet Sci.* **37** 345-66
[3] Rock N M S, Syah H H, Davis A E, Hutchison D, Styles M T and Lena R 1982 *Bull. Volcanol.* **45**(2) 127-152
[4] Singh S C, Moeremans R, McArdle J and Johansen K 2013 *J. Geophys. Res. Solid Earth* **118**
208-5224

[5] Cameron N R, Clarke M C G, Aldiss D T, Aspden J A and Djunuddin 1980 Proc. Indonesian Petroleum Assoc. the 9th Annual Convention (Jakarta) 149-187

[6] Crow M J 2005 Tertiary volcanicity, in Sumatra Geology, Resources and Tectonic Evolution, ed. A J Barber, M J Crow and J S Milsom (London: The Geological Society, London) p 98-119

[7] Dugda, M T, Nyblade A A and Julia J 2007 J. Geophys. Res. 112(B8) B08305
[8] Park S J, Lee J M and Ryu I C 2009 Tectonophysics 472 158-168
[9] Macpherson K A, Hidayat D, Feng L and Goh S H 2013 J. Asian Earth Sci. 64, 245-255
[10] Ligoria J P and Ammon C 1999 Bull. Seism. Soc. Am. 89 1395-1400
[11] Zhu L and Kanamori H 2000 J. Geophys. Res. 105 (B2), 2969-2980
[12] Macpherson K A, Hidayat D and Goh S H 2012 J. Asian Earth Sci. 46, 161-176
[13] Li J, Tian B, Wang W, Zhao L and Yao Z 2007 Bull. Seism. Soc. Am. 97(4), 1355-1363
[14] Syuhada, Hananto N D, Abdullah C I, Puspito N T, Anggono T and Yudistira T 2006 Acta Geophysica 64(6) 2020-2050
[15] Harmonn N, Timothy H, Frederik T, Andreas R and Penny B 2012 Geophys. J. Int. 189 1306-1314
[16] Bora D K, Borah K and Goyal A 2016 J. Asian Earth Sci. 121 127-138
[17] Condie K C 2005 Earth as an Evolving Planetary System (Elsevier Academic Press) p 13
[18] Zandt G and Ammon C J 1995 Nature 374 152-154
[19] Christensen N I 1996 J. Geophys. Res. 101 3139-3156
[20] Christensen N I and Moony W D 1995 J. Geophys. Res. 100 9761-9788
[21] Kaypak B 2008 J. Geophys. Res. 113 B07307
[22] Isaacs A J, Evans J P, Kolesar P T and Nohara T 2008 J. Geophys. Res. 113 B12408