Indonesian Journal on Geoscience Vol. 4 No. 3 December 2017: 169-179

INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Seismic Anisotropy Analysis Beneath Sumatra Revealed by Shear-Wave Splitting

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Manuscript received: December 2, 2016; revised: April 10, 2017;
approved: June 21, 2017; available online: September 6, 2017

Abstract - A shear-wave splitting analysis was determined to observe anisotropic structures of an upper mantle layer beneath Sumatra. The data were collected from 35 BMKG stations with the magnitude of more than 6.25 Mw and the epicentre of 85º - 140º. A shear-wave splitting measurement was calculated by using Splitlab based on three methods simultaneously. The result of the shear-wave splitting measurement in the Sumatra Forearc and Fault Zone shows that there are two anisotropic layers. The first layer has a dominant-fast-polarization direction that is parallel with a trench, and has the delay time duration of 0.5 - 0.9 s-. It is presumed that it is caused by a shear-strain as a result of the existences of Mentawai and Sumatra Fault Zones. The second layer has a dominant-fast-polarization direction that is perpendicular to the trench with the delay time duration of about 1.1 - 1.9 s-. It is presumed that it is caused by a movement of a subduction plate on a mantle wedge. The measurement in the backarc shows that there is only one anisotropic layer that is a subduction plate. It is also found that there is a transition of an orientation change on the subduction plate between Sumatra and Java. The change of the polarization direction is probably related to the age difference and the direction velocity of the absolute plate movement (APM) from Sumatra to Java.

Keywords: seismic anisotropy, Splitlab, subduction zones, fault zones, forearc, back-arc

How to cite this article:
Candra, A.D., Santosa, B.J., and Rachman, G., 2017. Seismic Anisotropy Analysis Beneath Sumatra Revealed by Shear-Wave Splitting. *Indonesian Journal on Geoscience*, 4 (3), p.169-179. DOI: 10.17014/ijog.4.3.169-179

Introduction

Sumatra is part of the Indonesian archipelago which has a unique geological condition. It is located between two big plates; Indo-Australian Plate in the south and Eurasian Plate in the north. The subduction of these two plates results in one of the most active seismic activities in the world. As the result, it makes Sumatra to be considered as one of the most ideal places to study subduction dynamics using the seismic image technique (Hammond *et al.*, 2010). Sumatra Subduction Zone is one of the best examples to study ocean-continental-subduction zone in a large scale. Thus, Sumatra is considered as an ideal environment to study the cause of earthquake mechanism in a subduction zone.

The Sumatra Subduction Zone is a place where the Indo-Australian Plate is converging beneath the Eurasian Plate. The Indo-Australian

Plate is moving northward at a relative velocity toward the Eurasian Plate at a rate of 7 cm/year (Wilson *et al*., 1998). This subduction movement influences tectonic activity that occurs in Sumatra and some smaller islands around it. A friction in the Benioff Zone that can be found on a subduction plate results in a magmatic activity along the Sumatra Island which in turn it shows up as a row of volcanoes. The angle of the subduction which exists along Sumatra can be linked to each other by a right lateral-strike-slip fault zone that can be found along this island called as Sumatra Fault Zone. The angle of subduction results form a rather big stretching along Sumatra Island (McCaffrey, 2009). The movement along the Sumatra Fault is various; it starts from 45 - 60 cm/ year in the north of Sumatra Island to 1 cm/ year in Sunda Strait (Pramumijoyo and Sebrier, 1991; Sieh and Natawidjaja, 2000). Besides the Sumatra Fault, there is also Mentawai Fault Zone which is considered as a right lateral-strike-slip fault zone located between Sumatra Island and a trench. It elongates along a row of some smaller islands in the forearc of Sumatra (Diament *et al*., 1992). Some previous studies that investigated the segmentation of Sumatra Microplates (Chlieh *et al*., 2008; Diament *et al*., 1992; Sukmono *et al*., 1997) show a probability of a more detailed segment division. The segment division is related to the division of some active seismic regions and to some possibilities of the energy collection that has the potential to cause earthquakes to happen in the future (Natawidjaja and Sieh, 2009).

Even though the previous studies have investigated a tectonic history of Sumatra Island, starting from the plate reconstruction to the tomography, the studies have not explored yet the subduction caused by the mantle movement. The knowledge of mantle movement can be obtained through a study of anisotropic structure of the earth mantle using a measurement such as share-wave splitting. A lot of attention had been given to investigate the other subduction zones, for example a subduction zone in Japan (Ando *et al*., 1983; Fouch and Fischer, 1998; Long and Hilst, 2005; Nakajima and Hasegawa, 2004; Tono *et al*., 2009) and in Cascadia (Eakin *et al*., 2010). On the other hand, Sumatra has a lack of such measurement. A study by Collings *et al*. (2013) is one of the most detailed studies focusing on the subduction zone and fault in the north of Sumatra. In addition, a study by Hammond *et al*. (2010) estimated anisotropic layers in Sumatra and Java by using a few stations. Consequently, it only involves some of the investigated regions.

The Sumatra Zone and Fault are regions that have a significant tectonic type. Up to this time, the study is still limited to an anisotropic observation which is close to the Sumatra Subduction Zone and Fault. These two factors are the background of a study of anisotropic structure in Sumatra. This article is provided with a shear-wave splitting observation using data taken from some seismic broadband stations of BMKG in Sumatra. The observation is consistent with the previous studies. Yet, it gives a denser density of earthquake monitoring station than the previous studies. Thus, it is possible to give a better constraint to determine an anisotropic structure in Sumatra.

Methods

This study employed data which were taken from thirty-five permanent stations of BMKG (IA), whilst GFZ (Geo Forschungs Zentrum) network was used to estimate the anisotropic characteristic beneath Sumatra. Figure 1 shows the location of earthquake monitoring stations. The data for this study were earthquake data recorded from January 2012 - December 2013. The earthquake event data were selected with the epicentre of around 85° - 140° in a distance. The reason for selecting the epicentre distance is because the event suited a shear-wave splitting analysis on SKS/SKKS wave phase. The epicentre distance could prevent an overlap between SKS/SKKS phase and the others. The distance also could guarantee that the seismic wave still have sufficient energy (Silver and Chan, 1991). Shear-wave splitting used teleseismic data, especially SKS/SKKS phase, mainly to reflect the anisotropic characteristics of the upper mantle (Vinnik

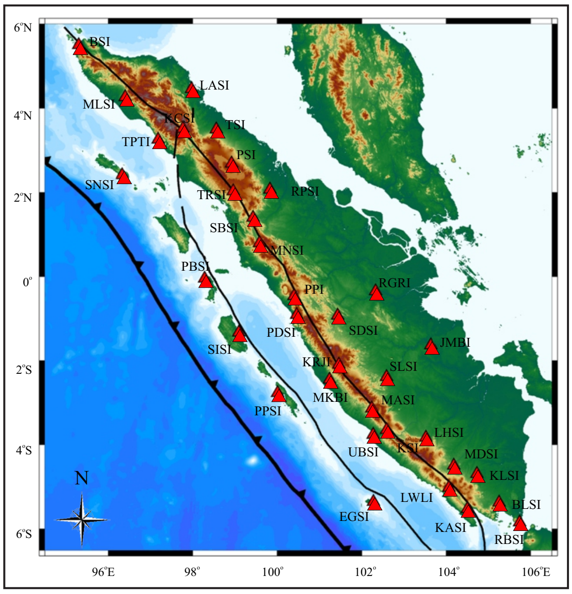

Figure 1. A map of the BMKG broadband IA network (triangles) in Sumatra. Data are obtained from GFZ network.

et al., 1989; Silver and Chan, 1991; Silver, 1996; Savage, 1999; Mainprice *et al.*, 2005), and to give some information on the strain of the earth mantle.

The 868 earthquake events have been observed, yet this study could only use about 35% of the data (thirty-one stations were used). Figure 2 shows most of the events that BMKG station observed in Sumatra and surrounding regions. Before conducting the shear-wave splitting analysis, first of all, the data of SKS/SKKS wave phase were filtered, aiming to increase signal to noise ratio (SNR) and a stability of the shear-wave splitting measurement by using bandpass filter (butterworth) with the frequency of 0.02 - 0.1 Hz. In some cases (<5%), the filtering was conducted on the frequency between 0.02 p0 - 0.125 Hz. This filtering resulted in, more or less, the same splitting parameter. Consequently, it shows that the high frequency scattering does not influence significant results.

A programme named SplitLab was employed to conduct a shear wave splitting analysis. To search a fast polarization direction (ϕ) and delay time (δt), a grid search having three different methods was used. They were minimum energy

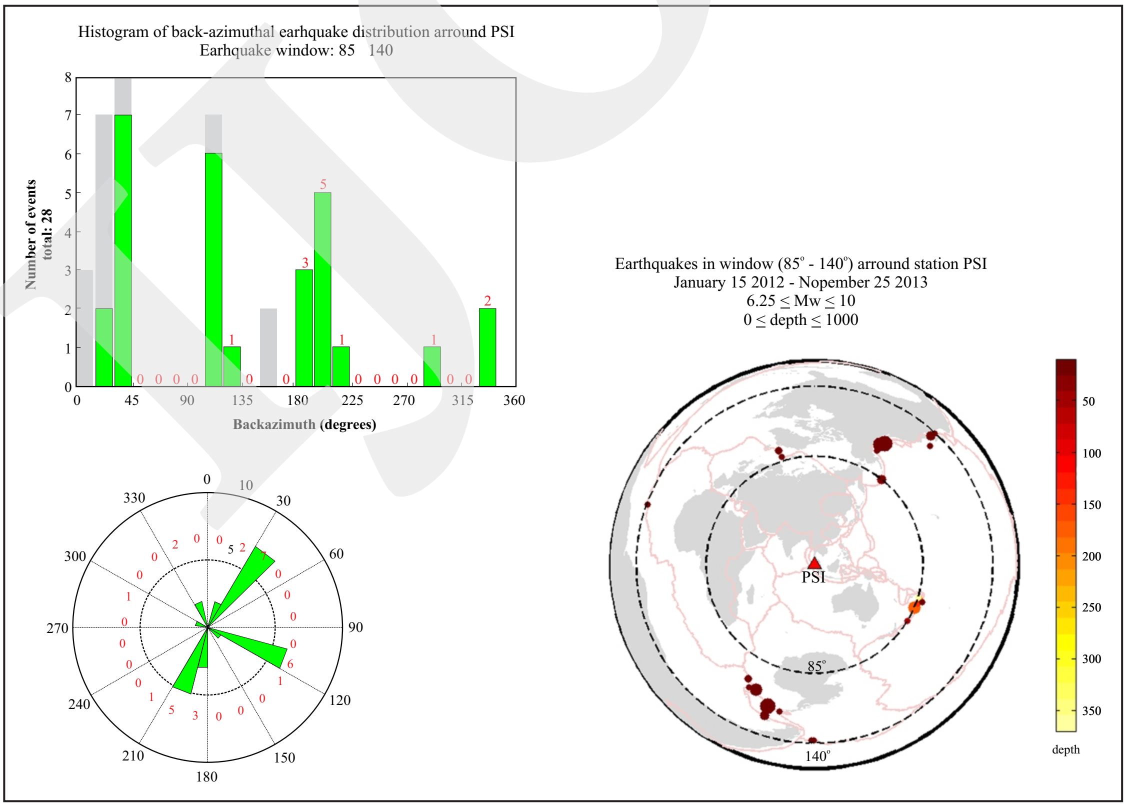

Figure 2. Teleseismic earthquake distributions used in this study. Triangle indicates the location of the BMKG network and lines indicate distances of 85 and 140 degrees of arc away from this location. Earthquakes investigated for this study are shown by the dots.

(Silver and Chan, 1991, 1988), rotation-correlation (Bowman and Ando, 1987), and Eigenvalue (Silver and Chan, 1991). A measurement by using the three different methods helped researchers to determine reliability of the measurement results. However, the result of the final measurement only used minimum energy, because it produced more stable values and bigger back azimuth distance (Wüstefeld and Bokelmann, 2007).

The Splitlab measurement estimated the delay time and the direction of fast polarization by removing splitting effect from a transversal component of seismogram using three different methods simultaneously which were: minimum energy (SC) method, rotation-correlation (RC), and eigenvalue (EV) (Wüstefeld *et al*., 2008). The quality of the measurement was determined by some criteria. First of all, it was a good signal to noise ratio (SNR) so that it could accommodate researchers to identify the phase; secondly, linearization from some particle motions; and thirdly , the selection process of the back azimuth direction after it had been corrected. Based on that rule, the three criteria were used to determine the quality of the measurement: good, fair, and poor. To test the quality of a gained shear-wave splitting parameter, this study employed F-test developed by Silver and Chan (1991). The results of the shear-wave splitting analysis at each station, then, were sketched onto a topographic map by using a Generic Mapping Tool (GMT) (Wessel and Smith, 1991).

Results and Analysis

Before plotting the parameter of the result of the shear-wave splitting measurement using a method developed by Silver and Chan (1991), some seismograms recorded from the earthquake data that did not meet the criteria had been deleted. A seismogram that produced the delay time of more than three seconds would be deleted. The delay time usually occurs for around 1 or 2 seconds. Every delay time of more than three seconds would be considered unrealistic to the understanding of anisotropic media beneath the earth mantle (Plomerová *et al*., 1998; Wüstefeld *et al*., 2008). The seismic phase was then checked visually and analyzed by using a seismogram displayer as Figure 3 shows.

The selection of SKS/SKKS wave phase on the seismogram window player was conducted by picking a desired phase with various widths, around 1 - 4 seconds. After the selection phase, the measurement results would be based on the results of the shear-wave splitting calculation (Figure 4).

The shear-wave splitting measurement in this study produced two types of output; a single layer and double layers of anisotropy. The anisotropic layers were determined by matching a measurement of the stereo plot result to theoretical modeling as provided in Figure 5. The calculation of the modeling values was conducted by using a method proposed by Silver and Savage (1994) that could be applied to various back azimuth values. The results of the calculation, in turn, was plotted every 7,5° at an incident angle of 10° that was considered as a representative of SKS wave (Wüstefeld *et al*., 2008). The use of a stereo plot comparison of a theoretical modeling had increased the variety of the delay time at the rate of about 0,5 - 1,9 s. Table 1 shows the data taken from the shear-wave splitting measurement.

Many seismic recording stations with a dense distance for each station were used to facilitate the researchers to obtain more detailed results of the shear-wave splitting measurement. This is very helpful to determine some anisotropic characteristics and the distribution of the mantle layer beneath Sumatra. The observation of the seismic anisotropy in Sumatra was divided into three main parts; forearc, Sumatra Fault, and back-arc zone. Figure 6 shows the results of the shear-wave splitting calculation.

Forearc Region

Forearc region is a region engulfing trench in front of Sumatra Forearc and Mentawai Islands. Part of the Sumatra Forearc consists of five recording stations; SNSI, PBSI, SISI, PPSI, and EGSI. On the other hand, in the forearc region

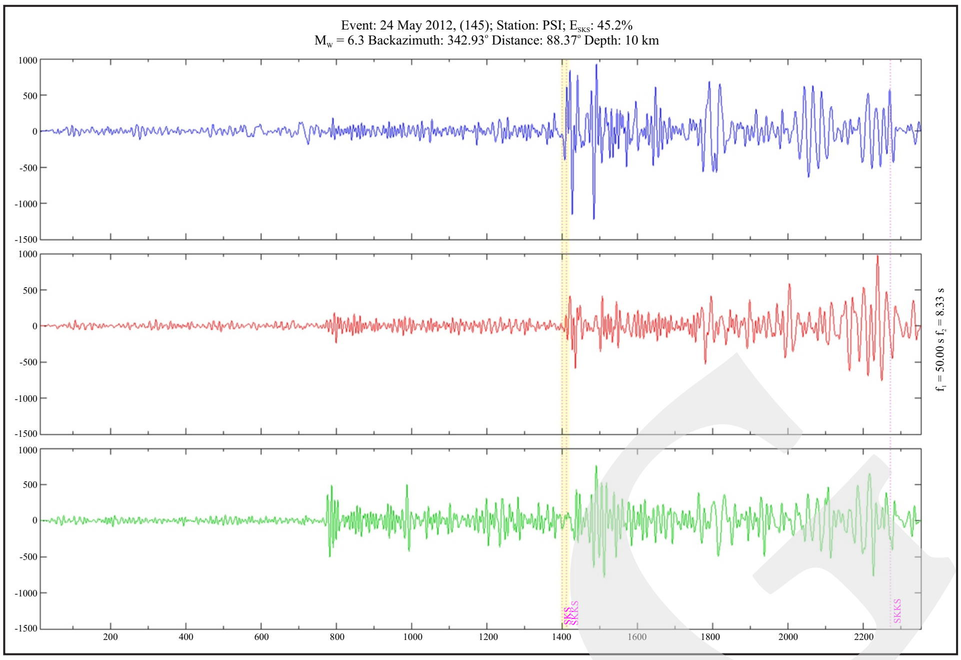

Figure 3. Seismogram viewer after changing into LTQ coordinates (Radial, Transverse, and Vertical) and applied Band Pass Filter to reduce noise.

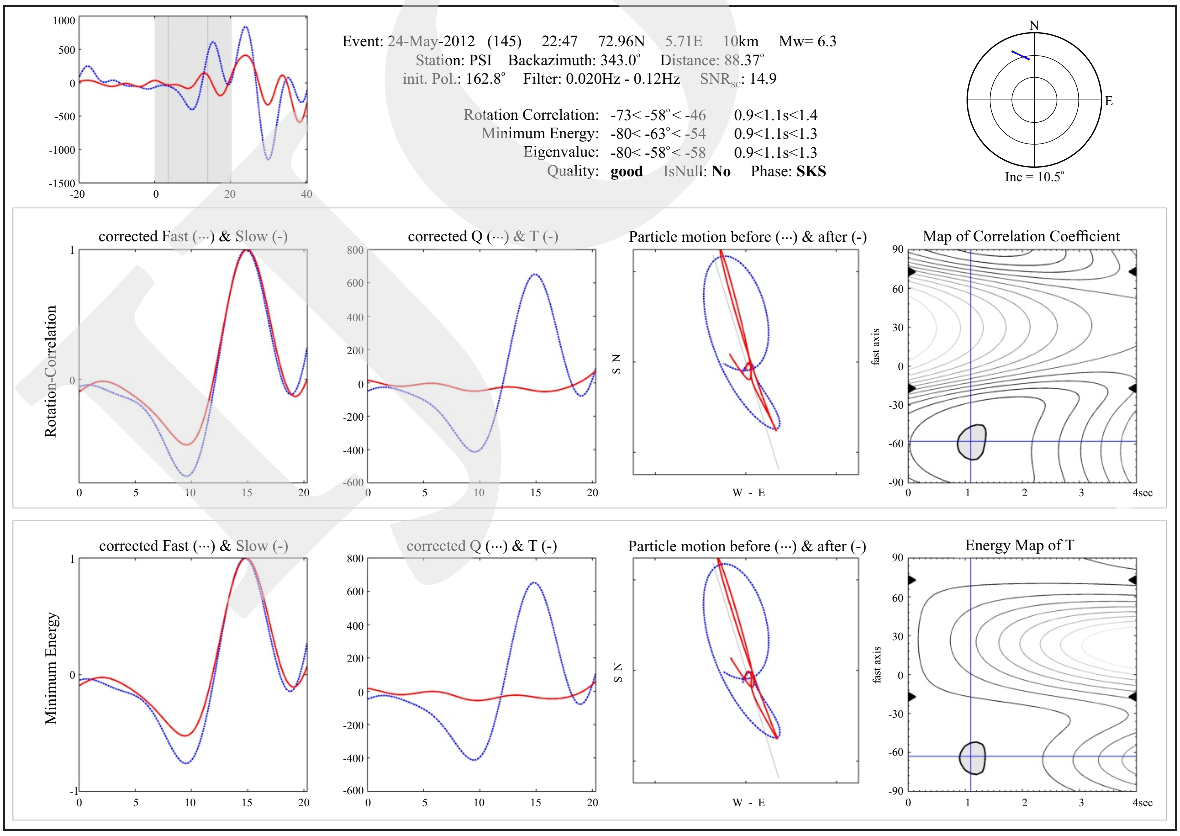

Figure 4. Examples of splitting measurements of typical quality at PSI stations obtained using SplitLab. Top left panel shows the uncorrected radial (dashed) and transverse (solid) components. The middle and bottom rows of panels show the diagnostic plots for the rotation-correlation method and the transverse component minimization method, respectively: from left to right, the corrected fast (dashed) and slow (solid) components, the corrected radial (dashed) and transverse (solid) components, the uncorrected (dashed) and corrected (solid) particle motion diagrams, and the maps of correlation.

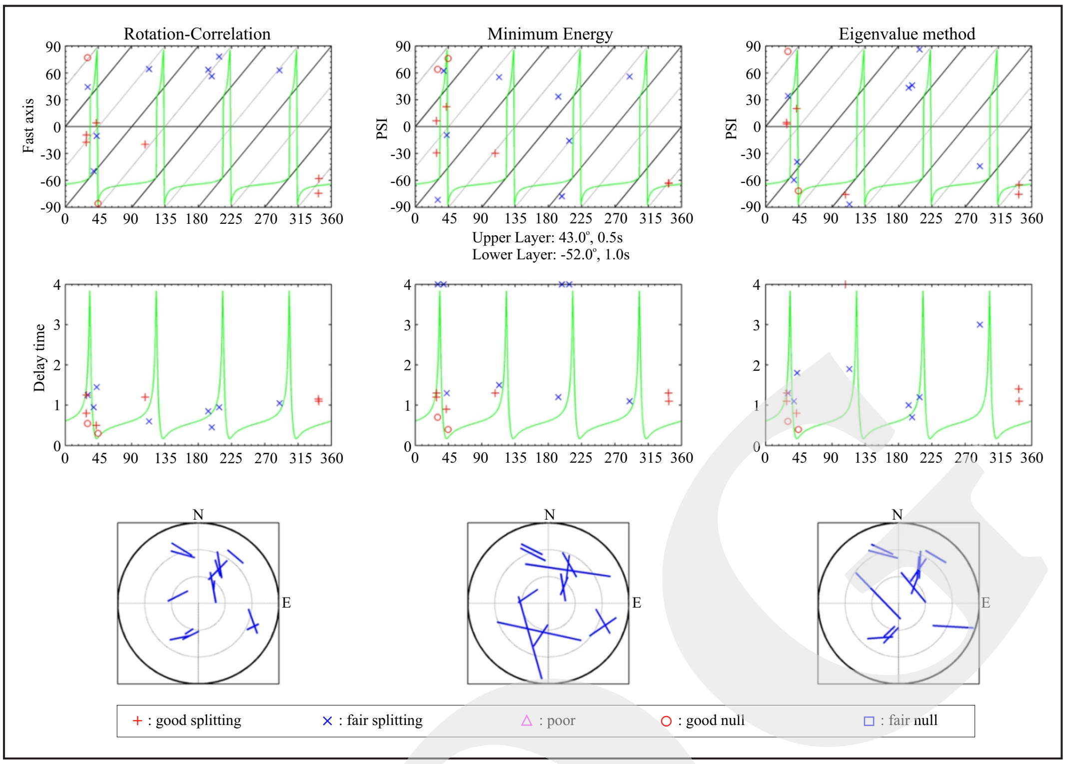

Figure 5. An example of double-layer model fit at PSI station. Three different splitting techniques are compared (Rotation-correlation, Minimum Energy, and Eigenvalue). For each technique the back azimuthal variation of fast orientation estimate (top row) and delay time estimates (center row) are shown. The bottom row displays a stereo plot of good and fair quality non-Nulls. Markers are plotted at their according backazimuth and incident angle (grid lines each 5°). Marker lengths are according to delay time. Comparing these plots constrains final splitting parameter estimates.

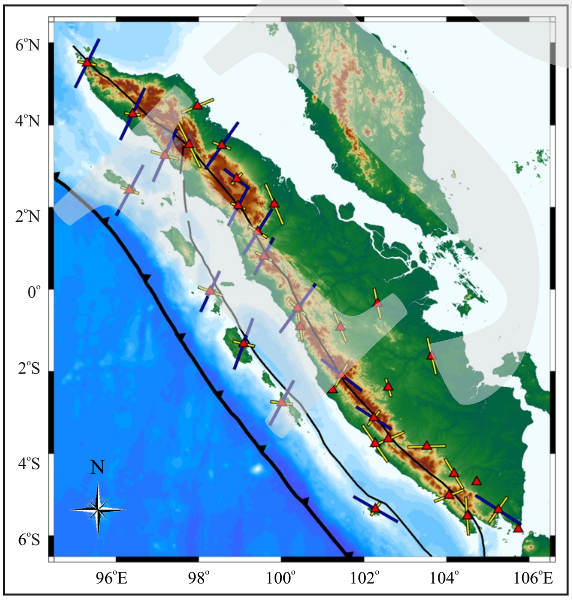

Figure 6. Distribution of average polarizations and average delay time from the shear-wave splitting results of this study. Yellow and blue markers indicate upper and lower layer respectively. Yellow markers, if only a single anisotropic layer has been identified. Direction of the yellow and blue lines show the average value of fast polarization, and the length of the lines shows the average value of the delay time.

of the Mentawai Islands, the results of the shear-wave splitting measurements show that there are two anisotropic layers; upper and lower layers.

The lower anisotropic layer produces the delay time at the rate of about 1.4 - 1.8 s that possesses the same polarization direction of NE - SW (northeast - southwest), and it is perpendicular to the trench located in front of the Sumatra Forearc. A shear-wave splitting study by Long and Silver (2008) shows that the result of the shear-wave splitting measurement is dominated by a polarization direction which is parallel to the trench with some exceptions in Cascadia (Currie *et al*., 2004) and southern Chile (Hicks *et al*., 2012). The result of the shear-wave splitting measurement on the Mentawai Islands shows that the direction is usually parallel with Indo-Australian Absolute Plate Movements. This result does not suit the global observation of trench that had been conducted by Long and Silver (2008). However, this result is relevant to the result of studies conducted by

Collings *et al*. (2013) and Hammond *et al*. (2010) which shows that the result of the share wave splitting observation conducted on the Mentawai Islands possesses a polarization direction which is parallel with the Absolute Plate Movements (APM). This finding indicates that there are anisotropic plates beneath the Mentawai Islands.

These layers are predicted to be subduction plates that exist beneath the Mentawai Islands.

On the upper anisotropic layer, it shows the delay time at the rate of around 0.5 - 0.8 s that possesses a polarization direction which is W - E (west - east) and parallel with the trench. This finding potentially indicates that there is a shallower anisotropic zone than a subduction zone. This anisotropic layer is presumed upon a Mentawai Fault that exists beneath the Mentawai Islands. An acceptable explanation describes the polarization direction which is perpendicular to the trench is the anisotropic layers beneath the earth crust. Crampin (1994) stated that the anisotropic layers beneath the earth crust could be linked to faults that were perpendicular to a maximum stress direction, and they could make 1,5% anisotropic layers on rocks become intact, and 10% on cracked rocks. The data show that the upper anisotropic layer above the continental lithosphere results from a fabric structure as a result of the Sumatra Fault, while the lower layer beneath the asthenospheric mantle wedge is caused by an angle flow of 2-D.

The forearc islands consist of low velocity sediments that are part of the accretionary prims formation before they were uplifted and, in turn, they formed some forearc islands (Collings *et al*., 2012; Kopp *et al*., 2001). The arrangement of faults and minerals which occured during the lifting process could possibly form an anisotropic layer on the low velocity sediments beneath the forearc islands occuring when an accretionary prims caused the high deformation. A study on the epicentre and local earthquake tomography by Collings *et al*. (2012) shows that there is a hydrated subduction slab and fault beneath the forearc islands that can contribute to the results of the shear-wave splitting measurement.

Sumatra Fault Zone Region

In this region, the data are taken from BSI, MLSI, KCSI, TPTI, PSI, TRSI, SBSI, MNSI, PPI, PDSI, KRJI, MASI, MBSI, KSI, LWLI, KASI, and UBSI stations. The result of the shear-wave splitting measurement shows that there is one anisotropic layer and two anisotropic layers. However, the two anisotropic layers are the results of a dominant measurement in this region.

The measurement, that results the two layers, shows that the upper layer is parallel with the Sumatra Fault with its delay time of about 0.5 - 0.9 s, and for the lower layer, it has a polarization direction which is perpendicular to the Sumatra Fault with its delay time of about 1 - 1.9 s. The result of the shear-wave splitting measurement on the upper layer is dominated by the polarization direction which is perpendicular to the Sumatra Fault. This is similar to some studies on San Andreas and Marlborough Faults in New Zealand (Zhang and Schwartz, 1994; Balfour *et al*., 2005; and Liu *et al*., 2008). The review above shows that shear stress given by the Sumatra Fault can form an anisotropic layer on the earth crust. Furthermore, the polarization direction on the upper anisotropic layer is probably influenced by a volcanic system located close to the Sumatra Fault. Meanwhile, the lower layer is formed by the Sumatra Subduction Plate beneath the Sumatra.

The result of the shear-wave splitting measurement at the PSI station shows a different result. The difference is probably caused by the existance of a different anisotropic zone compared to the other regions. It is relevant to the previous study by Candra and Santosa (2015) which shows that the difference of the data processing in the PSI station is caused by the presence of a complex layer beneath Toba Caldera. The geological structure in the region, at the PSI station, is the Toba Caldera Zone that is probably caused by the supervolcano activity. The previous study by Koulakov *et al*., (2009) shows that there are liquid molten rocks beneath the Toba Caldera which is moving upward, and then it is released from a subduction plate due to a transition phase. This phenomenon is assumed as the reason for the analysis result at the PSI station which is different and more complex than the other stations because of the anomali of the layer beneath the Toba Caldera.

Back-Arc Region

In this region, the data were taken from TSI, RPSI, RGRI, SDSI, SLSI, JMBI, LHSI, MDSI, and BLSI stations. The shear-wave splitting measurement shows that the duration of the delay time is about 0.6 - 1.4 s. This region shows the same result as those in the Sumatra Fault; that is a dominant polarization direction is parallel faults. This study also shows the same finding as that of by Collings *et al*. (2013) which shows that in the region of the Sumatra Backarc, the dominant polarization direction is parallel with the Sumatra Fault. This region shows more fair duration compared to that in the Sumatra Fault showing a deformation from an extensive shift to the continental lithosphere. However, this region shows more measurements that indicate an anisotropic layer. This result is similar to the finding of studies by Hammond *et al*. (2010) and Collings *et al*. (2013) which show that there is a thick anisotropic layer on overriding plate which is related to parallel fault layers. It is assumed that there is only one anisotropic layer beneath the Sumatra Backarc that is a subduction plate which is located beneath the Sumatra Backarc. On the other hand, the Sumatra Fault itself does not directly contribute to characteristics of the anisotropic layer located above the subduction plate.

Geometric Changes of Sumatra

A boundary between Indo-Australian and Eurasian Plates in the west of Sumatra and in the south of Java was formed by an arc-trench system called Sunda Trench which stretches, more or less, 5,000 km (Hamilton, 1979). Five stations located at the Mentawai Islands have a conformity of an anisotropic orientation direction in the north of Sumatra more or less corresponds to the absolute plate movement from a plate that slopes toward the trench. Yet, there is one station that produces a different polarization direction; that is EGSI station. Besides, a recording station located in the south of Sumatra shows different results. Based on the locations of EGSI and a recording station in the west of Sumatra which is closer to Java Island, it indicates that there is a transition of orientation change of subduction plates between Sumatra and Java. This finding is similar to a study by Hammond *et al*. (2010) that shows a change in the SKS phase. The study used the shear-wave splitting observation producing a fast polarization direction. It has a good correlation to a change of plate movement which is significant, from >100 Ma in Java to <100 Ma beneath Sumatra. It also probably shows a fundamental change in a mantle movement. The changes of the anisotropic characteristics which are reflected by the other geophysics changes are near the Sunda Strait. The magnetic anomaly shows an age change from ~60 to ~100 Ma from South Sumatra to West Java (Sdrolias and Müller, 2006). This location has yet to have a clear cut limit, especially in the depth of the subduction slab. Syracuse and Abers (2006) observed that this age limitation corresponded to a volcanic characteristic change that could be found in that region. They found that the location of volcanic mountains in Sumatra is 90 km above the slab contour, with a sudden change near the Sunda Strait in which a row of volcanic mountains formed.

Conclusion

The shear-wave splitting measurement using a SKS/SKKS phase was conducted by using teleseismic data taken from thirty-five permanent stations in Sumatra. Some valid results have been gained that they only correspond to thirty-one stations. The findings show that there are two main anisotropic layers formed in the forearc region (the Mentawai Islands) and the Sumatra Fault. The upper layer, which has the delay time duration of 0.5 - 0.8 s is the anisotropic layer located in the Mentawai and Sumatra Faults. On the other hand, the lower layer, which has the delay time duration of 1.4 - 1.8 s, is the subduction plate layer located beneath Sumatra. In the Sumatra Backarc, a dominant-fast-polarization direction is a single anisotropic layer with its polarization direction is parallel the fault located beneath the north of Sumatra and perpendicular to the fault located beneath the south of Sumatra.

In general, fast anisotropic polarization directions found in Sumatra are divided into two directions. The first, NE - SW found on the upper layer and E - W found on the lower layer beneath the north of Sumatra. The second, E - W found on the upper layer and NE - SW found on the lower layer beneath the south of Sumatra. The change of the polarization directions is probably related to the age difference and velocity of directions of the absolute plate movement from Sumatra to Java. The findings show that, even though a unique double-layer model is not able to be determined, compared to a single-layer model in general, the double-layer model is better in explaining the characteristics of the anisotropic parameter in Sumatra.

Acknowledgements

The first author greatly acknowledges the Directorate General of the Higher Education of the Republic of Indonesia (DIKTI) for supporting him through DIKTI Graduate Scholarship grant.

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