The seismotectonic of West Sumatra

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Abstract. tectonic region of West Sumatra is very active. In the western part there is a zone of deposition of the Indo-Australian plate and Mentawai fault while in the mainland is part of the Sumatra Fault System. This tectonic activity can be seen from the analysis of the distribution of seismicity in each fault or fault segment using earthquake data from 1990 to 2014 from regional and global stations. Analysis of the focal mechanism for shallow earthquakes shows the tectonic state of this region. One-dimensional surface wave analysis is also carried out to show surface wave propagation velocity. The results of this study indicate the type of fault in the West Sumatra region.

1. Introduction
Indonesian region is surrounded by several subduction zones [1] (Figure 1). In the northwestern to southern margins of the Indonesian region, there are Sunda arc systems, extending westward from Sumba, passing Java and Sumatra, to the Andaman Island, where the Indo-Australian plate is subducting beneath Sumatra, Java and Flores Islands. In the northern margin, the Philippine Sea and Pacific plates subduct beneath the Sangihe arc to the west of the Molucca collision zone with Halmahera and New Guinea islands.

The convergence rate of the Indo-Australian and Eurasian plates varies from about 60 mm/yr near Sumatra to 78 mm/yr in the easternmost part of the Sunda arc, with an azimuth of N20°E predicted by the RM2 plate model [2]. A recent study based on the first geodetic measurement of convergence rate across the Java trench [3] suggested convergence rate of 67±7 mm/yr between Christmas Island, southwest of Java and west Java in the direction of N11°E ±4°. This result is similar to the relative plate velocity of 71 ± 2 mm/yr between Australia and Eurasia plates according to the NUVEL-1 model [4].

For recent 5 million years (Ma), the continental lithosphere of Australia has been colliding the Banda arc whereas the oceanic part of the Indo-Australian plate subducts beneath the Java trench further to the west, Sumatra island. The age of the ocean floor varies from 50 to 90 Ma along Sumatra, from 100 to 135 Ma and 140 to 160 Ma near Java and Flores. The lateral variation of the age of the subducting plate influences the style of deformation and seismicity along the Sunda arc. Earthquakes with focal depths of up to 670 km are observed in steeply dipping seismic zone beneath the Java arc. Beneath Sumatra, the dip angles of seismic zone are about 30° to 45°, and there are no earthquakes deeper than 300 km, which has been attributed to the relatively young age of subducting plate [5].
Figure 1. Geographical features of SE East Asia reconstructed [1].

Sumatra is situated on the southern edge of Sunda land and north of the Sunda trench [Figure 1]. The Sumatra Arc has a classic morphology of trench, accretionary prism, outer-arc ridge, forearc and volcanic chain with active andesitic volcanism [6], and there is a well-defined Wadati-Benioff zone. Between northern Sumatra and Java, the subduction direction changes from oblique to almost orthogonal, and the India-Sundaland motion is partitioned into trench-normal subduction and dextral slip on the Sumatran Fault, and related strands [7]. In the Sumatra region, most active deformation occurs between the Sunda trench and Sumatran Fault. The right-lateral strike-slip Sumatra Fault is parallel to the Java trench. The fault was a result from the partitioning of oblique plate convergence into normal convergence at the trench and trench parallel movement further northeast.

The Sumatran active fault is divided into 20 main segments with a length of about 35 to 200 km per segment. The West Sumatra region is passed by 4 active fault segments, namely the Sumpur, Sianok, Sumani and Suliti fault segment [8]. The Sumpur segment is located from Rao to Lubuk Sikaping region with 35 km of length and segment rate 24 mm/year. In this segment, there has never been a major earthquake. The Sianok segment is around the city of Bukittinggi, and has a fault length of ± 90 km and a fault shift around 23 mm/year. The city of Bukittinggi is among those prone to land earthquakes sourced from the Sianok Segment fault. In the Sianok segment, a large earthquake occurred on March 6, 2007 with a magnitude moment (Mw): 5.8. The Sumani Segment is located south of Lake Singkarak, precisely located in Solok Regency. When passing through Sumani Subdistrict there are many small hills along the road, this indicates that the Sumani segment is located. The Sumani fracture has a fault length of ± 60 Km and the fault shift is around 23 mm/year. In the Sumani Segment there was a big earthquake in 1926 with 6.7 moment magnitude, and until now the Sumani segment has not shown its activity again. The Suliti Segment is in the Alahan Panjang area, South Solok Regency. These segment passes through Diatas and Dibawah Lake. These segment has a fracture length of about 25 Km and the shift ranges from 23 ± 5 mm/year.

In the western part of west Sumatra, there are the oceanic part of the Indo-Australian plate subducts beneath these region and Mentawai Fault System. The Mentawai fault is a horizontal fault in the sea that extends around the Mentawai islands from the south to the north of Nias.

The tectonic region of West Sumatra as part of the Sumatran region will be reviewed based on seismicity reviews, focal mechanisms and surface wave analysis. Seismicity data were analyzed for earthquakes occurring in the period 1990 to 2014 with M≥4 SR and observation areas of 2°N-4°S and 96°E-104°E. The earthquake data used came from National earthquake Information Centre (NEIC) / United States Geological Survey (USGS) and Meteorological, Climatological and Geophysical Agency (BMKG) catalog data.
2. Seismicity

The intensity of the seismicity in West Sumatra is very high. Based on the Catalog of Meteorology, Climatology and Geophysics Agency (BMKG), West Sumatra experienced recurrence of big earthquakes originating from faults. In the Sumpur segment 154 years ago and repeated in 1977, the Sianok segment in 1926 and repeated in 2007, the Sumani segment in 2007, the Suliti segment in 1943 and recurred in 2004 [8]. West Sumatra also experienced earthquakes originating from subduction zones in 2007 and 2009 with magnitudes 7.9 and 7.6. Mentawai Fault Systems also played a role in causing the earthquake in West Sumatra, namely in 2007 and the South Pagai-Mentawai earthquake in 2010. The earthquake that occurred was a sudden release of internal energy accumulation that created seismic waves.

Maps of earthquake distribution in the area of West Sumatra can be seen in Figures 2 and 3 for earthquake depths of up to 60 km and more than 60 km. Distribution based on this depth to see seismic activity that causes earthquakes in the region.

![Figure 2. Distribution of earthquakes at a maximum depth of 60 km with the earthquake periods from 1990 to 2014 and M > 4 SR.](image1)

![Figure 3. Distribution of earthquakes at depths between 60 to 350 km with M > 4 SR and earthquake periods from 1990 to 2014.](image2)

In figure 2, the seismic activity quite active in the south Nias Island - Mt. Sitoli, around the eastern part of the Siberut island and around the South Pagai island. The high seismicity in this area is influenced by subduction of Indo-Australia beneath Eurasia plate and in the south, there are an active fault under the sea such as Mentawai fault (Mentawai active fault) where, this result was in accordance with previous [9]. The yellow asterisk in the image states that a large earthquake of 6 SR occurred in the region. in the land area, there are also Sumatran fault activities. Shallow earthquakes that occur in this region are caused by the Sumatran fault.

The distribution of seismicity at a depth of 60-350 km (Figure 3) in the West Sumatra region and its surroundings is mostly located along the western coast of Sumatra and on the mainland of West Sumatra precisely along the volcanic front. Earthquakes that occur in this region at a depth of 60 - 350 km are affected by subduction zone activity which is quite deep and occurs under the subduction slab or in the Wadati-Benioff zone. The seismic activity that occurs in the Sumatra subduction zone which is quite deep has a depth of up to 300 km below the island of Sumatra and in general these earthquakes occur on the coast of Sumatra and on the mainland of Sumatra.

In detail the tectonic description of the West Sumatra region for earthquakes with a depth of 60-350 km can be shown in figure 4 and 5 for AA’ cross sections, figures 6 and 7 for BB’ cross sections and figures 8 and 9 for CC’ cross sections. From the three cross sections can be seen the distribution of earthquakes distributed at the subduction zone, especially in the slab area between the contact area of the Indo-Australian plate and the Eurasian Plate under the mainland of the island of Sumatra. This cross-sectional picture also proves that in this region no earthquake with a depth of more than 350 km.
Figure 4. Horizontal distribution of seismicity in the western Sumatra region in the AA' direction from the earthquake period from 1990 to 2014.

Figure 5. Vertical distribution of seismicity in the western Sumatra region in the AA' direction from the earthquake period from 1990 to 2014.

Figure 6. Horizontal distribution of seismicity in the western Sumatra region in the BB' direction from the earthquake period from 1990 to 2014.

Figure 7. Vertical distribution of seismicity in the western Sumatra region in the BB' direction from the earthquake period from 1990 to 2014.

Figure 8. Horizontal distribution of seismicity in the western Sumatra region in the CC' direction from the earthquake period from 1990 to 2014.

Figure 9. Vertical distribution of seismicity in the western Sumatra region in the CC' direction from the earthquake period from 1990 to 2014.
3. Focal Mechanism

The data used to analyze this focal mechanism comes from Global CMT in the form of moment tensor values. In this study, the focal mechanism for the Mentawai region and segments in West Sumatra was seen. Seismotectonic analysis is based on a focal sphere that displays the earthquake's focus mechanism. This mechanism explains the fault parameters that cause earthquakes. Seismic moment parameters are used to measure earthquake strength. Fault analysis is known through several parameters, namely strike ($\phi$), dip ($\delta$), and rake ($\lambda$) [10].

Figure 10 represent the map of focal mechanisms in the Mentawai fault area and segments in West Sumatra in three types.

![Figure 10. Distribution of focal mechanisms in the Mentawai fault area and segments in West Sumatra](image)

Distribution from the focal mechanism for several regions has been analyzed. First, the earthquake that occurred in mainland West Sumatra showed the same pattern was strike slip, for example an earthquake that occurred at coordinates 100.28 E, 0.17 N with a depth of earthquake at 15 km had a strike value = 66, dip = 81, and slip = 10 on nodal 1 and strike = 334, dip = 81, and slip = 170 in the nodal plane 2. Second in the area between the Mentawai islands and the Sumatran island at coordinates 104.08 E, 4.98 S with the depth of the earthquake at 33 km having a strike value = 230, dip = 68, and slip = -18 in nodal plane 1 and strike = 327, dip = 74, and slip = -157 in nodal plane 2. And third in Mentawai region at coordinates 100.85 E, 3.15 S with earthquake depth at 31.7 km having a value strike = 325, dip = 19, and slip = 120 in nodal plane 1 and strike = 113, dip = 74, and slip = 80 in nodal plane 2.

4. Surface wave analysis

Surface wave analysis are commonly applied to investigate velocity structures of the Earth's interior. It and has been used to delineate mantle structure for some specific features or regions based on inversions of travel time and phase/group velocity for seismic waves and splitting measurement of Earths free oscillation from world-wide earthquake records to obtain three-dimensional distributions of seismic velocity anomalies in the mantle with respect to a reference Earth model. Surface wave analysis can achieve good coverage in oceanic areas. Surface waves has been used to retrieve details of crustal and upper mantle structures for both regional and global scales in the forms of 2-D phase and group speed structures as well as 3-D shear wave speed models.

The data processing of surface wave analysis has been analysed the seismic waveforms to obtain reliable surface-wave dispersion curves. A single-station data based on a non-linear waveform fitting is used to estimate a path-average phase velocity for a ray path between source and receiver. In order to check the quality of the measured dispersion curves, we apply several empirical criteria to evaluate waveform fitting and phase speed measurements. The criteria include a total misfit of multiple time windows, the reliability parameter of phase speed measurements and average radiation amplitude of each mode. The selected phase speed data will be used in figured phase speed maps of this area. The phase speed maps are obtained for the fundamental mode and up to fourth higher-modes of Rayleigh
and Love waves. The 3-D shear wave velocity models are obtained from the fundamental and higher-modes phase velocity maps of Rayleigh and Love waves. The structure of the upper mantle in the depth range from 50 to 350 km is successfully imaged with satisfactory resolution as shown in figure 12.

In the cross section across the west Sumatra region (figure 11 for horizontal map), we can find a fast wave velocity anomaly associated with the subducting oceanic plate down to 400 km depth. Slower anomalies in the mantle wedge beneath West Sumatra also well resolved, corresponding to the volcanic front exists in Sumatra island. Cross section B-B’ (figure 11) across the western and eastern part of Sumatra, do not show any clear features of the continuation of the Indo-Australian plate beneath Sumatra Island.

5. Conclusions
The seismotectonic in West Sumatra has been investigated based on earthquake distribution, focal mechanism data and surface wave analysis. Earthquake distribution analysis found three earthquake source groupings were due to Mentawai fault, subduction of Indo-Australian plate under the island of Sumatra and in the presence of deep and shallow earthquakes in the west Sumatra region. Shallow earthquakes are caused by Sumatra's active fault activity and deep earthquakes are associated with subduction zones. These results are also relevant to the description of surface wave analysis. The cross section can be described as oceanic plate beneath the continent plate where the west Sumatra region is above it.

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