FAULT SEGMENTATION OF SOUTHERN SUMATRA (SIANOK SEGMENT-SEMANGKO SEGMENT) BASED ON ACTIVE FAULT MAPPING THROUGH DIGITAL ELEVATION MODEL (DEM) AND SEISMICITY

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ABSTRACT

Subduction with oblique dimensions causes the formation of structures in the Sumatra area, one of which is the formation of the Sumatran Fault System with dextral fault movements. Strike-slip Fault are Segmented in varying geometries and sizes. The Sumatran Fault has been extensively Segmented through geometric and structural analysis on the surface and seismic analysis using seismic clusters. This research was conducted to update fault Segmentation using surface structure analysis and earthquake data distribution. Surface mapping was carried out through DEM imagery and association with earthquakes and their focal mechanisms, as well as geological factors such as lithology and volcanoes related to the Sumatra Fault. There were 14 Segments based on geological and structural identification such as step over, bend, and discontinuity (gap). All the active fault in the region can produce >Mw 6.6 earthquake.

Keywords: *Sumatra Fault, Active Fault, Fault Segmentation, Step Over, Earthquake Potential*

INTRODUCTION

The Sumatran Fault stretches for 1900 km with a strike-slip mechanism resulting from accommodation from oblique convergence (Sieh and Natawidjaja, 2000). The basic kinematic role of the Sumatran Fault is simple: it accommodates a large number of strike-slip components of oblique convergence between the Australian/Indian and Eurasian Plates. The pole of rotation for relative motion between the Australia/India and Eurasian Plates is in East Africa, ~50 degrees west of Sumatra. Generally, strike-slip fault systems are often Segmented into several parts at various scales (Schwartz and Sibson, 1989 : McCalphin, 1996)
Previous researchers stated that the Sumatran Fault Segmentation was divided using different methods. Sieh and Natawidjaja (2000), divided the Sumatran Fault into 19 main Segments based on a review of geometric irregularities and structural complexity using satellite imagery sourced from Bellier, et al (1997). Another Segmentation proposed by Burton and Hall (2014) uses the k-means algorithm method to produce a seismic cluster with a total of 16 Segments. The Segmentation from Sieh and Natawidjaja (2000) was produced from a geological review, while the Segmentation by Burton and Hall (2014) produced a Segmentation model obtained from clustering the history of earthquake ruptures that have occurred.

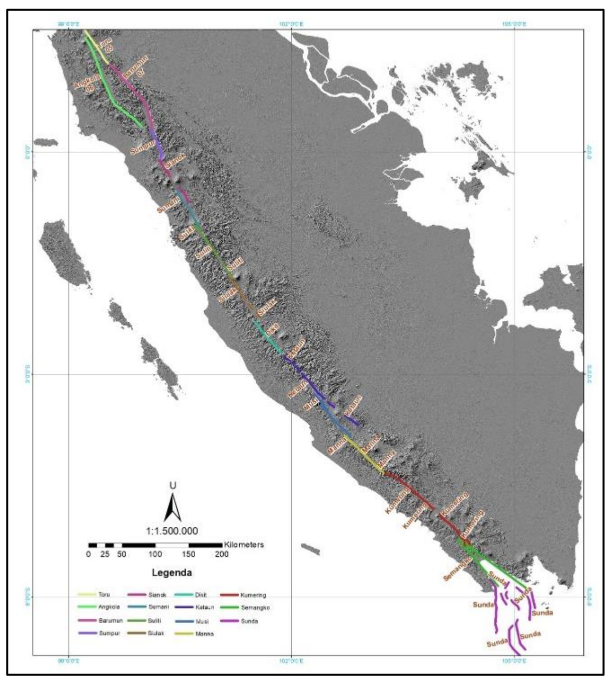

Figure 1. Research Area

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RESEARCH METHOD

This research is a study to determine the Segmentation of The Sumatran Fault through a geological and geometric aspect, especially in the Sianok Segment to the Semangko Segment. We review the results of previous research, process and observe DEM data, and review historical earthquake data. Seismic data shows the history of earthquakes with focal mechanisms related to rupture as well as the distribution of aftershock from the earthquake itself which indicates the similarity of the earthquake source.

At the end, we calculate the potential magnitude of the earthquake resulting from each active Segment through the empirical relationship between magnitude and surface rupture length proposed by Wells and Coppersmith (1994)

In this research, Digital Elevation model data will be used to map the surface structure, which will also be correlated with earlier studies. Surface rupture can be identified using shaded-relief, and slope from geomorphic features such as: fault scarps, linear depressions, stream offsets, pressre ridged, sag ponds. (McCalpin, 1996). Seismic data use to show the focal mechanisms and aftershock distribution to see the associated earthquake with active faults. The data obtained from USGS Earthquake Catalog and Global Centroid-Moment-Tensor (CMT). Then, calculation of the potential magnitude of each mapped active fault Segment was carried out using the empirical relationship between magnitude and surface rupture length.

RESULT AND DISCUSSION

Fault Segmentation

The Sumatran Fault that stretches along the islnad has a generally sinusoidal shape (Sieh and Natawidjaja, 2000). The northern half is concave to the southwest, while the southern half of the fault is concave to the northeast. In this section, the Segmentation of the Southern Sumatran Fault will be discussed, including geomorphic features, geological conditions and seismicity from North to South. Based on the results of identification and analysis, the author divides the Southern Sumatra Fault Segment into 14 Segments where the naming refers to Natawidjaja (2018), including Sianok Segment, Sumani Segment,Suliti Segment, Siulak Segment, Dikit Segment, Ketaun Segment (divided into two sub-Segments, namely 1 and 2), Musi Segment (divided into two sub Segments namely Musi 1 and Musi 2), Manna Segment, Kumering Segment (divided into two sub-Segments namely 1 and 2), Semangko Segment (divided into two sub Segments namely Semangko 1 and Semangko 2).

- **Sianok Segment**

The 80 km long Segment stretches from the northern part of Lake Maninjou to the southeastern wall of Lake Singkarak. In the southern part, this Segment forms a curve shaped at Lake Singkarak which is a step over 8.5 km wide. This step over acts as the southern boundary of the Sianok Segment and forms a depression in the form of Lake Singkarak.

Based on the Padang Geological Map (Kastowo et al, 1996) dan Solok Geological Map (Silitonga et al, 2007) in general, the Sianok Segment passes through volcanic quaternary deposits and surface deposits such as alluvium and terraced deposits. Quarternary volcanic deposits come from volcanoes in the northern part of Lake Singkarak such as Mount Marapi, Mount Tandikat and Mount Singgalang. On the step over zone, there are old rocks from Perm to Triassic (metamorphic rock) consist of Phyllite and Shale Member of the Kuantan Formation, Slate Member of Tuhur Formation. and Cretaceous Intrusions (granitic). The presence of old Perm to Triassic rocks in step over zone, writer proposed that old rocks, act as Segment boundaries which can terminate earthquake rupture.

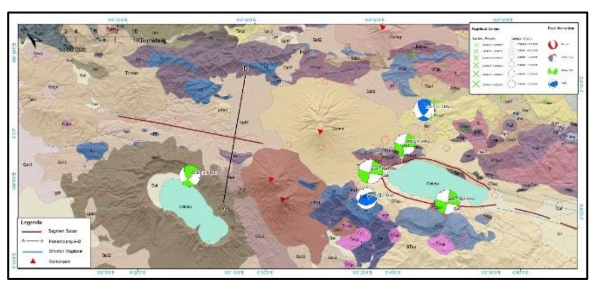

Figure 2. Lithology and Seismicity Distribution Map of Sianok Segment

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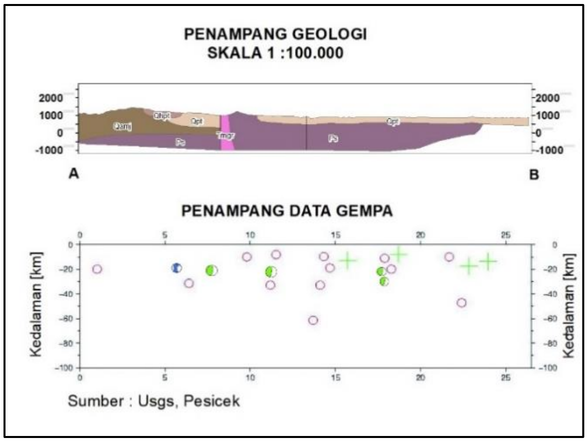

Figure 3. Cross Section A-B Sianok Segment

Recent large earthquake occurred on March 6, 2007 (Mw = 6.3) in this Segment originating from rupture along the Sianok Segment. This earthquake had a focal strike-slip mechanism in the northern part of Lake Singkarak. The epicenter of the earthquake was in the old rock which was discussed previously. Writer assumes that the presence of old rocks that are relatively shallow or reach the surface act as a locking zone for earthquakes. Where the old rock locks the movement of the fault up to the limit of the failure point (break) of the old rock.

- **Sumani Segment**

A ~64 km long Segment have southern boundary in the form of step over with a widht of ~4.6 km forming a geomorphic feature Lake Diatas and Mount Talang

Based on Solok Geological Map (Silitonga et al, 2007) and Painan Geological Map (Rosidi et al, 2011), Sumani Segment at the surface cuts through Quarternary Volcanic Deposits from volcanoes in the north and south of the Segment (Mount talang). On the A-B cross section (Figure 4.) of the Sumani Segment, there are old rocks just below the Quaternary Deposits. Older rocks consist of Slate and Shale of Tuhur Formation (Triassic), Phyllites and Shales of Kuantan Formation (Perm) and Limestones of the Tuhur Formation (Triassic).

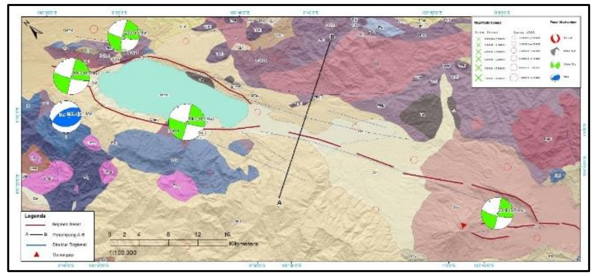

Figure 4. Lithology and Seismicity Distribution Map of Sumani Segment

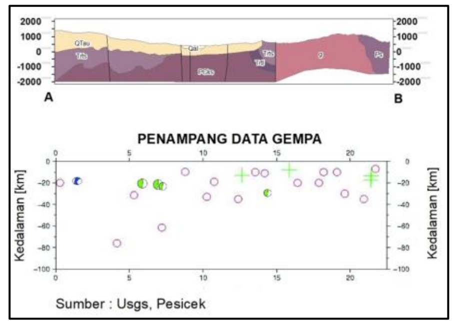

Figure 5. A-B Cross Section of Sumani Segment

Sumani Segment produced a large rupture on March 6, 2007 (Mw = 6.4) which was located around Lake Singkarak. Furthermore, an earthquake also occurred on July 21, 2018 (Mw = 5.2) which was different from the previous position of the epicenter which was in the southernmost part of the Sumani Segment. Based on A-B cross section (Figure 5.), it shows the depth of the earthquake at <30 km, indicating that the earthquake was classified as a shallow earthquake. It conclude that the location of the locking depth is in uplifted old rock where the old rock has appeared at a depth of ~1-2 km below the surface.

- **Suliti Segment**

The Segment has a straight, uncurverd shape with a length of ~96 km. The northern part of this Segment is right on the hilly features of Lake Dibawah (step over 4.6 km wide) until the southern part meets Mount Kerinci where a step over (4 km wide) occurs as the Segment boundary.

This Segment dominated by Quaternary Volcanic Deposits due to the presence of mountains in the north, southwest and south of this Segment (Figure 6.). Middle part of this Segment consist of old rocks (Barisan Formation : Perm) and Cretaceous Intrusions. Part of the Suliti Segment precisely become the

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stratigraphic boundary between the granite intrusive rock and surroundings rock. This condition is associated with the difference in the rheology of rock between the intrusive and other, where locking does not occur, resulting in creeping movement (slip) of the fault in this Segment. This kind of slip mechanism does not produce earthquake with large magnitudes.

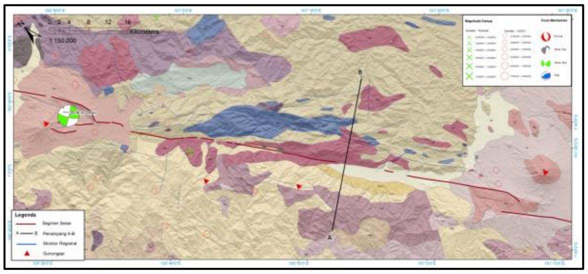

Figure 6. Lithology and Seismicity Distribution Map of Suliti Segment

Throughout the Suliti Segment, there are no earthquakes with a strike-slip focal mechanism, but there are scattered randomly earthquakes in the northeast and southwest parts of the Segment. An earthquake with a strike-slip focal mechanism was present in the northern part right at the Segment boundary (step over) with the Sumani Segment on July 21, 2018 (Mw = 5.2).

- **Siulak Segment**

The Segment bounded by step overs at both ends is ~74.6 km long. Step over 11 km wide in the southern part of this Segment act as Segment boundary. The middle part of the Siulak Segment contains Lake Kerinci, Quaternary deposits obscure the fault traces of this Segment up to ~32 km. In the southern part there are cone-shaped features (Figure 7.), just to the southwest of the Siulak Segment are Mount Raya and Mount Kunyit. This cone-shaped feature is related to volcanic activity in the area and influences the Segment boundaries.

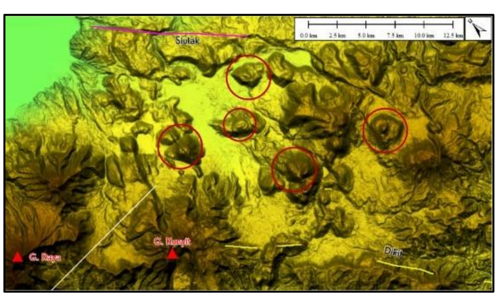

Figure 7. Cone-shaped Feature

Based on the Painan and Sungaipenuh Geological Map (Kusnama et al, 2010 ; Rosidi et al, 2011), Siulak Segment dominated by volcanic quarternary deposits, a small portion of Paleogene-Neogene age sedimentary rocks in the middle part of the Segment and Neogene Granite Intrusive (Figure 8.). Subsurface cross-section (Figure 9.) shows a Cretaceous-aged rocks (Peneta Formation) at a depth of 500 m which is right in the path of the Siulak Segment.

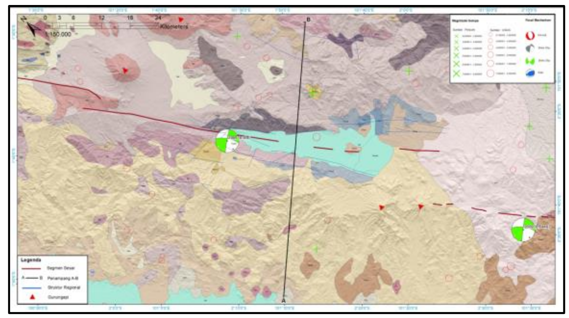

Figure 8. Lithology and Seismicity Distribution Map of Siulak Segment

A strike-slip focal mechanism earthquake occurred on Octobe 6, 1995 with a magnitude of 6.0 (Mw). Based on the cross section (Figure 9.), this earthquake was at a depth of <20 km (shallow earthquake). Presence of the old rocks at shallow depth associated with the locking zone which produces shallow depth earthquakes.

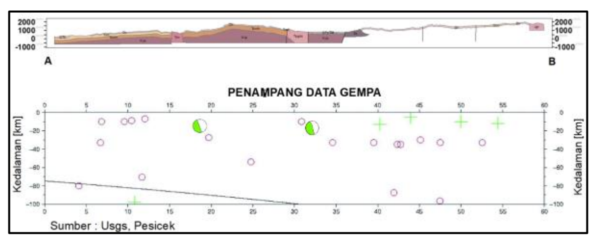

Figure 9. A-B Cross Section of Siulak Segment

- **Dikit Segment**

The Dikit Segment is ~60 km long starting from the northern part at the confluence with Mount Kunyit and a 10 km wide step over to the soutern part at the confluence with Mount Gedang. The southern boundary of this Segment does not show any obvious features such as bends or step overs. Looking to the deflection of the fault trace in the southern Segment (Figure 10.), the southern boundary of this Segment is a discontinuity and minor

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contractional bend as seen from the deflection of the fault trace down the the Ketaun Segment.

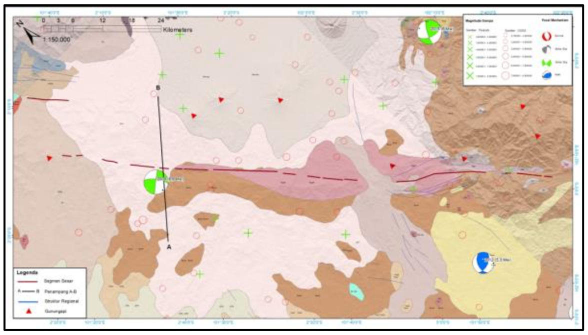

Figure 10. Lithology and Seismicity Distribution Map of Dikit Segment

Presence of series of volcanoes (Mount Masurai, Mount Sumbing, and Mount Hulu Nilo) affects the distribution of rocks dominated by quarternary volcanic deposits. There is also small portion of Neogene-aged rocks (Hulusimpang Formation), and Pliocene-aged Langkup Granodiorite which passes through by the Fault. A-B Cross Section (Figure 11.), shows the presence of Cretaceous age rocks (Peneta Formation) as well as Neogene-age Diorit Intrusions.

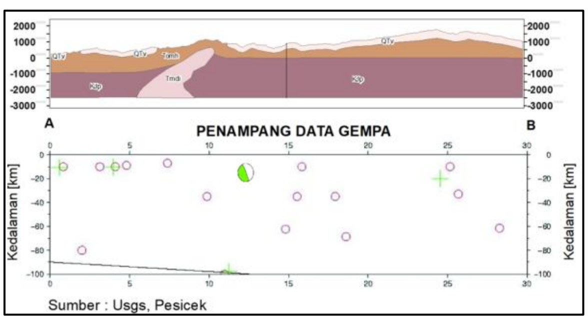

Figure 11. A-B Cross Section of Dikit Segment

The rupture of the Dikit Segment resulted in a large earthquake recorded on October 1, 2009 with a magnitude of 6.6 (Mw). This earthquake shows strike-slip focal mechanism so it's associated with the movement of the Dikit Segment Fault. The earthquake have depth around 10-20 km.

- **Segment Ketaun 1**

In Sieh and Natawidjaja (2000 ; Natawidjaja, 2018), the Ketaun Segment is ~85 km long. However, the writer found a momentary discontinuity where the Segment meets Mount Kaba, so the author divided the Ketaun Segment into two Segments, Ketaun 1 and Ketaun 2. The Ketaun 1 Segment has a length of ~107 km, which is longer than the Segment proposed by Sieh and Natawidjaja (2000; Natawidjaja, 2018). The Segment boundary in the northwest (Figure 12.) intersects with the presence of Mount Pendan and Mount Seblat. If you look at the boundary, there is a curve towards the west, this curve is associated with the contractional bend phenomenon.

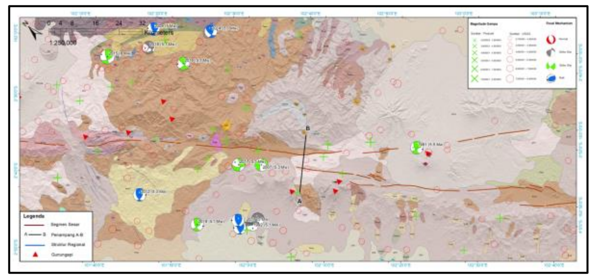

Figure 12. Lithology and Seismicity Distribution of Ketaun Segment

According to Sieh and Natawidjaja (2000), the southeastern boundary is a step over which has a width of 5 km to 18.5 km, where as you go south (closer to Mount Kaba) the width increases. The writer expresses a different opinion regarding this Segment boundary, the Segment boundary is not a step over but rather a fault bifurcation in a different direction. Because the step over characteristics of a fault line are not continuous on both sides but only continuous on one side, this is different from the case of the Ketaun Segment. Where in this Segment the two fault lines are continuous at a certain distance in different directions so that they do not fulfill the characteristics of a step over. That's why previous researchers calculated that the width of the step over gets higher as the fault line goes south.

The Ketaun 1 Segment is mostly included in the Bengkulu Geological Map (Gafoer et al, 2007), where the fault line passes through volcanic rocks of Quaternary and Tertiary age. The presence of a series of volcanoes in almost all Segments allows the dominance of volcanic products. In the northwest there are Mount Gedang, Mount Pendan, Mount Seblat, and Mount Belirang Beriti. In the southwest part of the Ketaun 1 Segment there is a collection of mountains consisting of Mount Tiga, Mount Hulu Palik, and Bukit Daun. Likewise, at the southern end of Ketaun 1 Segment there is Mount Kaba.

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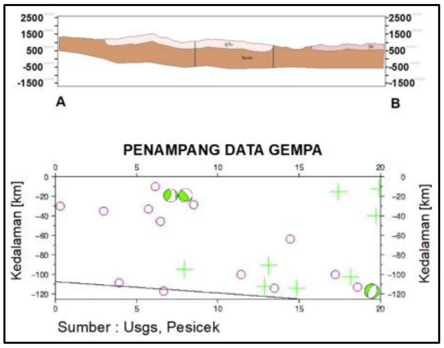

Figure 13. A-B Cross Section of Ketaun Segment

Apart from volcanic rock, there is a small portion of intrusive rock (granite) at several points close to the Segment route. In general, the age of the intrusive rocks present is Miocene-Pliocene. Cross section A-B (Figure 13.) does not show any old rock beneath the volcanic rock that appears on the surface due to the lack of subsurface data in this area

There were quite a lot of earthquakes along the Ketaun 1 Segment with varying magnitudes. An earthquake showing a strike-slip focal mechanism occurred on July 31 2017 with a strength of 5.1 Mw located southwest of the Ketaun 1 Segment. The depth of the 2017 earthquake (Figure 13.) was 20 km below the surface, which is considered a shallow earthquake. Shallow earthquakes are associated with the presence of active faults that are still experiencing movement, in this case the Ketaun 1 Segment itself.

- **Segment Ketaun 2**

The Ketaun 2 Segment starts from the southeastern slopes of Mount Kaba which shows a straight line cutting through the valley with a right offset. Measuring ~24.5 km to the southeast, the final southeastern boundary of the Ketaun 2 Segment is not clearly visible on topography. It can be seen in Figure 12. that the Ketaun Segment is interrupted when it meets Mount Kaba, so that Mount Kaba has a role in separating the Ketaun 1 Segment and the Ketaun 2 Segment.

Based on the lithology and seismicity distribution map (Figure 12.), the Ketaun 2 Segment at the surface completely cuts through Quaternary-aged volcanic rock units. According to the Bengkulu Geological Map (Gafoer et al, 2007) this unit consists of volcanic breccia, lava, andesite-basalt tuff originating from Mount Kaba. Below the surface there is no available rock distribution data so it cannot be identified what rocks are cut by the Ketaun 2 Segment.

Right on Mount Kaba there was an earthquake with a strike-slip focal mechanism that occurred on January 26 1991 with a magnitude of 5.5 Mw. When viewed from the cross section (Figure 13.), the depth of this earthquake is 120 km below the surface, including as a deep earthquake. At this depth, this earthquake is not directly related to the rupture of the Ketaun 2 Segment.

- **Segment Musi 1**

Sieh and Natawidjaja (2000) stated that the Musi Segment is ~70 km long, but the authors divide the Musi Segment into two sub-Segments, namely Musi Segment 1 and Musi Segment 2 based on new findings regarding Segment boundaries. The Musi 1 Segment is 31 km long and extends across the northeastern slopes of Mount Hulu Palik and Bukit Daun (Figure 14.). The northwestern Segment boundary is a branch of the Ketaun 1 Segment, while the southeastern Segment boundary experiences a step over with a width of 3.7 km. In Sieh and Natawidjaja (2000), this step over is not considered a Segment boundary but continues to the step over with the Manna Segment far to the south. The writer believes that the southeastern boundary is a step over because there is a small depression to the southeast of Bukit Daun. Apart from that, there is a feature that has a shape resembling a stairs on the wall facing northeast (Figure 15.). This feature is considered to be the dip slip component of a normal fault which is commonly present in step overs that form a depression.

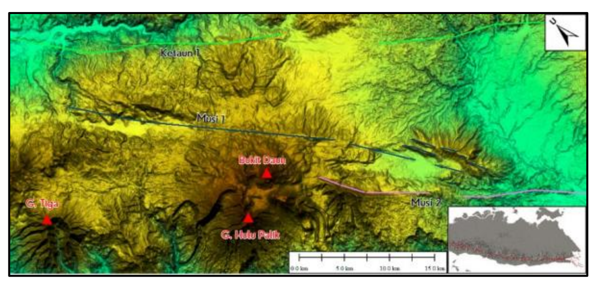

Figure 14. Topography Expression of Musi Segment

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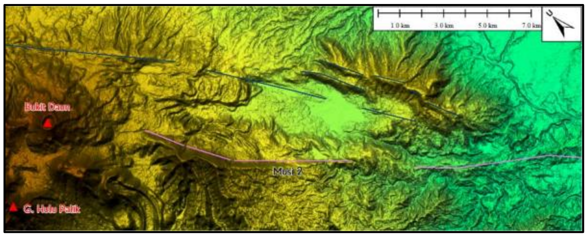

Figure 15. Depression and stairs feature in Musi 1 Segment

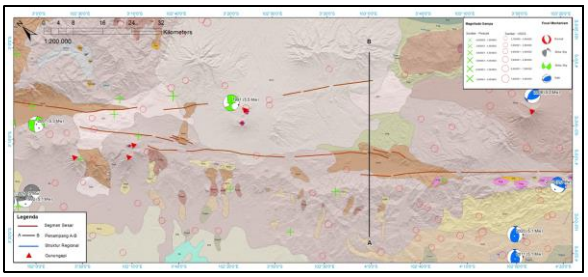

Figure 16. Lithology and Seismicity Distribution of Musi Segment

Based on the Lithology and Seismicity Distribution Map (Figure 16.), the Musi 1 Segment cuts through three rock units which are Andesite-Basal Volcanic Rock Unit Bukit Daun, Rio Andesite Volcanic Unit, and Hulusimpang Formation. In general, these rocks are volcanic rocks with Quaternary and Oligo-Miocene ages for the Hulusimpang Formation. Cross section A-B (Figure 17.) does not show the presence of old rock due to limited data available. The volcanic rocks that make it up come from volcanoes located around the Musi 1 Segment, namely Bukit Daun and Mount Hulu Palik which are right in the step over zone. Far to the northwest is Mount Tiga which also produces volcanic products around the Musi 1 Segment route.

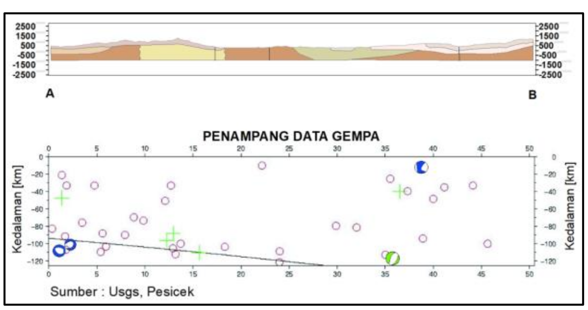

Figure 17. A-B Cross Section of Musi Segment

On September 14 2007, a rupture occurred caused by the movement of the Musi 1 Segment with a magnitude of 5.1 Mw. The depth of the earthquake was relatively shallow at ~20 km from the earth's surface. The presence of an earthquake with a focal strike slip mechanism proves that the Musi 1 Segment is actively moving and is one complete Segment. In Sieh and Natawidjaja (2000), the history of a large earthquake occurred on December 15 1979 with a magnitude of 6.6 Mw.

- **Segment Musi 2**

The Musi 2 Segment continues from a small step over with a width of 3.7 km in the northwest to a step over in the southeast which is 5.8 km wide with a Segment length of 70.5 km. In shape, this Segment is not completely straight, there is a minor deflection, especially when it reaches the Segment boundary in both the northwest and southeast parts. The trace of the fault is not clear because it is covered by quaternary deposits, but at several points, especially the southwest slope of Mount Kaba, there are offset valleys that indicate a right direction. The step over that occurs in the northwest is right on the southeastern slope of Bukit Daun. This condition shows a relationship between the presence of volcanoes and the boundary of a fault Segment.

From Lithology and Seismicity Distribution Map (Figure 16.), the Musi 2 Segment cuts through volcanic rocks, especially in the central part to the northwest. At the southeastern end, Musi Segment 2 cuts through Hulusimpang Formation rocks (Oligo-Miocene) which consist of lava, breccia and tuff. The existence of Mount Kaba in the northeastern part of the Musi 2 Segment and Bukit Daun at the boundary of the northwestern Segment means that the dominant distribution is volcanic rock. Below the surface, Musi Segment 2 passes through other rocks, namely the Seblat Formation (Oligo-Miocene) in the form of sandstone seen from the A-B cross section of the Musi Segment (Figure 17.). Limited data availability only shows rocks below the surface up to a depth of 1000 meters, so far there is no information regarding the old rocks present and cut by the Musi 2 Segment

Based on the data obtained and displayed on the map (Figure 16.), the Musi 2 Segment did not cause the latest rupture with large earthquake strength with a focal strike-slip mechanism.

- **Segment Manna**

The Manna Segment is ~80.8 km long and has a relatively parallel shape. The northwestern boundary is a step over with a width of 5.8 km

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with the Musi Segment. The southeastern boundary is in the form of a contractional bend seen from the shape of the trace of the Segment which curves and moves to become Kumering 1 Segment. According to Sieh and Natawidjaja (2000), this bend has a deflection angle of 17°. The southwest part of this Segment has hills that extend in the same direction as the Manna Segment. These hills have no particular connection with the dextrally moving Manna Segment. The southeastern boundary also contains elongated hills (marked in brown in Figure 18.) whose direction is quite different from those to the southwest of the trail Segment. Where these hills have the same direction as the bend from the boundary of the Manna Segment.

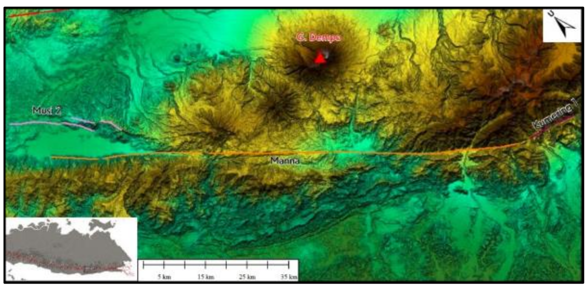

Figure 18. Topography Expression of Manna Segment

Based on geological data taken from the Manna and Enggano Geological Map (Amin et al, 2012), the Manna Segment passes through various rocks, starting from volcanic deposits, sedimentary rocks and intrusions. In general, the age of the rocks covered ranges from Paleogene to Quaternary. The trace of the fault is precisely in the intrusive rock (marked in pink in Figure 19.) which is of Miocene age. From cross section A-B (Figure 20.), it can be seen that there is a regional fault with upward movement (thrust). The existence of this thrust fault can be associated with the availability of earthquake data which appears at several points on the map but is not exactly on the Manna Segment so the writer does not make this the main discussion.

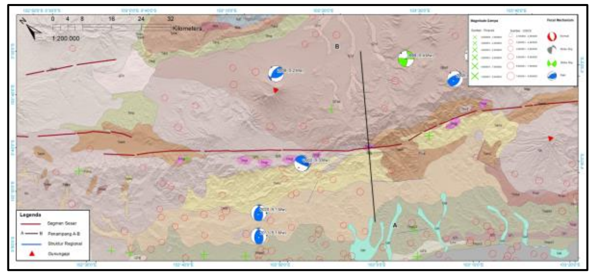

Figure 19. Lithology and Seismicity Distribution of Manna Segment

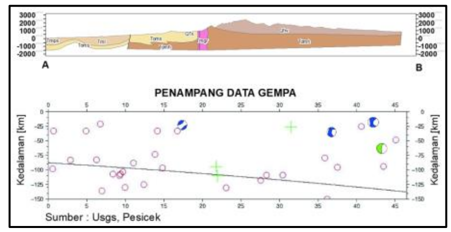

Figure 20. A-B Cross Section of Manna Segment

The distribution of earthquake data that has a focal mechanism is dominated by the thrust mechanism which is marked by the blue beachball in Figure 19. and Figure 20. Even though there was an earthquake with a strike-slip focal mechanism, its point was not exactly in the Manna Segment fault zone so it was not associated with rupture resulting from the Manna Segment. It is possible that there are other faults that do have a strike-slip mechanism in other locations.

- **Segment Kumering 1**

Sieh and Natawidjaja (2000), propose the Kumering Segment extends from the contractional bend northwest of Mount Pandan to the step over Lake Suoh in the south with a length of ~150 km. The writer has a different opinion regarding the Kumering Segment, which divides into two sub-Segments, namely Kumering 1 and Kumering 2. The separation of this Segment occurs at Lake Ranau which experiences a discontinuity (in this case a small step over) from the fault line. So the length of the Kumering 1 Segment is 111 km (Figure 21.).

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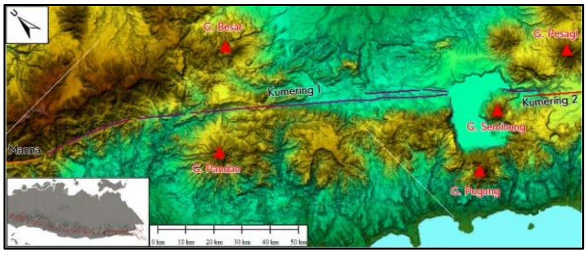

Figure 21. *Topography Expression of Kumering 1 Segment*

The boundary of the northwestern tip is right at the contractional bend, where there is a bend to the left from the movement of the dextral fault causing the characteristic that develops, namely contraction. Meanwhile, the boundary at the southeastern end is in the form of a small step over at Lake Ranau, 1 km wide. Lake Ranau, which is considered a fairly large lake, is crossed by Kumering Segment 1 and is almost at the southeasternmost tip of this Segment. Generally, lakes that form along the Sumatran Fault are the result of the influence of the movement of the fault itself, such as Lake Singkarak. However, the writer found something different about the formation of Lake Ranau. Judging from its shape (Figure 4.22), this lake does not extend towards the fault line, but is almost perpendicular to the fault line related to the extension of this lake. Apart from that, the presence of Mount Seminung right next to the lake convinces the writer that this lake was formed due to the process of volcanism which is a volcanic caldera.

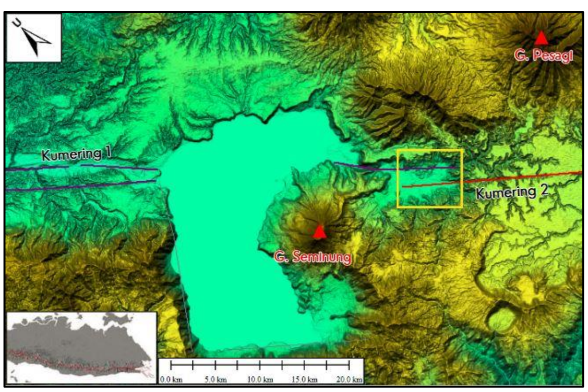

Figure 22. Ranau Lake

Based on the Manna Geological Map (Amin et al, 2012) and the Baturaja Geological Map (Gafoer et al, 2010) on Figure 23., the northwestern tip of the Kumering 1 Segment, where the contractional bend occurs, contains intrusive rocks crossed by a fault in the form of Miocene-aged granite. Not far from this position to the northeast there is a Miocene Granodiorite Intrusion. Apart from the presence of intrusive rocks, there are also many scattered quaternary volcanic rocks originating from Luncuk Hill and Garanggarang Hill (Andesite-Basalt Volcanic Rock Unit). The Kumering 1 Segment also cuts rocks from the Ranau Formation in the form of volcanic breccia. Right on the fault line, the Hulusimpang Formation is cut out, which consists of andesite-basalt lava. Below the surface through the cross-section (Figure 24.) it can be seen that the distribution of rocks is not much different from that on the surface. The insufficient availability of subsurface data results in a subsurface picture that is not optimal so that no information is obtained on other rocks more than 500 meters deep.

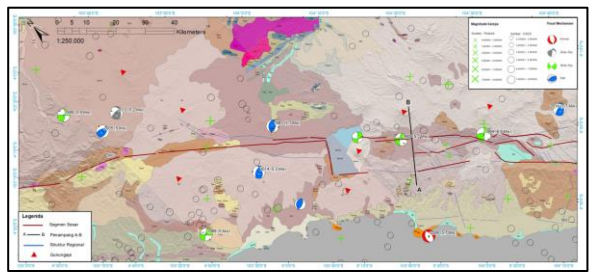

Figure 23. Lithology and Seismicity Distribution of Kumering Segment

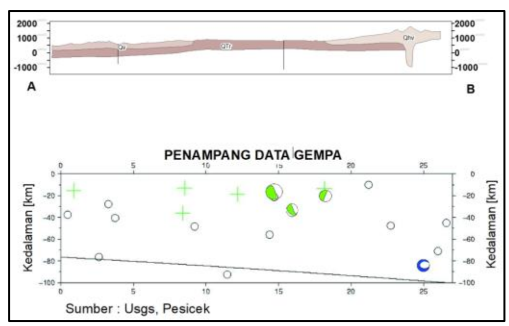

Figure 24. A-B Cross Section of Kumering Segment

The earthquake that occurred in the Kumering 1 Segment was in the Segment boundary zone, especially the southeastern Segment boundary (where the step over occurred). The rupture occurred on December 31, 1985 right at the boundary of the Kumering 1 and Kumering 2 Segments with 5.1 Mw. Section shows (Figure 24.), this earthquake was found at a depth of ~33 km, which is still considered a shallow earthquake. The movement of this Segment caused another rupture recorded on March 31, 2014 with a force of 4.2 Mw occurring at a depth of ~20 km.

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- **Segment Kumering 2**

The Kumering 2 Segment is in a complex fault zone where there are many regional faults around it. An example of a visible fault is the Liwa Fault which is to the southwest of the Kumering Segment 2. The northwestern boundary of this Segment is the step over in Lake Ranau, while the southern part is quite interesting, namely the 2 step overs in the Lake Suoh area which have different dimensions. This Segment with a length of ~60.25 km at the southeastern end occurs a step over which forms a depression in the form of Lake Suoh (western part) and the Roworejo Plain (eastern part). The Lake Suoh Depression has a width of ~7.5 km, while the depression on the Roworejo Plain has a smaller width of ~5 km.

The writer assumes, the formation of these two depressions is due to the fault bifurcation shortly before reaching Lake Suoh from Kumering Segment 2. This bifurcation also results in the continuation of the next Segments in the form of Semangko Segment 1 and Semangko Segment 2 (In Natawidjaja (2018), these two Segments are called Semangko West and East Semangko).

In general, the distribution of rocks in the Kumering 2 Segment is similar to the rocks along the Kumering 1 Segment. The presence of several mountains such as Mount Seminung, Mount Pesagi and Mount Sekicau Belirang means that the surface in this Segment is massively covered by volcanic products of quaternary age. . Based on the cross section across the Kumering Segment 2 (Figure 24.), the existence of a fault line below the surface cuts through volcanic breccia rocks from the Ranau Formation. Other rocks, especially old rocks, were not found due to limited subsurface data regarding rock distribution. The conditions are different from the Segment that is more in the middle of Sumatra Island, where old rocks are found at shallow depths or even appearing on the surface.

The presence of faults that can be seen from aerial image monitoring means that this area has a fairly high seismic intensity, indicated by a cluster of earthquakes with a focal strike-slip mechanism right in Kumering Segment 2. As can be seen on the map (Figure 23.), there was an earthquake that occurred in 1994 with a power of 6.9 Mw. Rupture from this earthquake produces a notch or mark that stands out on the surface.

- **Segment Semangko 1**

The Semangko Segment is divided into two sub-Segments, namely Semangko 1 and Semangko 2. In Natawidjaja (2018), these two Segments are called the East Semangko Segment and the West Semangko Segment. The Semangko 1 is 95 km long, the northwestern Segment boudnary is a step over 7.4 km wide. The southeasetern part of this Segment continues underwater along the western side of Semangko Bay, where this Segment bifurcates which turns clockwise to the trough in the Sunda Strait to form a triangular underwater graben.

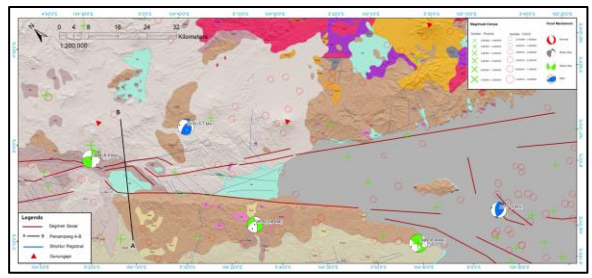

Figure 25. Lithology and Seismicity Distribution Map of Semangko Segment

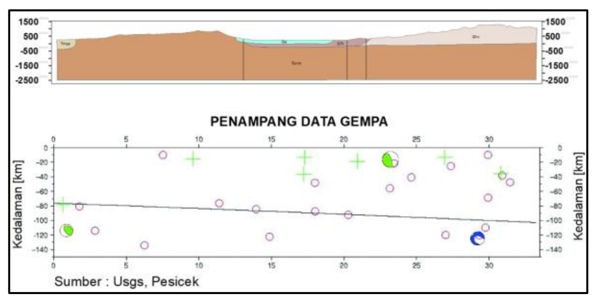

Figure 26. A-B Cross Section of Semangko Segment

Based on Kotaagung Geological map (Amin, et al, 2010) shows the distribution of rocks (Figure 25.) along the Semangko 1 on the surface in te form of volcanic products originating from the Tanggamus Young Quaternary volcano (breccia, lava, and tuff). In the southwest part of this Segment lies the Miocene Bal Formation (volcanic breccia), the Oligo-Miocene Seblat Formation (interbedded mudstone and sandstone) and the Oligo-Miocene Hulusimpang Formation (Volcanic Breccia). At the same location there are also Miocene Granite Intrusive.

The southwest of the Segment, occurred earthquake on May 19, 1979 (5.4 Mw) with 118 km depth. The second earthquake was at the tip

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of Cape Semangko occurred on August 14, 1999 with 99 km depth. Even though the mechanism of these two earthquakes includes strike-slip, writer assumes this earthquake is not a rupture of the Semangko 1 because the epicenter is relatively deep.

- **Segment Semangko 2**

This Segment is to the east of the Semangko 1 Segment which is 114 km long. The boundary of this Segment in the north is a step over with the Kumering 2 Segment which forms a small depression (pull-apart) called Roworejo (based on the name of the area). The name is different from Natawidjaja (2018), namely Natarang. The further south the trail of Semangko 2 Segment is less less visible because it is covered by sea water. However, from the bathymetry, the remains of the incisions from this Segment path are quite visible. The southern boundary of this Segment is not very visible, accroding to Natawidjaja (2018) the tip of this Segment shows a horsetail splay feature which commonly appears in strike-slip fault Segments. The writer propose different type of boundary which is step over with the Ujung Kulon Fault which forms the pull-apart of the Sunda Strait in the ocean as stated by Susilohadi (2009) and Mukti (2018)

This Segment doesn’t show any significant differences with Semangko 1 Segment. It has similarities of quaternary volcanic rocks suorced from Mount Seminung which is to the northeast of this Segment. Also, there is Oligo-Miocene Hulusimpang Formation present truncated in the southern part of this Segment.

Based on observing the distribution of earthquake data, both hypocenter and focal mechanisms along this Segment (Figure 26.), it does not show that there was an earthquake with a large magnitude. Rupture occurred at the Segment boundary in the north where a step over occurred formed a depression.

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Table 1. Fault Segmentation and Potential Earthquakes Magnitude

Segmen Sieh dan Natawidjaja (2000)	Updated Segment	Length, Km	Large Historical Earthquake (Years)	Potential Magnitude (Mw)	Southern Boundaries	Geological Condition	Geomorphic Features
Sianok	Sianok	80	*1822,*1926 2007 (Mw 6.3) 2008 (Mw 5.1)	7.5	Dilatational Step Over, 8.5 km widht	The southern boundary occurs as a stepover to form Lake Singkarak (pull-apart), there are old rocks (perem, carbonaceous, triassic), the middle part passes through mountains such as Mount Singgalang, Mount Marapi, Mount Tandikat so there are also quaternary deposits on the fault line. The northwestern tip meets Mt. Talamu and Mt. Pasaman and the boundary is a step over	Lake Singkarak
Sumani	Sumani	64	*1943 (Ms=7.6), *1926 (Ms~7) 2007 (Mw 6.4) 2018 (Mw 5.2)	7.4	Dilatational Step Over, 4.6 km width	The southern boundary is Mt. Talang, the northern boundary occurs a step over producing pull-apart (Lake Singkarak), there are various old rocks such as the Kuantan Formation (Perm-Carbon), Silungkang Formation (Perm-Carbon), Perem quartzite, limestone of the Tuhur Formation (Triassic), Miocene andesite, and diabase (perem-carbonaceous)	Lake Diatas, Caldera
Suliti	Suliti	96	*1943 (Ms=7.4) 2018 (Mw 5.2)	7.6	Dilatational Step Over, 4 km width	the southeast segment boundary borders Mt. Kerinci, the northwest segment boundary borders G. Talang, the middle part of the segment passes through old rocks such as the Barisan Formation (perem), limestone granite intrusions, Jurassic limestone	Mount Talang on the north, small depression
Siulak	Siulak	74.6	*1992 (M 5.6) *1995 (M 6.0)	7.4	Dilatational Step Over, 11 km width	The northwestern segment boundary meets Mount Kerinci. In the middle of the segment, it passes through the Bandan Formation (Eocene), Sungaipenuh Granite (Pliocene), and Painan Granite (mid-Miocene)	Lake Kerinci, Mount Kerinci
Dikit	Dikit	60	2009 (6.6)	7.3	Discontinuity, Mount Gedang	The fault line passes through Pliocene-aged Granodiorite (intrusions), in the northeastern part there are Mt. Masurai, Mt. Sumbing, and Mt. Hulu Nilo. The tip of the northwestern segment boundary is at the confluence with Mt. Kunyit	Long scarp facing Northeast
Ketaun	Ketaun 1	107.8	*1943 (Ms=7.3), *1952 (Ms=6.8) 2015 (Mw 6.0)	7.6	Bifurcation	The northwestern boundary of the segment intersects with the presence of Mt. Pendan and Mt. Seblat. And it is located in Pliocene-aged Langkup Granodiorite (intrusive)	Mountain range (Mount Gedang) on the northern part, Kaba Depression on the central part, and Mount Kaba at the southern part
	Ketaun 2	24.5	-	6.8	-	There is continuity of the fault line of this segment seen from the straightness and bend of the river in the southeastern part of Mt. Kaba, most of the fault traces are covered by Quaternary volcanic deposits	Mount Kaba
Musi	Musi 1	30.9	*1979 (Ms=6.6) 2017 (Mw 5.1)	7	Dilatational Step Over, 3.7 km width	There are Mt.Hulu Palik and Bukit Daun in the step over area	Depression
	Musi 2	70.5	-	7.4	Dilatational Step Over, 5.8 km width	In the southern step over area there is Mt. Kerinci, in the northern step over area there are Mt. Hulu Palik and Mt. Tiga	Small Depression
Manna	Manna	80.8	*1893 1999 (Mw 5.4)	7.5	Contractional bend	Along the middle part of the fault line there are Miocene Granite Intrusions (western part)	Series of mountain on the east side
Kumering	Kumering 1 (Ranau)	111.5	1985 (Mw 5.1)	7.6	Dilatational Step Over, 1 km width	Mt. Seminung, Mt. Pesagi	Lake Ranau, Mount Pesagi, Mount Seminung
	Kumering 2 (Suoh)	60.25	*1933 (Ms=7.5), *1994 (Mw = 7.0) 1994 (Mw 6.9)	7.3	Dilatational Step Over, 7.5 km width	In the northern part there are two mountains (Mt. Pesagi, Mt. Seminung) where the fault traces are between them until they reach before Lake Ranau. The step over occurred shortly before reaching the lake, it is assumed that the step over occurred due to the presence of volcanoes around the fault line	Lake Suoh (Depression)
Semangko	Semangko 1 (west)	95	*1908 1999 (Mw 6.4)	7.6	Southern tip of Sumatra	In the northern part, stepover occurs, producing Lake Ranau, there are also mountains which produce Quaternary deposits in the surrounding area. Fault passes through oligo-Miocene and Miocene-Pliocene sedimentary lithologies	Northeast facing Fault scarp
	Semangko 2 (east)	114	-	7.7	Dilatational step over	In the central eastern part there is Mount Tanggamus, causing Quaternary deposits to cover the traces of the fault but there is still visible river bending on the slopes facing southwest. The southern part continues to the East Graben of Sunda Strait experiencing a releasing bend. Most of the fault traces are under the waters of Semangko Bay	Lake (Pull-apart) at the north end result of a step over. Extends beneath the waters of Semangko Bay
Sunda	Sunda	~100	W 1998 (Mw 5.6) E 2002 (Mw 6.1)	7.6	Submarine Forearc	Pull-apart Sunda	Scarp (Graben)

*Source : Sieh and Natawidjaja (2000)

Empirical calculation : Mw = 5.16 + 1.12 x log10(SRL)

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Segment Rupture and Magnitude Potential

We have divided 14 fault Segments, almost all of the Segments are bounded by a step over, a few Segment by fault bends and discontinuities. The boundary of this Segment is generally the place where earthquakes occur (rupture) so that it becomes the rupture boundary of the earthquake itself. If we look at the presence of earthquakes that appear at Segment boundaries in the form of step overs, this is related to the width of the step over itself. The wider the step over, the more rupture will occur in that zone, meaning that a wide (mature) step over will terminate the rupture of a Segment.

We estimate the potential magnitude for the earthquake using an empirical relationship between surface rupture length and magnitude from Wells and Coppersmith (1994). The calculation is based on the observed length on land, some fault traces disappear when cross the coastline. Because of this, the fault trace may continue offshore, this condition include on our calculation. All the fault in Sumatran Fault System have strike-slip movement so the writer use same formula to each Segment.

All active faults have a average potential earthquake equal to 7.4 Mw (Table 1.). Largest potential magnitude of Mw 7.6-7.7 is attributted to the Semangko Segment if all Segments rupture simultaneously. The most active Segment based on the earthquake occurrence is Kumering Segment. This Segment have potential earthquake from 7.3 Mw to 7.6 Mw. Rupture history in this Segment occurred on 1994 (6.9 Mw) and on 1999 (6.4 Mw). If all Segments of Kumering rupture it will cause earthquake with more than 7.0 Mw.

CONCLUSION

Acive structures on land in Southern Sumatra have been mapped using DEMNAS. Features that appear in the form of step over, fault bend, and discontinuity are features that divide fault Segmentation. The writer identified 14 active fault on land in the Southern Sumatra most of the Segment bounded by step over and fault bend. A number of earthquake rupture occurred on the step over zone (Segment boundary), this shows a relation between the earthquake rupture and the Segment boundary. The active structure of Southern Sumatra capable generating earthquakes with a magnitude of 6.8 Mw to 7.7 Mw. The Semangko Segment possesses the largest seismic potential in the region.

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