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Updating active fault maps and sliprates along the Sumatran Fault Zone, Indonesia

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Abstract. The accuracy of active fault map, slip rate and its seismic parameters is crucial for seismic hazard analysis. Fault maps, segmentations and slip rates of the Sumatran Fault Zone (SFZ) have been revised in relation with ongoing activities for updating Indonesian seismic hazard map. In the northern part, several secondary fault strands in the eastern side of the main SFZ are added, including the Pidie, Biruen, Lhok-Sumawe, Peusangan, and Oreng faults. The Batee fault is now considered active. In the southern part, from Suoh pull-apart graben, SFZ branches into two major strands: the west and east Semangko fault segments. Toward south, the west and east Semangko faults are connected with series of marine grabens in the Sunda Strait, forming a 70-km-wide pull-apart structure that is bounded by SFZ and the Ujung Kulon fault, which carries SFZ dextral movement further south into southwest of Java island. Previously, slip rates along SFZ are considered increasing northward from about 5 mm/yr in Sunda Strait to 30 mm/yr in Toba Area. Consequently, fore arc region was thought to be stretched. Nowadays, according to the latest geological and GPS studies, slip rates appear to be more constant at ~15 mm/yr. The total amount of parallel-SFZ extension on the Sunda-strait marine grabens is estimated to be about 18.7 km, almost identical with the largest geomorphic offset along SFZ. In assumption, the SFZ onset since 2 Ma indicates a slip rate of about 9 mm/yr in Sunda Strait. New slip rate measurement near Lake Ranau yields 8-12 mm/yr. Revised slip-rate measurements in both Lake Maninjau and Lake Toba yield about similar rates, ~14-15 mm/yr. Thus, Sumatran fore-arc acts move northward along SFZ, which is more like a rigid block instead of much stretched.

1. Introduction

The 1900-km long NW-SE trending SFZ traverses the back-bone of Sumatra, within or near the active volcanic arc, bisecting Bukit Barisan, Sumatran mountainous range [1-4]. SFZ is a major dextral strike-slip fault zone that accommodates component of the oblique plate convergence between the converging India-Australian oceanic plate and the overriding Sumatran-Eurasian continental plate [1] (Figure 1 inset). At its northern terminus, SFZ transforms into the spreading centers of the Andaman Sea [5,6], and at its southern terminus, SFZ seems to end in the Sunda Strait, where the fault radiates toward the Sunda trench [3,7-12]. As the subduction front swings clockwise northward along with the increase in relative plate motions, the rate of dextral slip along SFZ has been postulated to also increase to the north [3,7,9,13].

Numerous destructive earthquakes have occurred along the fault zone in the history and instrumental records, including the recent 2007 and 2009 earthquake events around Lake Singkarak and Lake Kerinci.

On average, a major earthquake occurred once along the 1900-km long SFZ in every 5-year. From earthquake-mechanic point of view as well as historical earthquake data, fault segmentations seem to constraint the rupture lengths of these past major earthquakes along the Sumatran fault. Therefore, revising and updating active fault lines and their segmentations as well as slip rates are crucial for seismic hazard assessments. This paper discusses the latest studies on SFZ. This study is a part of activities to revise the Indonesian seismic hazard map that has been previously developed, and it was published by the national team in 2010 and then was incorporated in the SNI 1726 –2012 [14].

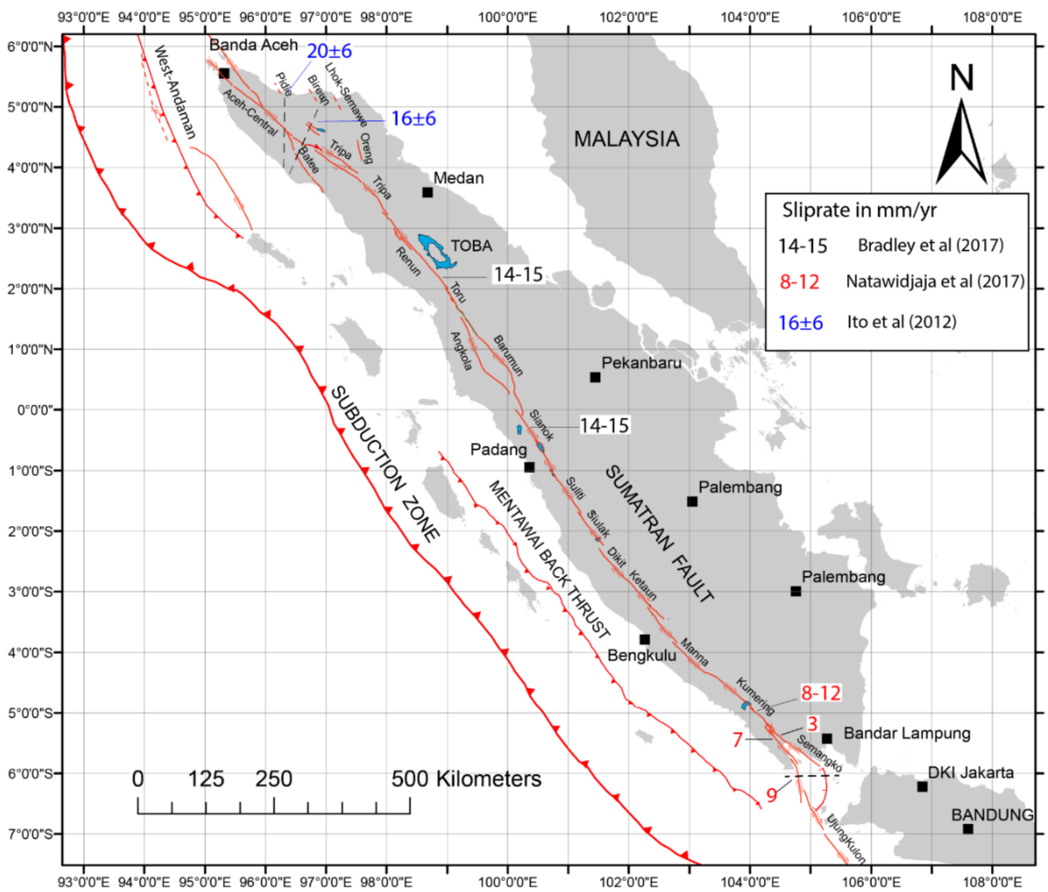

Figure 1. New revised (simplified) active fault map of the Sumatran Fault Zone (SFZ) according to the PuSGeN Team for Updating Indonesia Seismic Hazard Map (2016) with new slip rates from geological and geodetical (GPS) recent studies.

2. Previous Map and Slip-rates of Sumatran Fault Zone (SFZ)

The Sumatran fault zone (SFZ) has been mapped using mostly the 1:100,000-scale aerial photographs and the 1:50,000-scale topographic maps [3]. The results of their work are digitized and put into a GIS database. The map has a large-enough scale to enable discrimination of fault segmentations, so that it can be used for seismic hazard evaluation. It shows that SFZ is highly segmented, and it consists of 20 major geometrically defined segments, which varies in length from about 35 to 200 km separated by major fault discontinuities, mostly dilational jogs which are expressed as valleys and lakes. These segment lengths influence seismic source dimensions and have limited the magnitudes of large historical fault ruptures to between Mw 6.5 and about 7.7 [15].

Geological slip rates of the Sumatran fault have been measured in three locations [3]. From the southern part, at about 3.6 S on the western flank of Kaba Volcano, they are measured ~ 600 meters offset of the Musi river that flows on the ~60,000 years-old lava. The geological slip rates at this latitude, then, is ~10 mm/year (Figure.2). Near the Equator, the Sianok River is offset about 720 meters along the fault line that cuts the thick, ~60,000-year-old Maninjau tuff deposits. The geological slip rate here then is about 11 mm/year. On about 2N latitude, several streams of the Renun River are offset dextrally about 2 km along the Sumatran fault segment that cuts the 70,000 years-old Toba tuff on the western side of Lake Toba. They use this evidence to determine a slip rate in this location, which is about 27 mm/year. These geological slip rates have been published [15-17].

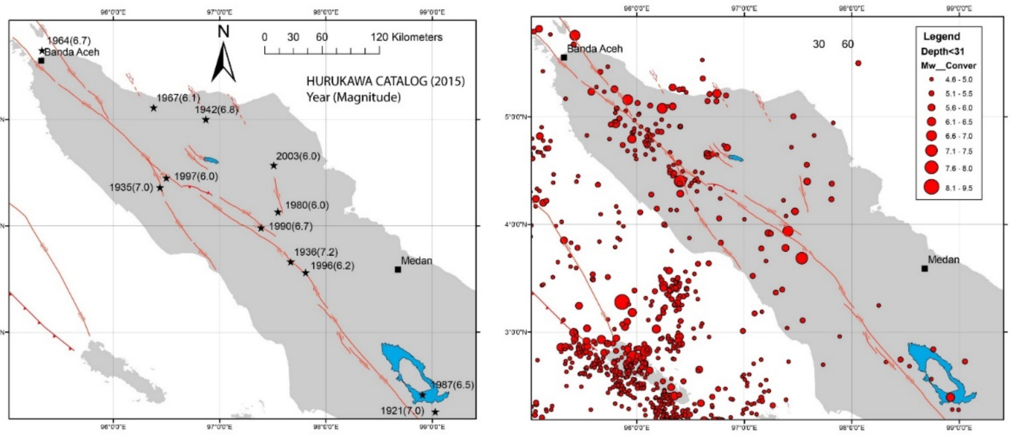

Figure 2. (A) Latest knowledge of historical large earthquakes Revised in the North Sumatra and Aceh region (Hurukawa et al 2015) and recent large earthquakes. (B) Data of instrumental seismicity in the North Sumatra and Aceh region based on the PuSGeN Catalog 2016.

Geological slip rates around Lake Toba have also been measured using similar method, but the result is slightly different, which is about 23 mm/yr [18]. Slip rates in few locations have been estimated using the principle that offset stream's age is linearly related to its length upstream from the fault [8]. Then they calibrate this relationship with one location (i.e. Toba) that has good offsets and known age of underlying geological unit, but these values are considered less reliable [19].

Fault slip rates have been determined in several locations from their GPS survey-mode study [20,21]. Their GPS slip rate values at 2.7°N, 2.2°N, 1.3°N, 0.6°N, 0.4°S, 0.8°S are 26 ± 2 mm/yr, 24 ± 1 mm/yr, 24 ± 2 mm/yr, 23 ± 2 mm/yr, 23 ± 3 mm/yr, 23 ± 5 mm/yr respectively. The GPS slip rate at latitude ~2°N is about similar to the geological slip; but at latitude ~0.8°S in Bukit Tinggi area, the slip rate deducted from the GPS measurements is about twice as much as that of geological slip rate. Hence, further study is required to resolve this discrepancy.

A right-laterally offset about 2.5 km along the Sumatran fault on the south side of Lake Ranau has been proposed [22]. Hence, based on their K-Ar dating of plagioclase of the Ranau Tuff that yielded an average age of 0.55 ± 0.15 Ma, and assuming those geomorphic features were formed right after the paroxysmal eruption of Ranau Tuff blanketed the old topography, they estimated a slip rate of 5.5 ± 1.9 mm/yr for the Kumering Fault (or they called it as the Ranau-Suoh fault). However, this measurement has fatal mistakes on both the dating and their interpreted offset [23].

In general, previous measurements of slip rates indicated that the SFZ slip rates increased from about 6 mm/yr in the southern-end to 27 mm/yr at Toba, and in the northernmost-end the rate of opening across the Andaman spreading centers has averaged about 38 mm/yr for the past 10 million years [5,6]. Thus, it appears to confirm the postulate that slip rates increase due to clock-wise rotation of the subduction trench. Moreover, slip rates increasing northward, the overriding plate, called 'fore-arc sliver-plate', sandwiched between SFZ and the trench, shall be stretched [24] or shall be accommodated by other structures, such as by deformation in back-arc region [8].

Below, we will briefly discuss latest studies on detailed mapping along SFZ and new geological slip-rates based on stream offset analysis near Toba, Maninjau, and Ranau Lakes. Having accurate fault

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locations and their segmentations as well as their slip rate values is crucial for understanding fault kinematics and for assessing seismic hazard.

3. Updating SFZ Fault Map and Slip-rates

In the past two years, based on current availability of modern digital elevation maps of SRTM-30m and TERRASAR World-30m data, coupled with high-resolution satellite images, I relocated previously identified active fault strands and identified new fault strands to update the Sieh and Natawidjaja's map. New fault strands are particularly mapped in the northern and southern parts of SFZ which runs toward the Andaman spreading center and the Sunda Strait grabens respectively. The new map of Sumatran fault zone is presented in Figure 1.

3.1 Revised active fault map

The SFZ map that has been significantly revised is of the northern and the southern parts. In the northern part of Sumatra, Renun – Tripa segments of SFZ run along the west side of Lake Toba toward north and make a compressive bend before it merges with the Batee fault ascending from the west coast line (Figure 2). Previously, in Sieh and Natawidjaja [3] as well as in the 2010 Indonesian PSHA map, the Batee fault was not taken into account since it was previously considered not active. Recent data and analysis indicate conversed situation [25].

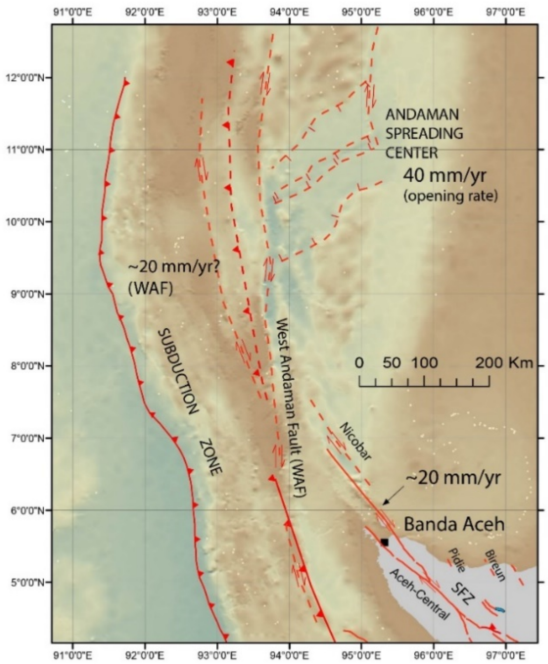

Figure 3. Simplified active fault map in the northernmost of the SFZ for the purpose of seismic hazard analysis.

In the past few years, two destructive earthquakes occurred not in the known Sumatran main fault strands but in the region east of SFZ. The first is the M6.4 earthquakes occurring near Lake Lot Tawar on 2 July 2013 (M6.2) on a 30-km fault segment which was previously unmapped. Now, it is called the Peusangan Fault (Figure 3). The second is the M6.5 event which devastated Pidie town, Aceh on 6 December 2016. This earthquake ruptured a few tens of fault trending NW-SE with a right-lateral strike-slip movement as indicated by aftershock region and focal mechanisms, which is now known as Pidie fault (Figure 2A). These two recent events give a new insight to the unmapped active fault strands in the eastern region. Furthermore, inspections of morphotectonics on SRTM-30, historical earthquakes,

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and seismicity of the region indicate that there are two more fault strands to the east from the Pidie fault, namely the Bireun and Lhok-Sumawe faults. Broad seismicity of shallow earthquakes in the east of the SFZ main fault zones (i.e. Renun-Tripa-Seulawah-Aceh) highlight the existence of these secondary fault strands (Figure 2B). Looking at some historical data, the Pidie earthquake in 2016 is not the first one in this region in the historical time. There was an M6.1 in 1967 near Pidie, and there was a M6.8 in 1942 around Bireun fault strand (Figure.2A).

In the northernmost Sumatra, the Aceh fault segment runs through the west side of Banda Aceh and its activity seems to die out northward as the dextral movement is transferred, right step, on to the Seulawah fault segment that runs north bisecting the Weh Island. Therefore, the wide plain of Aceh is actually a pull-apart basin of these two major segments. From Weh Island, the movement is along the Seulawah segment and it continues to the Nicobar fault segment through a similar extensional stepover structures, and then it merges with the WAF zone before going into the Andaman spreading center (Figure.3). Mapping these sub-marine active faults was made possible by high-resolution bathymetry and many seismic-reflection profiles from marine-geophysical cruises. The west Andaman fault (WAF) zone runs from around northern Simelue Island toward the Andaman spreading center. WAF is a complicated fault zone that has strike-slip and thrust fault components. From the Andaman Spreading center, the SFZ dextral movement then is transferred northward to the Sagaing fault zone that goes north bisecting the Thailand Peninsula.

In the southern part of SFZ, the Kumering segment bisecting Lake Ranau ends in the south at the 10-km wide ellipsoidal Suoh pull-apart basin (Figure 4). Suoh is an active geothermal field consisting of few active maar lakes, fumaroles and hot springs on its northwestern part of the basin. Two weeks after the 1933 earthquake events, there was a big phreatic eruption from Suoh [26]. During the 1994 Liwa earthquake, there was a sudden increase in geothermal activities including some phreatic eruptions in Suoh, which appears to be at the south-end of the 1994 Liwa earthquake's rupture [27,28].

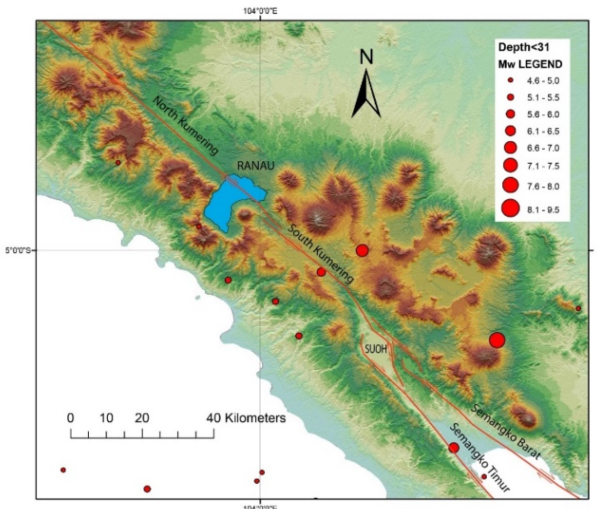

Figure 4. Revised (simplified) active fault map in the Southern Sumatra and Lampung region.

From Suoh toward south, SFZ branches into two major strands, namely the west Semangko and the east Semangko fault segments. The west Semangko fault is previously known as the Semangko fault [3,29] and the East Semangko segment was previously mapped as the North-Semangko fault [29] but it was unmapped in Sieh and Natawidjaja [3]. The west Semangko segment bounds the east side of the Tertiary Baribis mountain ranges and seems to be continued under the sea along the west side of the Semangko Bay, then it radiates into two branches which swing clock wise toward the oceanic trench in the Sunda strait forming a triangular-shape deep marine graben.

The north-end of East Semangko fault is connected with Kumering segment in a rather complicated fashion forming a smaller pull-apart basin than Suoh, named Natarang, on the east side of Suoh (Figure 4). Toward south, the Kota Agung Town, the East Semangko fault gradually loses its expression on alluvial planes, and seems to radiates into few branches which then disappears before reaching the east side of Semangko Bay. These structural radiations are often called horsetail structures that commonly mark the termination of a strike-slip fault zone. However, bathymetry expressions indicate that fault movements have continued along the east side Semangko bay and have ended forming a wide extensional graben marine basin between Semangko Bay and Krakatau volcanic complex (Figure 5). The absence of seismicity and clear geomorphic evidences suggest that the submarine part of east Semangko bay may have become less or in-active presently.

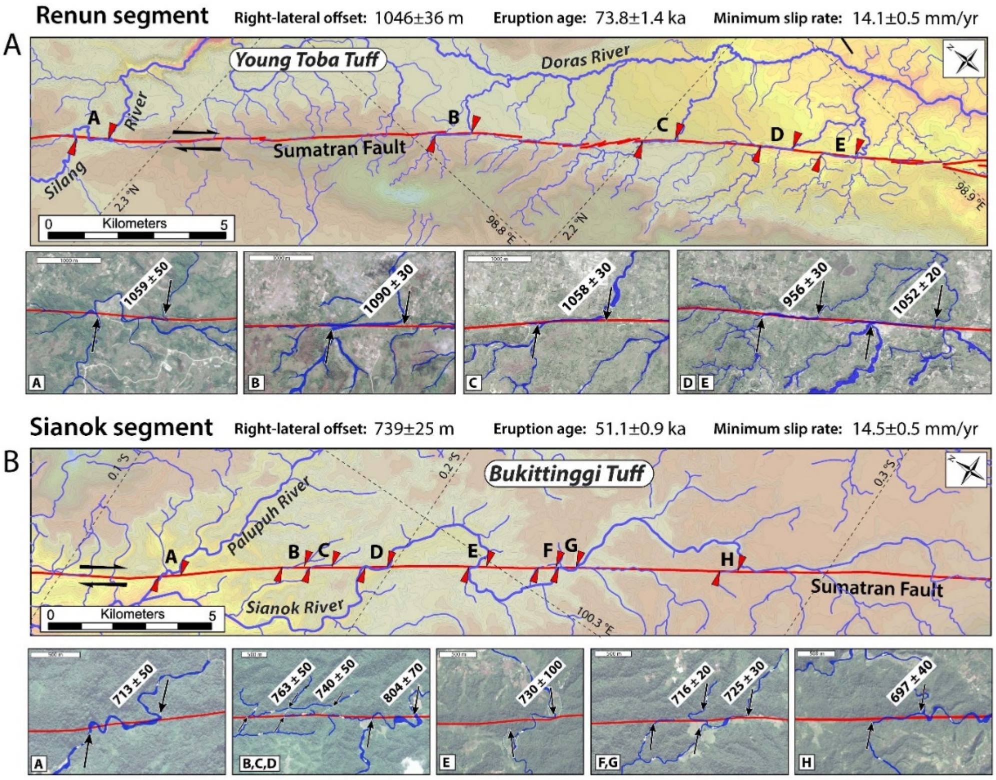

Figure 5. Geological slip-rates measured from lateral offsets of isochronous river channels incising thick homogeneous volcanic tuffs at: A. Renun Segment cutting Toba Tuff near Lake Toba, B. Sianok segment cutting Maninjau Tuff in West Sumatra – Central Sumatra.

3.2 Revised and new slip rates

Bradley et all [19] reevaluated slip rates along SFZ based on multiple offsets of isochronous streams incising Toba tuffs in North Sumatra and Maninjau Tuffs in central/west Sumatra. The results of their measurements yielded that geological slip rates near Lake Toba and Lake Maninjau have nearly similar values, 14 – 15 mm/yr (Figure 5). In other word, slip rates at Sianok valley increase a bit higher, and slip rates near Toba become only half as much as those of the previous study. In south Sumatra, a new measurement on geological slip rates of the Kumering segment in the south of Lake Ranau has been conducted [23]. Their analysis yields about 8 to 12 mm/year, which is twice as much than the previous measurement [2].

Bradley et al [19] also conducted robust geodetic modelling and slip rate analysis for Sumatra region based on continued GPS data from SuGAr and all available campaign-GPS data along with coral uplift rate data (Figure.6). Their detail slip rate analysis at Toba and Maninjau area shows geodetic slip rates of ~15 mm/yr (Figure.7). Hence, these new geodetic slip rates are similar to new geologic slip rates.

In Aceh region, two geodetic slip rate measurements using the AgNess and GPS campaign data have been conducted [30]. Their study revealed geodetic slip rates of 16 ±6 mm/yr from the transect across Aceh fault Segment and 20 ±6mm/yr for the transect across Batee and Tripa segments (Location of transects of measurements are marked in Figure 1). The rate of opening of the Andaman spreading center is about 38 mm/yr [5,6]. So, since the SFZ and WAF are merging toward the spreading center, the slip rate of WAF is possibly about 15 to 20 mm/yr (Figure 3).

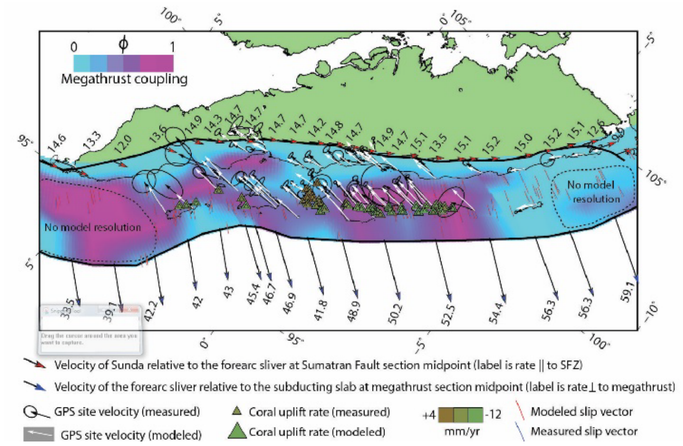

Figure 6. Tectonic modelling based on continuous GPS – SuGAr 9 Sumatran GPS Array) and coral uplift rates [19].

4. SFZ in Sunda Strait

The east and west Semangko faults are both continued south under the sea. Their traces can be seen as linear submarine fresh ridges and scarps. At their southern-end, the faults orientation sways clockwise from southeast to south toward the deep marine trench, forming two graben formations (Figure.8). First, the rectangular-shaped, wide-shallow marine graben reaching the depth of 800 meters is connected to the east Semangko fault inland. This graben is previously mapped as the East Semangko graben by Susilohadi [31]. The deeper graben on the west side reaching 1800 m depth under the sea surface has a triangular shape opening to the trench. This graben is formed at the south-end of the west Semangko fault, named as the West Semangko graben [32]. Their geometry and cross-cutting relationships of the fault traces, as expressed in the ocean floor, suggest that the shallow graben on the east side, connected to the east Semangko fault, had been formed first, then it was consecutively followed by the onset of the triangular-shape deep graben. Hence, this extensional block faulting seems to progress growth clock-wise, in pace with the northward – dextral movements along SFZ.

Most strikingly, these N-S graben structures abut on their south bound on a NW-SE trending dextral strike-slip fault zone that continues to the west side of the most western tip of Java Island and then runs toward Java-Sea trench (Figure. 8), here named as the Ujung Kulon fault. This fault has been previously mapped as (part of) the eastern boundary of the Ujung Kulon fracture zone [33], and it is continued further south to south of Java Sea approaching the subduction front [32]. Fresh linear ridges and fault scarps of the Ujung Kulon fault are clearly depicted on detailed bathymetry acquired during BGR marine expedition [32]. Hence, the array of graben structures at the termination of SFZ is actually a very wide pull-apart stepover that connects SFZ to the relay fault in the south.

Aa analysis of geological data and seismic stratigraphy based on single and multi-channel seismic reflection profiles around the Sunda Strait indicates that the onset of the Semangko graben formation and rapid sedimentation fills graben starting in Upper Miocene or early Pliocene, about 5 Ma [31, 32, 34]. Previous geological study around Sunda Strait also indicated that the extensional tectonic deformation started from about 5 Ma [35]. The thickness of Plio-pleistocene sediments, on the center of west graben based on multi-channel seismic profiles, estimates the thickness of sediments above the Upper Miocene unconformity, which could be up to 1 second TWT or more than 1000 m in both west and east grabens assuming 2200 m/sec seismic velocity. Both east and west grabens are bounded on each side by normal faults. Hence, we can estimate that the amount of throw (fault vertical offset) in the west and east grabens are at least 2700 and 1700 meters, respectively, measured from the water depth on the top edges of graben to the Upper Miocene unconformity or the top of the basement beneath the graben floors.

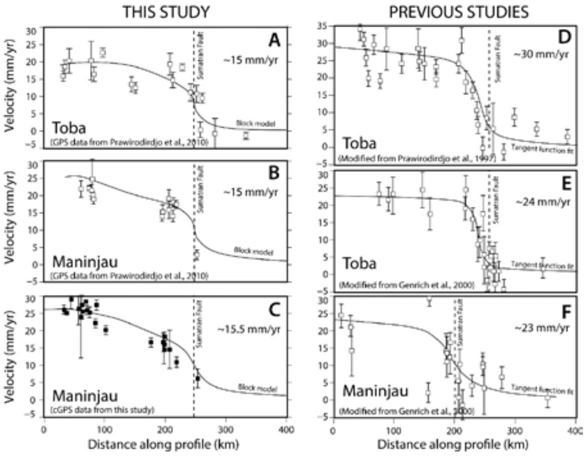

Figure 7. Comparison of GPS velocity profiles across the Sumatran fore arc inferred from (left) kinematic block models (right) with previously published velocity profiles. Modeling all fore-arc site velocities with a single strike-slip fault results in anomalously high inferred slip-rates (>22mm/yr) and missing the Sumatran Fault trace by up to 40km. Incorporating the effect of oblique locking of the Sunda megathrust results in lower inferred slip - rates for the Sumatran Fault (~15mm/yr) that are more consistent with updated geological slip rates [19].

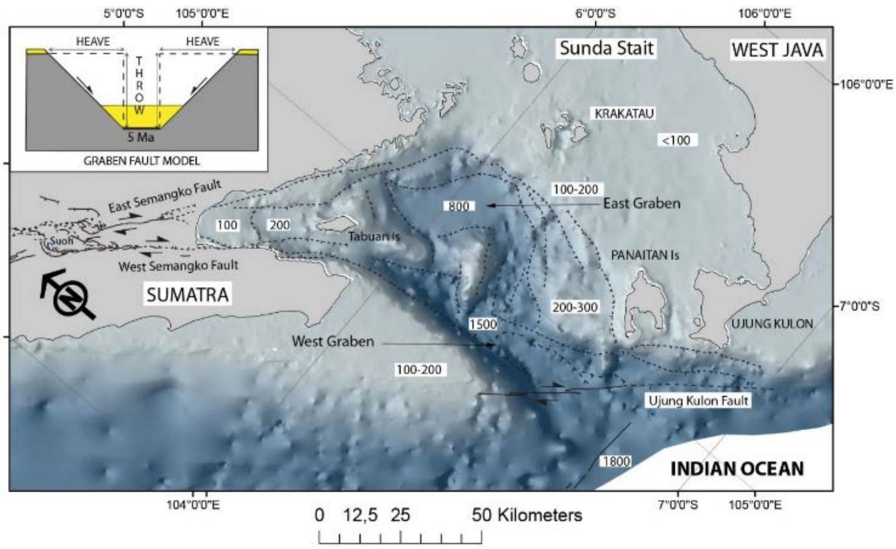

Figure 8. Active fault map in the southern-most part of SFZ in Sunda Strait.

Assuming the fault dips of 45°, we can estimate that the amount of opening (i.e. amount of extension), which is twice of the fault's heave (i.e. equivalent to the fault's throw) (Figure.8 Inset), is at least 5400 meters on the west graben and 3400 meter on the east graben. Thus, the total amount of opening across the east and west Semangko grabens since 5 Ma is at least about 8800 meters or 8.8 km. Susilohadi [32] estimated that the total opening perpendicular to the North-South striking Semangko graben is about 13 km; and it can be translated to the amount of translation along the NW-SE striking SFZ of about 18.7 km. It is almost equivalent to the amount of the largest geomorphic dextral offset, represented by the major-river drainage in North Sumatra, which is about 21 km [3]. Despite the previous seismic stratigraphy, studies suggest that the Semangko grabens were initiated since 5 Ma and were related to the southern-most of SFZ. Sieh and Natawidjaja [3] suggested that the formation of the active SFZ as we see today was only formed since 2 Ma. If we divide the 18.7 km translation related to the grabens opening with 2 Ma, the slip rate on the southern-most-end SFZ connected to the grabens is about 9.3 mm/yr, which is similar to slip rates on the Kumering-Semangko segment inland. Lassal et al. [34] roughly calculated the stretching factor of the tectonic subsidence across the Semangko grabens to be about 3.4 along the SFZ strike or equivalent to about 50 to 70 km opening since 5 Ma. Hence, it suggested the slip rate of about 10 to 14 mm/yr. However, they also observed apparent hiatus between the Upper Miocene conformity (~5 Ma) and sedimentation in Pliocene. Therefore, it is reasonable to suspect that the inferred hiatus was much longer than the previously thought one. It is likely that graben-filling sedimentations after 5Ma were not started until Upper Pliocene (~2 Ma).

5. Summary and Discussions

In summary, the latest studies and new measurements show that slip rates along SFZ do not increase much northward as thought previously, but they are generally constant or nearly so. Slip rate along SFZ in Sunda Strait is estimated to be ~9mm yr, yet similar to the one on Kumering fault in south Sumatra, which is about 8 to 12 mm/yr. Slip rate in central Sumatra (i.e. west Sumatra) near Lake Maninjau is about 14 – 15 mm/yr, and it appears to be constant up to Lake Toba in North Sumatra. To the north, a total slip rate across Batee and Takengon segments in Aceh region is about 16±6 mm/yr, and it becomes 20±6 mm/yr across Aceh segment. Thus, if we use average values with their uncertainty, slip rates along SFZ appear to be generally constant. However, if we take their average values, it may indicate a slight increase of up to a 10 mm/yr from its southernmost in Sunda Strait to its northern part at Aceh region. So, it may still support previous hypothesis about stretching fore-arc sliver but at significantly lower value.

Furthermore, given that the slip rate along SFZ is averaged only about 15 mm/yr and since the rate of opening of the Andaman spreading center that bounds the northern end of the continuation of SFZ is about 38 mm/yr as well as the similar amount of total the trench-parallel plate vector along SFZ, a large amount of trench-parallel slip should be accommodated by mechanisms other than SFZ. The most likely candidate is by oblique slip on the megathrust [19]. In the northernmost part, large parts of the trench-parallel slip may also be accommodated by the NS striking west Andaman dextral fault that runs below the ocean from lat. in Aceh region toward north, merging onto SFZ continuation then ends at Andaman spreading center [36]. In the southernmost end, SFZ does not stop at Sunda Strait but continues further south onto the Ujung Kulon dextral fault, connected through a mega extensional stepover structures, represented by two major pull-apart marine grabens.

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