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Overview and Research Needs to Achieve Improved Understanding of Earthquake Hazards Affecting the Western Sumatra Coast

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Abstract

Natural hazards that are affecting humans are mostly related to geological processes, for example earthquake, volcanic eruption, flooding and landslide. The geological processes itself is a naturally occurring event, it is only become hazardous in the presence of humans as it may cause loss of life and properties. Understanding aspects of geological-related hazards of a region is important to reduce the danger they may pose. Indonesia is located within an active and complicated tectonic setting. Three major tectonic plates: Eurasia, Indo-Australia and Philippine are collide and interact in the vicinity of Indonesia. The mechanism of plate interaction in Indonesia is dominated by subduction, where one plate is subducted beneath the other. The subduction processes are commonly associated with formation of volcanoes as well as active deformation in the crust associated with earthquakes.

Keywords: Natural Hazard, Earthquake, Tsunami

Introduction

The most prominent convergence margin in Indonesia, the Sunda subduction zone stretches from Sumatra, passes along the south shore of Java and Bali and terminated near Flores Island where it is continued by the Banda subduction zone. In Sumatra, the Indo-Australia plate obliquely converge northward and subducted beneath the Eurasian plate. The dip slip component of the oblique convergence motion of the plate is accommodated by the megathrust fault near the trench while the horizontal component is accommodated through a large inland strike slip fault of Sumatran fault (Figure 1, Bradley *et al*., 2017; McCaffrey, 1991, 1992; Sieh dan Natawidjaja, 2000; Fitch, 1990). These two main faulting regions are known to be active and have produced numerous large earthquakes in recent years. The most memorable event along the Sunda megathrust is the 2004 M9.4 Aceh (Indian Ocean) earthquake which was followed by a devastating tsunami. The earthquake and tsunami claimed more than ~280,000 fatalities globally and was considered as one of the deadliest natural disasters in recorded history. Another large earthquake occurred along the subduction interface in 2009, the deep foci of the earthquake sending a long amplitude seismic wave and causing extensive destruction in Padang, killing more than 1000 people. Large earthquakes also frequently occurred along the Sumatran fault, some of the recent ones are the Sianok and Sumani earthquakes in 2007 (Daryono *et al*., 2012; Hermon, 2014). The high seismic activity affecting Sumatra, particularly West Sumatra is of main concern to the government and resident of the heavily populated region.

Development and placement of critical facilities such as school, hospital, and power plants need to consider the geological aspects of the site. One of the most important geohazard aspect that need to be

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considered is earthquake. An earthquake may cause ground deformation (ground break, failure, fissured, subsidence and uplift). Strong vibration from earthquakes may also affecting buildings and other infrastructures, causing them to collapse and fail. Information regarding seismic potential in a developed region is important to minimize the risk.

This writing focuses on the identification of seismic sources as well as research review and updates on the current research and research needs to better understand seismic hazards affecting the West Sumatra coast. First, I will layout the geologic setting and the identification of seismic sources in Sumatra, it will then followed by a wealth review of researches that has been conducted in the area. I will then discuss about current work particularly in West Sumatra, the challenges and provide summary of the research needs.

Geologic Setting of West Sumatra

The Indo-Australia plate is converge northward and subducted beneath the Eurasian plate at a rate of 52-60 mm/year (Bock *et al*., 2003; Prawirodirdjo et al., 2000, McCaffrey, 1991). The convergence is responsible for the development of two main fault zones in Sumatra: the Sunda megathrust and the great Sumatran Fault. These two main fault systems are separated by a narrow crustal fragment (fore-arc sliver) where in Sumatra it encompasses the entire region between the active volcanic arc and the trench (Figure 1; Bradley *et al*., 2017; McCaffrey *et al*., 2000). Understanding how the slip from the convergence being accommodated by these fault systems is important to anticipate their hazard, this has been the subject of many studies (Bradley *et al*., 2017; McCaffrey, 1991, 1992).

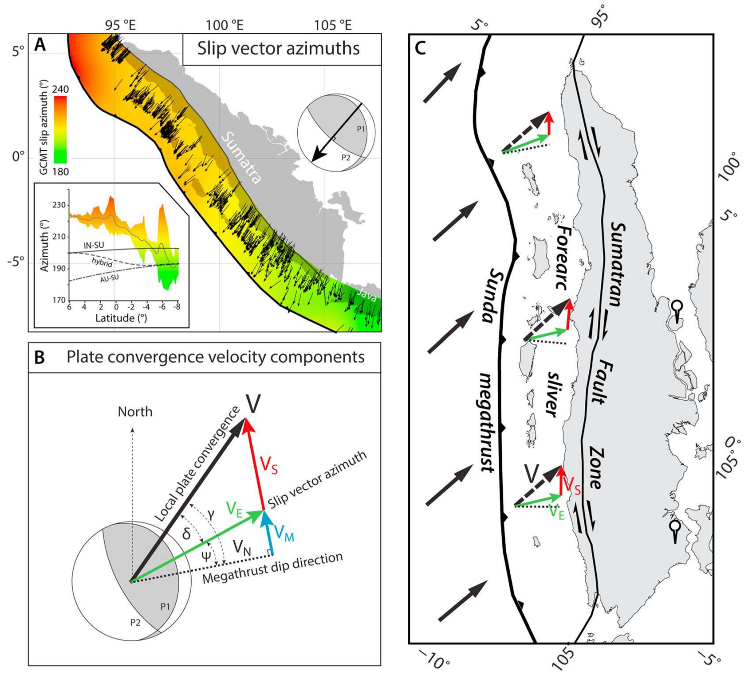

Figure 1. Tectonic configuration and slip partitioning and distribution of Sumatran convergence margin (adapted from Bradley *et al*., 2017). A) Slip vector azimuths of earthquakes are summarized from rupture of the Sunda megathrust or reverse faults within the fore-arc crust and accretionary wedge, the earthquakes were selected from the Global Centroid Moment Tensor catalog (Ekström *et al*., 2012). IN-SU: MORVEL India-Sunda plate convergence by DeMets et al., 2010. AU-SU: MORVEL Australia-Sunda plate convergence. Hybrid model: a nonplate model that smoothly transitions from AU-SU to IN-SU convergence

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between 4°N and 4°S. B) Components of plate convergence velocity (relative to Sunda) in a simply partitioned system and their estimation from focal mechanisms (McCaffrey, 1992). The strike-slip fault parallels the strike of the obliquely slipping megathrust. VS: predicted slip rate of the strike-slip fault; VM: strike-parallel component of convergence velocity accommodated by oblique slip on the megathrust; VE: velocity of underthrusting beneath the fore arc. VN: margin normal convergence velocity. γ: convergence obliquity between the subducting slab and the stationary upper plate. δ: angle between the plate convergence direction and the direction of underthrusting beneath the fore arc. Ψ: obliquity of underthrusting of the oceanic slab beneath the fore arc. C) Map view of a simplified slip partitioning system in Sumatra, in which oblique plate convergence is distributed onto two plate boundary faults: Sunda megathrust and Sumatran fault.

Seismicity and Active Faults of West Sumatra

Sumatra is very active seismically, the distribution of earthquakes in Sumatra is illustrated in Figure 2. Large earthquakes in Sumatra is dominated by thrust faulting from the megathrust while the inland faults deformation is dominated by strike slip events. Occasionally, intra-slab events may occur, one of such event is the 2009 Padang earthquake (Shiddiqi, 2015). Large offshore thrust faulting events may cause tsunami affecting the lowland region.

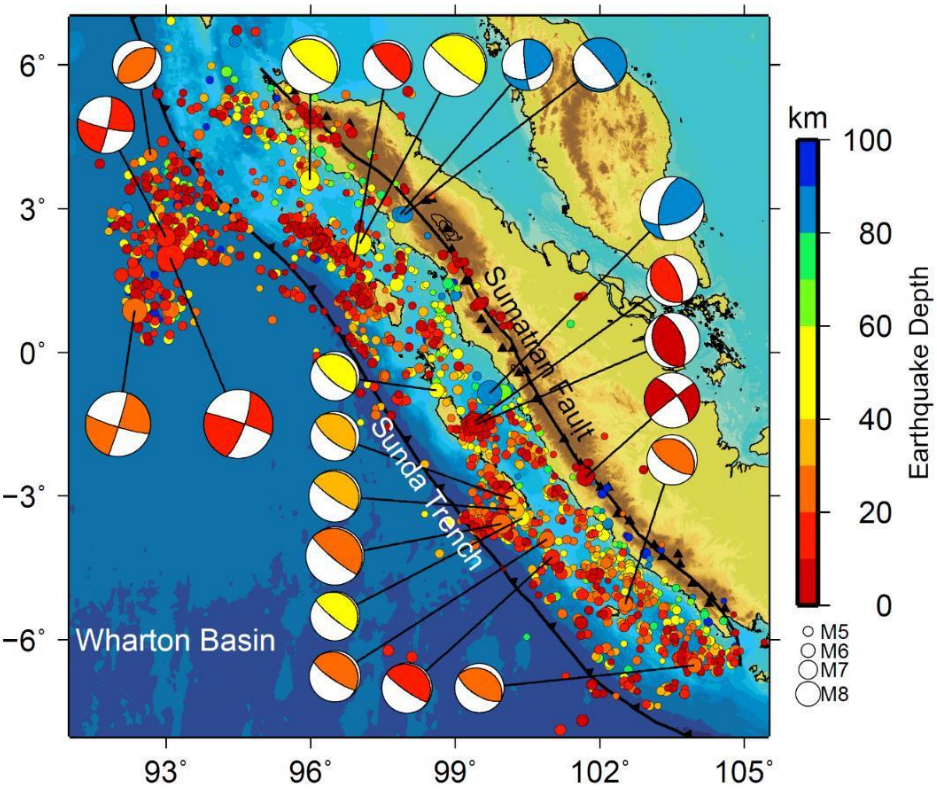

Figure 2. Map of relocated seismicity of Sumatran earthquakes with magnitude larger than 4.0 (Team for Updating of Seismic Hazard Maps of Indonesia, 2017), the beachball diagram is focal mechanism of events larger than 6.0 adapted from the Global Centroid Moment Tensor (GCMT) (Dziewonski *et al.*, 1981; Ekström *et al.*, 2012; Shiddiqi, 2015).

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Offshore earthquake source: Sunda Megathrust

The Sunda Megathrust consist of several fault segments, the closest one to West Sumatra region is the Mentawai segment, which located at the southernmost of the fault zone (Figure 3, Sieh *et al*., 2008; Chlieh *et al*., 2007; Briggs *et al*., 2006; Natawidjaja *et al*., 2004; Konca *et al*., 2008). The 700 km long fault segment is forming the island chain of Siberut, Sipura, and North and South Pagai islands. Some of notable earthquakes along this segment including the M7.9 in 2000, a M7.9 in 2007 and the most recent one M7.7 in 2010. Two great earthquakes occurred in 1797 and 1833 with magnitude of 8.4 and 9.0 respectively. Figure 3 show the extent of rupture caused by each of these earthquake events (Sieh *et al*., 2008; Meltzner *et al*., 2012a; Meltzner *et al*., 2012b).

The deformation in the region of Mentawai fault segment has been modeled by several researcher using coral and instrumental geodetic data (Sieh *et al*., 2008; Chlieh *et al*., 2007; Natawidjaja *et al*., 2007). Their studies indicate that most of the Mentawai fault segment have been highly coupled (the overlying and underlying blocks were locked together) since at least in the past 50 years and strains continue to accumulate. Sieh *et a*l. (2008) investigating records of relative sea-level change from corals of the Mentawai islands, their study imply that this fault segment generated broadly similar sequences of great earthquakes every 200 years for at least the past 700 years. The 2007, portions of the Mentawai patch broke in a M8.4 earthquake, but the large portion of the fault remained unbroken. Sieh et al. (2008) stated a concern that the remaining unbroken Mentawai segment will rupture soon given that it had been dormant since two great earthquakes in 1797 and 1833 (Figure 4). The 2010 earthquake event also released only some portion of the accumulated strain the fault and the Mentawai segment still carrying a potential of producing earthquake in the near future, probably within the next several decades.

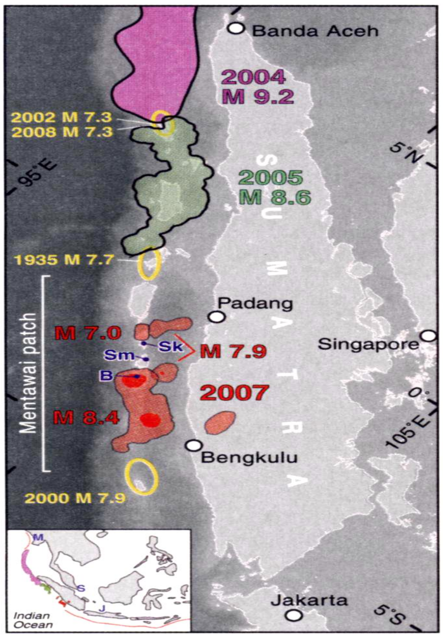

Figure 3. Recent seismic ruptures of the Sunda megathrust offshore of Sumatra, delineate highly coupled large (pink, green, and orange) and weakly coupled small (yellow) patches (adapted from Sieh et al., 2008). The September 2007 earthquake sequence involved partial rupture of the Mentawai patch, which last broke in 1797 and 1833. B (Bulasat), Sm (Simanganya), and Sk (Sikici) indicate principal paleoseismic sites by Sieh et al., 2008.

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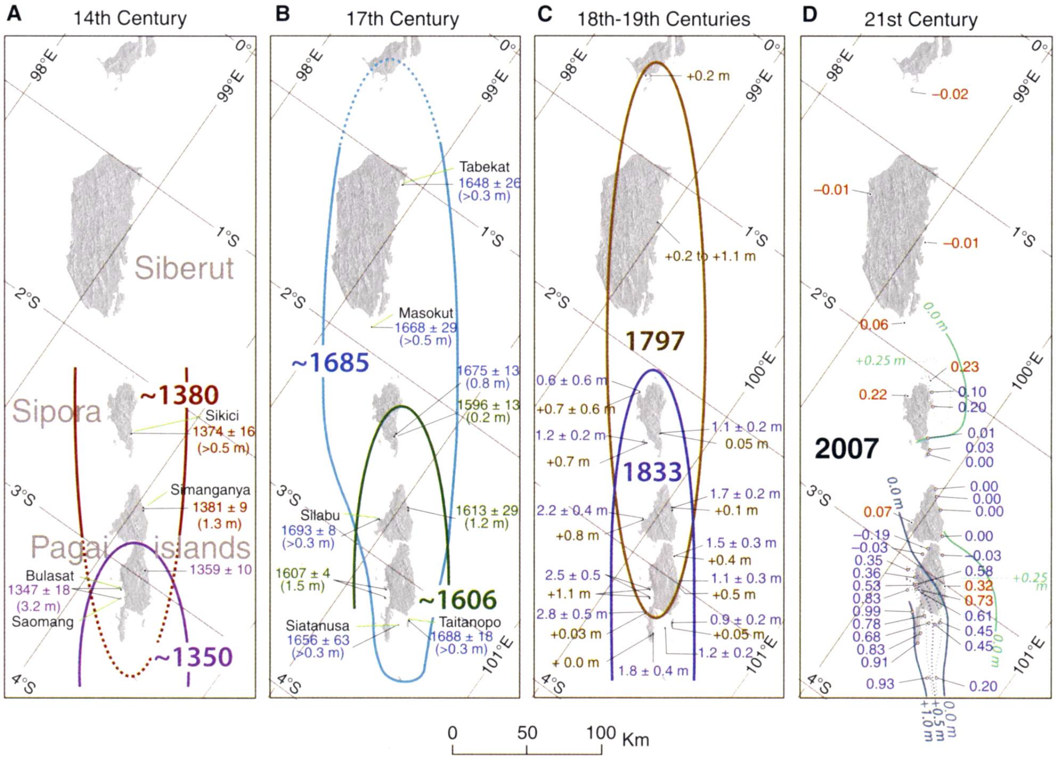

Figure 4. Four emergence episodes of the past seven centuries using paleogeodetic indicator of coral growth (adapted from Sieh *et al*., 2008). Each episode consists of more than one major event (A and B) Emergence amounts are below the year of emergence (±2σ); colors indicate proposed event correlations. (C) Emergences attributed to the 1797 and 1833 earthquakes are brown and blue, respectively. (D) Uplift values for the 12 to 13 September 2007 sequence are red (GPS) and blue (coral). Contours of uplift in blue and green show the amounts attributable to the /Ww 8.4 and Mw 7.9 events, respectively (SOM, including table SI). The 2007 events probably herald the beginning of the next failure sequence

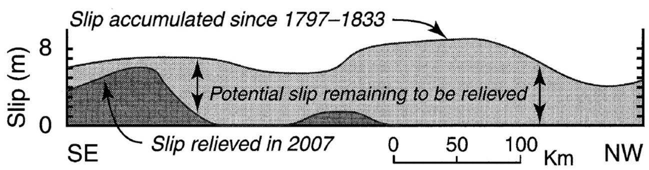

Figure 5. Diagram showing the comparison of slip during the 2007 events and remaining potential slip on the Mentawai segment of the Sunda megathrust (adapted from Sieh *et al*., 2008). The long axis is parallel to and through the Mentawai island chain.

Inland earthquake sources: Sianok and Sumani segments of Sumatran Fault

The Sumatra fault in is easily recognized through the prominent topography of Bukit Barisan. Although the existence of this fault has been known since the 1960, due to the dense vegetative cover and inaccessibility, there are only few detailed mapping of the fault prior to 2000. In 2000, Sieh and Natawidjaja released a detailed map of the fault based on geomorphological mapping methods. The 1900 km-long Sumatra fault is consist of 20 fault segments with their length ranging from 35 to 200 km (Sieh and Natawidjaja, 2000). These fault segments are (from north to south): Aceh, Seulimeum, Batee, Tripa, Renun, Toru, Angkola, Barumun, Sumpur, Sianok, Sumani, Suliti, Siulak, Dikit, Ketaun, Musi, Manna, Kumering,

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Semangko, and Sunda (Figure 6). Fault segments that are closer to West Sumatra region are Sianok and Sumani segments. With the slip rates ranges from 10 to 27mm/yr, the Sumatran Fault Zone (SFZ) is classified as a highly active fault. Using known slip rate of fault segments, a fixed depth of seismogenic zone of 15 km, and recurrence interval of 100-200 years, and assumption that the fault segments are entirely locked, Natawidjaja and Triyoso (2010) estimated the accumulated strain for each segments of the SFZ. Their result suggest that in average, the accumulated strains in each segments of the SFZ for every 100 years are equivalent to strain released for earthquakes range of Mw 7.2 - 7.4 while for a 200 years recurrence, the magnitude range increase to Mw 7.4-Mw 7.7.

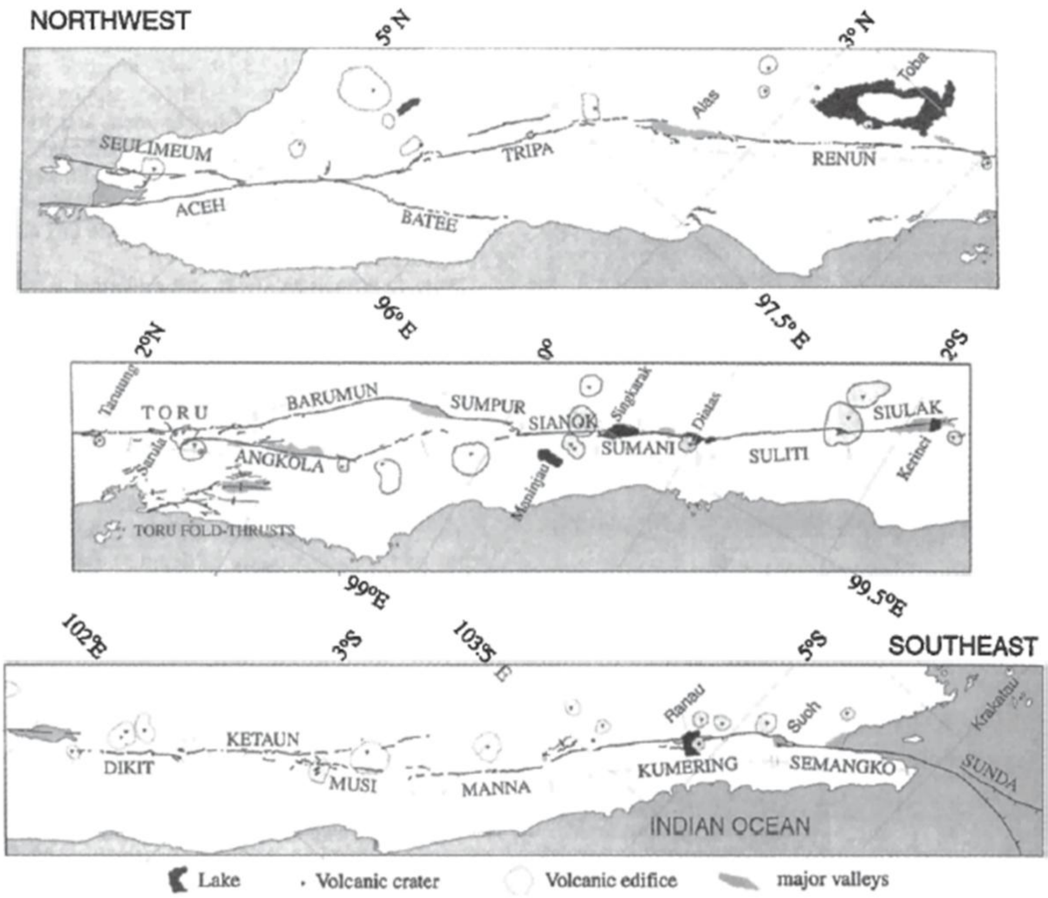

Figure 6. Map of 20 fault segments of the Sumatran faults system
(adapted from Sieh and Natawidjaja, 2000)

The Sumani segment is a 60-km long segment that runs northwestward from the volcanic terrane of Lake Diatas to the southwestern flank of Lake Singkarak (Sieh and Natawidjaja, 2000; Figure 6). The fault consist of two opposing arcuate normal oblique faults, forming a 400 m high topographic scarps (Sieh and Natawidjaja, 2000). Two large earthquakes occurred along this fault segment in recent years: the M7.4 earthquake in 1943 and in 1926 (Pacheco and Sykes, 1992; Natawidjaja *et al*., 1995). The shaking intensities of the 1943 event indicate that the rupture was terminated below the Singkarak Lake at the northwest. Natawidjaja *et al*. (1995) suggests ~1m right lateral offset of this event. Another earthquake also occurred in 1822, this event caused severe damage in area between Marapi and Talang volcanoes (Visser, 1927), suggesting rupture along the Sumani segment. The strain accumulation during early to mid-1990s was

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estimated by Genrich *et al*. (2000) using GPS data is consistent with 23 ±5 mm/yr of dextral slip along Sumani fault segment.

The relatively straight and continuous Sianok fault segment runs -90 km from the northeast shore of Lake Singkarak, continuous along the southwest flank of Marapi and terminated at a 10-km wide right step over at the equator (Figure 6). This fault segment cut through the flank of Marapi volcano and the young pyroclastic flow deposit of Maninjou volcano. Using the age of the tuff deposit that were deflected by the fault, Sieh and Natawidjaja (2000) determined a dextral slip of 11 mm/yr. Bradley *et al*. (2017) recalculated the slip rate estimation of the Sianok segment by measuring the offset of Bukittinggi tuff, which was erupted during the formation of Maninjau caldera, using a higher resolution topographic data. Adopting eruption age of 51.1±0.9 ka and ~736m lateral offset, they calculate a slip rate of 14.5±0.5 mm/yr (Figure 7).

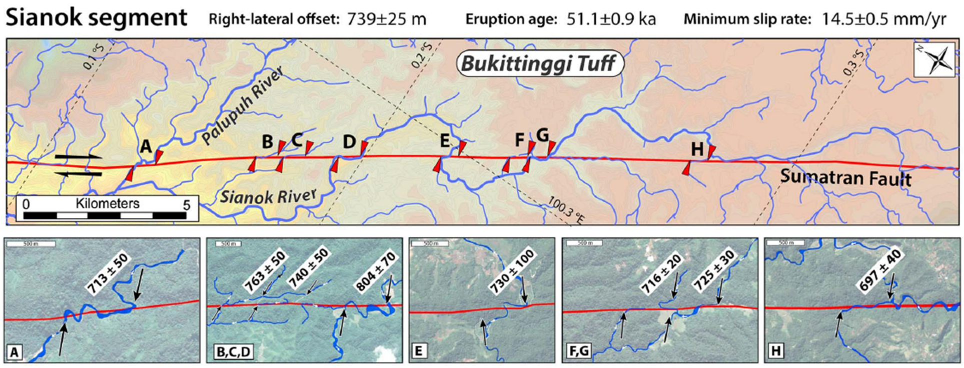

Figure 7. Geological slip rates estimated from measuring the systematic lateral offset of river channels along the Sianok segment, the closest Sumatran fault segment to West Sumatra (adapted from Bradley *et al*., 2017). Refer to Figure 6 for estimate locations. The measured channels incised into thick caldera tuffs from Toba volcanic eruption and used to estimate of the average slip rate since the eruption. Channel offsets are labeled in meters, with uncertainties estimated from the width of the laterally offset feature. The minimum slip rate of the Sianok segment (14.5±0.5 mm/yr).

Earthquake and Tsunami Hazard Assessment of West Sumatra

The first step to evaluating seismic hazard of an area is determining the potential for damaging earthquakes by identifying any active or potentially active faults and reviewing their seismic history (Marliyani, 2016; Blair *et al*., 1979). In this regard, information about the last earthquake event on a fault is important to estimate how much energy has been accumulated. In certain degree, the seismic hazard can be defined as the ground-response hazard associated with earthquakes. This will then lead to the development of seismic risk assessment.

Earthquake hazards are classified into two categories: primary and secondary. Primary effects are hazards that are directly associated with surface faulting and ground motion while secondary effects are hazard that are triggered by the ground motion (these include landslides, liquefactions, and tsunami). Seismic hazard assessment usually prioritize the primary earthquake hazards as they usually causing the largest numbers of damage and casualties. Some exceptional events, for example, tsunami, caused by large vertical displacement of the ocean floor, may cause greater loss than their primary effects. This has been the case of Aceh earthquake and tsunami in 2004.

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Earthquake hazard assessment

There are two different approaches in Seismic Hazard Analysis: the deterministic seismic hazard assessment (DSHA) and probabilistic seismic hazard assessments (PSHA) (Frankel *et al*., 1996, 2002, 2004). The DSHA estimate possible range value of shaking affecting the strength of built constructions. This assessment is time-independent with only consider the worst-case scenario. Meanwhile, the PSHA using probabilistic approaches, which basically mathematical procedures to sum-up the contribution of all seismic sources to the shaking level in certain region within certain period of time (Frankel *et al*., 1996, 2002, 2004; Campbell, 1981, 2003). This particularly useful to adjust the lifetime hazard estimate of built construction. Both methods requires a thorough and accurate data of active faults and earthquake source parameters (fault geometry, their maximum magnitudes, slip rate, historical and paleoseismic record and recurrence interval).

The DSHA describe the probability of range values of shaking, these parameters is described in the term of Peak Ground Acceleration (PGA), velocity (PGV), and ground displacement at a site caused by a specified seismic source. The possible ground motion caused by an earthquake event is calculated using attenuation relationship. The attenuation relationship is a function of earthquake magnitude, distance of the seismic source to the site, and the lithological condition along the seismic path and around the site (Frankel *et al*., 1996, 2002, 2004; Campbell, 1981, 2003).

The PSHA estimate the probable annual shaking by summing the probability of rate function of each specified seismic source around the site. In PSHA, the result is presented as a map describing the likelihood of earthquake occurrences or exceedance of specific parameters (PGA or PGV) during a specified time (Yeats *et al*., 1997; Campbell, 1981, 2003). The probabilistic approaches used in the PSHA calculation are basically mathematical procedures to sum-up the contribution of all seismic sources to the shaking level in certain sites/areas for certain period of time.

A team for updating of seismic hazard maps of Indonesia was established in 2015 (Tim Pusat Studi Gempa Nasional, 2017). The main task of the working group is to deliver an updated map of seismic hazard map of Indonesia. The report is finalized in September 2017. The newly released report provide the most up to date seismic hazards maps of Indonesia region (Figure 8-12) and has been approved by the Ministry of Public Work and Housing as the official guide map to establish the National Standard of Indonesia for construction and development.

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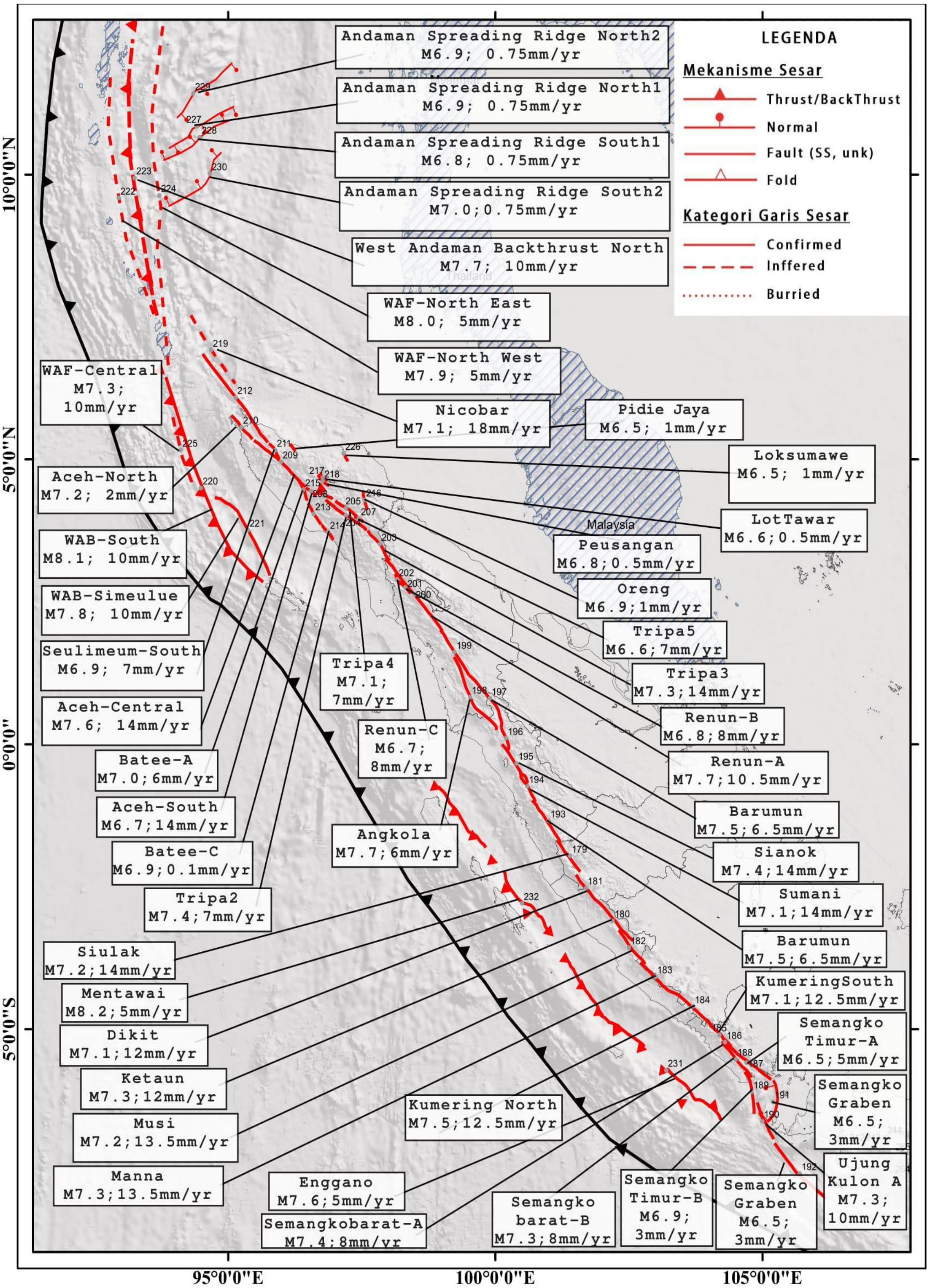

Figure 8. The seismic sources Sumatra region and their attributed slip rate listed in the Earthquake Source and Hazard Map of Indonesia (Tim Pusat Studi Gempa Nasional, 2017)

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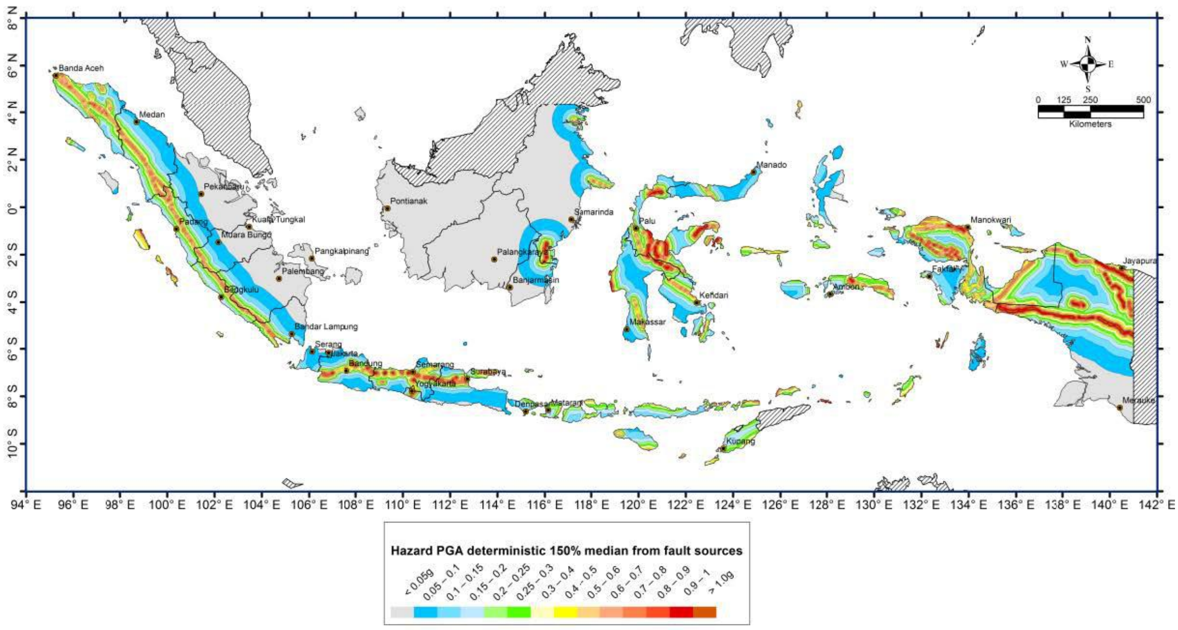

Figure 9. Peak Ground Acceleration (PGA) deterministic seismic hazard map of Indonesia region from inland shallow faults with 84 percentile (150% median), warmer color represent higher seismic hazard (Tim Pusat Studi Gempa Nasional, 2017).

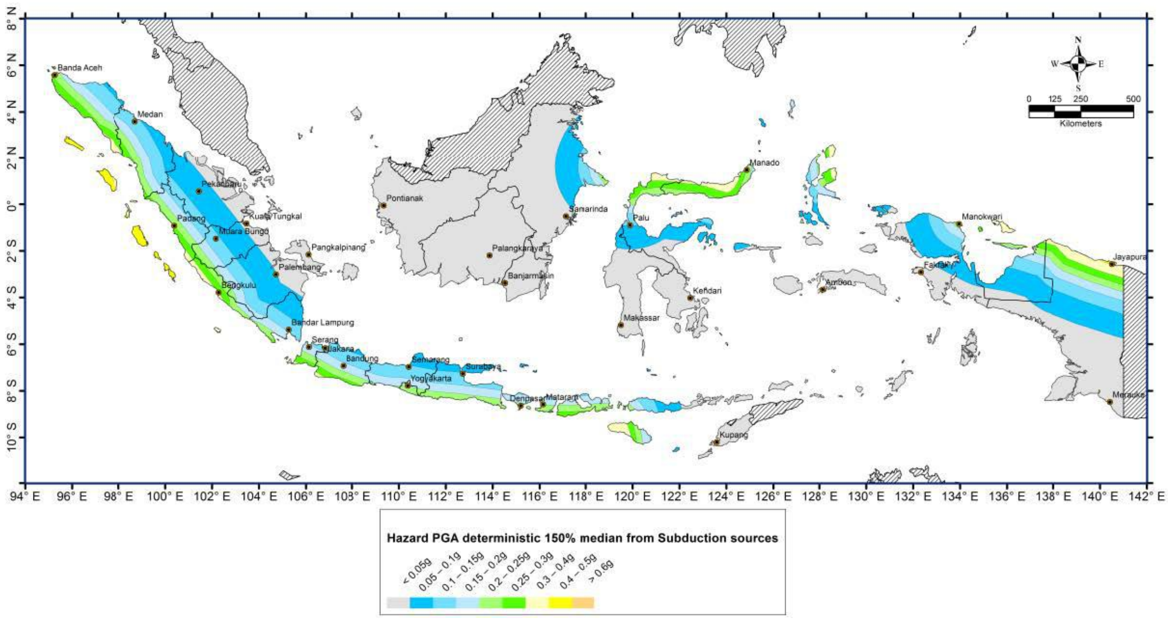

Figure 10. Peak Ground Acceleration (PGA) deterministic seismic hazard map of Indonesia region from subduction faults with 84 percentile (150% median), warmer color represent higher seismic hazard (Tim Pusat Studi Gempa Nasional, 2017).

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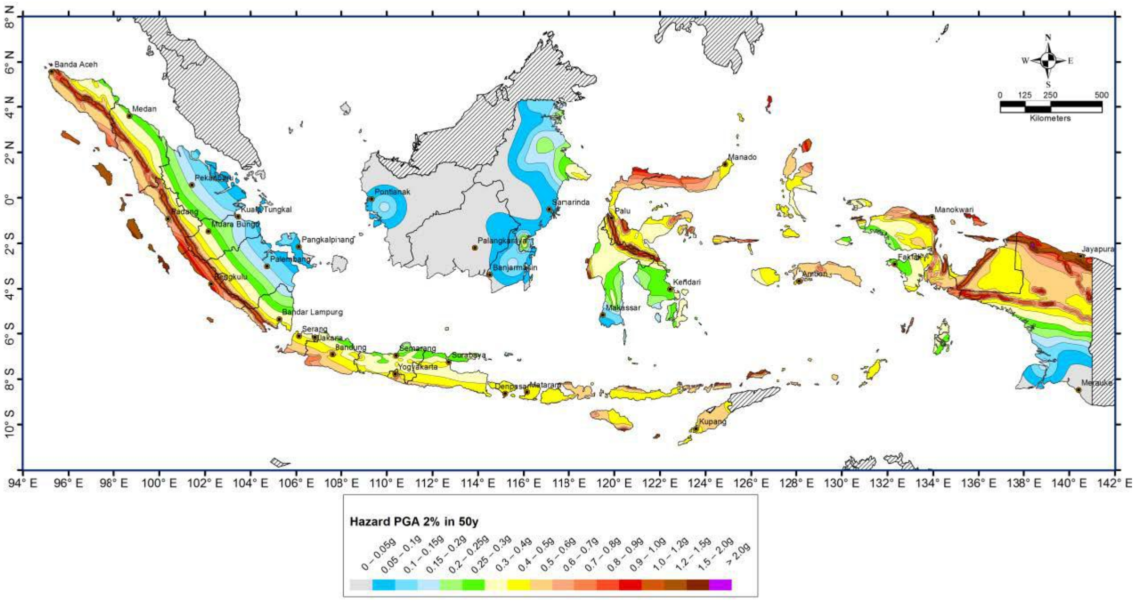

Figure 11. Peak Ground Acceleration (PGA) 2% probabilities of exceedance map in 50 years of Indonesia region, the map show the 2% probability of PGA will exceed the mapped value within 50 years (Tim Pusat Studi Gempa Nasional, 2017).

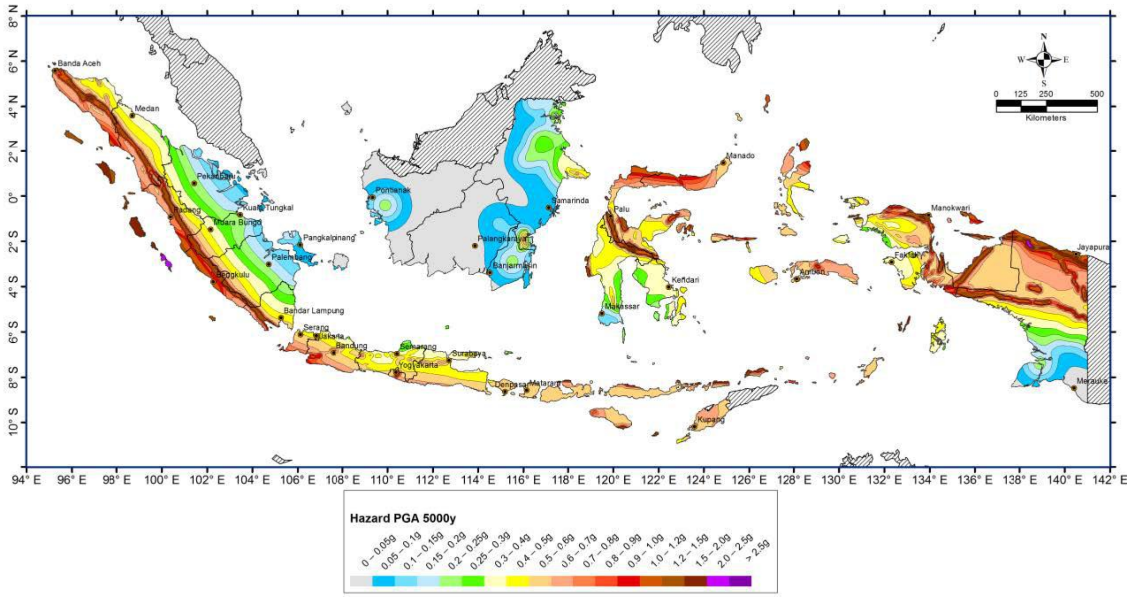

Figure 12. Peak Ground Acceleration (PGA) 2% probabilities of exceedance map in 100 years of Indonesia region, the map show the 2% probability of PGA will exceed the mapped value within 100 years (Tim Pusat Studi Gempa Nasional, 2017).

Tsunami Hazard Assessment

The wave height and inundation zone of tsunami is influenced by the amount of vertical slip of the faulting, topography and bathymetry (Borerro et al., 2006). If important parameters are known, such as the deformation type and magnitude, as well as the coast topography and bathymetry, the tsunami inundation zone can be modeled using a modeling software for tsunami. The physical parameters for Sumatra region is relatively well-known in compared to other region in Indonesia so a reliable tsunami model can be developed for the region. Recent tsunami events can be used to calibrate the model to observe if the empirical parameters are suitable to be implemented in constructing the tsunami model for the area. Borerro et al. (2006) calculate the tsunami propagation and inundation to model the flow depths and inundations for western Sumatra. Their model is consistent with sparse historical accounts for the last two great earthquakes in the area: the 1797 and 1833. The model implement various plausible future ruptures, it produce flow depths of several meters and inundation up to several kilometers inland near the most populous coastal cities (Figure 13), confirm a substantial exposure of coastal Sumatran communities to tsunami surges. They estimate potential losses from the future tsunami event can be as great as those that occurred in Aceh in 2004. Further, the simulations shows that the effects at Bengkulu is more severe than Padang because it is unprotected by offshore islands like in Padang.

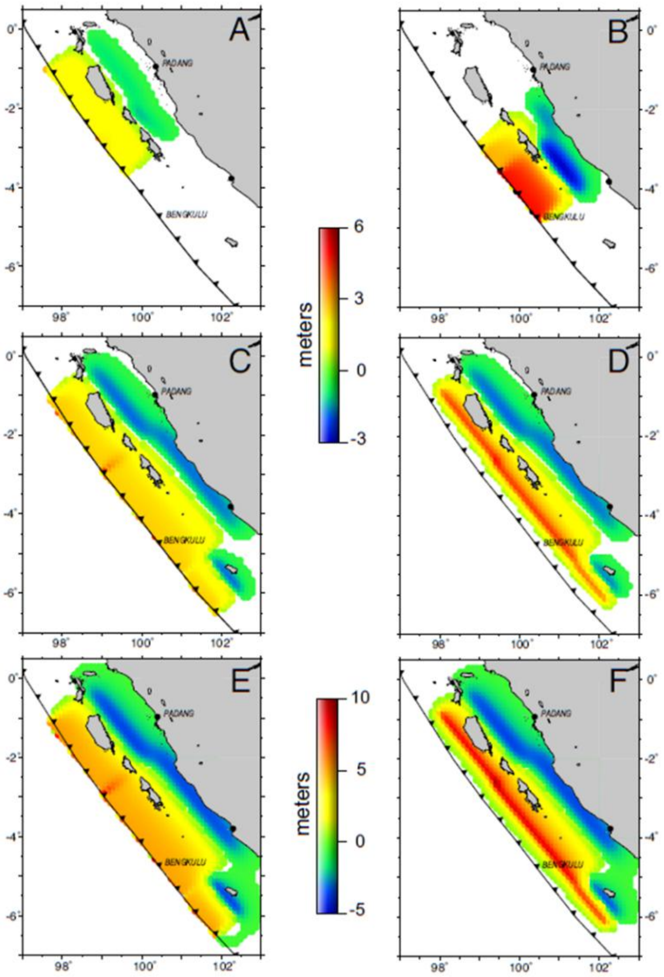

Figure 13. Vertical deformation patterns produced by six megathrust ruptures used in the Borerro *et al.* (2006) study to model the tsunami affecting west Sumatra coast presented in Figure 14 (adapted from Borerro et al., 2006). (A and B) Effects of the 1797 (A) and 1833 (B) ruptures adapted by Borrerro *et al.*, 2006 from Natawidjaja et al. (2006). (C) In scenario 1, uniform slip of 10 m extends to trench. (D) In scenario 2, uniform slip of 10m extends up-dip only to a depth of 15 km. (E) In scenario 3, uniform slip of 20m extends to trench. (F) In scenario 4, uniform slip extends up-dip only to a depth of 15 km.

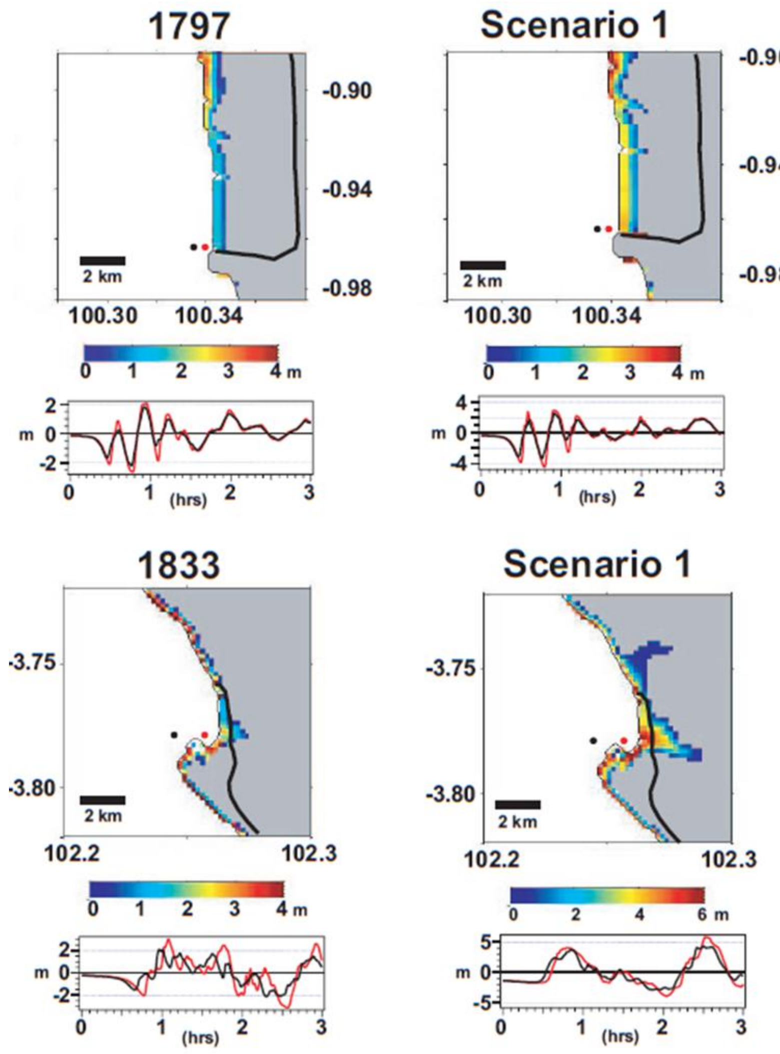

Figure 13. Modeled tsunami flow depths and inundations over local coastal topography near Padang (upper) and Bengkulu (lower) for a subset of the model scenarios (adapted from Borerro *et al*., 2006). The pixel dimension is ~200x200 m. In each panel, tsunami time series begin at the time of rupture and are for offshore locations at 5 m (red dot) and 10 m (black dot). Solid black line represents the extent of densely populated urban areas.

Conclusion

Scientific investigations confirms that the west Sumatra region is vulnerable from both primary and secondary effect of large earthquake events. The main earthquake sources that are affecting the west Sumatra region are: the Mentawai segment of the Sunda Megathrust and the Sumani and Sianok segments of the Sumatran Fault Zone. The secondary effect of tsunami also threatening communities residing the western Sumatra coast. The amount of potential slip along the Mentawai segment that was not relieved in the 2007 event is enough to generate a Mw 8.8 earthquake (Sieh *et al*., 2008). This event would producing a strong, widely distributed seismic shaking in western Sumatra and are likely to occur within the next few decades. Tsunami model of earthquake along the entire Mentawai segment yield several meters tsunami al]ong the Padang and Bengkulu coast, with around 1 km of inundation distance (Borrerro *et al*., 2006, 2007). To anticipate potential future disasters, it is important to increase the awareness of people residing the affected zone. This can be done by education and training of both the government and local communities on the eminent hazard and disaster and risk reduction that are relevant to their area. The ground-shaking hazards can be anticipated by constructing a reliable deterministic and probabilistic seismic hazard assessments of the area. As the quality of seismic hazard assessments can be improved by increasing the knowledge of active faults in the area, further investigation of the seismic sources is crucial. This can be done by applying new knowledge and advanced methods and monitoring devices. In addition, mapping of area that are vulnerable to secondary hazards associated with future surface faulting such as landslides, rock fall and liquefactions is also necessary. All of these can only be achieved with a full support at the national level by elaborating a long-term research plan in the subject of disaster and risk reduction. In addition, established seismic hazard maps need to be incorporated in the development plan and regulation to increase earthquake resilience prior, during, and post-earthquake events.

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