

# Recurrence Time Analysis of the 1883 (Mw 8.6 ~ 9.1) Paleo Megathrust Earthquake in West Bengkulu, Sumatra, Indonesia, Using Plate Kinematic Model for Supporting Mitigation Program

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## Research Letter

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# **Recurrence time analysis of the 1883 (Mw 8.6 ~ 9.1) paleo megathrust earthquake in West Bengkulu, Sumatra, Indonesia, using plate kinematic model for supporting mitigation program**

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## **Abstract**

The great paleo-megathrust earthquake occurred in west Bengkulu-Sumatra on November 25, 1833 and it was estimated to have the magnitude of about Mw 8.6–9.1. This earthquake triggered a tsunami that has 3-4 m height in the Bengkulu coastal and its vicinity. The fundamental earthquake parameter was not known exactly, thus it was difficult to conduct the analysis. We tried to analyze it using scaling law relations of earthquake parameter and magnitude scenarios to estimate the recurrence time based on the plate kinematic model to support the long-term mitigation program. The recurrence time was estimated at 179 years, 250 years, and 314 years if the earthquake is assumed to have a dip-slip mechanism, plate slip rate about 7 cm/year, and magnitude scenarios of 8.6, 8.8, and 9.1 respectively. Then, the recurrence time was estimated at 314 years, 438 years, and 550 years respectively if the earthquake is assumed to have a plate slip rate about 4 cm/year. The other estimation was used the strain rate value of about  $1.19 \times 10^{-14}/\text{s}$  for Sumatra region and the rigidity modulus of  $3.10^{11} \text{ dyne/cm}^2$ .

We found the recurrence estimation of about 161 years (Mw 8.6), 222 years (Mw 8.8), and 220 years (Mw 9.1) for the dip-slip model. Meanwhile, if this study used all rupture models, the recurrence time of the Bengkulu paleo megathrust earthquake would be about 370 years (Mw 8.6), 558 years (Mw 8.8), and 553 years (Mw 9.1).

**Keywords:** Paleo megathrust, recurrence time, stress drop, strain rate.

## 1. Introduction

The great earthquake occurred in 1833 in west Bengkulu-Sumatra, Indonesia, and this earthquake triggered a tsunami to struck the coastal area and its vicinity (Pararas, 2000). A seismograph did not exist yet in this era and the earthquake was only noted in the form of the macroseismic data. Therefore, the fundamental earthquake parameters were not known exactly, such as the location of the epicenter, focal depth, magnitude, or moment magnitude (Mw). There were only simple reports of the earthquake impact based on the macroseismic data, including the tsunami impact data. Some scientists estimated that Bengkulu paleo megathrust 1833 has a varying magnitude of Mw 8.8 (Prawirodirdjo et al. 2010), Mw 9.0 (Subarya et al. 2006), Mw 8 ¾ (Newcomb and McCann 1987) and Mw 8.8-9.1 (Zachariasen et al. 1999). The magnitude was still not clear exactly, so several magnitude moment scenarios were used to analyze the recurrence time of the Bengkulu earthquake 1833. The moment magnitude is a basic parameter to calculate a seismic moment ( $M_0$ ), rupture length (L), area (S), and static stress drop ( $\Delta\sigma$ ) using scaling law earthquake relations. After considering the magnitude uncertainty in this study, we used the magnitude scenarios of  $8.6 \leq M_w \leq 9.1$  to calculate its recurrence time. The epicenter location could not be determined exactly (see Figure 1) and it was estimated based on the simple macroseismic data. Based on the earthquake catalog, the several earthquakes occurred on June 25, 1914 (M 7.6), June 04, 2000 (Mw 7.9), September 12, 2007 (Mw 8.4 and 7.9), October 25, 2010 (Mw 7.8), and recently on August 19, 2020 (Mw

6.9 and 6.8), has an identical location (or almost) with the Bengkulu earthquake occurred on November 25, 1833 area.

To minimize the uncertainty of Mo value, we presented earthquakes which has the same (or almost) magnitude, such as Chili Bio-Bio earthquake Mw 8.8, Japan Tohoku earthquake Mw 9.1, and outer rise earthquake in western Aceh Mw 8.6. Meanwhile, L and W of fault were used to do the scaling law relations of earthquake formula proposed by (Wells and Coppersmith 1994). This is one of the reconstructions of the paleo earthquake which limits the earthquake parameters data to estimate the recurrence time (Tr) using a plate kinematic model. In this paper, we determined the recurrence time estimation using the slip rate of the Bengkulu arc segment of about 5-7 cm/year (Bock et al. 2003) and the strain rate value for Sumatra region of about  $1.19 \times 10^{-14}/\text{s}$  (Murjaya, 2011).

The recurrence is dependent upon stress drops and in their study, the static stress drop is calculated using seismic moment measured from seismogram and estimated rupture area ((Beeler et al. 2001) (Kanamori and Allen 1986). The recurrence time of earthquakes within one segment is controlled by the tectonic load as a slip rate for a long time, stress accumulation, rheology rocks, and release mechanism on the fault plane. The recurrence time or return period of the tectonic earthquake will last longer if it has a larger static stress drop and the return period of the earthquake will paradoxically last shorter in time if it has a smaller static stress drop ((Kanamori and Allen 1986). This parameter is important to support earthquake mitigation planning in the future.

The tectonic of the Sumatra region in the western part of Indonesian tectonic is characterized by a complex tectonic region. The western part of Sumatra is a convergence or joint land between Eurasian and Australian plates characterized by oblique subduction. Also, there is a right-lateral large Sumatran fault along almost 1600 km from north to the south (southeast). Mentawai islands (see Figure1) is one of the effects of oblique convergence plates between

Eurasian and Australian plates (Hall, 1998) and the other effect is the large Sumatran fault. Based on the focal mechanism distribution of earthquakes, there is a dip of  $10^\circ$  -  $30^\circ$  with the dominant dip of  $20^\circ$  (Murjaya, 2011). According to Handayani (1993) devided three earthquake distribution zones in Sumatra and there are earthquake zones in its vicinity along the trench region (subduction zone), Mentawai fault, and Large Sumatran Fault (LSF).

The slip rate value of convergence is estimated between 5 - 7 cm/year (Bock et al. 2003) and 4 cm/year (Irsyam et al. 2017). According to the large earthquakes historical data, it has occurred in Sumatra and its vicinity, such as earthquakes that occurred in 1797, 1833, 1861, 2000, 2004, 2005, and 2007 (Newcomb and McCann 1987). The three earthquakes event of 1797, 1833, and 1861 occurred before the seismograph existed.

## 2. Data and Methods

The magnitude data of the Bengkulu paleo earthquake occurred in 1833 was taken from the secondary data which has been published with a magnitude scenario (Mw 8.6 - 9.1) and it has been checked in the Indonesia Agency for Meteorology, Climatology, and Geophysics (BMKG) catalog. Seismic Moment ( $M_0$ ), Length of fault (L), and rupture area (A) was determined using scaling law relations. We used the slip rate of Bengkulu arc segment of about 7 cm/year (Bock et al. 2003), the minimum is about 4 cm/year (Irsyam et al. 2017), the strain rate value for Sumatra region  $1.19 \times 10^{-14}/\text{s}$  (Murjaya, 2011).

### 2.1. Scaling Law Relations of Earthquake

#### a. Fault Length and Rupture Area

The Bengkulu paleo megathrust earthquake occurred in 1833 had limited information only about the earthquake impacts. Therefore, we did not have the aftershocks distribution, geodetic data to describe the fault length and/or the rupture area. We assumed that the focal mechanism of the earthquake is dip fault and/or all rupture models, then the L and A value is calculated using (Wells and Coppersmith 1994) formula in equation (1) and (2).

$$L = 10^{(a+b M_w)} \quad (1)$$

$$A = 10^{(c+d M_w)} \quad (2)$$

Annotation:

$a = -2.86$ ;  $b = 0.63$ ;  $c = -3.99$  and  $d = 0.98$  for dip slip fault

$a = -3.22$ ;  $b = 0.69$ ;  $c = -3.49$  and  $d = 0.91$  for all rupture model

By assuming the average value of L and A, it is possible to calculate the W value from equation (1) and (2).

#### *b. Static Stress Drop Theory*

Several tectonic energies will release during a co-seismic event after the critical stage of rock is passed over. This energy is accumulated—along the interseismic period since the last earthquake event has occurred. Figure 2 shows the illustration of the built-up stress and released stress. It begins from the initial stress ( $\sigma_0$ ), the build-up stress along interseismic period until it achieves the critical stress ( $\sigma_1$ ) stage. After the critical stress stage passes over, it will release several stresses called a stress drop. Furthermore, to describe the stress release effects, we used one type only, i.e. a static stress drop. Then, we used the (Kanamori and Anderson 1975) formula as follows:

$$\Delta\sigma = c \mu \frac{\bar{D}}{L} \quad (3)$$

$\mu$  is rigidity (SI),  $\frac{\bar{D}}{L}$  is strain change, and C is a non-dimensional shape factor. To determine the shape factor (C) and L, we referred to shallow infinite transverse shear (dip-slip) faults. (Kanamori and Anderson 1975) show  $C = \frac{4(\mu + \lambda)}{(2\mu + \lambda)}$ , where  $\lambda$  is the Lame constant, then a seismic moment is:

$$M_o = \mu S \bar{D} \quad (4)$$

$M_o$  is a static seismic moment ( $\text{Nm}^{-1}$ ) and S is a rupture area ( $\text{m}^2$ ). Based on the substitute equation (3) and (4), then the static stress drop formula for strike-slip fault is:

$$\Delta\sigma = \frac{2}{\pi} \left( \frac{M_o}{W.W. L} \right) \quad (5)$$

Equation (5) is similar to (Beeler et al. 2001) which reveals that static stress drop is calculated using seismic moment measured from seismogram and estimated rupture area, while the recurrence interval is estimated from historic records.

### *c. Seismic Energy and Moment Magnitude Relation*

The relation between the surface wave magnitude ( $M_s$ ) and the total energy of seismic waves ( $E_s$ ) has been studied by (Gutenberg and Richter 1955) which is revealed by Kanamori and Anderson (1975). They obtained the relation as:

$$\log E_s = 1.5 M_s + 11.8 \quad (6)$$

Then, we used the conversion  $M_w$  to  $M_s$  with the formula as:

$$M_w = 0.9239 M_s + 0.5671 \quad (7)$$

The equation (7) is used for magnitude interval  $6.2 \leq M_s \leq 8.7$  with  $R^2 = 0.8183$ .

## **3. Results**

Having explained above, the Bengkulu earthquake that occurred in 1833 has limited macro-seismic data, magnitude estimation ( $M_w$  8.6 - 9.1), and it has been published in some journals. We made magnitude scenarios to calculate some fundamental earthquake parameters using scaling law relations. We then referred to the earthquake which has identical magnitude with the magnitude scenario such as  $M_o$  of Nias-Sumatra earthquake for the magnitude scenario  $M_w$  8.6 (March 28, 2005),  $M_o$  of Chili earthquake for the magnitude scenario  $M_w$  8.8 (February 27, 2010), and  $M_o$  of Tohoku earthquake  $M_w$  9.1 (March 11, 2011) for the magnitude scenario,  $M_w$  9.1.

### 3.1. Fault Length and Static Stress Drop

Table 1 shows the relations between earthquake parameters, such as  $M_w$ ,  $M_o$ ,  $L$ , and  $A$ . These

parameters were used to estimate of the static stress drop ( $\Delta\sigma$ ) value after being combined with scenarios of slip models (dip slip-DS) and all rupture-AR). The slip model scenario is needed to select a formula to calculate L and A based on (Wells and Coppersmith 1994). The  $\Delta\sigma$  estimation was verified with plotting at Log Mo-Log S diagram by (Kanamori and Anderson 1975) in Figure 3 and there are still consistent for interplate earthquake.

**Table 1.** The relations between Mw, Mo, L, A, and  $\Delta\sigma$  by the scaling law relations of

earthquakes.

Mw (Scenario)	Mo (dyne-cm)	Type of Focal Mechanisms	L (km)	A (km <sup>2</sup> )	W app (km)	$\Delta\sigma$ (x 10 <sup>7</sup> dyne/cm <sup>2</sup> )	Earthquake Ref. (Mw and Mo)
8.6	$8.87 \times 10^{28}$	Dip slip (DS)	361	27,415	76	3.61	March 28, 2005
		All rupture	518	21,677	42	8.30	
8.8	$2.26 \times 10^{29}$	Dip slip (DS)	483	43,053	89	5.0	Feb 27, 2010
		All rupture	711	32,960	46.4	12.54	
9.1	$5.59 \times 10^{29}$	Dip slip (DS)	746	84,723	113.5	4.94	March 11, 2011
		All rupture	1000	61,801	62	12.43	

### 3.2. Recurrence Time Estimation

We used strain rate, slip rate data, and substitute the above scenarios to estimate the recurrence time. (Frederick C. Davison and Scholz 1985) and (Kanamori and Anderson 1975) calculated the recurrence time of the earthquake by dividing the moment of an earthquake by source time function or moment rate accumulation. This method needs the slip rate data of the fault or velocity rate of the plate.

**Table 2.** List of the estimation of recurrence time for earthquake Mw scenarios and scaling law.

Parameter		Mw (scenarios)	Mo (dyne-cm)	Type of Mechanism focal	Tr (years)
Kinematic	Value				
Strain rate	$1.19 \times 10^{-14}/\text{s}$	8.6	$8.5 \times 10^{28}$	Dip slip (DS)	161
				All rupture (AR)	370
		8.8	$2.26 \times 10^{29}$	DS	222
				AR	558
		9.1	$5.59 \times 10^{29}$	DS	220
				AR	553
		8.6	$8.5 \times 10^{28}$	DS	314
				AR	341
		8.8	$2.26 \times 10^{29}$	DS	438
				AR	570
Slip rate	4 cm/yr	9.1	$5.59 \times 10^{29}$	DS	550
				AR	753
		8.6	$8.5 \times 10^{28}$	DS	251
				AR	273
		8.8	$2.26 \times 10^{29}$	DS	350
				AR	456
		9.1	$5.59 \times 10^{29}$	DS	440
				AR	603
	5 cm/yr	8.6	$8.5 \times 10^{28}$	DS	209
				AR	228
		8.8	$2.26 \times 10^{29}$	DS	292
				AR	380
		9.1	$5.59 \times 10^{29}$	DS	367
				AR	503
		6 cm/yr	8.6	DS	179
				AR	195
			8.8	DS	250
				AR	326
			9.1	DS	314
				AR	431

Bock et al. (2003) revealed that the movement of the Australian and Eurasian plate relatively for arc Bengkulu segment with the velocity rate is about 5-7 cm/year, while (Irsyam et al. 2017) estimated that the movement is 4 cm/year only. Another method is passthrough of the physical basic approximation where we estimated the theoretical stress accumulation per unit time. This

method contains the strain rate parameter value for the Sumatra region (Murjaya, 2011). Table 2 presents the estimation result of the return period or recurrence time of the Bengkulu earthquake that occurred in 1833 using the passthrough approach of the strain rate and subduction slip rate values.

### 3.3. Seismic Energy

If we used the formula (6) and (7), and magnitude scenarios Mw 8.6, 8.8 and 9.1, the total seismic energy of about  $5.0 \times 10^{24}$  ergs,  $10^{25}$  ergs, and  $2.8 \times 10^{25}$  ergs respectively. Furthermore, we calculated the total seismic energy for Mw 6.9 and 6.8 (2020), Mw 7.8 (2010), Mw 8.4 and 7.9 (2007), Mw 7.9 (2000) and Mw 7.4(1914) which has identical (and or almost) location with the earthquake 1833 is about  $3.9 \times 10^{24}$  ergs.

### 3.4. Potential Shaking Impact of Earthquake Magnitude Scenario

One of the secondary effects of the earthquake is a shaking impact on infrastructures and the surrounding area. Figure 4a shows the shake map of the Bengkulu earthquake using scenario Mw 8.6, focus depth 30 km, and it does not discriminate the type of slip. If the earthquake occurs with a magnitude of more than Mw 8.6, the impact has an intensity of more than Mw 8.6. Also, Figure 4b and 4c shows the simulation of Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) using magnitude scenario Mw 8.6.

## 4. Discussion

Bengkulu paleo megathrust earthquake occurred in 1833 in western Bengkulu coastal zone, the location between subduction zone and Mentawai strait in Bengkulu area (Figure1). We tried to determine the recurrence time for the Bengkulu paleo megathrust earthquake that occurred in 1833 by choosing the magnitude moment scenarios Mw 8.6 – 9.1 and assuming that the faults

are dip-slip and all rupture models. We considered that the strain energy was accumulated along the inter-seismic period for several years until a hundred years without breaking this area. The strain energy or stress accumulation will release during co-seismic events after the critical stage of rock passes over or called a stress drop. Table 1 shows the relations among Mw, Mo, L, A, and  $\Delta\sigma$  by scaling law relations of the earthquake.  $\Delta\sigma$  is an important variable in the dynamic model as the basic parameter to estimate the recurrence time of an earthquake. (Dębski 2018) explains that to describe the stress release effects, seismology uses three basic parameters namely the static stress drop, the Coulomb stress transfer, and the dynamic stress drop. Furthermore, the  $\Delta\sigma$  result can be compared to some earthquakes as showed in Figure 3. All results of static stress drop value have the range around 36-125 bars and it is located in the fixed-line. (Kanamori and Anderson 1975) demonstrate that the average stress drop is higher for intraplate than interplate earthquakes and since intraplate events have generally longer repeat times than interplate events.

Kanamori (1994) revealed that for a typical sequence along active plate boundaries,  $\Delta\sigma \approx 30$  to 100 bars, and  $Tr \approx 300$  years, and it is agree with the Figure 3. The other it also presents the largest earthquake at active plate margins that has a relatively short repeat time of 30-200 years (Kanamori and Allen 1986), while some intraplate events have repeat times of thousand years, even if they are relatively close to a plate boundary. Meanwhile Natawidjaja et al. (2006) investigated the growth patterns and U-Th dating of the coral microatolls vertical deformation associated with the 1797 and 1833 earthquakes. They revealed also that paleoseismic evidence indicates that over the past millennium, the island has risen during giant earthquakes or earthquakes couplets about every 230 years. Subarya et al. (2006) revealed that if all slip was released only by the repetition of event like the Sumatra-Andaman earthquake 2004 would occur on average every 230-600 years. If we refer to their research result related of the recurrence time of earthquakes (Kanamori and Allen 1986; Kanamori 1994; Subarya et al.

2006; Natawidjaja et al. 2006), our result for the static stress drop value have a range around 36-125 bars it is still a good result. Also, if it is related with the estimation of the recurrence time of large earthquake in Western Bengkulu 1833 as showed on table 2. Furthermore, we used two approximations to estimate the recurrence time of earthquake. First, we calculated the recurrence time based on the plate kinematic model (Frederick C. Davison and Scholz 1985) by using the slip rate of the convergence plate of Australian and Eurasian plates. The maximum values of the slip rate data about 5-7 cm/year (Bock et al. 2003), and minimum is about 4 cm/year (Irsyam et al. 2017) as well as the Mw scenario for arc Bengkulu segment 8.6-9.1. The maximum value of convergence plate of the Australian-Eurasian is about 7 cm/year has an almost identical with the data by McCaffery (McCaffrey et al. 2000) from the NUVEL-1. Second, we used the strain rate value in Sumatra (Murjaya, 2011) and assumed an average value for the modulus of rigidity  $3.10^{11}$  dyne/cm<sup>2</sup>, and the result is presented in Table 2. If it is assumed that the source has a dip-slip (DS) fault, a slip convergence plate rate value of 4 cm/year (Irsyam et al. 2017) and the magnitude scenarios 8.6, 8.8 and 9.1, the recurrence time result are 314 years, 438 years, and 550 years for DS model respectively. If the slip convergence plate rate value is of about 7 cm/year (Bock et al. 2003), the recurrence time of earthquake are 179 years, 250 years, and 314 years respectively. This return period of the earthquake with the slip rate of 7 cm/year is faster than the slip rate of 4 cm/year.

If it used the strain rate value for Sumatra earth crust  $1.19 \times 10^{-14}$ /s (Murjaya, 2011), we would find the recurrence time of the Bengkulu paleo earthquake of about 161 years (Mw 8.6), 222 years (Mw 8.8), and 220 years (Mw 9.1) respectively. Meanwhile, if we used all rupture models, the recurrence time of Bengkulu paleo earthquake about 370 years (Mw 8.6), 558 years (Mw 8.8), and 553 years (Mw 9.1). The recurrence time of earthquake results in this study is in line with (Kanamori and Anderson 1975) explained above.

Although it uses the strain rate approach, it still has an ambiguity like what has been revealed

by White (1994) that the calculated strain rates are not constant, but it varies between  $10^{-18}/\text{s}$  until  $10^{-15}/\text{s}$ , such as a surface deformation strain rate near the Alpine arc in Switzerland of around  $16.3 \times 10^{-16}/\text{s}$  (Houlié et al. 2018). In this paper, we used the strain rate for Sumatra area is around  $1.19 \times 10^{-14}/\text{s}$  for  $\lambda$  buckling  $\sim 300$  km and the thick crust ( $h$ ) in the Western Bengkulu segment based on the distribution of earthquake hypocenter (from the surface to depth) of around 70 km (Murjaya, 2011). Meanwhile, the strain rate in the Indian Ocean is around  $2 \times 10^{-16}/\text{s}$  (Gerbault 2000). Furthermore, the total energy released for all earthquakes based on term 5.3 is a small value if it is compared with the seismic energy based on the magnitude scenarios.

## 5. Conclusion

Based on Table 1, the  $\Delta\sigma$  result is still consistent (Figure 3) to reconstruct the Bengkulu paleo earthquake that occurred in 1833 using magnitude scenarios 8.6-9.1. All the static stress drop values have a range of around 36-125 bars and it is consistent at the fixed-line. Furthermore, to estimate the recurrence time, if we assumed the earthquake with the dip-slip (DS) fault model, the slip rate value of 4 cm/year (Irsyam et al. 2017) and the magnitude scenarios 8.6, 8.8, and 9.1, the recurrence time of earthquake are 314 years, 438 years, and 550 years respectively. If we changed it with the slip rate value of about 7 cm/year (Bock et al. 2003) and the magnitude scenarios 8.6, 8.8, and 9.1, the recurrence time of the earthquake are 179 years, 250 years, and 314 years respectively. This recurrence time of earthquake with a slip rate of 7 cm/year is faster than the slip rate of 4 cm/year.

When we used the strain rate value for Sumatra earth crust  $1.19 \times 10^{-14}/\text{s}$  and the mechanism source is dip-slip, we found the recurrence time of about 161 years (Mw 8.6), 222 years (Mw 8.8), and 220 years (Mw 9.1) respectively. Meanwhile, we assumed that the mechanism source is all rupture models, the strain rate value for Sumatra earth crust  $1.19 \times 10^{-14}/\text{s}$ , and we found

the recurrence time of about 370 years (Mw 8.6), 558 years (Mw 8.8), and 553 years (Mw 9.1) were found. Based on the term 5.3 in the Bengkulu earthquake 1833 area it is still stored a large total seismic energy.

## **Data and Resources**

The earthquake data used in this study was compiled by BMKG. The slip rate of Bengkulu arc segment extracted from (Bock et al. 2003) and (Irsyam et al. 2017), while the strain rate value for Sumatra region  $1.19 \times 10^{-14}/\text{s}$  was taken from Murjaya (2011).

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## **Availability of data and material**

Data are available from the author upon request.

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## **Authors' contributions**

J.M., D.K., S.P., S.S., P.S., R.S.Y., and S.R. conceived the study and contributed to the writing of the manuscript. All authors contributed to the preparation of the manuscript

## **Competing Interests Statement**

We declare that we have no competing financial, professional, or personal interests that might

have influenced the performance or presentation of the work described in this manuscript.

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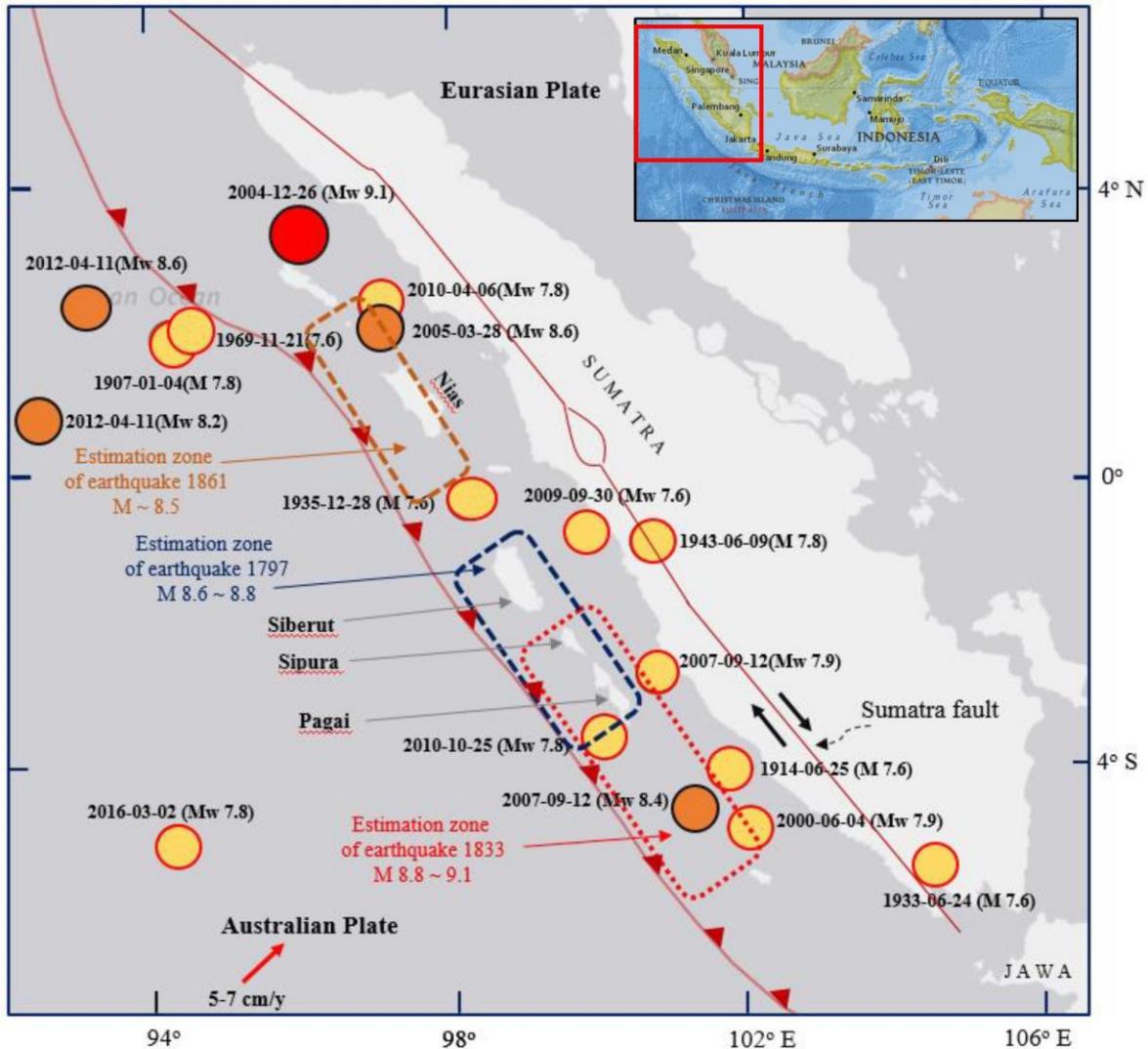
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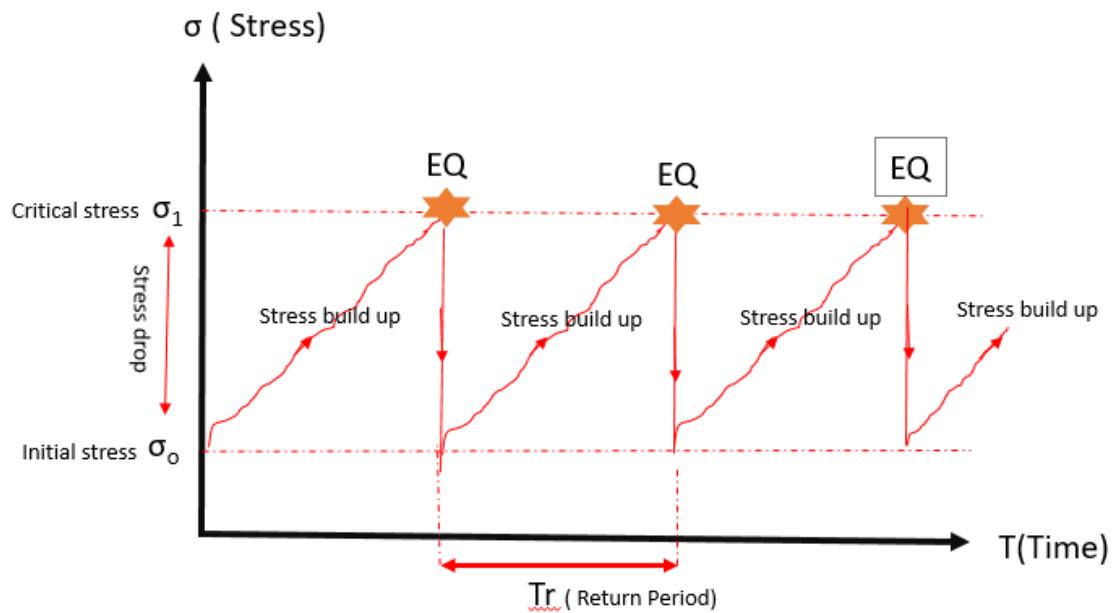
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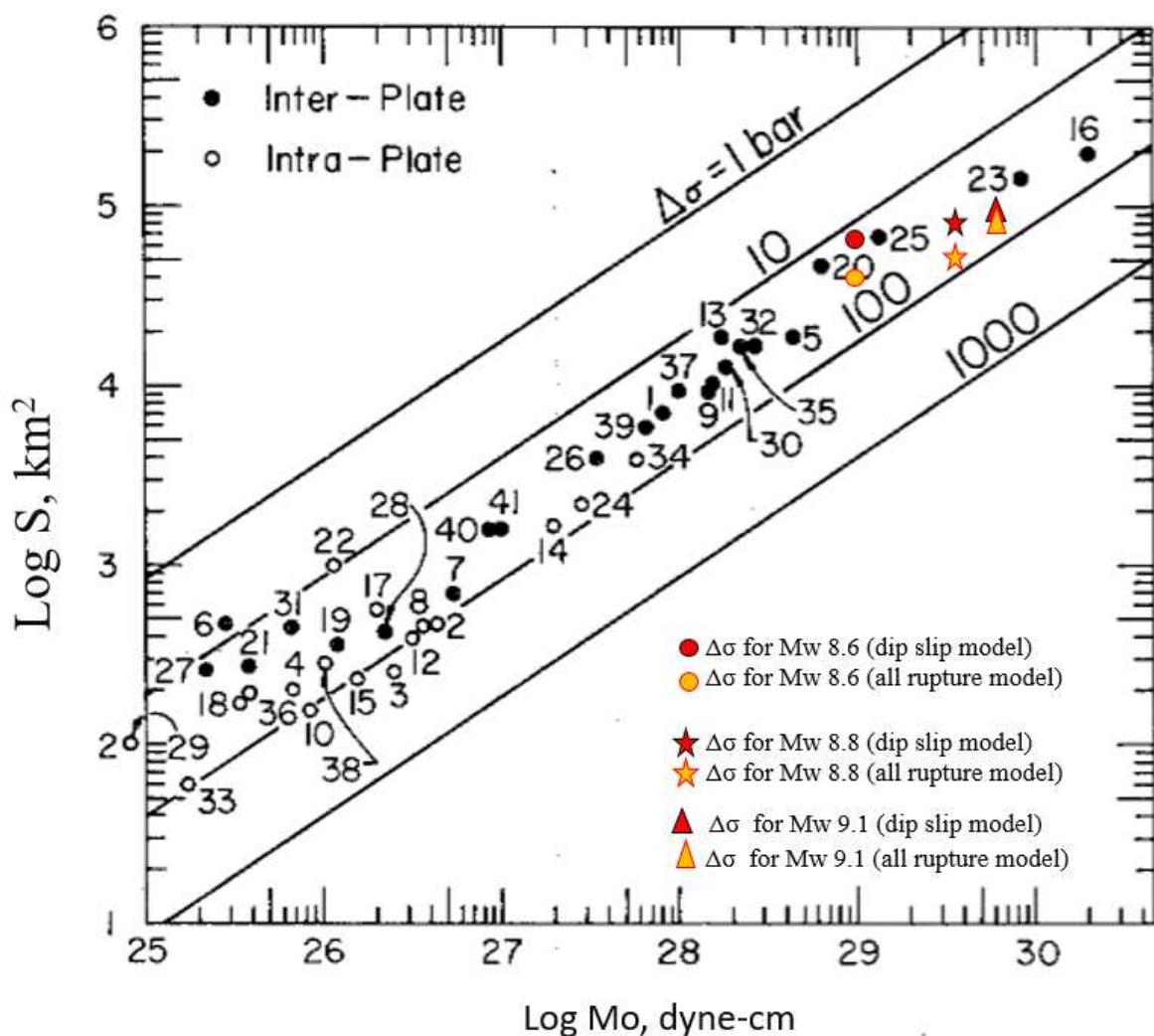
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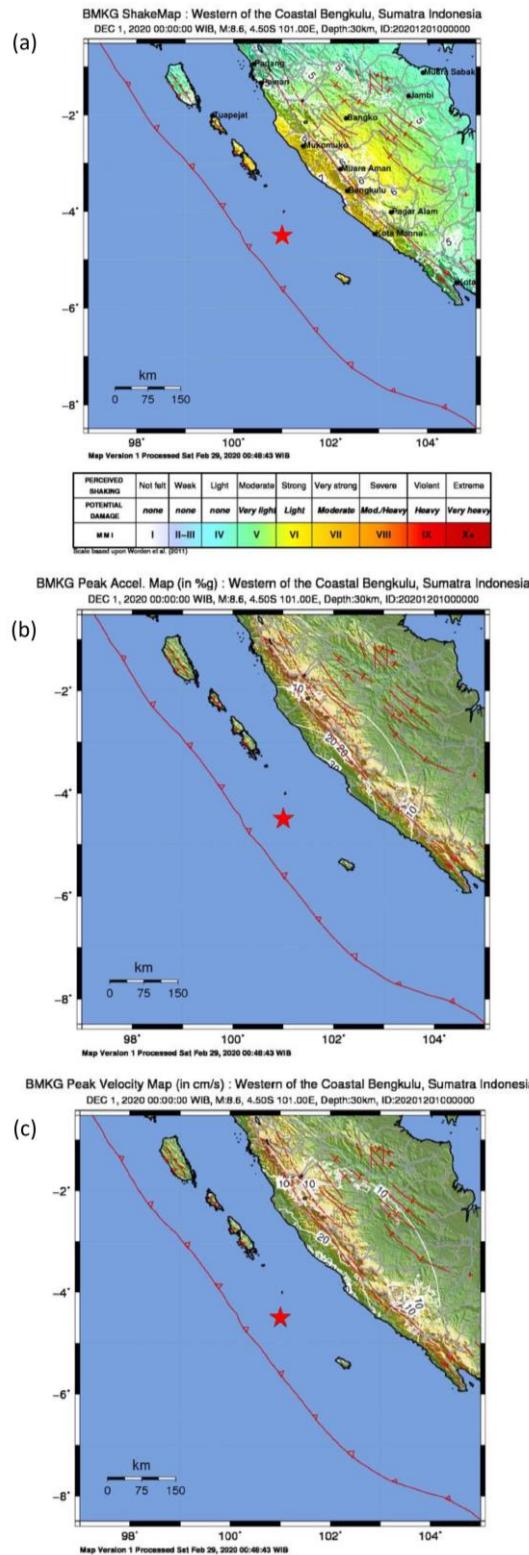
**Figure 1.** Tectonic setting, seismicity large earthquake ( $M_w \geq 7.0$ ) for the time period 1900 to 2019, and the ruptures area estimation of major intraplate earthquakes along the Sunda megathrust. The red circle shows  $M_w \geq 9.0$ , the brown circle shows  $8.0 \leq M_w < 9.0$ , and the yellow circle shows  $7.5 \leq M_w < 8.0$ .



**Figure 2.** Illustration of the stress drop and return period interval of earthquake relations. The time interval between two events of earthquakes is called return period ( $Tr$ ) and the difference between the critical stress ( $\sigma_1$ ) value and initial stress ( $\sigma_0$ ) value is called return period ( $Tr$ ) and stress drop, respectively.



**Figure 3.** Relations between Log S and Log Mo diagram (modified from Kanamori and Anderson, 1975). The red circle, star, and triangle indicate the  $\Delta\sigma$  estimation for the dip-slip model of Mw 8.6-9.1. The yellow circle, star, and triangle indicate the  $\Delta\sigma$  estimation for all rupture models for Mw 8.6-9.1 of the scenario result of the Bengkulu megathrust earthquake that occurred on November 25, 1833, and it is appropriate.



**Figure 4.** (a) Shake map estimation, (b) PGA, and (c) PGV for the Mw 8.6 earthquake simulation in Bengkulu. The red star shows the epicenter location for the earthquake. For Mw > 8.6 shows the earthquake intensity more than the scale as described on the shake map with Mw 8.6.

# Figures

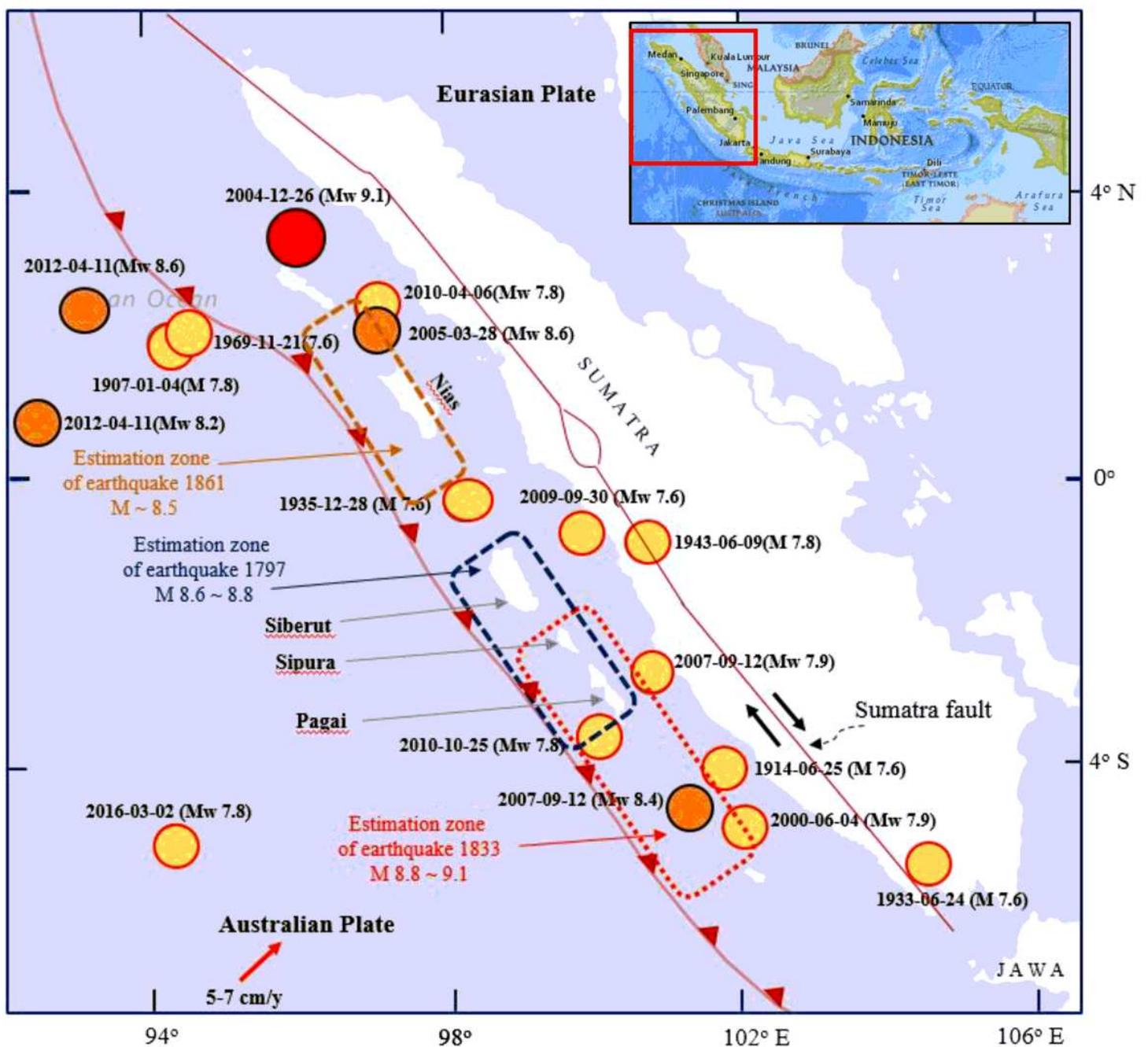
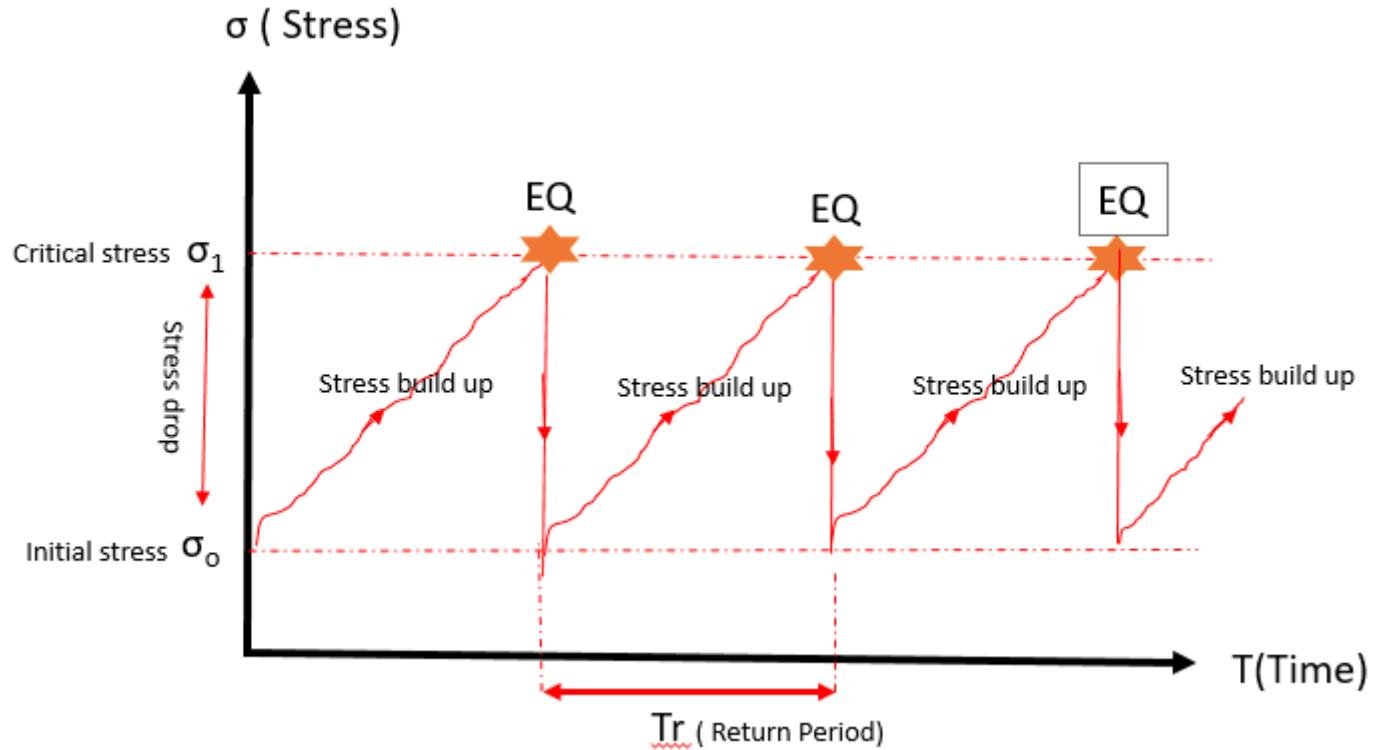


Figure 1

Tectonic setting, seismicity large earthquake ( $Mw \geq 7.0$ ) for the time period 1900 to 2019, and the ruptures area estimation of major intraplate earthquakes along the Sunda megathrust. The red circle shows  $Mw \geq 9.0$ , the brown circle shows  $8.0 \leq Mw < 9.0$ , and the yellow circle shows  $7.5 \leq Mw < 8.0$ . Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country,

territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.



**Figure 2**

Illustration of the stress drop and return period interval of earthquake relations. The time interval between two events of earthquakes is called return period ( $Tr$ ) and the difference between the critical stress ( $\sigma_1$ ) value and initial stress ( $\sigma_0$ ) value is called return period ( $Tr$ ) and stress drop, respectively.

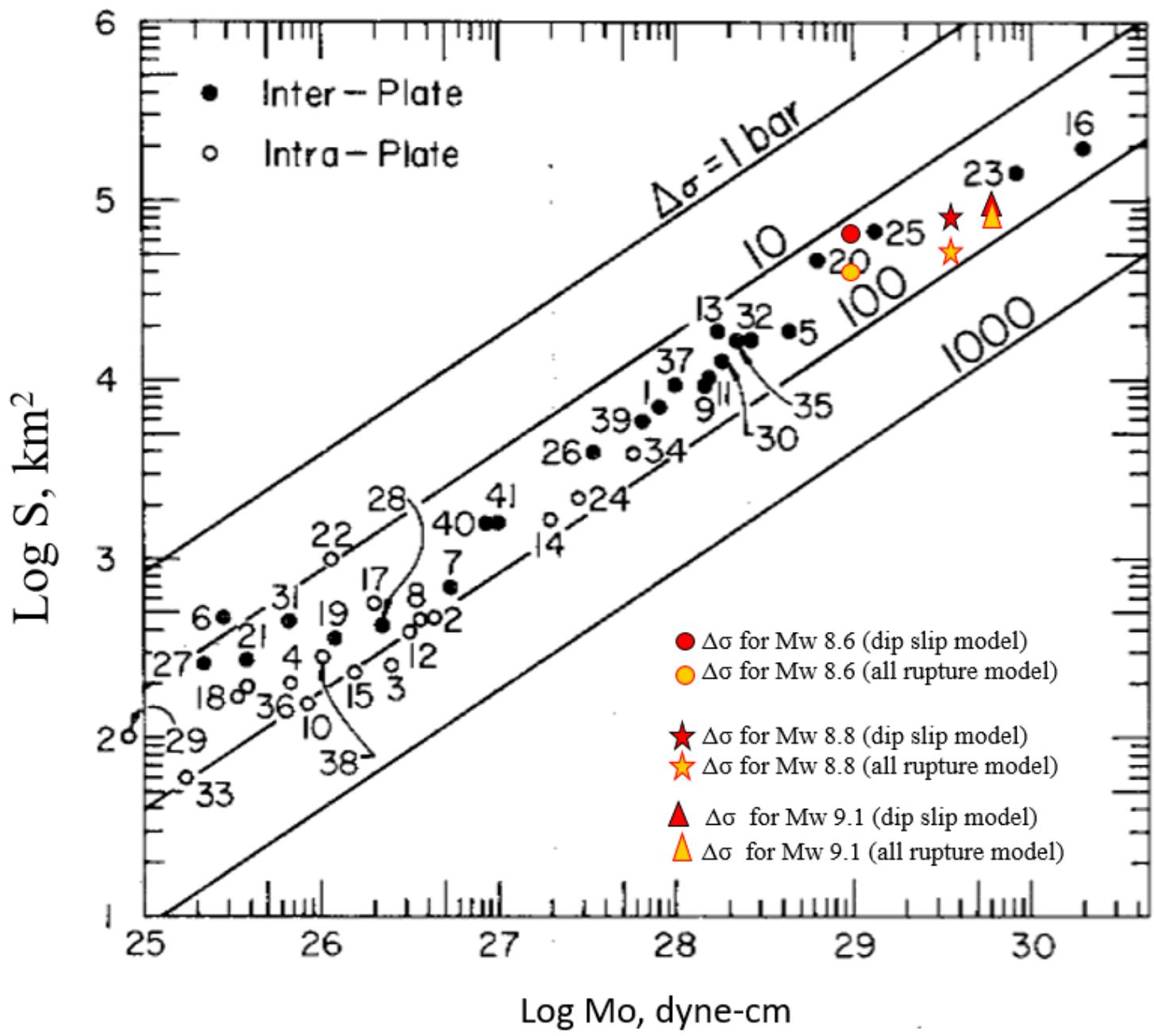
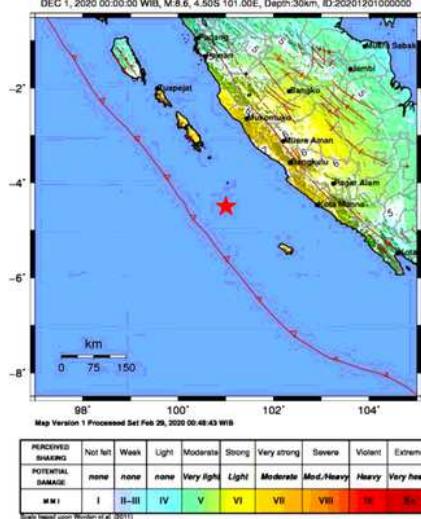


Figure 3

Relations between Log S and Log Mo diagram (modified from Kanamori and Anderson, 1975). The red circle, star, and triangle indicate the  $\Delta\sigma$  estimation for the dip-slip model of Mw 8.6-9.1. The yellow circle, star, and triangle indicate the  $\Delta\sigma$  estimation for all rupture models for Mw 8.6-9.1 of the scenario result of the Bengkulu megathrust earthquake that occurred on November 25, 1833, and it is appropriate.

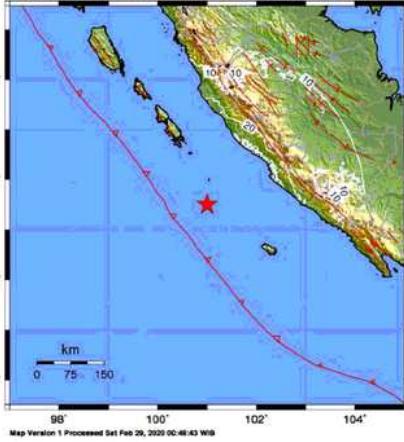
(a)

BMKG Peak Accel. Map (in %g) : Western of the Coastal Bengkulu, Sumatra Indonesia  
DEC 1, 2020 00:00:00 WIB, M:8.6, 4.50S 101.00E, Depth:30km, ID:20201201000000  
Map Version 1 Processed Set Feb 29, 2020 00:48:43 WIB

(b)

BMKG Peak Velocity Map (in cm/s) : Western of the Coastal Bengkulu, Sumatra Indonesia  
DEC 1, 2020 00:00:00 WIB, M:8.6, 4.50S 101.00E, Depth:30km, ID:20201201000000  
Map Version 1 Processed Set Feb 29, 2020 00:48:43 WIB

(c)

**Figure 4**

(a) Shake map estimation, (b) PGA, and (c) PGV for the Mw 8.6 earthquake simulation in Bengkulu. The red star shows the epicenter location for the earthquake. For Mw > 8.6 shows the earthquake intensity more than the scale as described on the shake map with Mw 8.6. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its

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