Preliminary study of stress changes evolution on central part of Sumatran Fault influenced by large interplate earthquakes and tectonic stress rates

Muhammad Taufiq Rafie1*, Phil R Cummins2,3, David P Sahara2, Sri Widiyantoro2,4, Wahyu Triyoso5, Andri Dian Nugraha2

1Graduate Program of Geophysical Engineering Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia
2Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia
3Research School of Earth Sciences, Australian National University, Canberra ACT 2601, Australia
4Faculty of Engineering, Maranatha Christian University, Bandung 40164, Indonesia

*Corresponding author: taufiqrafie@students.itb.ac.id

Abstract. The inland seismic activity in Great Sumatran Fault (GSF) has significantly increased over the past several decades after the occurrence of historical large interplate earthquakes along the plate boundary. This condition led to some occurrences of historical intraplate earthquakes along Sumatran fault. To quantitatively examine the physical mechanisms between intraplate earthquakes and interplate earthquakes, we estimated the static coseismic stress changes of Coulomb failure function (ΔCFF) using receiver fault approach from large historical-recorded interplate earthquakes and the increase in tectonic stress rates. We examined this research in the central part of GSF since this zone is assumed to have the most heterogeneous stress field and thus became our focus study area. The cumulative ΔCFF models showed almost all segments in the central part of GSF suffered negative changes (< -0.1 MPa) which assumed to be unlikely to rupture in short time. However, the preliminary analysis of the increase in tectonic stress rate indicated that large intraplate earthquakes occurred on Angkola and Siulak segments were dominantly influenced by the increase in interseismic stress rate just after the series of large subduction earthquake occurrences, apart from the decreased stress changes from those major interplate earthquakes.

Keywords: Interplate earthquakes, Sumatran Fault, Tectonic stress rates

1. Introduction
The Sunda subduction margin is an active tectonic convergence zone between the subducting Indian-Australian plate and the over-riding Sundaland plate. Along this plate boundary, the accumulated strain energy during earthquake cycle have resulted in numerous large interplate-subduction earthquakes occurrences such as the great 2004 Sumatra-Andaman and 2005 Nias-Simeulue earthquakes (see Fig. 1a and Table 1). Sumatran fault system or known as Great Sumatran Fault (GSF) which is close to these large subduction earthquake ruptures was formed by where the accumulated strain is partitioned into right-lateral/dextral strike-slip component due to oblique plate motion which almost parallel to the subduction trench [1, 2]. One interest GSF segment is the largest fault bends in the central part of GSF.
which formed strike-slip duplex structure and named as ‘equatorial bifurcation zone’ [2]. For our focus study area, we treated the central part of GSF from Angkola segment to Siulak segment which we have found interesting since it is assumed to have the most heterogeneous stress field along GSF [3]. As shown in Fig. 1b, many historical inland earthquakes have occurred repeatedly for over the past 40 years after many historical large interplate-subduction earthquakes occurrence. To explain the activity of inland earthquakes, we estimated the effect of static coseismic stress changes from historical large subduction earthquake and the tectonic stress rate increase on GSF. This is a crucial thing to consider that if the tectonic stress rate is quite steep, then the stress drop on a fault caused by the earthquakes will vastly recover by the interseismic stress rate increase. Using the calculated coseismic stress changes and the tectonic stress rate increase, we try to analyse the possible linkage that can explain the occurrence of large inland earthquakes in the central part of the Great Sumatran Fault (GSF).

![Figure 1](image)

Figure 1. Map of rupture area of each large interplate earthquake in Sumatra subduction zone (a) and map of epicenter location of historical large intraplate earthquakes along GSF (b). The rupture area of large interplate earthquakes based on slip model listed in Table 1 while large intraplate earthquake along GSF based on [4].

Table 1. Lists of historical earthquakes recorded in Sumatra subduction zone.

| List historical earthquake       | Mw  | Slip model used for ΔCFF models |
|----------------------------------|-----|----------------------------------|
| 1797                             | ~8.0| [5]                              |
| 1833                             | ~9.0| [5]                              |
| 1861                             | ~8.5| [6]                              |
| 2004 Sumatra-Andaman             | ~9.0| [7]                              |
| 2005 Nias-Simeulue               | ~8.6| [8]                              |
| 2007 Bengkulu                    | ~8.4| [8]                              |
| 2009 Padang                      | ~7.5| [8]                              |
| 2010 Mentawai                   | ~7.8| [8]                              |
2. Methodology

2.1. Estimation of static Coulomb Failure Function (ΔCFF) by large interplate earthquakes
ΔCFF is calculated using Coulomb failure assumption which defined as follows [9]:

\[ ΔCFF = Δτ + μ(Δσ + ΔP) \]  

Where \( Δτ, Δσ \) and \( ΔP \) are the changes in shear stress on a fault plane (positive in fault slip direction), normal stress on a fault plane (positive in extension/clamping fault) and changes in pore pressure, respectively. The changes in pore pressure are often related to the mean stress changes and assumed to be proportional to compressional stress changes (normal stress changes), thus the equation (1) is redefined as follows:

\[ ΔCFF = Δτ + μ′Δσ \]  

Where \( μ′ \) is the apparent (effective) friction which derived from the [10]'s coefficient effect and homogeneous medium [11]. Its value can be considered in the range of 0.2-1.0, and in this study, we used the value of 0.2 because we consider the Sumatran fault as major transform fault system which assumed to have low friction coefficient [12]. Here we used the receiver fault of specific orientation approach in resolving the ΔCFF with fixed geometries (strike, dip, and rake) of a well-known GSF orientation. To calculate ΔCFF, we need the source and fault parameter of large interplate earthquake. The fault parameters of historical records of large interplate earthquakes are estimated from previous studies while fault of orientations of Sumatran segment are based on geological measurements by [2]. Then, we estimated the static coseismic Coulomb stress changes under the assumption of elastic dislocation approach [13] from a given fault slip model by using COULOMB3.4 code [14,15].

2.2. Calculation the increase in tectonic stress rate
We estimated the tectonic stress rate increase under the assumption of Time Predictable (TP) model by [16] which stated that stress drop of interplate-subduction earthquake will recover by tectonic stress rate increase prior to the next one, so that we can infer the tectonic stress rate increase as \( Δτ/T \), where \( Δτ \) is the static coseismic stress drop by a large earthquake occurred on a fault and \( T \) is the fault average recurrence time interval. [17] calculated right-lateral slip rates along GSF and used those slip rates to estimate the average event recurrence intervals of each segment from their expected maximum magnitude of earthquake. They roughly found that average recurrence intervals are ranging from about \( 4x10^2 \) year in Southern Sumatra to \( 2x10^2 \) year in Northern Sumatra. In this case, we took the value of 200 year of mean recurrence interval time in central part of GSF. For simplicity, we assumed the maximum earthquake to be occurred along those segments. From the given assumption, we estimated the uniform stress drop to be 4 MPa. Thus, we expected the uniform tectonic stress rate increase to be 0.02 MPa/year.

3. Results and discussion
Coseismic stress changes were calculated using coseismic slip models. These models were obtained from various authors included [5] for 1797 and 1833 earthquake and [8] for 2005, 2009, 2007 and 2010 earthquakes which collected through SCRMOD [18]. The ΔCFFs were resolved at 10 km depth. For simplicity, we also assumed that ΔCFF of 1861 earthquake has the same effect as 2005 Nias-Simeulue earthquake since 1861 rupture area was in the rupture patch of 2005 earthquake [19]. Fig. 2 showed stress changes on each receiver fault for each large interplate earthquakes. For 1797 earthquake, increase stress zone was located from Sianok segment to Siulak segment with > 1 bar while Angkola to Sumpur segments were decreased (< -1 bar). Positive stress changes also recorded in Siulak segment due to 1833 earthquake while the rest had negative stress changes (< -1 bar in Sianok, Sumani and Suliti segments). The ΔCFF model caused by 2004 Sumatra-Andaman earthquake showed any no significant effect, and this is happened since its stress changes distribution is far away and did not reach into the central part of Sumatran segment. When 2005 Nias-Simeulue earthquake occurred, part of Angkola, Barumun, Sumpur and Sianok segments recorded high stress up to > 1 bar. Almost all segments in central part
Sumatra suffered stress shadow zone caused by 2007 Bengkulu earthquake except Sumpur segment which recorded a slight increase of stress. ΔCFF models of 2009 Padang and 2010 Mentawai earthquakes showed a small effect of stress changes on each segment and it was expected since those two recent earthquakes had moderate magnitude (< 8) compared to other interplate earthquakes. Fig. 3a showed a cumulative ΔCFF of all large interplate earthquakes, we can see that almost all segments recorded negative ΔCFF (<= -0.1 MPa) which initially might assume that central part of Sumatra segment is unlikely to rupture in short time. Some of those stress shadow zones correlated well with zone of seismic gap inferred by [4] especially on Barumun, Sumpur, and Sianok segments. Stress changes evolution after 1861 earthquakes (Fig. 3b) showed that Siulak segment is likely to have been advanced towards failure since it recorded increase stress changes and later ruptured as 1909 earthquake. However, Angkola and Suliti segments which suffered decrease stress changes ruptured during 1892 and 1943 earthquakes, respectively. In this case, we still need more analysis on the assumption that the central part of Sumatra is retreat from failure because stress shadow zone can be triggered if the increase in tectonic stress rates is high enough to recover the fault so that the fault could meet its critical point [20 21 22]. To initially investigate this, we have calculated the uniform tectonic stress rate increase which is around 0.02 MPa/year. To make the calculation simple, we used 4 MPa as uniform stress decrease in Sumatra fault system/GSF where this value is actually almost similar to the coseismic stress drop around the rupture zone of large subduction earthquake [23]. We analysed the effect of tectonic stress rate increase in triggering the intraplate earthquakes that occurred in Angkola and Siulak segments. Fig. 4 illustrated the ΔCFF time evolution of Angkola and Siulak segment since 1771 as time reference where the time was taken only after a year of 1770 event [24]. From Fig. 4a, we can see that after the series of large interplate earthquakes occurrence, Angkola segment ruptured around 3 decades (1892 M7.5) and 8 decades (1977 M6.1) afterwards while Siulak segment (Fig. 4b) ruptured for about 5 (1909 M7.3) decades and 8 decades (1995 M6.7) afterwards. Generally, these results are in agreement with study by [25] where the next large inland earthquake can only be occurred during several decades before the subsequent large subduction earthquake. From this preliminary analysis, we initially hypothesize that the increase of tectonic stress rate around central part of GSF is dominantly influence the faults to be closer failure, triggering a major inland earthquake, and less affected by the ΔCFF loading on the fault.

Figure 2. Coulomb stress models resolved on receiver faults of central part of GSF from coseismic slip model of each large interplate earthquakes. The color represents the maximum stress changes at 10 km depth with a scale saturated at 1 bar.
4. Conclusions
We investigated the effect of stress changes in central part of GSF using static ΔCFF by the large interplate earthquakes along Sunda subduction margin. Based on the estimated stress changes on inland faults, we infer that the stress changes accumulation is low enough around the central part of GSF to be ruptured. However, the initial analysis of the uniform increase in tectonic stress rates on Angkola and Siulak segments showed that the tectonic stress rates is high enough to recover the segments to be critical to failure and become stress trigger zones. Since it is a preliminary analysis, we still need more investigation to better explain the triggering mechanisms, need more historical interplate earthquakes to give well-details ΔCFF models, and detailed tectonic stress rate increase on each segment. Furthermore, an advanced approach is also necessary to explain the postseismic stress loading (i.e., viscoelastic response function).

Figure 3. Cumulative ΔCFF of each earthquake listed in Table 1 (a) and cumulative ΔCFF of 1797, 1833, and 1861 earthquakes (b). The cyan ellipses are the damage area of large intraplate earthquakes marked as green star. The ΔCFF is calculated at 10 km depth with a scale saturated at 1 bar.

Figure 4. ΔCFF time evolution which included the simple estimation of tectonic stress rates on Angkola segment (A) and Siulak segment (B) with historically recorded large intraplate earthquakes.
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