The pattern of local stress heterogeneities along the central part of the Great Sumatran fault: A preliminary result

David P. Sahara¹, Sri Widiyantoro¹

¹Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha 10, Bandung 40132, Indonesia
E-mail: david.sahara@gf.itb.ac.id

Abstract. Based on world stress map, the in-situ stress along the Great Sumatran Fault (GSF) is assumed to be strike-slip, and the maximum principal stress is oriented N14°E. However, this estimation neglects the local impact of fault branching and material heterogeneity which might have a significant impact on the stress heterogeneity. Despite its importance, very few studies have been performed on this issue in GSF. We intend to analyze variations of the in-situ stress in GSF from the geological data and seismicity pattern. This was performed on a catalogue data set of 707 earthquakes with magnitude (Mw) >3.5 between January 1, 1970 and April 1, 2017. The preliminary results of this study highlight the stress rotation of around 30° clockwise in the central part of GSF. Geological observation also shows faults branching and bifurcation which are interpreted as the product of the stress changes. Furthermore, the seismicity analysis quantifies this issue by showing a sharp different of b-values for subduction and GSF zones, i.e. 1.0 and 0.7, respectively. Therefore, it can be concluded that the stress heterogeneity in the central part of GSF affects both the seismicity occurrence and magnitude.

1. Introduction

Stress in Earth’s crust, tectonic or non-tectonic, might generate earthquakes according to the failure law [1]. The main source of tectonic stress is mostly horizontal as it originates from forces due to plate motions [2]. In Sumatra, the source of tectonic stress is the Sunda subduction megathrust, along which the Indian and Australian plates subduct north-eastward beneath the Sunda shelf [3] (Fig. 1). Along Sumatra the convergence is oblique to the trench and the intra-plate motion is right lateral slip along GSF at 11 to 28 mm yr⁻¹ [4].

The information of the in-situ stresses can be estimated from a variety of sources: earthquake focal mechanisms; geologic data of the fault slip, observation of volcanic alignments, stress-induced wellbore breakouts and drilling induced tensile fractures [5–7]. Information of the state of stress in the lithosphere is the key information for constructing the hazard mitigation strategy. It has been shown in previous studies that the key features of earthquake triggering, inhibition, and clustering can be explained by Coulomb stress changes [8,9]. Slip on fault plane drops most of the stress at the adjacent crust and increases particularly in the vicinity of the fault edge. Thus, this might trigger slip on secondary faults and produce broadly distributed aftershocks.

However, this estimation disregards the local impact of fault branching and material heterogeneity which might have a significant impact on the stress heterogeneity, e.g. San Andreas [10] and the Alps [11]. The local stress heterogeneity often overrules the far-field stress in governing the local deformation. So far, very few studies on this issue have been performed in GSF.
We intend to infer the stress heterogeneity along the central part of GSF from the geological data and seismicity pattern. In this study, we take advantage of a dense local network surrounding the central part of GSF in order to provide a vast seismic catalogue data from January 1970 to mid 2017. The aim of this study is to obtain a preliminary result of the stress heterogeneity pattern in the central part of GSF for further geomechanics analysis, including stress modeling and hazard assessment.

![Location map showing the tectonic setting of the Sumatran margin.](image)

**Figure 1.** Location map showing the tectonic setting of the Sumatran margin. The continuous dotted line on the land surface indicates the Great Sumatran Fault (GSF). The black arrow shows the convergence rate of the Indo-Australian plate (modified from Weller et al. [4]).

2. **Geological and Tectonic Settings**

Earthquake focal mechanism solutions indicate that the present day maximum horizontal stress in Sumatra is oriented primarily N14°E, perpendicular to the trench [10]. This is confirmed by the world stress map data on a regional scale [12] and by the log data and hydraulic test on a local scale [13,14]. The stress orientations observed in GSF essentially perpendicular to the strike of the adjacent subduction zone, suggesting that the regional stress orientation is dominated by forces generated at this plate boundary.

However, there are also arc–normal stresses observed in Sumatra associated with the formation of the back–arc basins, e.g. the South and Central Sumatra Basins [15]. This type of stress is oriented primarily N45°E. Arc–normal stresses can be generated in the over-riding plate in advancing subduction zones, where the velocity of convergence between the two plates is faster than the velocity of subduction [16]. Alternatively, Mount and Suppe [10] suggest that it was the slip history on the GSF which is responsible for this stress rotation.

Sieh and Natawidjaja [16] studied the geomorphology of GSF in detail and found that it is highly segmented, i.e. the fault was fragmented into 19 major segments. The largest irregularity is at the central part of GSF (around equator) where the fault splits into two sub-parallel strands up to 35 km apart; they named it ‘equatorial bifurcation’. Due to its branching and irregularity, this zone is suspected to endure the most stress heterogeneity along GSF.
3. Seismicity Analysis

To confirm the suspected stress heterogeneity from geological and tectonic study in the previous section, we analyzed the seismic history along the central part of GSF. This was performed on a catalogue data set of 707 earthquakes data with Mw $>3.5$ and depth $<40$ km between January 1, 1970 and April 20, 2017. The data catalogue was a compilation of seismic data from BMKG, USGS, IRIS, and GFZ, with the data of BMKG are treated as the main database. The distribution of the earthquakes within the study area is shown in Fig. 2.

Due to the different nature (geological and tectonic settings) between the subduction zone and the inland GSF, the study area was divided into two segments, i.e. the subduction and the fault zone. The earthquake magnitude frequency distributions for these zones are shown in Fig. 3. We estimate a b-value of 0.9 for all of these source zones. However, we have calculated the b value from each of these zones separately as presented below.

The central part of Sumatra subduction zone is a very active feature that has ruptured in 630 independent events with magnitude greater than or equal to 3.5 within the past 47 years. The largest of these events was M 7.6, which occurred on September 30, 2009 near Padang, West Sumatra. Using a range of magnitudes between 4.0 and 7.0, we obtained a b value of 1.0 for this distribution.

This second zone covers the area around the central part of GSF, ranging from $-0.5^\circ$ to $3.0^\circ$ in latitude. Seventy seven events with magnitude greater than or equal to 3.5 have occurred during the last 47 years. This zone has not been as productive as the Sumatra subduction zone. A b-value of 0.7 was acquired between M 4 and 7 for this zone from the seismicity data since 1970.
4. Conclusion

The results of this study pick out the stress heterogeneity at GSF from the global N14°E in-situ stress in Sumatra. This hypothesis is supported by the local in-situ measurements performed in the previous studies depicting ~30° clockwise rotation of the principal stress orientation [13,14]. Geological observation also shows faults branching and bifurcation which are interpreted as the product of the stress changes. Furthermore, the seismicity analysis quantifies this issue by showing a sharp different of b-values for subduction and GSF zone of 1.0 and 0.7, respectively. Even though in the last 47 years the central part of GSF was only hit by 77 events, compared to 630 events hitting the subduction zone in the same period, they tend to have a higher magnitude ratio and the hypocenter is relatively shallow (< 40 km). Therefore, it can be concluded that the stress heterogeneity affects both the seismicity occurrence and magnitude in the central part of GSF. Following this study, a numerical modelling of stress changes in the central part of GSF is required to further understand the impact of the stress changes to the seismicity pattern.

Acknowledgement

Authors thank Kementrian Riset dan Pendidikan Tinggi Indonesia which has supported this research with Riset Unggulan ITB 2017 scheme. The title of the research project is “Analisis potensi gempabumi dan stress heterogeneity sepanjang segmen sesar Sumatera bagian tengah”.

References

[1] Zang A and Stephansson O 2010 Stress field of the earth’s crust (Heidelberg: Springer Netherlands).
[2] Barber A J, Crow M J and Milsom J (Eds) 2005 Sumatra: geology, resources and tectonic evolution, The Geological Society, London, Memoirs, 31.
[3] Curray J 2005 Tectonics and history of the Andaman Sea region J Asian Earth Sci 25 187–232.
[4] Weller O, Lange D, Tilmann F, Natawidjaja D, Rietbrock A, Collings R and Gregory L 2012 The structure of the Sumatran Fault revealed by local seismicity Geophys. Res. Lett. 39 L01306.
[5] Hudson J A, Cornet F H and Christiansson R 2003 ISRM Suggested Methods for rock stress estimation—Part 1: Strategy for rock stress estimation Int. J. Rock Mech. Min. Sci. 40 991–998.
[6] Fairhurst C 2003 Stress estimation in rock: a brief history and review Int. J. Rock Mech. Min. Sci. 40 957–973.
[7] Maury J, Cornet F H and Dorbath L 2013 A review of methods for determining stress fields from earthquakes focal mechanisms; Application to the Sierentz 1980 seismic crisis (Upper Rhine graben) Bull. Société Géologique Fr. 184 319–34.

[8] King G C P, Stein R S and Lin J 1994 Static stress changes and the triggering of earthquakes Bull. Seismol. Soc. Am. 84 935–953.

[9] Lin J and Stein R S 2004 Stress triggering in thrust and subduction earthquakes and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults J. Geophys. Res. Solid Earth 109 B02303.

[10] Mount V S and Suppe J 1992 Present-day stress orientations adjacent to active strike-slip faults: California and Sumatra J. Geophys. Res. Solid Earth 97 11995–12013.

[11] Müller B, Wehrle V, Zeyen H and Fuchs K 1997 Short-scale variations of tectonics regimes in the western European stress province north of the Alps and Pyrenees Tectonophysics 275 199–219.

[12] Tingay M, Morley C, King R, Hillis R, Coblentz D and Hall R 2010 Present-day stress field of Southeast Asia Tectonophysics 482 92–104.

[13] Yi X, Goodman H E, Williams R S and Hilarides W K 2008 Building a Geomechanical Model for Kotabatak Field with Applications to Sanding Onset and Wellbore Stability Predictions SPE-114697-MS (SPE: Society of Petroleum Engineers).

[14] Hennings P, Allwardt P, Paul P, Zahm C, Jr R R, Alley H, Kirschner R, Lee B and Hough E 2012 Relationship between fractures, fault zones, stress, and reservoir productivity in the Suban gas field, Sumatra, Indonesia AAPG Bull. 96 753–72.

[15] Forsyth D and Uyedaf† S 1975 On the Relative Importance of the Driving Forces of Plate Motion Geophys. J. R. Astron. Soc. 43 163–200.

[16] Sieh K and Natawidjaja D 2000 Neotectonics of the Sumatran fault, Indonesia J. Geophys. Res. 105 28295–28326.