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Impact of The 2004 Sumatra-Andaman Earthquake to The Stress Heterogeneity and Seismicity Pattern in Nothern Sumatra, Indonesia

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Abstract. Sumatra Island is a highly seismic active region due to its close location to the convergent zone between the Indo-Australian and Eurasian plates, and the existence of the Great Sumatran Fault (GSF). These conditions caused the island of Sumatra suffered from hundreds of earthquakes with Mw > 4 per year. Particularly, a 9.0 Mw Sumatra-Andaman 2004 earthquake occured in northern Sumatra which changed the in-situ stress and seismicity pattern. In such case, quantifying the tectonic stress perturbation prior and after 2004 Sumatra-Andaman earthquake is becoming key issue in assessing the seismic hazard. To invert the in-situ stress information in Sumatra, first we identify the fault plane from its auxiliary plane in the focal mechanism solutions using the fault instability criterion. There are 354 focal mechanisms data of earthquake with Mw > 5 and focal depths < 250 km along northern Sumatra Island from 1976 to 2010. This catalogue was compiled by combining the data from Global Centroid Moment Tensor (GCMT) catalogue and the International Seismological Centre (ISC) bulletin. We then divided the focal mechanism catalogue into two parts, i.e. prior and after Sumatra-Andaman 2004 earthquake. An iterative joint inversion is then implemented to estimate the in-situ stress orientation and its magnitude ratio. The in-situ principal stress orientation and magnitude ratio obtained from this study will be used to build a Sumatran stress map and its correlation with the seismicity pattern variations in the region. Our results produce remarkable changes of maximum principal stress orientation after 2004 megathrust earthquakes along the region. As the seismic hazard potential is controlled by stress concentration, the obtained results from this study could also be used further for seismic hazard mitigation in northern Sumatra.

Keyword : Stress Estimation, Iterative Joint Inversion, Sumatera Island

1. Introduction

Sumatra Island is located around the active ocean-continent collision zone which caused this island to have hundreds of earthquakes with Mw > 4 per year. This condition makes Sumatra Island is a perfect

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place to study the role of the principal stress orientation and the driving force due to plate movement to the crustal deformations. Regarding to the historical seismicity in this region, International Seismological Centre (ISC) bulletin shows that there are two megathrust earthquakes occurred; December 26th 2004 with magnitude Mw 9.0 (see Fig.1) which generated the tsunami in the northern part of Sumatra island and March 28th 2005 with magnitude Mw 8.6 around Nias island. According to this region, it is quite considerable to determine the change in principal in-situ stress orientations and seismicity pattern prior and after those mega-earthquakes for assessing the seismic hazard in the region.

Principal stress directions in the earth's crust are commonly close to vertical and horizontal directions [1]. Anderson [2] differs three angles defining the magnitudes of principal stresses i.e, the maximum horizontal (SHmax), minimum horizontal (Shmin) and vertical stresses (Sv). The previous stress inversion studies by [3,4,5] showed that the most convenient information of in-situ stress is obtainable from focal mechanisms. Because they are so widespread, earthquake focal mechanisms would seem to be a ubiquitous indicator of stress in the crust [6].

In this study, we infer the stress heterogeneity based on principal stress directions and shape ratio along northern Sumatra from focal mechanisms catalog data using iterative joint invesion. From the results of this study, we obtained several regions which remarkably changing in maximum stress direction near to the area that posess two mega-earthquakes. Furthermore, a better understanding of the correlation between the stress direction patterns prior and after 2004 Sumatra-Andaman earthquke is reached.

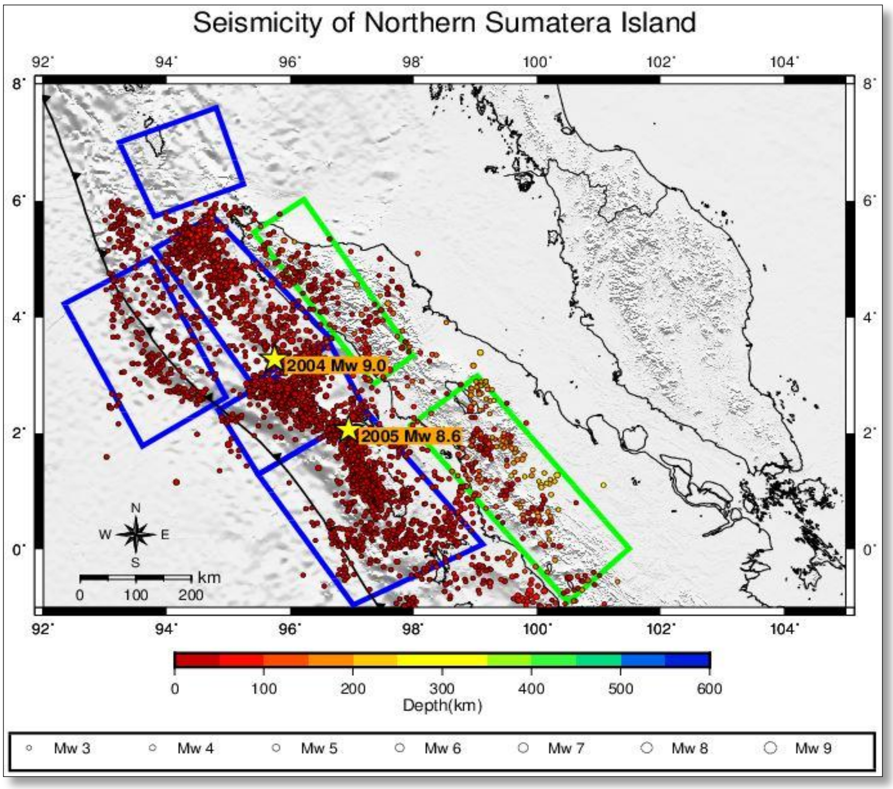

Figure 1. Map of relocated seismicity patterns along northern Sumatra (red dot) from [7] overlays with two megathrust earthquakes from ISC (yellow star). Colour rectangulars showed the segmentation used for obtaining the principal stress orientations and shape ratio (blue rectangulars indicate segmentation which modified from [8,9] whereas green rectangulars are from the authors).

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2. Data and Method

2.1. Focal Mechanisms Solution Catalog

We used focal mechanisms catalog compiled by Global Centroid Moment Tensor (GCMT) catalog and International Seismological Centre (ISC) bulletin from June 1976 to December 2010. We divided the catalog into two parts, i.e. June 1976 to December 2004 and January 2005 to December 2010 with magnitude Mw > 5 and focal depth < 250 km. This data separation was made for analyzing prior and after 2004 Sumatra-Andaman earthquake. The study area was located at latitudes -1°S - 8°N and longitudes 92°W - 105°E. The distribution of the focal mechanisms within the study area prior and after 2004 Sumatra-Andaman earthquake is shown in Fig. 2.

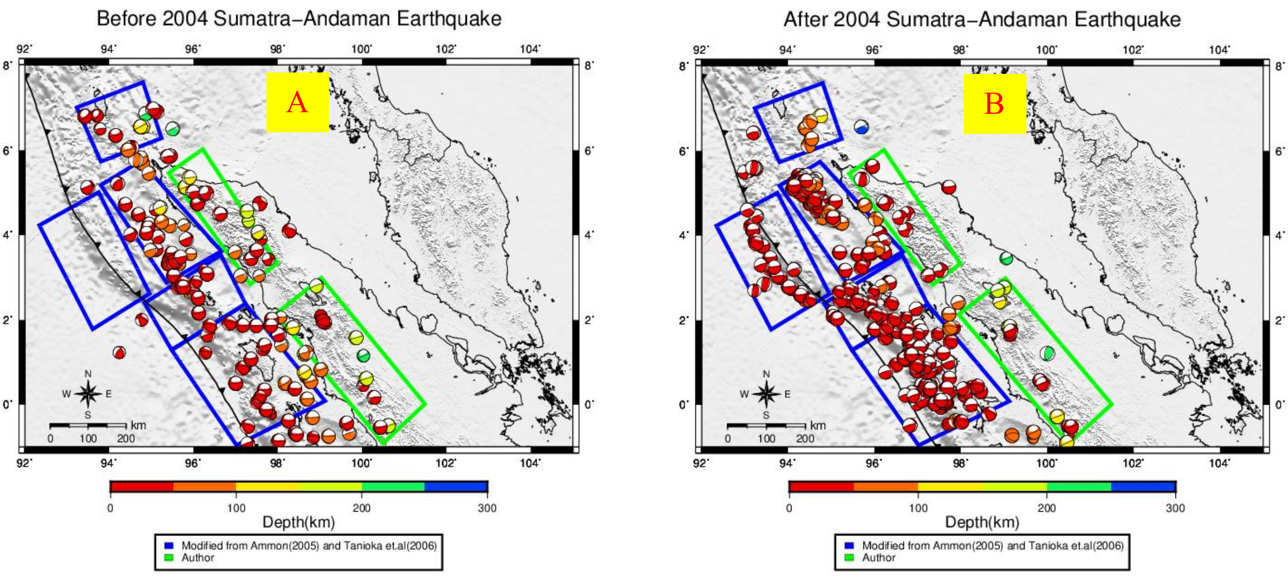

Figure 2. The distribution of focal mechanisms around the study area. Colour represents the depth of the centroid. (A) Focal mechanisms prior to 2004 Sumatra-Andaman earthquake. (B) Focal mechanisms after 2004 Sumatra-Andaman earthquake. Blue and green rectangulars are the segmenatation which used for inverting focal mechanisms.

2.2. Methodology

2.2.1. Stress Inversion. The methods for determining in-situ stress orientation from focal mechanisms solution usually assume that (a) tectonic stress is uniform (homogeneous) in the region, (b) earthquakes occur on pre-existing faults with varying orientations, (c) the slip vector points in the direction of shear stress on the fault (Wallace-Bott hypothesis; [10,11]), and (d) the earthquakes do not interact with each other and do not disturb the background tectonic stress [1]. To satisfy the condition, we divided the area into some segments then distinguished and performed the inversion from clustered earthquakes; not only in space but also in time and periods between prior and after a large earthquake.

The common method used for inverting focal mechanisms is proposed by [12] which quite fast and can be run repeatedly. However, one drawback of this method is that we need to identify the fault orientation which prone to exhibit inaccuracy if the incorrect orientations of fault planes were selected. Vavryčuk [3] coped this disadvantage by using iterative joint inversion of fault plane and applying [13] approach for fault instability constraint. By using this method, we can select arbitrarily one nodal plane from focal mechanisms solution without identifying which one is the fault. Afterwards, the stress inversion method is capable in determining four parameters of the stress tensor : three angles defining the directions of the principal stress, SHmax, Shmin and Sv as well as shape ratio (*R*) which represent as magnitude value of principal stresses. The absolute value of stress tensor is achieved by normalizing the maximum compressive stress in order to overcome the difficulty in obtaining the remaining two parameters of the stress tensor. The details mathematical expression of stress inversion are shown in [12,13].

The procedures of inversion technique proposed by [3] are implementing Michael's method with randomly selected nodal planes. Then, the principal stress directions and shape ratio obtained from this method are evaluated by applying fault instability constraint. The fault planes are the nodal planes which have higher ratio of shear to normal stress known as the unstable nodal planes. The orientations of the fault plane found in the first iteration are used for the next iteration using Michael's method and continued repeatedly until it converges to some optimum values.

3. Results and Discussion

We analysed the variation of the stress orientation and shape ratio within northern Sumatra Island prior and after 2004 Sumatra-Andaman earthquake obtained in this study. The stress inversion was successfully applied for 73 focal mechanisms solutions prior 2004 Sumatra-Andaman earthquake and 281 focal mechanisms solutions after 2004 Sumatra-Andaman earthquake. Following the modified zones of Sumatra Island of [8] and [9], the stress inversion was implemented for 6 segments. One additional segment is introduced after the 2004 Sumatra-Andaman earthquake, in which a new cluster of events were formed. The details of focal mechanisms data and stress orientations prior and after 2004 Sumatra-Andaman earthquake are shown in Table 1 and 2.

In inverting focal mechanisms solution, it is essential to know which one of the nodal planes is the fault. The interchanged between fault and auxiliary planes led to the inaccuracy of the results. To evaluate the robustness of the inversion scheme, Vavryčuk [3] conducted sensitivity tests and concluded that the accuracy of the stress inversion depend on the number of focal mechanisms data, the variance of the nodal plane and on the noise level in the data. Moreover, when evaluating the fault instability, a friction coefficient parameter μ is needed. Byerlee [14] showed frictions of faults most often in range between 0.4 and 0.8, but its value is usually unknown. Vavryčuk [3] used μ from 0.2 to 1.2 in steps of 0.05 and revealed from numerical tests that the inversion is insensitive to μ so one has to be careful in defining the range of μ. In this study, we applied μ from 0.4 to 1 in steps of 0.05 and the inversion is run for range friction values and adopt the value which yields the highest overall instability faults for inverted data. We found that there was no significant changes of the obtained principal stress orientations and, hence, concluded that the inversion is stable.

3.1. Prior to 2004 Sumatra-Andaman Earthquake

Fig. 3(a). shows the maximum principal stress direction of 4 segments; ranges from N192.2°E ± 2.8° to N215.3°E ± 7.3°. The trends are tend to have NE – SW direction are in agreement with the surface horizontal displacement observed by Khan and Gudmundsson [15]. Additionally, fig. 4(a). shows the maximum principal stress direction for 2 segments which located on land to see if there is an influence of the 2004 Sumatra-Andaman Earthquake to the in-situ stress along the Great Sumatran Fault (GSF). The result showed that the maximum principal stress is aligned horizontally in a NNE orientation and is consistent with general trend of maximum horizontal stress in GSF [16, 17].

The shapes ratio obtained in our inversion scheme (see Table 1.) are high, except the D segment. It was expected as the area in subduction zone tends to have a high stress concentration due to the accumulation of the subducted energy. This high stress zone is reflected by the high seismicity density observed. Except for segment D, in which the seismicity density is only $2.6*10^{-4}$ data/km^2. Judging from fig. 3(a) and 4(a), we concluded that seismicity rate in a region highly controlled by the level of the in-situ stress. The shape ratio obtained in this study can be used as a first approximation to the real in-situ stress condition.

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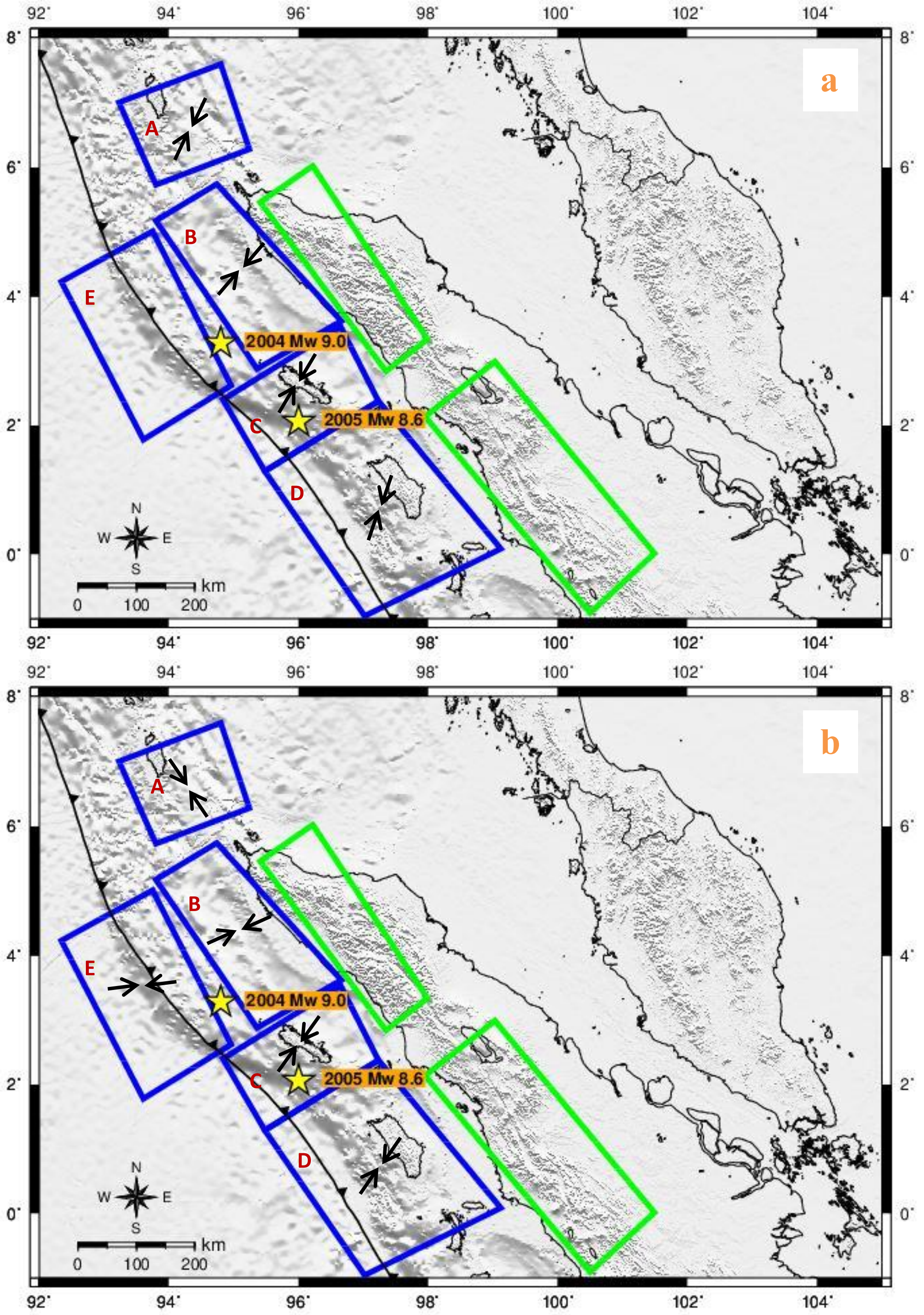
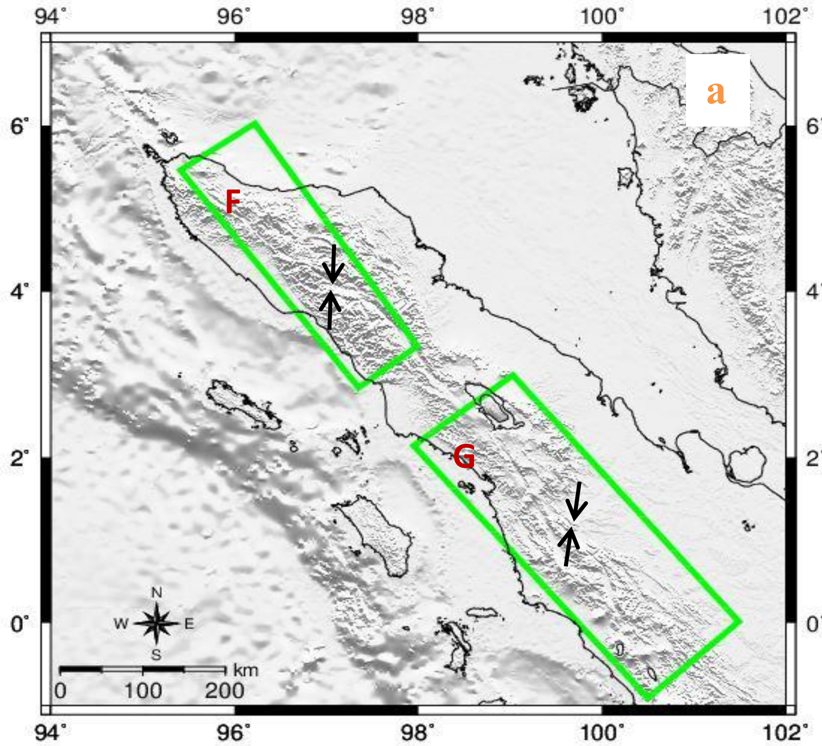


Figure 3. Map showing the variation of maximum principal stress orientation from focal mechanisms data. (a) Prior to 2004 Sumatra-Andaman earthquake and (b) after 2004 Sumatra-Andaman earthquake. Two megathrust earthquakes (yellow triangle) are overlaid. The details of the value of principal stress orientations and shape ratio for each segment are shown in Table 1 and 2.



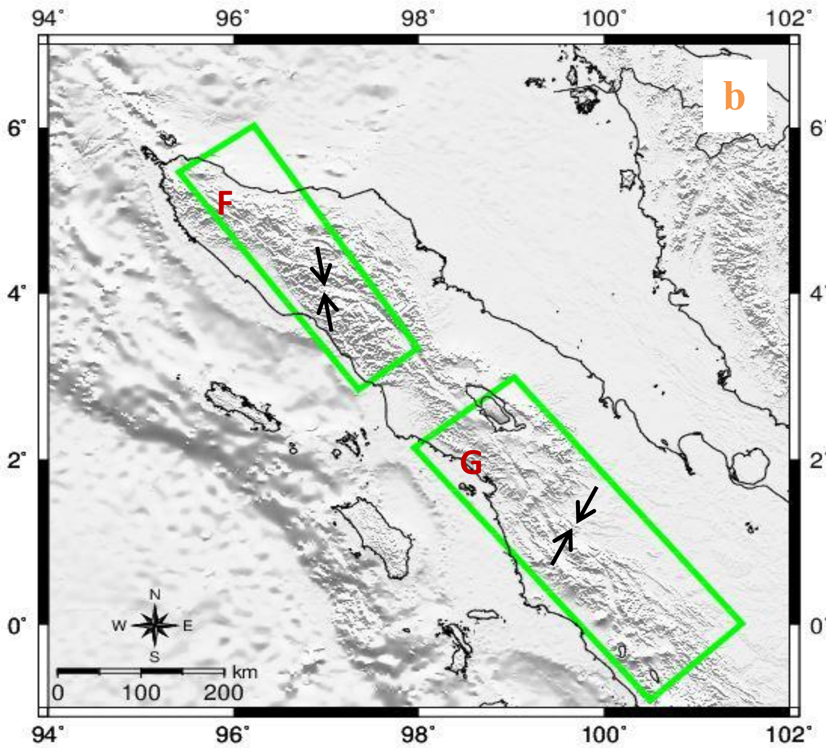


Figure 4. Map showing the variation of maximum principal stress orientation from focal mechanisms data along the Great Sumatran Fault (GSF). (a) Prior to 2004 Sumatra-Andaman earthquake and (b) after 2004 Sumatra-Andaman earthquake. The details of the value of principal stress orientations and shape ratio for each segment are shown in Table 1 and 2.

Table 1. Results of the stress inversion prior to 2004 Sumatra-Andaman earthquake.

Segment	Orientations			Shape Ratio
	σ_1(°) azimuth/plunge	σ_2(°) azimuth/plunge	σ_3(°) azimuth/plunge	
A (9 data)	192.2/8.4 ± 2.8	99.8/26.2 ± 20.4	308.8/72.7 ± 20.3	0.82 ± 8 %
B (12 data)	203.1/27.5 ± 1.5	305.7/22.8 ± 2	69.5/52.9 ± 1.6	0.75 ± 3 %
C (14 data)	215.3/31.7 ± 7.3	308.6/5.4 ± 14.8	47.3/57.7 ± 15.7	0.73 ± 14 %
D (20 data)	201.3/25.4 ± 17.2	293/3.5 ± 19.2	30.3/64.3 ± 11.5	0.42 ± 35 %
F (12 data)	6/6.3 ± 1.1	97/8.3 ± 8.6	239.4/79.5 ± 8.7	0.94 ± 2 %
G (6 data)	189.9/5.7 ± 3.8	99.6/3.2 ± 6.7	340.5/83.5 ± 6.6	0.89 ± 9 %

Note: The errors are the maximum differences between the results calculated for the noise-free and noisy focal mechanisms with 100 random realizations.

Table 2. Results of the stress inversion after 2004 Sumatra-Andaman earthquake.

Segment	Orientations			Shape Ratio
	σ_1(°) azimuth/plunge	σ_2(°) azimuth/plunge	σ_3(°) azimuth/plunge	
A (4 data)	337.4/11.1 ± 12.3	234.8/48.2 ± 85.6	76.8/39.7 ± 84.6	0.79 ± 13 %
B (89 data)	232.8/25 ± 2.8	325.3/5.3 ± 3.7	66.4/64.3 ± 3.3	0.65 ± 3 %
C (37 data)	217.2/16.2 ± 8.1	307.9/2.2 ± 9.1	45.5/73.6 ± 8.3	0.74 ± 35 %
D (110 data)	217.3/38.3 ± 4	126.7/0.6 ± 7.3	35.9/51.7 ± 7	0.96 ± 15 %
E (23 data)	267.2/19.4 ± 3.7	0.2/8.5 ± 3.8	112.8/68.6 ± 2.8	0.48 ± 9 %
F (10 data)	353.4/19.1 ± 1.2	229.2/58.4 ± 19	92.4/24.2 ± 19.1	0.8 ± 7 %
G (8 data)	24/1.4 ± 1.8	275.6/85.6 ± 1.2	114.1/4.2 ± 1.7	0.6 ± 15 %

Note: The errors are the maximum differences between the results calculated for the noise-free and noisy focal mechanisms with 100 random realizations.

3.2. *After 2004 Sumatra-Andaman Earthquake*

Fig. 3(b). Shows the maximum principal stress orientation for 5 segments; ranges from N24°E ± 1.8° to N337.4°E ± 12.3°. Note that there are some significant changes of the direction of maximum principal stress in some segments. We noticed remarkable clockwise principal stress rotations (relative to prior 2004 events) in segment A, B and D of about 145.2°, 29.7° and 16°, respectively. The orientation of the principal stress in segment C is relatively unperturbed by the 2004 events. On land, we also notice a modest stress perturbation of about 12.6° counter clockwise in segment F and of almost 14° clockwise in segment G. In spite of that, it is worth to note that the accuracy of stress inversion depend on the total number of focal mechanisms data. We can see from Table 1 and 2 that segment A, F and G only have a small quantity of data (less than or equal to 12 data), in which we have to be careful to interprete those three segments.

Furthermore, after 2004 Sumatra-Andaman earthquake, we also notice that there is a new seismicity cluster observed at the western part of Sumatra Island (along the Sumatran subduction zone from latitudes of ~2° to ~5°). Interestingly we also observed an increase of shape ratio value in segment E which coincides with the increase of the seismicity density.

4. Conclusion

According to our results, we came up with a conclusion that megathrust earthquakes change the direction of maximum principal stress along northern Sumatra Island, particularly around segment B northern of Sumatra Island and segment D close to the NE direction of Nias Island. A further study of stress modelling is required to analyse the mechanism of the stress changing following the 2004 earthquake. We also showed some positive correlation between in-situ stress level (inferred from the shape ratio) and the seismicity rate in the region. This suggests that the shape ratio need to be determined along the subduction zone in Indonesia to analyse the stress level and, hence, its seismic hazard potential. Following this study, a further stress modelling is planned to have a further insight on how the mechanism of the stress rotation after the 2004 earthquake in the Northern part of Sumatra.

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