Off-fault aftershocks of the 2005 West Off Fukuoka Prefecture Earthquake: Reactivation of a structural boundary?

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After the occurrence of the 20 March 2005 West Off Fukuoka Prefecture Earthquake (M_j 7.0), off-fault aftershocks occurred in and around Hakata bay adjacent to the main fault of the earthquake. The locations of the activity seem to coincide with the Ishido-Uminonakamichi fault (I-U fault), which is a structural boundary and not considered as an active fault. In order to elucidate relations between these off-fault aftershocks and the I-U fault, we determine the double-difference earthquake locations and focal mechanism solutions. Results of the present study show that the off-fault aftershocks are aligned in a sense of left-lateral faulting striking 120° from the north and in that of their conjugate right-lateral fault structures striking 30° from the north. Comparing the trends of these aligned structures with the orientation of the I-U fault, we conclude that earthquakes in and around the Hakata bay occurred along these aligned structures, not along a fault plane inferred from the surface trace of the I-U fault. The analysis of Coulomb failure stress due to the mainshock also supports this conclusion. Stress tensor inversion shows that the stress field in and around the Hakata bay is characterized by a strike-slip faulting. The angles between the fault trends and the maximum principal stress suggest that the aligned structures found in this study are favorably oriented, while the fault plane inferred from the surface trace of the I-U fault is unfavorably oriented.

Key words: 2005 West Off Fukuoka Prefecture Earthquake, off-fault aftershocks, Ishido-Uminonakamichi fault, focal mechanism solutions, double-difference location, stress field.

1. Introduction

The 20 March 2005 West Off Fukuoka Prefecture Earthquake (M_j 7.0) occurred at the region where background seismicity is significantly low (Fig. 1). Here M_j is a magnitude determined by Japan Meteorological Agency (JMA). There are no historical records that large earthquakes occurred at the same place in the past. The aftershock locations suggest that the earthquake occurred over a NW-SE trending zone nearly vertically dipping and extending over a length of about 30 km and a width of about 15 km (e.g., Uehira *et al.*, 2005). The strike-slip focal mechanism of the mainshock was reported by several institutes (e.g., JMA, Harvard University, and U.S. Geological Survey), which is consistent with a left-lateral fault trending about N120°E. Matsumoto *et al.* (2006) obtained the moment tensor solutions of aftershocks around the focal region with M_j exceeding 3.0, and showed that the focal mechanisms of these aftershocks are mainly strike-slip type. Slip distributions derived from waveform inversions suggest that the slip is concentrated at southeast side from the hypocenter (e.g., Horikawa, 2006). The Kego fault exists at the southern end of this earthquake source region and is running through the central part of Fukuoka-city, which is one of large cities in Japan. The length of the Kego fault is estimated about 20 km (e.g., Research Group for Active Faults in Japan, 1991), so that the fault has a potential to cause a M7 earthquake in future. Toda and Horikawa (2005) computed Coulomb failure stress (ΔCFS) on the Kego fault caused by the mainshock and indicated that the period till the next earthquake along the fault has been shortened about 1000 yr by the stress increase due to the mainshock.

After the occurrence of the 2005 West Off Fukuoka Prefecture Earthquake, seismicity in and around Hakata bay became active significantly. Figure 2(b) shows earthquakes per day occurring in and around the Hakata bay (gray bars) along with the cumulative number of earthquakes (solid line). The total number in this region reaches to 1080 at the end of June 2005. Since the region was not ruptured by the mainshock (e.g., Horikawa, 2006; Nishimura *et al.*, 2006), it is likely that the activity was triggered by the stress change due to the mainshock. The magnitude of these earthquakes is mostly less than 2, in which the largest event was M_j 3.8. There is a structural boundary between granitic rocks of Cretaceous and sedimentary rocks of middle to late Eocene, which is named as Ishido-Uminonakamichi fault (I-U fault) (Fig. 2(a)). The fault had been mainly active during the period from the Late Cretaceous to the Pre-Tertiary system (Karakida *et al.*, 1994). It should be noted that locations of the activity seems to coincide with the I-U fault (Fig. 2(a)). Although the fault is not considered as an active fault, the fault might have been reactivated due to the stress increases induced by the 2005 West Off Fukuoka Prefec-

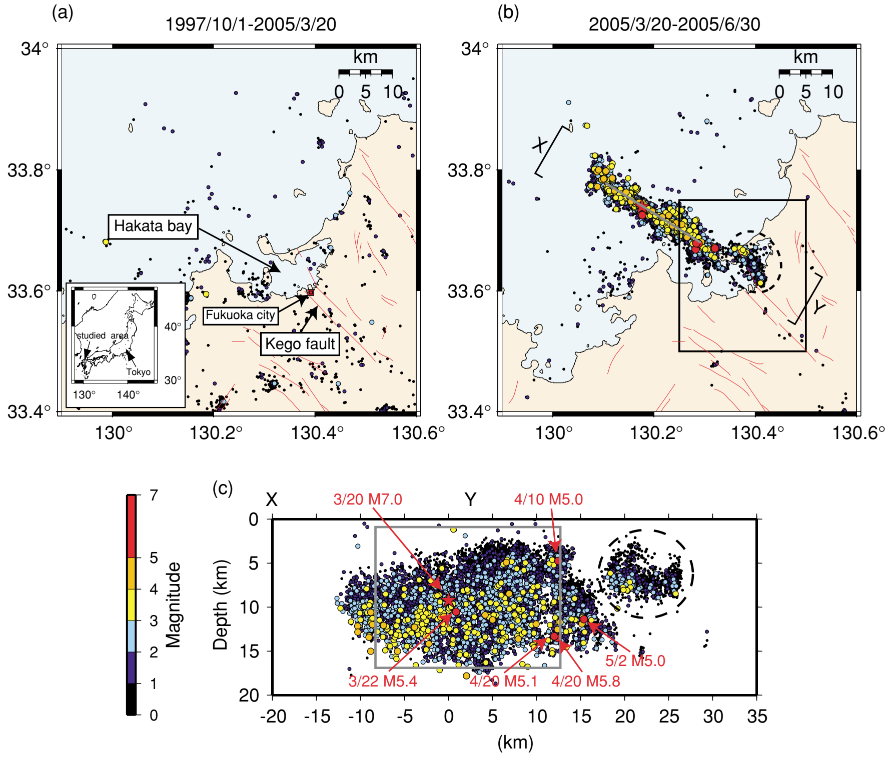

Fig. 1. Seismicity before and after the 2005 West Off Fukuoka Prefecture Earthquake based on JMA catalogue. (a) Background seismicity during about the 7.5-year period before the mainshock. (b) Seismicity during about 3-month period after the mainshock. Red lines represent active faults (Research Group for Active Faults in Japan, 1991). (c) Aftershock locations in a cross-section along X-Y shown in (b). A gray line and rectangle in (b) and (c) define the fault plane assumed by Horikawa (2006). A dotted ellipse shows seismicity in and around the Hakata bay.

ture Earthquake. If it is the case, the I-U fault as well as the Kego fault must be taken into consideration to evaluate the seismic risk in and around the Fukuoka city.

In this paper we determine precise relative locations and focal mechanism solutions of off-fault aftershocks occurring in and around the Hakata bay. Based on these results, we investigate the relationship between the I-U fault and the seismicity. We also calculate the stress transfer in and around the Hakata bay from the mainshock and examine quantitatively whether the mainshock could trigger the seismicity. Finally we estimate the stress field using stress tensor inversion and discuss the stress state in the area. As seen in Fig. 2(a), the I-U fault has different fault strikes in the Hakata bay and in the inland area. For the sake of convenience, we call the former and the latter as the northern part and the southern part of the I-U fault, respectively.

2. Data

Figure 3 shows distributions of permanent stations used in this study, which are operated by NIED (National Research Institute for Earth Science and Disaster Prevention), JMA, and Kyushu University. Each station is equipped with a set of three-component velocity transducers having a natural frequency of 1 or 2 Hz. In particular, seismometers deployed by NIED are installed at the bottom of a borehole with a depth of several hundred meters (Okada *et al.*, 2004). Based on JMA hypocenter catalogue, we selected 829 earthquakes that occurred in and around the Hakata bay during the period from the occurrence of the 2005 earthquake to April 30, 2005. The velocity model (Table 1),

Table 1. Velocity structure.

Depth (km)	P-wave velocity (km/s)
0–5	4.8–5.8
5–30	5.8–7.0
30–	8.0

Vp/Vs is assumed to be 1.73.

which is slightly revised from JMA velocity structure, is used in the following analysis.

3. Relation between Off-fault Aftershocks and the I-U Fault

In order to reveal fine distributions of off-fault aftershock locations, we applied the double-difference earthquake location algorithm of Waldhauser and Ellsworth (2000) to routinely determined P- and S-phase arrival time readings from JMA. Each event is linked to their neighbors through commonly observed phases, with the average distance between linked events being 5 km. Compared to the diffuse locations seen in the JMA catalogue, the relocated hypocenters cluster in narrower zones nearly vertically dipping and reveal several discrete aligned structures (Fig. 4). These aligned structures are mainly trended about 120° from the north, which is similar to the mainshock fault direction. The most remarkable one exists in the northern part, whose length reaches about 4 km. Although not so clear, another aligned structures (30° from the north) might be found, which correspond to conjugate faults of the former ones.

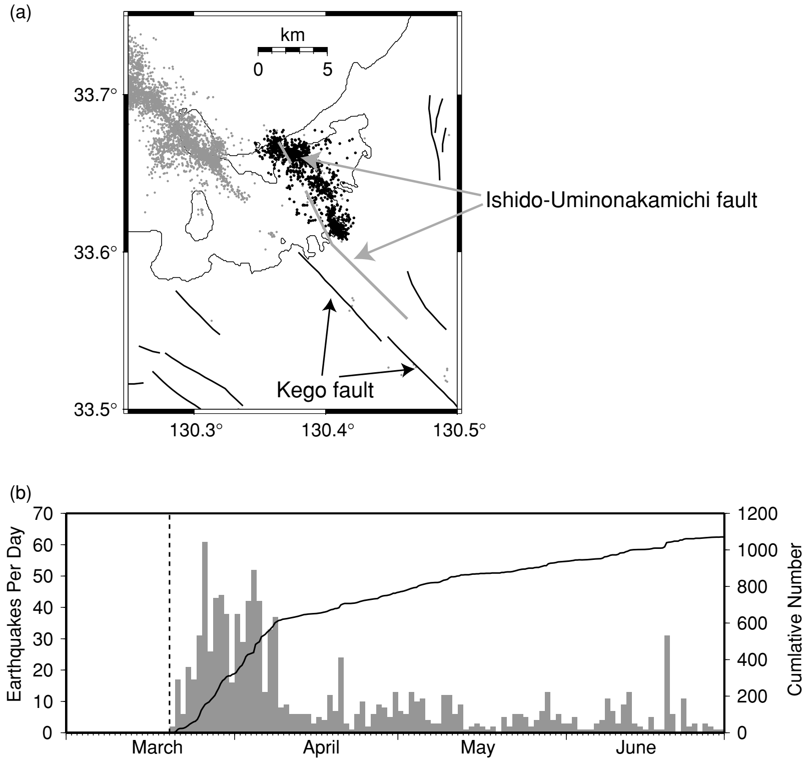

Fig. 2. (a) Seismicity within a solid square in Fig. 1(c) during the period from March 20 to June 30 based on JMA catalogue. Black and gray lines represent active faults and I-U fault, respectively. (b) A plot of earthquakes per day occurring in and around the Hakata bay (gray bars) along with the cumulative number of earthquakes (solid line). Earthquakes shown by black circles in (a) are counted. Dotted lines correspond to the occurrence of the 2005 West Off Fukuoka Prefecture Earthquake.

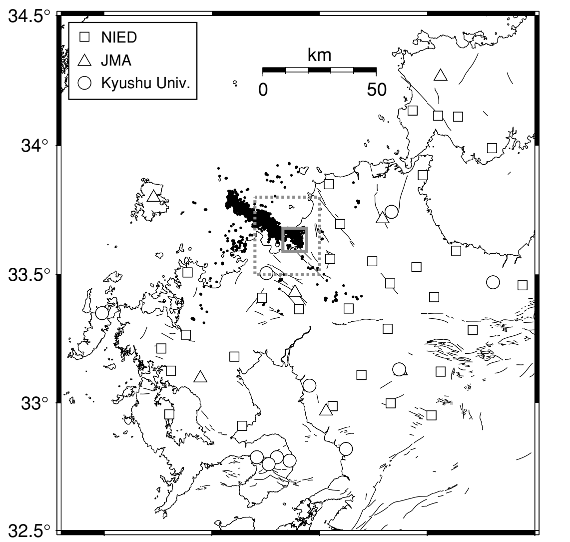

Fig. 3. Station distribution used for the relocation and the focal mechanism determinations. Stations belong to NIED (squares), JMA (triangles) and Kyushu university (circles). Aftershocks of the 2005 West Off Fukuoka Prefecture Earthquake and fault traces are also shown.

Focal mechanisms of earthquakes also provide us information about the aligned structures. Focal mechanisms are ordinarily determined from P-wave polarity data. In the case of small earthquakes like the activity in and around the Hakata bay, however, it is difficult to obtain a unique focal mechanism solution, because the number of stations detecting events is decreased and their azimuthal coverage becomes poor. In order to overcome the problem, we use absolute P- and SH-wave amplitudes as well as P-wave polarity. We first determined focal mechanism solutions and seismic moments of earthquakes with M_j larger than 2, where the number of P-wave polarity data is 15 or greater. We then calculated the logarithmic average of the ratios between theoretical and observed amplitudes of those events, which is used as amplitude station corrections at each station. Using these amplitude station corrections, we redetermined focal mechanism solutions and seismic moments. The stability of the solution was checked by plotting all focal mechanisms whose residual is less than 1.1 times of the minimum residual value. We omitted ambiguous solutions where several solutions were possible. In total, 50 focal mechanisms could be calculated. Most of events are strike-slip faulting, although several events contain some dip-slip components (Fig. 5). Histogram of the orientation of their nodal planes is shown in the inset of Fig. 5. Here 180° is subtracted to fault strike, if necessary, to ensure that all orientations plot in the range from 0° to 180°. The orientations are concentrated on 30° and 120° from the north, which agree well with those inferred from earthquake locations. It should be noted that the trends of both structures are different from the direction of the surface trace of the northern part of the I-U fault (≈150° from the north).

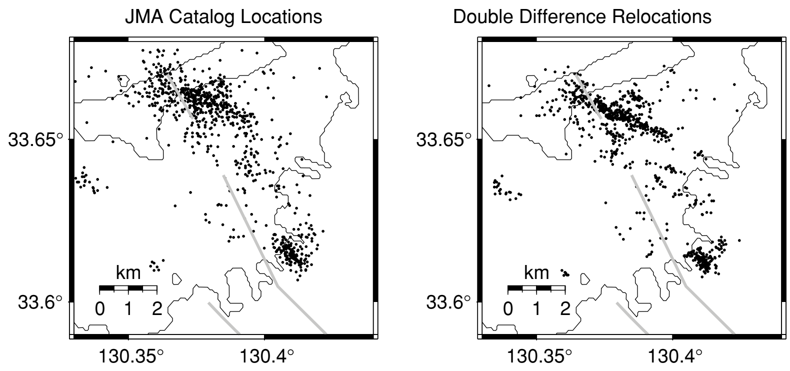

Fig. 4. March 20 to April 30 Hakata bay seismicity before (left) and after (right) double-difference relocation (Waldhauser and Ellsworth, 2000). The region within a gray square is shown.

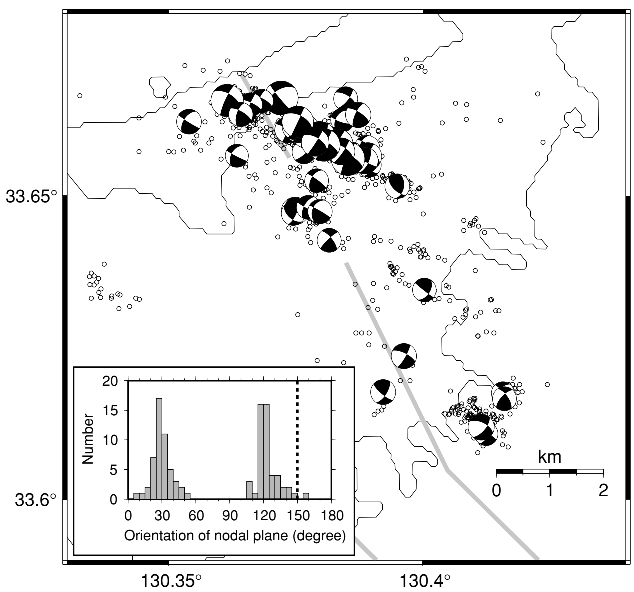

Fig. 5. Focal mechanism solutions determined in this study. The region within a gray square in Fig. 3 is shown. Lower hemisphere of each solution is shown using equal-area projection. Histogram and a dotted line in the inset show the orientation of their nodal planes and the direction of the northern part of the I-U fault, respectively.

4. Stress Transfer in and around the Hakata Bay from the Mainshock

In order to investigate quantitatively whether earthquakes in and around the Hakata bay were triggered by the 2005 West Off Fukuoka Prefecture Earthquake, we computed Coulomb failure stress (ΔCFS) due to the mainshock. Calculations were made in an elastic half-space following Okada (1992) by assuming a shear modulus of 30 GPa and a Poisson's ratio of 0.25. An apparent friction coefficient, which includes the influences of both mechanical friction and pore fluid pressure, was assumed to be 0.4. We used the variable slip model of Horikawa (2006) derived from inversion of near-source ground motions. The location of assumed fault plane is shown in Fig. 1. Although the modeled rupture is 21 km long, the slip is concentrated at southeast side from the hypocenter.

We first evaluated the influence on a fault plane inferred from the surface trace of the northern part of the I-U fault, whose strike is about 150° from the north. In the calculation of ΔCFS, we assume the fault as a vertical left-lateral strike slip fault. As shown in Fig. 6(a), the Hakata bay belongs to the negative ΔCFS regions, which cannot explain the activity in and around the Hakata bay. We then calculated ΔCFS resolved onto the planes of vertical left-lateral strike slip fault (strike 120°, dip 90°, rake 0°) and vertical right-lateral strike slip fault (strike 30°, dip 90°, rake 180°). These receiver faults are expected from earthquake locations and focal mechanism solutions determined in this study. Note earthquakes in and around the Hakata bay occurred in positive ΔCFS regions in both cases (Fig. 6(b) and (c)), which is consistent with the observational evidence that these earthquakes became active following the 2005 event. As seen in Fig. 1(c), the activity is clustered at shallower depth (<10 km). However the stress changes alone can not account for the observation, because the spatial patterns of CFS are similar regardless of depths. These aligned structures might exist only in the shallower part.

5. Stress Field Estimation

Using focal mechanism solutions determined in this study, we inferred the stress field in and around the Hakata bay by applying the inversion method of Michael (1984). The inversion solves for the orientation of the three principal stress axes and the relative magnitude of the principal stresses defined by $\phi = (S_2 - S_3)/(S_1 - S_3)$, where S_1, S_2, and S_3 are the maximum, intermediate, and minimum compressive principal stresses. The 95% confidence region was computed by the bootstrap resampling technique (Michael, 1987a). We use 2000 bootstrap resampling, which is adequate to produce stable confidence regions up to the 95% level (Michael, 1987a). One nodal plane must be selected from each focal mechanism as the actual fault plane. Considering a predominant trend seen in earthquake locations, we selected northeast striking planes. In order to include the effects of mispicked fault planes on the confidence region, we presumed that another nodal plane has a 20% probability of being chosen during the resampling. The results of the stress inversion are plotted in Fig. 7. Average misfit angles between the predicted tangential traction on the fault planes and the observed slip direction on each plane are 18°, indicating a valid fit to a single stress tensor (Michael, 1991). The orientations of the principal stress axes are nearly ver-

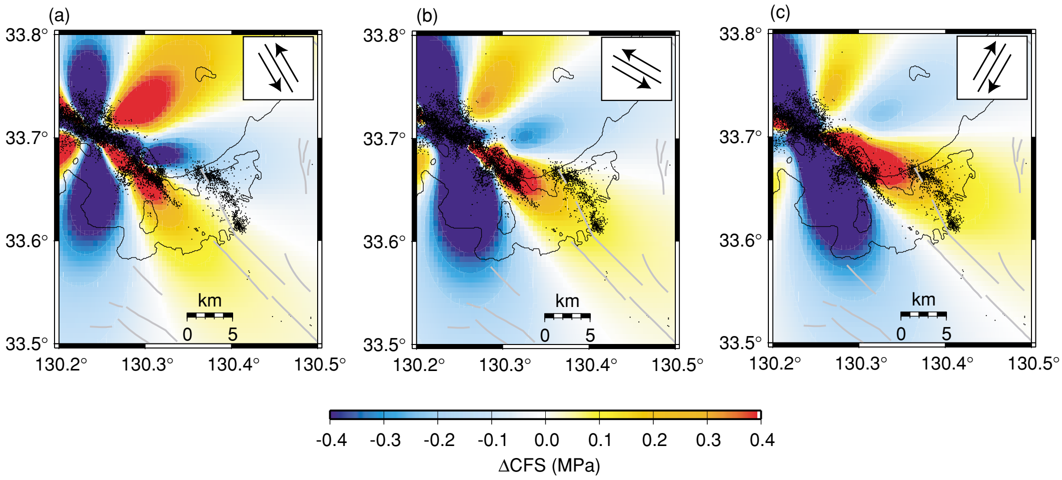

Fig. 6. Map views of Coulomb failure stresses at a depth of 7 km caused by the mainshock of the 2005 West Off Fukuoka Prefecture Earthquake. The values within a gray broken rectangle in Fig. 4 are shown. The receiver faults are the northern part of the I-U fault (a), predominant aligned structures found in this study (b), and their conjugate structures (c). Circles show aftershock locations determined by JMA during the period from March 20 to June 30.

tical for S_2 and horizontal for S_1 and S_3. This suggests that the stress field in and around the Hakata bay is characterized by a strike-slip faulting. The S_1 trended N80°±9°E, where the error bar represents the 95% confidence limits. The ϕ value is 0.43 ± 0.05, implying that the intermediate principal stress S_2 is close to $(S_1 + S_3)/2$.

The estimated stress tensor equals the premainshock stress tensor plus the stress change tensor due to the mainshock. When the amount of stress change is a large fraction of the pre-stress level, the stress field would change before and after the mainshock. In fact, there are several observations that the stress rotations happened due to the occurrence of large and moderate earthquakes (e.g., Michael, 1987b; Hauksson, 1994; Zhao *et al.*, 1997; Yamashita *et al.*, 2004). Assuming hydrostatic pore pressure, a coefficient of friction of 0.6, a vertical stress S_v equal to the overburden pressure, and $S_2 = S_v = (S_1 + S_3)/2$, the Coulomb failure criterion predicts a maximum shear stress is about 60 MPa at a depth of 7 km. On the other hand, the changes of the maximum shear stress due to the mainshock are 0.5 MPa at most in and around the Hakata bay. It is likely that the 2005 earthquake did not change the orientations of the principal stresses in and around the Hakata bay. Thus we consider our estimated stress tensor represents a permanent stress field in the area.

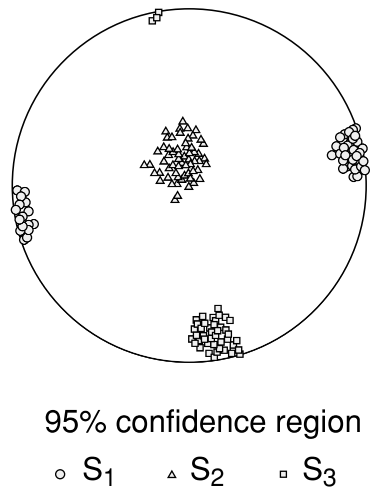

Fig. 7. Stress inversion result. Principal stress axes with their 95% confidence limits are plotted on lower hemisphere stereonets.

6. Discussions

We have shown that the strikes of small-aligned structures in and around the Hakata bay are different from that of the surface trace of the northern part of the I-U fault. This suggests that earthquakes in and around the Hakata bay occurred along some small-aligned structures, not along a fault plane inferred from the surface trace of the I-U fault.

The angle between the fault trend and the maximum principal stress is important to investigate the stress state along the faults. The angles are about 30° for the predominant aligned structures found in this study, 50° for their conjugate ones, and 70° for the northern part of the I-U fault, respectively. This implies that the shear stress resolving along the fault plane is large for the predominant aligned structures and especially small for the northern part of the I-U fault. It is likely that the permanent stress field makes it difficult to reactivate the fault plane inferred from the surface trace of the northern part of the I-U fault within Byerlee's (1978) range of rock friction coefficients ($0.6 < \mu < 0.85$), which are widely applicable to natural faults (e.g., Sibson, 1994). In addition to that, the Coulomb failure stresses resolved onto the fault plane inferred from the surface trace of the northern part of the I-U fault are negative (Fig. 6(a)), thereby rendering the fault less likely to produce an earthquake.

At present, there are no information about stress field in and around the Kego fault and the southern part of the I-U fault. Because the stress field can be spatially heterogeneous with a length scale of tens of kilometers or less (e.g., Hardebeck and Hauksson, 2001), it is not appropriate to apply the stress field estimated in the Hakata bay to the region. Since seismic activity in the region is low and their magnitudes are mostly less than 2 (Fig. 1(a) and (b)), we should establish a dense seismic observation to determine accurate focal mechanism solutions of those microearthquakes and/or conduct in-situ stress measurements.

7. Conclusion

Based on precise earthquake locations and focal mechanism solutions, we have resolved detailed aligned structures in and around the Hakata bay. We found that there are predominant aligned structures for left-lateral faulting striking 120° from the north. Conjugate right-lateral aligned structures (30° from the north) might be also delineated. Since the trends of these structures are different from the orientation of the northern part of the I-U fault by about 30° and 60°, respectively, we conclude that earthquakes in and around the Hakata bay occurred along some small-aligned structures, not along the fault plane inferred from the surface trace of the I-U fault. The analysis of ΔCFS also supports this conclusion. Stress tensor inversion reveals that the stress field in and around the Hakata bay is characterized by a strike-slip faulting. The maximum principal horizontal stress trends 80° from the north, suggesting that the aligned structures found in this study are favorably oriented, while the fault plane inferred from the surface trace of the northern part of the I-U fault is unfavorably oriented.

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