Aftershock seismicity and fault structure of the 2005 West Off Fukuoka Prefecture Earthquake ($M_{\rm JMA}$7.0) derived from urgent joint observations

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On March 20, 2005, a large $M_{\rm JMA}$7.0 earthquake occurred in the offshore area, west of Fukuoka prefecture, northern Kyushu, Japan. A series of joint observations were carried out by teams from several universities in Japan with the aim of investigating the aftershock activity. Six online telemetered and 17 offline recording seismic stations were installed on land around the aftershock area immediately followed the occurrence of the mainshock. Because aftershocks were located mainly in offshore regions, we also installed 11 ocean bottom seismometers (OBSs) just above the aftershock region and its vicinity in order to obtain accurate locations of hypocenters. The OBS observation was carried out from March 27 to April 13, 2005. We further conducted temporary GPS observations in which ten GPS receivers were deployed around the aftershock region. The aftershocks were mainly aligned along an approximately 25-km-long NW-SE trend, and the hypocenters of the main aftershock region were distributed on a nearly vertical plane at depths of 2–16 km. The mainshock was located near the central part of the main aftershock region at a depth of approximately 10 km. The largest aftershock of $M_{\rm JMA}$5.8 occurred near the southeastern edge of the main aftershock region, and the aftershock region subsequently extended about 5 km in the SE direction as defined by secondary aftershock activity. Enlargement of the aftershock region did not occur after the peak in aftershock activity, and the aftershock activity gradually declined. The distribution of hypocenters and seismogenic stress as defined by aftershocks suggest that the 2005 West Off Fukuoka Prefecture Earthquake occurred on the fault that is the NW extension of the Kego fault, which extends NW-SE through the Fukuoka metropolitan area, and that the largest aftershock occurred at the northwestern tip of the Kego fault.
Key words: The 2005 West Off Fukuoka Prefecture Earthquake, intraplate earthquake, mainshock, aftershock, seismic observation, hypocenter distribution, active fault, Kego fault.

1. Introduction

On March 20, 2005, a large intraplate earthquake with a Japan Meteorological Agency magnitude ($M_{\rm JMA}$) of 7.0 occurred in Genkainada, in the offshore region west of Fukuoka prefecture, in northern Kyushu, Japan. Many houses and infrastructure were damaged in the surrounding area, especially on Genkaijima Island and in and around Fukuoka City. One resident was killed by the collapse of a concrete-block wall and more than 1,000 people were injured in the earthquake.

Kyushu is located at the junction of the Southwestern Japan Arc and the Ryukyu Arc. Interplate earthquakes of $M = 7$ occur here in response to subduction of the Philippine-sea plate at Hyuganada, east of Kyushu, in offshore regions at an interval of several tens of years. The tectonics of onshore Kyushu is characterized by north-south extension (e.g. Tada, 1984), where the Beppu-Shimabara graben has been formed in central Kyushu (Matsumoto, 1979). Strain in central Kyushu is very high. Geodetic data acquired during the past 100 years by the Geographical Survey Institute reveals a N-S extension at a rate of about 1.4 cm/year (strain rate=20–30$\times10^{-8}$/year) and subsidence of 2 mm/year in the graben (Tada, 1985; GSI, 1987). The rate of intraplate earthquake production is also high in central Kyushu (e.g., Shimizu *et al.*, 1993). Alternatively, the tectonics in northern Kyushu is relatively inactive: the crustal

Table 1.

Station code	Organization	System	Start day	End day	Sensor type	Sampling rate [Hz]	Resolution of AD converter [bit]	Notes
KU.FKSQ	Kyushu Univ.	VSAT	2005.3.21	2005.5.20	1Hz/3D	100	22	moved to KU.FKS3
KU.FKS3	Kyushu Univ.	ISDN line	2005.5.20		1Hz/3D	200	24	
KU.FKGQ	Kyushu Univ.	Radio	2005.3.21	2005.4.1	2Hz/3D	100	14	moved to KU.FKG2
KU.FKG2	Kyushu Univ.	VSAT -> ISDN line	2005.4.1		2Hz/3D	200	24	
KU.FKKQ	Kyushu Univ.	Radio -> ISDN line	2005.3.23		2Hz/3D	200	14	
DP.AINS	Kyoto Univ.	VSAT	2005.3.24		2Hz/3D	100	22	
KU.FORQ	Kyushu Univ.	ISDN line	2005.3.27		2Hz/3D	200	24	
TU.NJH	Tohoku Univ.	offline -> ISDN line	2005.3.23		2Hz/3D	200	24	
KU.FKUQ	Kyushu Univ.	offline	2005.3.21		2Hz/3D	200	16	
HU.KTZ	Hokkaido Univ. and Kagoshima Univ.	offline	2005.3.21	2005.6.28	strong motion accelerometer	100	24	
HU.KIY	Hokkaido Univ. and Kagoshima Univ.	offline	2005.3.21	2005.12.19	strong motion accelerometer	100	24	
HU.GKJ	Hokkaido Univ. and Kagoshima Univ.	offline	2005.3.21	2005.6.29	strong motion accelerometer	100	24	
G.KEYA	Kagoshima Univ.	offline	2005.3.21	2005.7.28	2Hz/3D	100	16	moved to KU.KEYA
KU.KEYA	Kyushu Univ.	offline	2005.7.28		2Hz/3D	200	16	
G.NOKO	Kagoshima Univ.	offline	2005.3.21	2005.7.28	2Hz/3D	100	16	
KU.FTYQ	Kyushu Univ.	offline	2005.3.21	2005.6.23	1Hz/3D	200	14	moved to KU.FTY2
KU.FTY2	Kyushu Univ.	offline	2005.6.23	2005.12.12	1Hz/3D	200	14	moved to KU.FTY3
KU.FTY3	Kyushu Univ.	offline	2005.12.12		1Hz/3D	200	14	
KU.FOSQ	Kyushu Univ.	offline	2005.3.21		2Hz/3D	200	16	
KU.FMKQ	Kyushu Univ.	offline	2005.3.21		1Hz/3D	200	16	
KU.FOR2	Kyushu Univ.	offline	2005.3.22	2005.4.21	1Hz/3D	200	20	
G.HAGI	Kagoshima Univ.	offline	2005.3.22	2005.7.28	2Hz/3D	100	24	
G.KASG	Kagoshima Univ.	offline	2005.3.22	2005.7.28	2Hz/3D	100	24	moved to KU.KASG
KU.KASG	Kyushu Univ.	offline	2005.7.28		2Hz/3D	200	16	
KU.FKS1	Kyushu Univ.	offline	2005.3.22	2005.9.19	2Hz/3D	200	14	
KU.FKS2	Kyushu Univ.	offline	2005.3.22	2005.9.19	2Hz/3D	200	16	
TU.AIN	Tohoku Univ.	offline	2005.3.22	2005.6.1	2Hz/3D	200	24	
G.SIGE	Kagoshima Univ.	offline	2005.3.23	2005.7.28	2Hz/3D	100	24	
OBS01	Tokyo Univ.	OBS	2005.3.26	2005.4.14	4.5Hz/3D	128	16	
OBS02	Kyushu Univ.	OBS	2005.3.26	2005.4.13	4.5Hz/3D	128	16	
OBS03	Kyushu Univ.	OBS	2005.3.26	2005.4.13	4.5Hz/3D	128	16	
OBS04	Tokyo Univ.	OBS	2005.3.26	2005.4.13	4.5Hz/3D	128	16	
OBS05	Kyushu Univ.	OBS	2005.3.27	2005.4.13	4.5Hz/3D	128	16	
OBS06	Tokyo Univ.	OBS	2005.3.26	2005.4.14	4.5Hz/3D	128	16	
OBS07	Kyushu Univ.	OBS	2005.3.26	2005.4.13	4.5Hz/3D	128	16	
OBS08	Tokyo Univ.	OBS	2005.3.26	2005.4.14	4.5Hz/3D	128	16	
OBS09	Kyushu Univ.	OBS	2005.3.27	2005.4.13	4.5Hz/3D	128	16	
OBS10	Kyushu Univ.	OBS	2005.3.27	2005.4.13	4.5Hz/3D	128	16	
OBS12	Kyushu Univ.	OBS	2005.3.27	2005.4.13	4.5Hz/3D	128	16	

strain rate near the northern coast of Kyushu has been approximately 5×10^{-8}/year during the past 100 years (GSI, 1987), and fewer than 20 earthquakes with magnitudes of less than 2.5 have been detected at the source region of the 2005 West Off Fukuoka Prefecture Earthquake during the past 20 years.

The 2005 West Off Fukuoka Prefecture Earthquake was one of the major intraplate earthquakes in the inner arc of both the Southwestern Japan Arc and the Ryukyu Arc, and the largest event in northern Kyushu since the 1700 Iki-Tsushima earthquake ($M = 7$). In northern Kyushu, a destructive earthquake of $M_{\mathrm{JMA}}6.0$ occurred in 1898 at the Itoshima peninsula about 20 km south of the 2005 West Off Fukuoka Prefecture Earthquake (Usami, 1966). However a detailed hypocenter location and focal mechanism were not determined for this event. Our investigations of the 2005 Fukuoka Earthquake are therefore important in terms of revealing the generation mechanism of intraplate earthquakes occurring in northern Kyushu, the junction of the Southwestern Japan Arc and the Ryukyu Arc. Furthermore, the Kego fault, which is an active fault crossing the Fukuoka metropolitan area, extends towards the source region of the 2005 Fukuoka Prefecture Earthquake, and it is possible that the Kego fault slipped in the 2005 earthquake (Meteorological Research Institute, 2005; Geological Survey of Japan, 2005). We carried out joint observations in a collaborative effort by several universities in Japan with the aim of investigating the aftershock activity of the 2005 earthquake. In this paper, we report these observations and the space-time patterns of the aftershock sequence.

2. Aftershock Observation

Seismic networks of the Japan Meteorological Agency (JMA), the National Research Institute for Earth Science and Disaster Prevention (NIED), and Kyushu University are operative in northern Kyushu, and their seismic data are mutually exchanged in real time. These networks consist of permanent seismic stations and they were spaced at about 30-km intervals in the inland area, which enabled us to determine the hypocenter of the 2005 West Off Fukuoka Prefecture Earthquake and define the aftershock sequence.

In an effort to determine the aftershock activity in more detail, observations of aftershocks began the day after the mainshock by Kyushu University, Hokkaido University, Tohoku University, the University of Tokyo, Kyoto University, and Kagoshima University. The installation of all 17 offline seismic stations was completed within 3 days after the mainshock occurred. In addition to the offline stations, we also installed six online temporary seismic stations. These seismic stations were located on islands and along the coast-

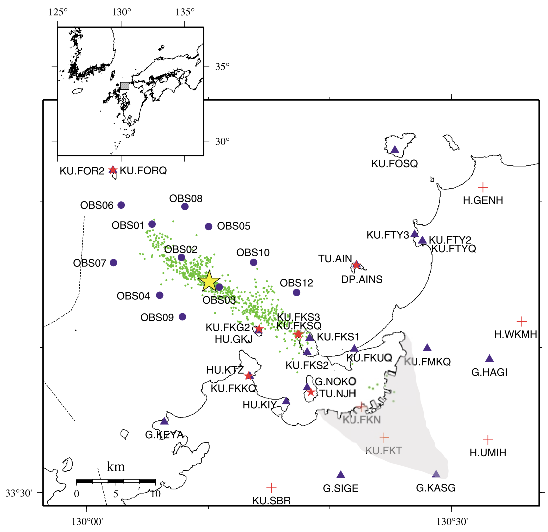

Fig. 1. Location map of the seismic stations. Crosses, small stars, triangles and circles indicate the permanent online, temporary online, temporary offline and temporary OBS stations, respectively. The epicenter distribution before the urgent joint observation period is also shown in the map. The large star represents the epicenter of the mainshock (M_{JMA}7.0), and the green dots denote the epicenters of aftershocks. The grey shaded area shows the Fukuoka metropolitan area.

line of Fukuoka prefecture in a 50×50-km area surrounding the aftershock region (Fig. 1).

Each offline station consisted of a three-component geophone and digital data logger with GPS clock (accuracy of approx. 1 ms). Seismic data were continuously recorded at the logger with a sampling frequency of 100 or 200 Hz. The dynamic range of the system varied by logger-type and ranged from 14 to 24 bit. Each online station consisted of a three-component geophone and a telemetry system that mainly used the Integrated Services Digital Network (ISDN). The dynamic range of the telemetry system was from 14 to 24 bit. On Genkaijima and Shikanoshima Islands, which were close to the aftershock region and strongly damaged by the mainshock, we first deployed portable radio-wave and satellite (VSAT: Very Small Aperture Terminal) telemetry systems, respectively, because they were able to be set up in a damaged area without usable infrastructure. These two stations were operative from March 21, the day after the mainshock, and were moved to the neighborhoods, thereby replacing the telemetry system with the ISDN system, on April 1 for Genkaijima and May 20 for Shikanoshima. Seismic data of the online stations were telemetered to the Institute of Seismology and Volcanology (SEVO), Kyushu University, and were processed together with data from the permanent seismic networks. In addition, seismic data of the four stations among online stations were transmitted to the JMA in order to support monitoring of the aftershock activity.

Because most of the aftershocks occurred offshore, we deployed ocean bottom seismometers (OBSs) for the accurate determination of hypocenter locations. Temporary observations for 19 days with 11 pop-up type OBSs were carried out around the aftershock area starting 6 days after the mainshock by SEVO, the Earthquake Research Institute (ERI), and the University of Tokyo (Fig. 1). The deployment of OBSs was conducted using M/V Fujisan-maru (Dokai Marine Co., Japan) chartered by Kyushu University on March 26 and 27, and all the OBSs were successfully recovered by P/V Genkai belonging to the Fukuoka Fisheries and Marine Technology Research Center, Fukuoka Prefecture, on April 13 and 14. The OBSs used in our observations had been originally developed by The Earthquake Research Institute and consisted of a three-component 4.5-Hz geophone and a continuously recording hard-disk unit housed in the pressure sphere. The sampling frequency and dynamic range of the system were 128 Hz and 16 bit, respectively.

Seismic event data recorded at offline land stations and the ocean bottom were combined with those recorded at online stations and subsequently used for the hypocenter determination and focal mechanism analysis. The specification of all the temporary seismic stations in the observations is listed in Table 1.

In addition to seismic observations, a temporary GPS observation was carried out by Kyushu University, Hokkaido University and Kagoshima University in order to detect the post-seismic crustal deformation. We installed ten GPS receivers around the aftershock region, and analyzed our GPS data together with the GEONET data of the Geographical Survey Institute (GSI), Japan. The results of the GPS observation are reported by Nakao *et al.* (2006).

3. Hypocenter Distribution of Aftershocks

Hypocenter determination of the earthquakes, based on detection by the seismic network of SEVO, Kyushu University, was carried out. Event detection and the picking of P- and S-wave arrival times were performed using the WIN system (Urabe and Tsukada, 1991), and a maximum-likelihood method was used in the calculation of hypocenter locations (Hirata and Matsu'ura, 1987). In the calculation of hypocenters and focal mechanisms, we assumed the one-dimensional velocity structure model used in the data processing at SEVO (see figure 2 of Uehira *et al.*, 2006). The magnitudes of aftershocks were determined using maximum amplitudes of velocity seismograms, which are empirically consistent with JMA magnitudes (Watanabe, 1971).

About 13,000 hypocenters were determined from March 20 to November 20, 2005 for the aftershocks, with magnitudes ranging from 0.0 to 5.8. With respect to the mainshock and the aftershocks that occurred within a day of the mainshock, data from the permanent seismic networks were used in the hypocenter determination because the temporary observation stations were not yet operating. The number of seismic stations subsequently used in the hypocenter determination subsequently increased with the deployment of temporary seismic stations. The accuracy of the hypocenter locations therefore improved with time, and the most precise hypocenters were obtained from March 27 to April 13 because of the OBS observations. Since details of the hypocenter distribution in the period of OBS observation are discussed by Uehira *et al.* (2006), we limit our discussion in this article to the distribution of aftershocks in the sequence and the fault system inferred from aftershock activity.

Figure 2 shows the hypocenter of the mainshock of

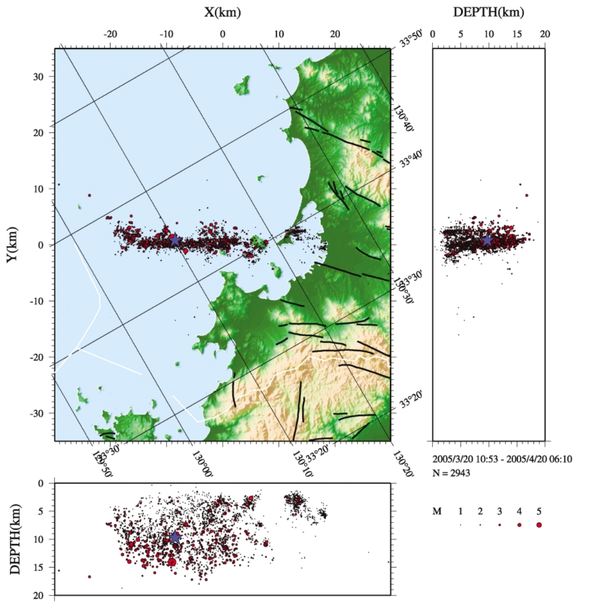

Fig. 2. Hypocenter distribution of the aftershocks before the largest aftershock of MJMA5.8 occurred (March 20–April 20, 2005). The star indicates the mainshock (M_{JMA}7.0) on March 20. The distribution of active faults, as determined by the Research Group for Active Faults of Japan (1991), is shown by the thick lines in the map. Note that the map is rotated counterclockwise by 30° so that the cross sections become approximately parallel and perpendicular to the alignment of aftershock distribution.

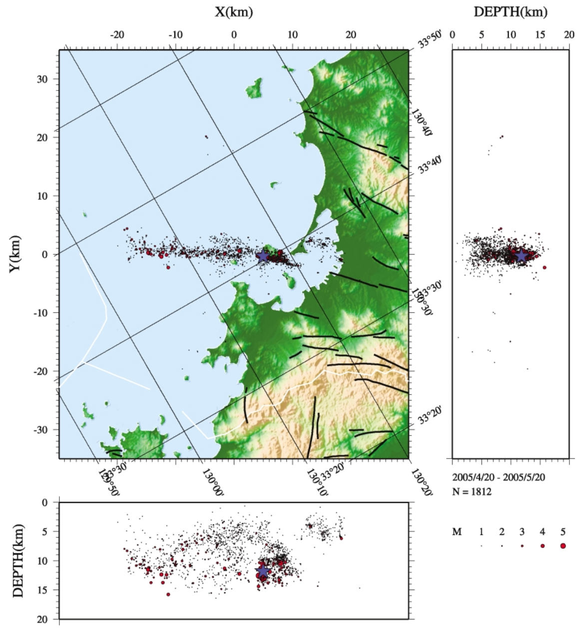

Fig. 3. Hypocenter distribution of the aftershocks during the month immediately following the largest aftershock (April 20–May 20, 2005). The star indicates the largest aftershock (M_{JMA}5.8) on April 20. The cluster of the secondary aftershocks of the largest aftershock is recognized at the SE side of the largest aftershock.

March 20 and aftershocks from March 20 to April 20. The epicenters were mainly aligned NW-SE in an approximately 25-km-long trend. Minor clusters are located at the SE extension of the main aftershock region. Hypocenters of the main aftershock region are distributed on a nearly vertical plane, and their depths range from 2 to 16 km. The mainshock was located near the central part of the region at a depth of approximately 10 km. The focal mechanism solution of the mainshock was a strike-slip fault type, and one of the nodal planes was consistent with the trend of the aftershock distribution (Matsumoto *et al.*, 2006; Uehira *et al.*, 2006).

These results revealed the orientation of the fault plane of the 2005 West Off Fukuoka Prefecture Earthquake: the strike and dip of the fault were approximately N60°W and 90°, respectively, and the length and width of the fault were about 25 km and 14 km, respectively. The rupture with a left-lateral strike-slip dislocation initiated near the center of the aftershock sequence and expanded bilaterally about 10 km toward the NW and 15 km toward the SE. The rupture of the mainshock stopped beneath Shikanoshima Island, about 10 km northwest of the central Fukuoka City. About 5 km from the northwestern end of the fault, it changed geometry in a bend oriented about N45°W as based on the hypocenter distribution (Fig. 2). Focal mechanism solutions of the aftershocks also changed near the northwestern end of the fault in correspondence to the bend (Uehira *et al.*, 2006).

The largest aftershock of M_{JMA}5.8 occurred near the southeastern edge of the main aftershock region on April 20, 2005. The secondary aftershock activity followed the largest aftershock, and the aftershock region subsequently extended about 5 km in the SE direction (Fig. 3). The focal mechanism solution of the largest aftershock was a strike-slip fault type with E-W compression and N-S extension, similar to that of the mainshock (Uehira *et al.*, 2006). These suggest that the largest aftershock occurred by the southeast extension of the rupture of the mainshock fault. However, the distribution of epicenters of the secondary aftershocks in Fig. 3 and a nodal plane of the focal mechanism solution for the largest aftershock imply that the strike of the largest aftershock fault was oriented here approximately 10° to the south compared with that of the mainshock (Ito *et al.*, 2006; Uehira *et al.*, 2006).

The aftershock activity decreased gradually with time, although the seismicity increased during periods associated with major aftershocks. Figure 4 shows the monthly distribution of aftershock epicenters from May 20, 2005 to November 20, 2005. The enlargement of the aftershock region was not obviously recognizable in this period. The aftershock occurrence was roughly uniform, and no spatial bias of seismicity was found in the aftershock region. However, major aftershocks ($M > 4$) had a tendency to occur near the hypocenter of the mainshock, the northwestern end, and the southeastern end of the aftershock region.

4. Discussion

The JMA (2005) determined the hypocenter distributions of the mainshock and aftershocks of the 2005 West Off Fukuoka Prefecture Earthquake with the aim of monitoring seismic activity. The hypocenters determined by the JMA are distributed about 30 km in the NW-SE direction and 5–16 km in depth. Alternatively, the hypocenters in this study are about 2–16 km deep, as shown in Fig. 2, and the upper boundary of the distribution is about 3 km shallower than those by the JMA. It was confirmed that the

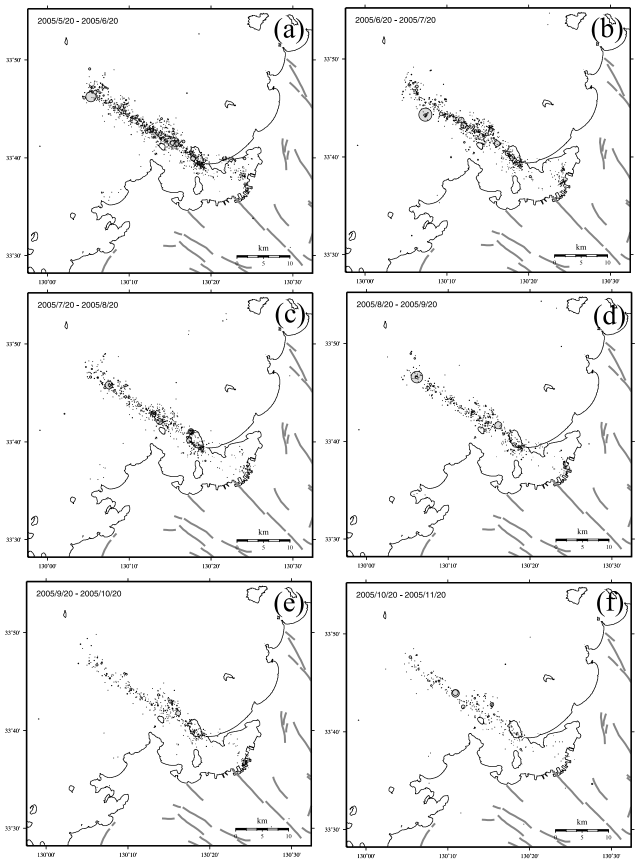

Fig. 4. Epicenter distributions of aftershocks from May 20 to November 20, 2005. The thick lines represent the active faults. The major aftershocks ($M > 4$) are shown by the large circles. (a) May 20–June 20, 2005, (b) June 20–July 20, 2005; (c) July 20–August 20, 2005; (d) August 20—September 20, 2005; (e) September 20–October 20, 2005; (f) October 20–November 20, 2005.

hypocenter depths for the shallow events were less accurate and assessed to be deeper in the absence of data from the temporary stations close to the source region (Uehira *et al.*, 2006). The accuracy of hypocenter locations, especially the hypocenter depths, was clearly improved by the joint observations produced by our work.

The 2005 West Off Fukuoka Prefecture Earthquake and most of the major aftershocks are consistent with EW-compressional and NS-tensional stresses. Figure 5 shows the orientation of the maximum principal stresses (compression axes) and the minimum principal stresses (tension axes) derived from focal mechanism solutions of the earthquakes shallower than 30 km in the Kyushu district. The compression and tension axes are oriented roughly in the E-W or NE-SW direction and the N-S or NW-SE direction, respectively, in the region. Both compression and tension axes are nearly horizontal, and thus strike slip faults are dominant in northern Kyushu. In central Kyushu, however, we note that some compression axes are inclined and some of them are nearly vertical. This is consistent with the development of normal faults that form the Beppu-Shimabara graben. The orientation of principal stresses in southwestern Kyushu is slightly rotated counterclockwise compared with that in northern Kyushu; consequently, the NE-SW compression and NW-SE tension become dominant.

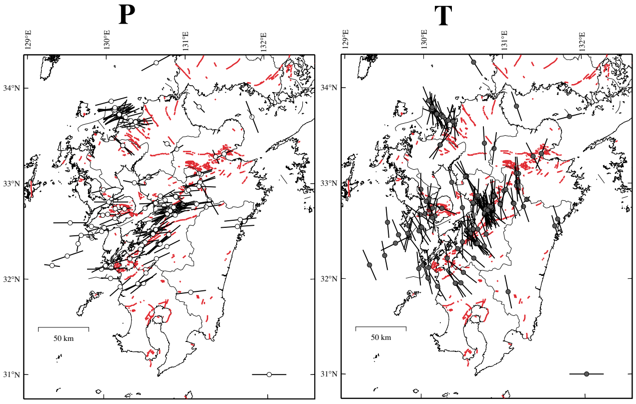

Fig. 5. Distribution of the principal stress orientation inferred from the focal mechanism solutions for the earthquakes shallower than 30 km in Kyushu. The results of the focal mechanism analysis for the 2005 West Off Fukuoka Prefecture Earthquake and its major aftershocks are included in the distribution of the principal stress orientation. (a) The maximum principal stresses (compression axes); (b) the minimum principal stresses (tension axes).

The past major earthquakes in the inner-arc of the Southwestern Japan Arc, such as the 1943 Tottori Earthquake of $M_{\mathrm{JMA}}7.2$ (Kanamori, 1972), the 1995 Hyogo-ken Nanbu Earthquke of $M_{\mathrm{JMA}}7.2$ (JMA, 1995), and the 2000 Western Tottori Earthquake of $M_{\mathrm{JMA}}7.3$ (JMA, 2001), were all generated by strike slip faulting with nearly horizontal E-W compression and N-S tension axes. These features are the same as those earthquakes in northern Kyushu shown in Fig. 5 and imply that the 2005 West Off Fukuoka Prefecture Earthquake was caused by the regional stress field in the inner-arc of the Southwestern Japan Arc.

There are several active faults formed in the regional tectonic stress field in northern Kyushu (The Research Group for Active Faults of Japan, 1991). Although the active fault which corresponds to the 2005 West Off Fukuoka Prefecture Earthquake has not been mapped previously as such, the Kego fault is located at the SE extension of the aftershock region. The Kego fault strikes in the NW-SE direction and is aligned with secondary aftershocks of the largest aftershock (Fig. 3). Based on seismic sounding and piston coring exploration in the Hakata bay, Okamura *et al.* (2006) found that the Kego fault extends about 7 km northwestward and extends nearly to Shikanoshima Island. Therefore, it is considered that the fault of the 2005 West Off Fukuoka Prefecture Earthquake is the offshore extension of the Kego fault, as mapped on Shikanoshima Island. The mainshock occurred as a slip on the NW segment of the fault system. Alternatively, the largest aftershock probably initiated at the junction of the segments and partially fractured the northwestern tip of the SE segment (i.e., the Kego fault). Because the aftershock region has not been extended after the largest aftershock activity in May 2005 (Fig. 4), we argue that most of the SE segment did not slip in this event. Iio *et al.* (2006) showed that the secondary aftershocks of the largest aftershock are characterized by large stress drops. These features suggest the possibility of the stress concentration on the northwestern part of the SE segment.

5. Conclusion

The urgent joint observations conducted after the 2005 West Off Fukuoka Prefecture Earthquake (M_{JMA}7.0) by teams from Kyushu University, Hokkaido University, Tohoku University, the University of Tokyo, Kyoto University, and Kagoshima University were based on data collected at temporary seismic stations on the islands and along the coast surrounding the aftershock region. In addition, we deployed pop-up type OBSs on the sea floor just above and around the aftershock area.

The urgent joint observations revealed the space-time characteristics of the aftershock activity. The aftershocks were mainly aligned approximately 25 km in the NW-SE direction, and the hypocenters of the main aftershock region were distributed on a nearly vertical plane at depths of 2–16 km. The mainshock was located near the central part of the main aftershock region, with a depth of approximately 10 km. The largest aftershock of M_{JMA}5.8 occurred near the southeastern edge of the main aftershock region, and the aftershock region extended about 5 km in the SE direction as a result of secondary aftershock activity. Following the most intense aftershock activity, the enlargement of the aftershock region did not obviously occur, and the aftershock activity gradually declined.

The hypocenter distribution and seismogenic stress of the aftershocks suggest that the fault of the 2005 West Off Fukuoka Prefecture Earthquake belongs to the same fault system as the Kego fault and that the main aftershock region corresponds to the NW segment of the fault system. The largest aftershock activity probably occurred at the northwestern tip of the SE segment.

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