Shear wave polarization anisotropy in and around the focal region of the 2005 West off Fukuoka Prefecture earthquake

Atsushi Watanabe, Satoshi Matsumoto, Takeshi Matsushima, Kenji Uehira, Norimichi Matsuwo, and Hiroshi Shimizu

Institute of Seismology and Volcanology, Faculty of Sciences, Kyushu University, Shimabara, Japan

(Received October 15, 2005; Revised June 20, 2006; Accepted June 22, 2006; Online published February 2, 2007)

Crustal shear wave polarization anisotropy is caused by the alignment of vertical microcracks. Leading shear wave polarization directions (LSPDs) are presumed to be consistent with the maximum horizontal compressional axis in many cases. We analyzed shear wave polarization anisotropy in and around the focal region of the 2005 West off Fukuoka Prefecture earthquake. Almost all of the LSPDs are oriented in the E-W direction, which is consistent with the maximum horizontal compressional axis inferred from the mechanism of the main shock. These E-to W-oriented LSPDs are caused by the alignment of stress-induced microcracks. Crack densities at most stations are estimated to be 0.02. Little spacial stress variation around focal region is suspected.

Key words: Shear wave polarization anisotropy, 2005 West off Fukuoka earthquake

1. Introduction

On March 20, 2005, the 2005 West off Fukuoka Prefecture earthquake occurred with a JMA magnitude 7.0. The maximum of JMA intensity 6 lower was recorded in the Fukuoka and Saga prefectures. Since the focal region is near the urban area of Fukuoka City, this earthquake caused major damage, with one person dead, more than 1000 people injured, and more than 800 buildings destroyed or damaged. One of the hardest hit locations was Genkai-jima Island, just above the focal region, where many houses collapsed and landslides occurred, forcing all residents to evacuate. The fault is left-lateral strike slip directed NW-SE with length of 25 km (Nishimura *et al.*, 2005). The Kego fault is the SE extension of this fault with almost the same strike, passing through the urban area of Fukuoka city (Fig. 1). The residents of Fukuoka City fear that an earthquake will occur at the Kego fault. However, because this region had been seismicity inactive until this 2005 earthquake, we do not have seismological information on this area. We started joint observations on the day of the 2005 earthquake (in cooperation with Hokkaido University, Tohoku University, Kyoto University, and Kagoshima University) and observed aftershock activity. Our aim was to investigate the mechanism of the earthquake and to estimate heterogeneous structure around the fault. Since crustal anisotropy is caused by stress-induced alignment of vertical microcracks, we can use shear wave splitting as a tool to investigate and monitor the stress beneath the seismic stations. Previous studies (e.g., Tadokoro *et al.* 1999, 2002; Mizuno *et al.* 2001) investigated the structure of the rupture zone or its temporal changes by analyzing shear wave anisotropy. Saiga *et al.* (2003) found temporal variation in the anisotropy associated with a moderate-sized earthquake. In this paper, we estimate spacial stress variation in and around the focal region by analyzing shear wave polarization anisotropy.

2. Shear Wave Splitting

Shear wave splitting is a phenomenon in which the shear wave splits into two quasi-shear waves as it propagates through an anisotropic medium (Fig. 2). These two split quasi-shear waves propagate at different velocities in the anisotropic medium, and their oscillation directions are orthogonal to each other. We consequently observe the faster quasi-shear wave as the initial arrival of the *S* phase almost irrespective of source mechanism and/or back azimuth. The oscillation direction of the faster quasi-shear wave is called the Leading Shear wave Polarization Direction (LSPD). The LSPD is one of the parameters that characterizes polarization anisotropy. Another parameter is delay time between the two quasi-shear waves (DT), which is characteristic of the intensity of anisotropy. Crustal anisotropy is thought to be caused by the parallel alignment of vertical microcracks (Crampin, 1978). Two quasi-shear waves have oscillation directions that are parallel and perpendicular to the crack normal, and the quasi-shear wave oscillating perpendicular to crack normal propagates faster than the other. For most directions of wave propagation, the LSPD indicates the axis of maximum horizontal compressional stress, because anisotropy is caused by the alignment of vertical microcracks parallel to the axis of maximum compression.

3. Data and Analysis

Twenty-five temporary seismic stations were installed under the auspices of the five universities for joint observation of aftershocks (as of August 1, 2005). We used seven stations around the focal region for the analysis. Markproducts L-22 velocity seismometers with a natural frequency of 2 Hz are installed at FORQ, FKKQ, KEYA, NOKO,

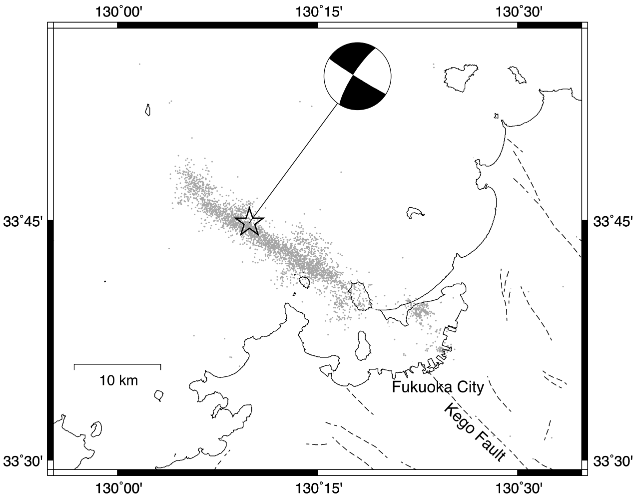

Fig. 1. The distribution of main and aftershocks (after Uehira *et al.,* 2006). The star and gray dots indicate the epicenter of the main shock and aftershocks, reciprocity. The focal mechanisms of the main shock is determined by F-net, NIED and plotted in the lower focal hemisphere projection.

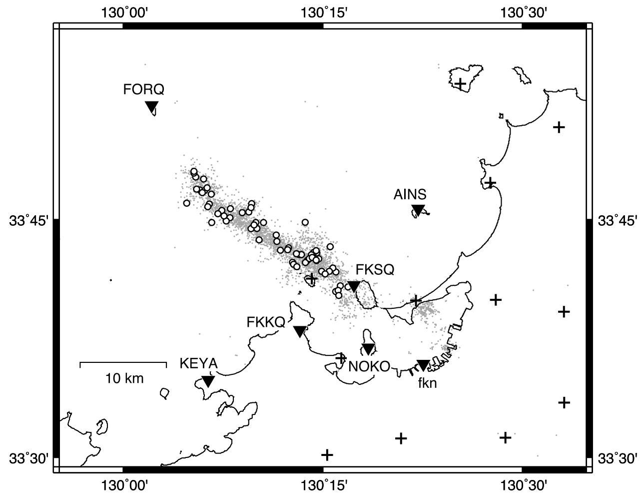

Fig. 3. Distribution of seismic stations and epicenters of analyzed aftershocks of the 2005 West off Fukuoka Prefecture earthquake. The open circles and inverted triangles indicate the epicenter of analyzed events and seismic stations, respectively. The crosses are other temporary and permanent stations. The gray dots are the epicenters of the events occurring in March, 2005.

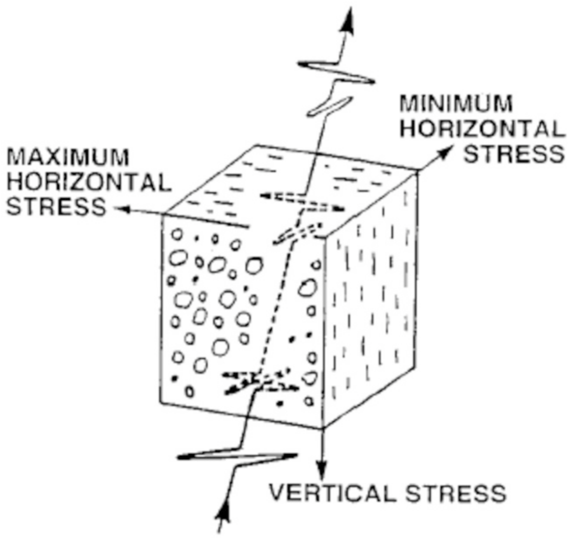

Fig. 2. A schematic drawing of shear wave splitting. A shear wave is splitting into two quasi-shear waves in the anisotropic body (after Crampin, 1981).

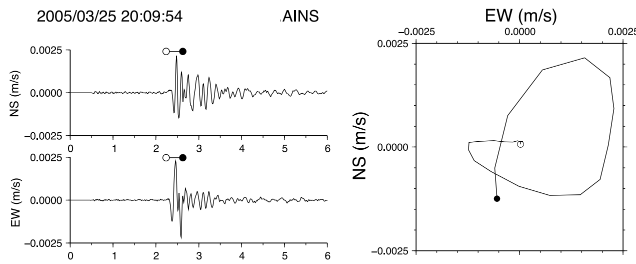

Fig. 4. An example of particle motion. This particle motion is made from seismogram of station AINS for the event occurred at 20:09 on March 25, 2005. The duration of particle motion is 0.2 s. The open circle and black circle indicate the start point and end point of particle motion, respectively. The depth of the hypocenter is 13 km, and its distance and azimuth from the station are 9.97 km and N124°W, respectively.

AINS; the Lennartz LE-3D Lite velocity seismometer with a natural frequency of 1 Hz is installed at FKSQ; the Tokyo Sokushin VSE-11A and 12A broadband strong motion seismometers are installed at fkn. We selected 66 events for analysis, all of which satisfied the following conditions: (1) occurred before March 31, was in the range of magnitude 2.5–3.5, and had a clear direct *S* phase pulse. In total, 197 phases were used in the analysis. When the incident angle to the surface is greater than the critical angle, the shear wave is converted into a compressional wave traveling along the surface. In order to avoid the influence of this converted wave, we used stations at which the incident angle was less than 35°. Figure 3 shows the distribution of seismic stations and epicenters we used in analysis. To detect LSPD and DT, we drew the particle motion of the initial part of the direct *S* phase in the horizontal plane (e.g. Crampin, 1985), as shown in Fig. 4. We selected small events in order to ignore the source process; consequently, the direct *S* phase passing through in isotropic medium should show linear particle motion. However, the particle motion of the direct *S* phase passing through the anisotropic medium shows ellipsoidal motion following the linear motion. In the horizontal particle motion of the initial part of the direct *S* phase, we read LSPD and DT from the early linear part. The accuracy of the LSPD and DT readings was about ± 5° and ± 15 ms, respectively. The measured LSPDs and DTs are shown in Table 1.

4. Shear Wave Polarization Anisotropy

Figure 5 shows rose diagrams of LSPD at each station. In many stations, the LSPDs indicate an E-W direction that is similar to the direction of the horizontal compressional axis inferred from the mechanism of the main shock (see Fig. 1). The focal mechanism solution is a strike of N122°E, a rake of −11°, and Dip of 87°. This result is consistent with crustal anisotropy in other regions (e.g., Kaneshima, 1990), and the anisotropy can be explained by the E-to W-oriented

Table 1. Table of measured LSPDs and DTs.

Station	Number of events	Mode of LSPD (degree)	Average of DT (ms/km)
AINS	44	100	6.2
FKKQ	12	100	4.2
FORQ	40	110	3.9
FKSQ	118	110	4.3
KEYA	44	90	4.3
NOKO	66	40	3.9
fkn	56	90	4.3

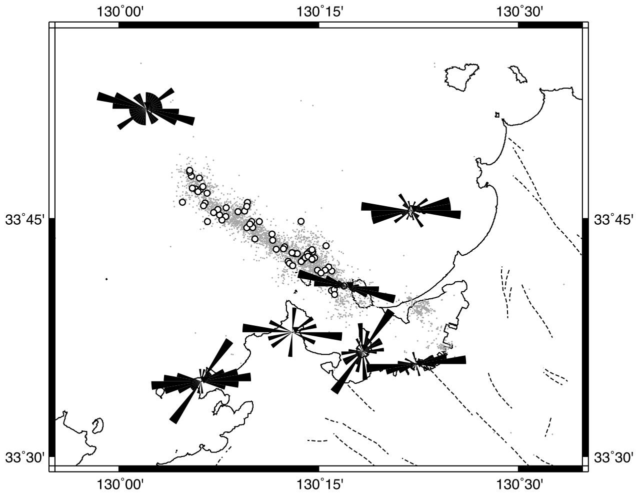

Fig. 5. The rose diagrams of LSPDs. Each rose diagram is plotted on the station and normalized by mode.

alignment of stress-induced microcracks. However, at station NOKO on Nokono-shima Island, LSPDs do not show a concentration in the E-W direction. Tadokoro *et al.* (1999), in a similar study of the aftershock of the 1995 Hyogo-ken Nanbu earthquake, showed that LSPDs are not parallel to the axis of maximum horizontal compressional stress butinstead-parallel to the fault strike of the Nojima fault zone. These researchers inferred that the origin of anisotropy with LSPDs parallel to the fault strike is, in fact, fractures parallel to the fault. There are some faults with a strike of N-S, NW-SE, and NE-SW on Nokono-shima Island; however, these faults cut Late Eocene formations and show no evidence of recent activity. Tadokoro *et al.* (2002) indicated that the fractures of shear fault origin healed quickly and that the LSPDs changed to being parallel to the axis of maximum horizontal compressional stress. Therefore, it seems unlikely that the origin of anisotropy on Nokono-shima Island is the fractures of shear faults. Mizuno *et al.* (2001) found that the LSPDs change near the end of the fault system, indicating that the LSPDs should change from parallel to the axis of maximum horizontal compressional stress to parallel to the fault strike. However, the LSPD on Nokono-shima Island is not parallel to the fault strike. According to Crampin *et al.* (1990), the LSPD is not only parallel to the crack but varies with incident angle to the crack when the incident angle to the crack is small. Figure 6 shows the LSPDs measured on Nokono-shima Island on an equal-area

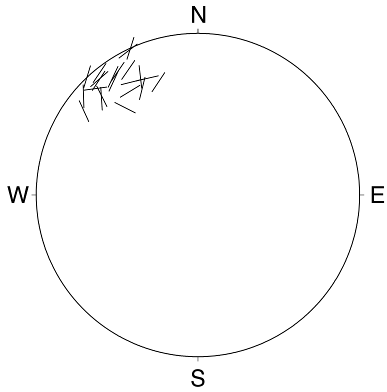

Fig. 6. The equal area stereogram of LSPD in NOKO out to 40°. Bars are parallel to the LSPD.

stereograph out to 40°. Most events are plotted around the NW end of the circle, NE-to SW-oriented LSPDs seem to be caused by the low incident angle of the ray to the crack. Another characteristic of anisotropy is DT. Assuming vertical microcracks, crack density is inferred from DT. Johnson and Rasolofosaon (1996) showed that the difference between two quasi-shear waves increases with the differential stress, both by the theory and uniaxial stress experiments. As such, spatial variation of anisotropy can be characteristic of the differential stress underground. The measured DTs per 1 km for each station are shown in Table 1. Assuming the parallel vertical circular microcracks are aligned homogeneously in the isotropic medium, these lead to the crack density (νa^3) of 0.02. This is equivalent of ten cracks with a diameter of about 0.25 in each unit cube. Since the LSPDs and crack densities at each station are not varied, we suspect that there is little spacial stress variation around the focal region of the 2005 West off Fukuoka Prefecture earthquake.

5. Conclusion

Shear wave polarization anisotropy is found in and around the focal region of the 2005 West off Fukuoka Prefecture earthquake. The LSPDs indicate an E-W direction at most stations. This direction is consistent with the horizontal compressional axis inferred from the mechanism of the main shock. Therefore, the origin of shear wave polarization anisotropy is the alignment of vertical stress-induced microcracks. We estimate the crack density to be 0.02 at the most stations. Consequently, there is little spacial stress variation around the focal region of the 2005 West off Fukuoka Prefecture earthquake.

Acknowledgments. We would like to thank Dr. Sheila Peacock and Dr. Takashi Mizuno for their constractive remarks and comments. We would also like to thank H. Takahashi, M. Ichiyanagi (Hokkaido Univ.), T. Okada, N. Uchida (Tohoku Univ.), Y. Iio, H. Katao, B. Enescu, T. Ueno (Kyoto Univ.), H. Miyamachi, K. Goto, S. Nakao, H. Yakiwara, S. Hirano (Kagoshima Univ.), Y. Kohno, M. Saito, M. Hori, N. Kame, and A. Otakara (Kyushu Univ.) for installation and maintenance of the temporary seismic stations on land. We used moment tensor solutions determined by F-net, National Research Institute for Earth Science and Disaster Prevention (NIED; http://www.fnet.bosai.go.jp).

References

Crampin, S., Seismic wave propagation through a cracked solid: Polarization as a possible dilatancy diagnostic, *Geophys. J. R. Astron. Soc.*, **53**, 467–496, 1978.

Crampin, S., A review of wave motion in anisotropic and cracked elastic-media, *Wave Motion*, **3**, 343–391, 1981.

Crampin, S., Evaluation of anisotropy by shear-wave splitting, *Geophysics*, **50**, 142–152, 1985.

Crampin, S., D. C. Booth, R. Evans, S. Peacock, and J. B. Fletcher, Changes in shear wave splitting at Anza near the time of the North Plam Springs Earthquake, *J. Geophys. Res.*, **95**, 11,197–11,212, 1990.

Hori, M., S. Matsumoto, K. Uehira, T. Okada, T. Yamada, Y. Iio, M. Shinohara, H. Miyamachi, H. Takahashi, K. Nakahigashi, A. Watanabe, T. Matsushima, N. Matsuwo, T. Kanazawa, and H. Shimizu, Three-dimensional seismic velocity structure as determined by double-difference tomography in and around the focal area of the 2005 West off Fukuoka Prefecture earthquake, *Earth Planets Space*, **58**, this issue, 1621–1626, 2006.

Imanishi, K., Y. Kuwahara, and Y. Haryu, Off-fault aftershocks of the 2005 West Off Fukuoka Prefecture Earthquake: Reactivation of a structural boundary?, *Earth Planets Space*, **58**, 81–86, 2006.

Johnson, P. A. and P. N. J. Rasolofosaon, Nonlinear elasticity and stress-induced anisotropy in rock, *J. Geophys. Res.*, **101**, 3113–3124, 1996.

Kaneshima, S., Origin of crustal anisotropy: Shear wave splitting studies in Japan, *J. Geophys. Res.*, **95**, 11,121–11,134, 1990.

Karakida, Y., S. Tomita, S. Shimoyama, and K. Chijiwa, Geological Sheet Map 1:50,000 "Fukuoka", Geological Survey of Japan, 1994.

Mizuno, T., K. Yomogida, H. Ito, and Y. Kuwahara, Spatial distribution of shear wave anisotropy in the crust of the southern Hyogo region by borehole observations, *Geophys. J. Int.*, **147**, 528–542, 2001.

Nishimura, T., S. Fujiwara, M. Murakami, H. Suito, M. Tobita, and H. Yarai, Fault model of the 2005 Fukuoka-ken Seiho-oki earthquake estimated from coseismic deformation observed by GPS and InSAR, *Earth Planets Space*, **58**, 51–56, 2006.

Saiga, A., Y. Hiramatsu, T. Ooida, and K. Yamaoka, Spatial variation in the crustal anisotropy and its temporal variation associated with a moderate-size earthquake in the Tokai region, central Japan, *Geophys. J. Int.*, **154**, 695–705, 2003.

Shimizu, H., H. Takahashi, T. Okada, T. Kanazawa, Y. Iio, H. Miyamachi, T. Matsushima, M. Ichiyanagi, N. Uchida, T. Iwasaki, H. Katao, K. Goto, S. Matsumoto, N. Hirata, S. Nakao, K. Uehira, M. Shinohara, H. Yakiwara, N. Kame, T. Urabe, N. Matsuwo, T. Yamada, A. Watanabe, K. Nakahigashi, B. Enescu, K. Uchida, S. Hashimoto, S. Hirano, T. Yagi, Y. Kohno, T. Ueno, M. Saito, and M. Hori, Aftershock seismicity and fault structure of the 2005 West Off Fukuoka Prefecture Earthquake (M_{JMA}7.0) derived from urgent joint observations, *Earth Planets Space*, **58**, this issue, 1599–1604, 2006.

Tadokoro, K., M. Ando, and Y. Umeda, S wave splitting in the aftershock region of the 1995 Hyogo-ken Nanbu earthquake, *J. Geophys. Res.*, **104**, 981–992, 1999.

Tadokoro, K. and M. Ando, Evidence for rapid fault healing derived from temporal changes in S wave splitting, *Geophys. Res. Lett.*, **29**, 10.1029/2001GL013644, 2002.

Takenaka, H., T. Nakamura, Y. Yamamoto, G. Toyokuni, and H. Kawase, Precise location of the fault plane and the onset of the main rupture of the 2005 West Off Fukuoka Prefecture earthquake, *Earth Planets Space*, **58**, 75–80, 2006.

Uehira, K. ,T. Yamada, M. Shinohara, K. Nakahigashi, H. Miyamachi, Y. Iio, T. Okada, H. Takahashi, N. Matsuwo, K. Uchida, T. Kanazawa, and H. Shimizu, Precise aftershock distribution of the 2005 West Off Fukuoka Prefecture Earthquake (Mj=7.0) using a dense onshore and offshore seismic network, *Earth Planets Space*, **58**, this issue, 1605–1610, 2006.

A. Watanabe (e-mail: atsushi@sevo.kyushu-u.ac.jp), S. Matsumoto, T. Matsushima, K. Uehira, N. Matsuwo, and H. Shimizu