Spatial distribution for moment tensor solutions of the 2003 Tokachi-oki earthquake ($M_{JMA} = 8.0$) and aftershocks

Yoshihiro Ito, Hirotoshi Matsubayashi, Hisanori Kimura, Takumi Matsumoto, Youichi Asano, and Shoji Sekiguchi

National Research Institute for Earth Science and Disaster Prevention, 3-1, Tennodai, Tsukuba, Ibaraki, Japan

(Received November 21, 2003; Revised January 22, 2004; Accepted January 28, 2004)

The 2003 Tokachi-oki earthquake with M_w 7.9 is the largest interplate earthquake occurred ever since the high dense broadband seismometer network, the National Research Institute for Earth Science and Disaster Prevention (NIED) F-net, has been established over Japan. We determine the spatial distribution of moment tensor solutions and centroid depths of the mainshock and aftershocks. All aftershocks are divided to three groups: (1) the thrust fault type whose nodal plane is similar to the main shock; (2) the other thrust type with nodal plane different from the main shock; and (3) the normal fault type. The type (1) shows a depth distribution inclined to NW gently, coincident to the upper boundary of descending Pacific Plate. The active area of the type (1) does not overlap with the co-seismic slip area of the main shock at all. On the other hand, the type (2) shows no characteristic depth distribution with centroid depth scattered above and beneath the upper plate boundary. The type (3) are distributed, mainly, at about 40 km depth above the upper plate boundary. P axes of some aftershocks occurred above the plate boundary show the direction from ENE-WSW to ESE-WNW that suggests the effect of the Hidaka collision.

Key words: The 2003 Tokachi-oki Earthquake, moment tensor solution, aftershock, focal mechanism, subduction, collision.

1. Introduction

A M_{JMA} 8.0 earthquake occurred off Tokachi, Hokkaido, Northern Japan at September 26, 2003. This earthquake shook the ground strongly and caused tsunami with a height of over one meter. Historically, a few major earthquakes have occurred in this region, and the most recent one was the 1952 off Tokachi earthquake (M8.2) (Utsu, 1984).

The Pacific plate, overridden by the North American Plate, subducts obliquely at the Kuril trench situated to the southeast of Hokkaido at a rate of about 90 mm/year (Heki, 1989) (Fig. 1(a)). Nakanishi *et al.* (2001) estimated the geometry of the plate boundary by a seismic survey using ocean bottom seismometers around the off Nemuro region to the northeast of the off Tokachi region. Hasegawa *et al.* (1994) and Katsumata (2003) revealed the geometry of double-planed deep seismic zone of deep and intermediate-depth earthquakes. Earthquake Research Committee (2003) compiled these 3 studies and proposed the depth distribution of the upper plate boundary around the region.

The Kuril forearc sliver and the North American Plate form the arc-arc type Hidaka collision zone and it is still in progress near the trench (Kimura, 1986). DeMets (1992) also pointed out that the Kuril Island arc was moving toward the southwest at a speed of 6–11 mm/year.

In this paper, we determine the moment tensor solutions and the centroid depths for the 2003 Tokachi-oki earthquake and its aftershocks using NIED F-net broadband seismographic network. Then we compare the results with the depth distribution of plate boundary. The aftershocks distribution is also compared with the co-seismic slip distribution of the main shock obtained by Yagi (2004). Finally we show a characteristic distribution of P axes of aftershocks occurred in the overriding land crust.

2. Data and Method

Waveform data are obtained from the NIED F-net broadband seismographic network (Fukuyama *et al.*, 1996) (Fig. 1(a)). A three-components broadband seismometer (STS-1/2) and a three-components strong motion velocitymeter (VSE-311/355) have been installed at each station. We calculate focal mechanisms of the main shock and aftershocks by moment tensor inversion approach (Fukuyama *et al.*, 1998). Different band-pass filters are used according to magnitude, M_{JMA}, estimated by JMA (2003): 0.02–0.05, 0.01–0.05 and 0.005–0.02 Hz pass band are used for the magnitude range of $3.5 \leq M_{JMA} < 5.0$, $5.0 \leq M_{JMA} < 7.5$, and $7.5 \leq M_{JMA}$, respectively. The velocity structure used for the Green's function is shown in Table 1. This structure is based on Ukawa *et al.* (1984) for the shallower part and Fukao (1977) for the deeper part.

In this procedure, the error is evaluated with variance reduction (VR) defined by:

$$\mathrm{VR}[\%] = 100 \times \sum_i w_i \left(1 - \frac{\int ((s_i(t) - o_i(t))^2 dt}{\int ((o_i(t))^2 dt}\right),$$

where $s_i(t)$ and $o_i(t)$ are the synthetic and observed waveforms, respectively. w_i are weight constants that are proportional to the epicenter distance of station, i.

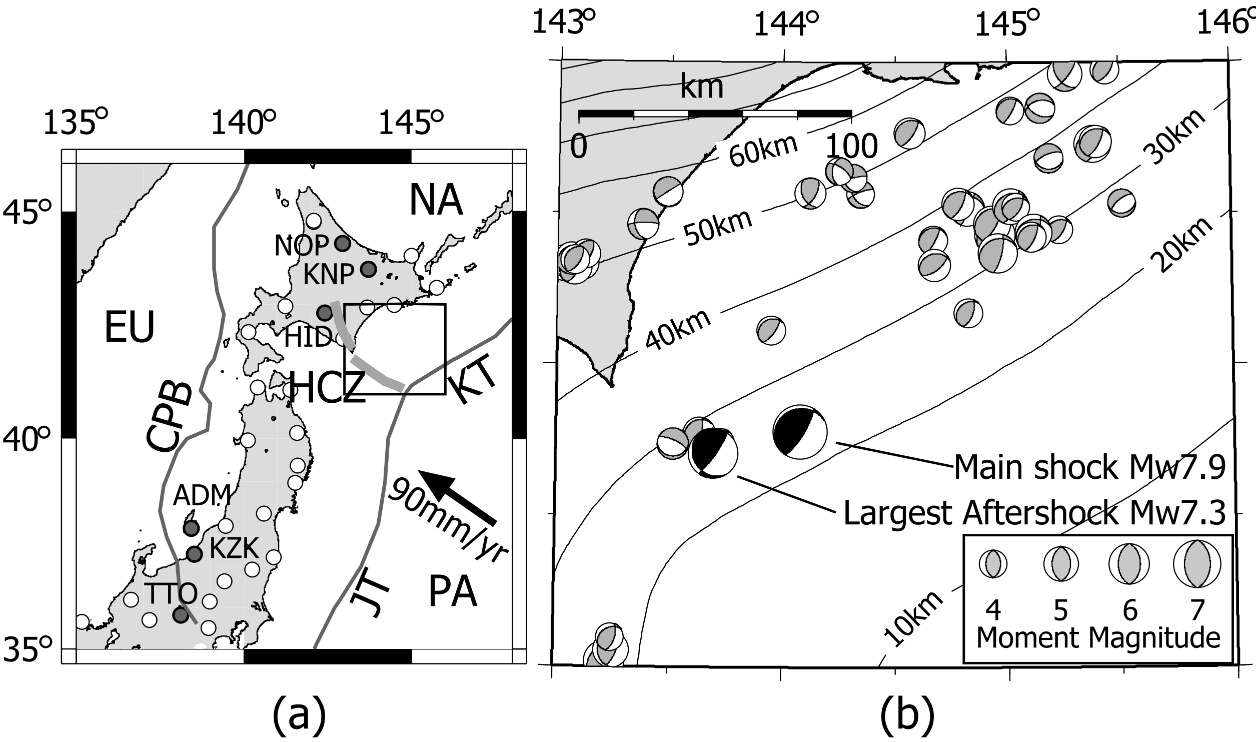

Fig. 1. (a) Station distribution of NIED F-net and tectonic setting around northern Japan. Solid and open circles show locations of NIED F-net broadband seismic stations. The seismic stations shown with solid circles are used in moment tensor inversion. Relative motion of the Pacific plate (PA) with respect to the North American plate (NA) (Heki, 1989) is shown by an arrow. EU: Eurasian plate, KT: Kuril trench, JT: Japan trench, CPB: embryonic convergent plate boundary (after Nakamura, 1983) and HCZ: Hidaka collision zone (after Kimura, 1986). (b) Focal mechanism distribution of background seismicity at less than 60 km depth and the main shock and the largest aftershock. Gray focal mechanisms indicate focal mechanisms of the background seismicity determined by NIED moment tensor routine processing. The depth contours of upper boundary of the Pacific plate proposed by Earthquake Research Committee (2003).

Table 1. Velocity structure for the used Green's function.

Depth (km)	Thickness (km)	P velocity (km/s)	S velocity (km/s)	Density (kg/m^3)	Q_p	Q_s
0	3	5.50	3.14	2300	600	300
3	15	6.00	3.55	2400	600	300
18	15	6.70	3.83	2800	600	300
33	67	7.80	4.46	3200	600	300
100	125	8.00	4.57	3300	600	300
225	100	8.40	4.80	3400	600	300
325	100	8.60	4.91	3500	600	300
425	—	9.30	5.31	3700	600	300

Mechanisms of the main shock and the largest aftershock are calculated by using three stations, ADM, KZK and TTO (the solid circles in Fig. 1(a)), that are 650–850 km away from the source of the main shock to ensure the validity of the point source assumption. However, for the aftershocks, we use stations, NOP, KNP, and HID, those are a few hundred kilometers away from the source to get better signal to noise ratio in wide magnitude range and those were in operation stably after the main shock.

The epicentral locations are taken from the unified JMA hypocenter catalogue (Japan Meteorological Agency, 2003). The variance reduction approach has also applied to focal depths from 5 km to 65 km with an interval of 3 km. The results with maximum variance reduction is taken as the optimal focal depth.

3. Results

We have determined focal mechanisms of the main shock and aftershocks ($4.0 \leq M_w \leq 7.9$) with variance reduction greater than 70%. Figure 1(b) shows the distribution of focal mechanisms of the main shock and the largest aftershock (black). The focal mechanism of the main shock shows a thrust fault with one nodal plane dipping toward northwest with dip angle of 16° while the centroid depth is estimated at 29 km. The strike, rake, and moment are 246°, 124° and 6.9×10^{20} Nm, respectively. Other moment tensor solutions for the main shocks are following: strike, dip, rake and moment are 250°, 11°, 132° and 3.1×10^{21} Nm in Harvard CMT catalogue (2003), and 234°, 7°, 103° and 1.6×10^{21} Nm in USGS moment tensor solutions (2003). Our result is comparable with them approximately. However, moment

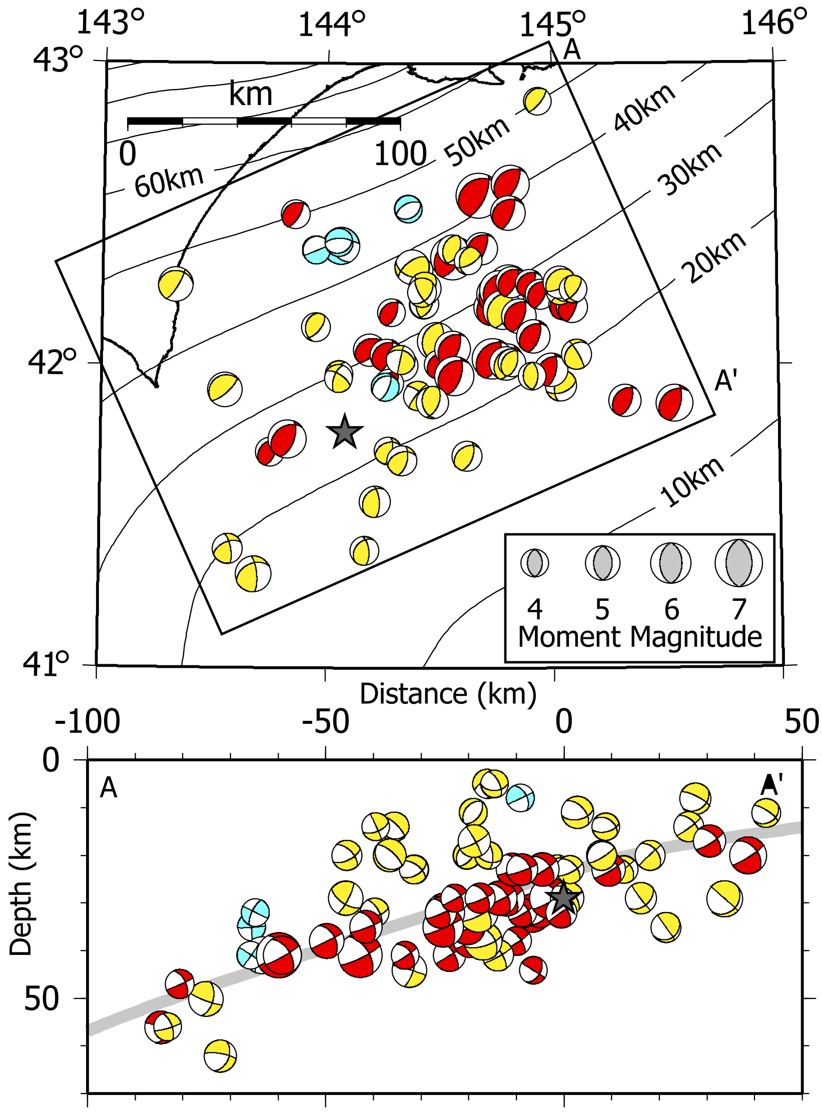

Fig. 2. The focal mechanisms distribution of aftershocks. Red, yellow and light blue indicate the TH-type, OT-type and the NF-type, respectively. The star represents the epicenter of the main shock (Japan Meteorological Agency, 2003). The bottom panel gives the corresponding vertical cross section along A–A' supporting that the hypocenters of TH-type events are distributed along the subducting slab of the Pacific plate. The focal mechanisms are projected on the WSW hemisphere of the focal sphere using the equal-area projection. The thick gray line indicates the upper plate boundary.

obtained by us is smaller than other two result's one. This discrepancy seems to be due to no assumption of a finite source time function in moment tensor inversion approach.

The obtained focal mechanism and centroid depth of the main shock suggest that it is thrust type events occurred on the upper Pacific Plate boundary. The focal mechanism of the largest aftershock with M_w 7.3 is slightly different with that of the main shock and its centroid depth is 59 km.

Focal mechanisms, with magnitude $M_w \geq 4.0$ and variance reduction VR $\geq$ 70% of the background earthquakes occurred from 1997 till the occurrence time of the main shock are also shown in Fig. 1(b) (gray). Focal mechanisms of the background earthquakes are given by NIED seismic moment tensor catalogue (www.fnet.bosai.go.jp). Figure 1(b) indicates that the main shock occurred in a low background seismicity area.

The distribution of focal mechanisms of aftershocks that occurred from September 26 to October 14, 2003, are shown in Fig. 2. According to the type of focal mechanisms, we have divided the aftershocks into three groups: (1) the thrust type with nodal plane similar to the main shock (TH-type); (2) the thrust-fault type with nodal different to the main shock (OT-type); and (3) the normal fault type (NF-type), respectively. The TH-type are defined by conditions: $220^\circ \leq \phi \leq 260^\circ$, $5^\circ \leq \delta \leq 35^\circ$ and $100^\circ \leq \lambda \leq 140^\circ$, where ϕ is the strike, δ is the dip, λ is the rake.

The TH-type aftershocks are distributed, mainly, in the northeastern from the epicenter of the main shock, while the others are distributed variously. The depth distribution of the TH-type aftershocks are inclined to the northwest with dip angle of 20° along the plate boundary, approximately. However, the OT-type aftershocks are scattered above and below the plate boundary without characteristic depth dependence. Most of the NF-type aftershocks are located at 40 km depth, approximately, extended along descending distribution of active aftershock area.

Figure 3 shows the centroid depth and moment tensor solution as a function of VR as an example. This earthquake is

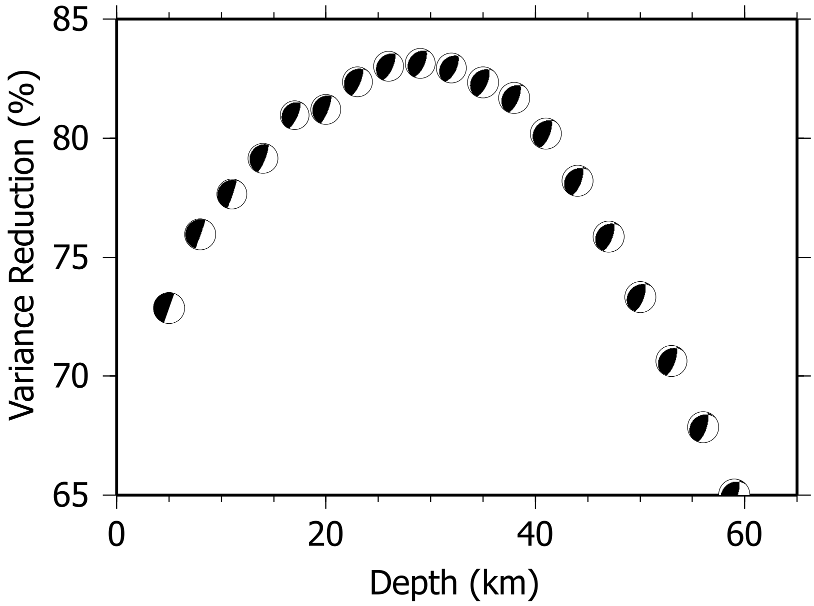

Fig. 3. The example of variance reduction and moment tensor solutions plotted against centroid depth. The focal mechanisms are projected on the lower hemisphere.

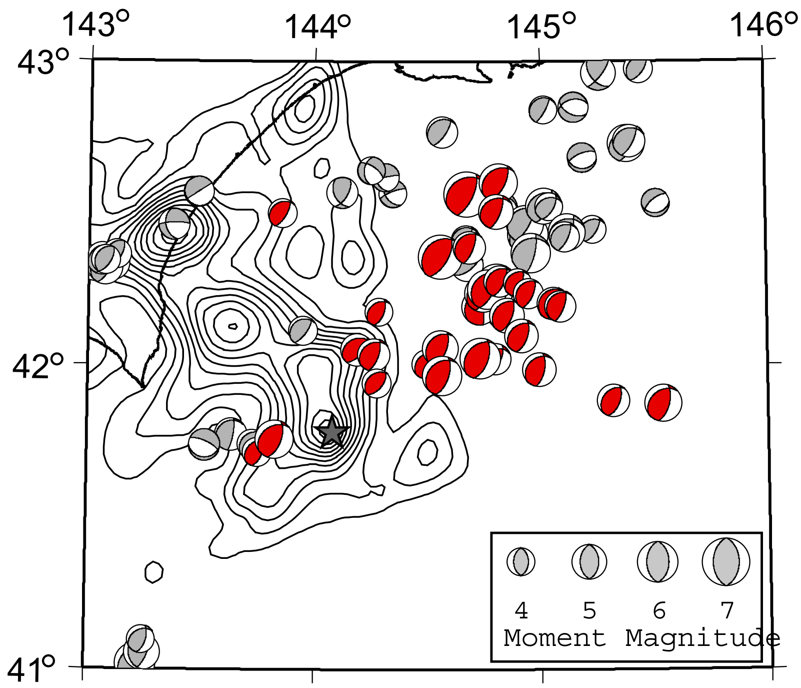

Fig. 4. The comparison of the TH-type aftershocks (red), background seismicity (gray), and the co-seismic slip area of the main shock. The contour shows the co-seismic slip obtained by Yagi (2004) and the contour interval of co-seismic is 0.5 m.

TH-type with moment magnitude 4.4. There is a pronounced maxima and the highest VR is obtained with the centroid depth of 29 km in Fig. 3. Moment tensor solution at the most suitable centroid depth is consistent with those around the most suitable depth.

4. Discussion

The consistence of the focal mechanisms and the depth distribution of the TH-type aftershocks with the descending upper Pacific Plate boundary suggests that the TH-type aftershocks occurred on the plate boundary between the subducting Pacific plate and overriding plate. However the OT-type aftershocks are distributed in both the subducting and overriding plates (Fig. 2).

Using ocean bottom seismometer data, Hino *et al.* (2000) obtained accurate distribution of aftershocks and focal mechanisms around focal area of 1996 Sanriku-harukaoki earthquake occurred on the plate boundary. They demonstrated that some aftershocks had occurred in both the subducting and overriding plates. In the off Tokachi region, some aftershocks also occurred in the crust of the subducting Pacific

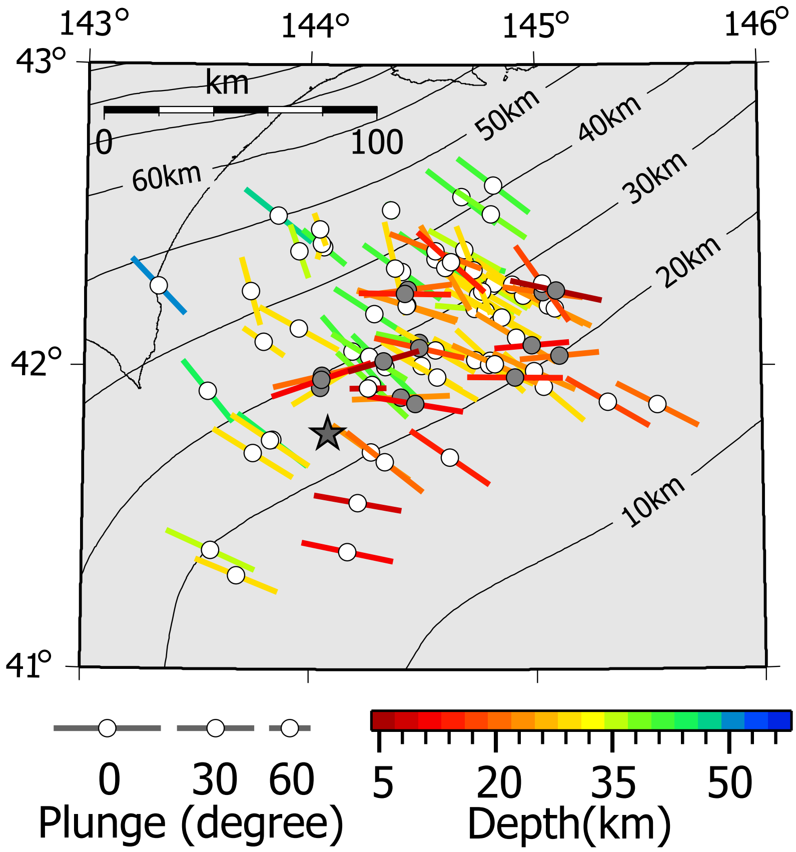

Fig. 5. The P axes distribution of all aftershocks. Color scale of each axis show depth variation of centroid source depth. Solid circles show the epicenters whose P axes are at azimuth from NEN-WSW to SES-WNW.

plate and overriding plate.

Some models for the co-seismic slip of the main shock were estimated (e.g. Yamanaka and Kikuchi, 2003; Yagi, 2004; Honda *et al.*, 2004; Koketsu *et al.*, 2004). Yagi (2004) estimated the co-seismic slip distribution using teleseismic body waves and strong ground motion. Figure 4 shows the comparison of the spatial distribution of the TH-type aftershocks and the co-seismic slip. Clearly, these two areas do not overlap at all. We see that these area are not overlapped with the background seismicity area neither.

Yagi *et al.* (2001) demonstrated that the areas of co-seismic slip, post-seismic and aftershocks had not overlapped in the case of two large earthquakes of October 19 (M_w 6.8) and December 2 (M_w 6.8), 1996, in Hyuga-nada, Japan. They suggested a possibility that these sites might have their own constitutive laws to control moment release. Our results also suggest that the way to release the stress concentrated on plate boundary in the aftershocks area is different with that in the co-seismic area: the stress in the aftershock area is released on some small asperities surrounded by the aseismic site, while that in the co-seismic area of the main shock is released on a larger asperity.

Figure 5 represents the P axes distribution of all aftershocks. Some shallower aftershocks occurred above the plate boundary show characteristic P axes with the direction from ENE-WSW to ESE-WNW, while the others are mainly SE-NW that is almost the same as the convergence direction of subducting of the Pacific plate suggested by Heki (1989). According to Kimura (1986), thrust faults of the Hidaka collision zone has developed in this area (Fig. 1(a)). DeMets (1992) concluded that the Kuril Island arc is moving toward the southwest with a speed of 6–11 mm/year. These P axes are comparable with the direction of collision approximately. They may indicate the compressional stress field is dominated by this collision after the main shock.

5. Conclusions

We have determined focal mechanisms for the main shock and aftershocks of the 2003 Tokachioki Earthquake M_{JMA} 8.0 (M_w 7.9). The result of the main shock shows a thrust fault with a nodal plane dipping to northwest. Aftershocks with focal mechanisms similar to the main shock are distributed along the boundary between the Pacific plate and North American plate, and their distribution are inclined to northwest with dip angle of about 20°. Aftershocks with focal mechanism similar to the main shock are scattered in the northeast of the main shock and the epicentral area does not either overlap with the co-seismic slip area of the main shock, nor with background seismicity area. On the other hand, aftershocks with the other type of focal mechanisms are, mostly, distributed above or beneath the plate boundary. Particularly, shallower aftershocks show characteristic P axes with the direction from ENE-WSW to ESE-WNW which suggests the effect of the Hidaka collision.

Acknowledgments. We would like to thank the Japan Meteorological Agency for providing us unified hypocenter catalogue. Reviews by Dr. A. Pinar and Dr. Y. Yagi were valuable in improving the manuscript. We are grateful to Dr. K. Kasahara and Dr. K. Obara for many valuable discussions. We thank Dr. A. Jin for polishing the language in the manuscript and fruitful discussions. We also thank Mr. K. Nonomura for his assistance in data processing. GMT (Wessel and Smith, 1995) was used to make the figures. This work was conducted under the project "Operation of Seismic Observation Networks" at the National Research Institute for Earth Science and Disaster Prevention.

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Y. Ito (e-mail: yito@bosai.go.jp), H. Matsubayashi, H. Kimura, T. Matsumoto, Y. Asano, and S. Sekiguchi